VIII International Conference on Fracture Mechanics of Concrete and Concrete Structures
FraMCoS-8
J.G.M. Van Mier, G. Ruiz, C. Andrade, R.C. Yu and X.X. Zhang (Eds)

ENERGY ABSORPTION AND FLEXURAL TOUGHNESS EVALUATION OF FIBRE REINFORCED POLYMER MODIFIED CONCRETE

Nassim Ghosni*, Bijan Samali† and Kirk Vessalas†

* University of Technology Sydney
Centre for Built Infrastructure Research, Sydney, Australia
E-mail: Nassimsadat.ghosni@uts.edu.au

† University of Technology Sydney
Centre for Built Infrastructure Research, Sydney, Australia

Key words: Polypropylene, SB latex, toughness, flexural strength, fibre reinforced concrete, energy absorption

Abstract: This paper presents the effect of fibres on the behaviour of fibre reinforced concert (FRC) which nowadays is recognised for its energy absorption capacity as well as other benefits. Incorporating fibres in concrete, results in an ameliorated mix design which can dissipate energy and improve the fracture performance of concrete matrix. There are different types of test methods developed to measure the concrete energy absorption capacity, one of which is the four point bending test. This research work is on the flexural behaviour characterisation of polymer modified synthetic fibre reinforced concrete incorporating polypropylene (PP) fibres and styrene butadiene (SB) latex copolymer. Results of this study show that by adding PP fibres to concrete, toughness and energy absorption characteristics can be enhanced. By increasing the amount of fibre used in the concrete matrix this value can be increased. It has also been concluded that by adding fibres to the concrete matrix, the energy absorption characteristics can consequently be improved.

1 INTRODUCTION

Known as the most widely used construction material that is generally made of gravel, sand, cement and water; concrete is one of the most popular structural materials in the world. Structures are subjected to different types of static and dynamic loading. Although the design of a structure is important in its load bearing capacity, material used in the structure has a very important role. As a load is applied, structural elements are subjected to a series of compression and tension forces and stresses. As a matter of fact, the compressive strength of the concrete is incomparably higher than that of its tensile strength. Because of this deficiency, steel bars are used to reinforce the concrete structure in tensile zones.

Another problematic issue regarding concrete structures is the energy dissipation and ductile properties of this widely used material.

The stress-strain relationship for concrete is non-linear and the material does not generally obey hook’s law, therefore an elastic limit cannot be identified. This phenomenon results in sudden failure of the concrete and categorises it as a brittle material. If the ductility of concrete material can be improved to a certain level, the reinforcement steel bars can ultimately be eliminated or at least reduced in concrete structures which results in savings of money, time, energy and effort.

Failure in concrete matrix starts with the crack propagation which may occur at the aggregate-paste interface, also, the position of crack initiation depends on the bonds and the local stress positions[1]. So as to be able to discuss this behaviour, interfacial transition zone (ITZ) is introduced. ITZ is categorised as the weakest zones in the matrix which highly affects the strength of the concrete[2]. ITZ is referred to the zone around the aggregates or fibre in which the microstructure of the paste is different than that of the paste itself. For instance, it is stated that increase in ductility is usually associated with bond failure in the ITZ of the fibres, which needs large amounts of energy [3]. In order to be able to improve the mechanical characteristics of concrete, these weak zones must also be strengthened.

In order to overcome above challenges in concrete as well as improving its behaviour in mentioned areas, special materials can be added to concrete mix. FRC has been introduced to construction world around 1900 and its theoretical concepts have been developed since 1960's [4]. From among different types of fibres introduced into concrete, polypropylene (PP) fibres are well known but investigations on their behaviour on the ductile properties of concrete, is limited. Furthermore, an elastomeric material, namely styrene butadiene latex (SB latex) is used together with PP fibres to improve the energy absorption properties of concrete.

Polypropylene fibres have been investigated more closely in recent decades. PP is one of the widely used fibres for different applications such as automobile, interiors, textiles etc. [5]. PP is a thermoplastic, hydrophobic material with long polymer structure; generally produced by polymerising the polypropylene monomers consisting of carbon and hydrogen atoms[6].

2 MECHANICAL PROPERTIES

2.1.Flexural characterization

Ductility of a material can be defined as the ability to absorb the inelastic energy without losing its load capacity. Higher inelastic energy absorption in a system means higher ductility. At crack location, as the tensile strain increases, fibre crossing becomes more and more activated as the crack increases. Pantazopoulouet et.al. [7] claim that evidently, fibres contribute to tensile resistance due to the post peak ductile behaviour before failure but addition of fibre prevents particle movement in matrix which lowers the Poison's ratio regardless of the fibre type. The reason flexural test is very famous is that it simulates the real condition in a more practical and simpler way than that of the tension test [8]. Research on different length of PP fibres mostly ranging from 20 - 50 mm [9] show that flexural strength of concrete can be improved by adding PP fibres. Post crack behaviour in fibre reinforced concrete is known to be greatly improved than that of conventional concrete [10]. Ductility and toughness of FRC with the addition of 1% of 12 – 15 mm monofilament and fibrillated PP fibres has been reported to increase [11]. It is also concluded that before the initiation of the first crack the performance of fibre is hardly influential and the flexural behaviour and peak load highly depends on the concrete quality itself [12].

2.2.**Toughness**

To measure the toughness, the methods recommended by ACI Committee 544 and ASTM C1609 seem to be reliable techniques. These methods calculate this value by means of the areas under the load-deflection curves[13]. Moreover, Barr et al. have presented toughness index of PP fibres as "the ratio of the area under the load/deflection curve up to the point of twice the deflection at first crack to four times the area under the load/deflection graph at the point of first crack". Studies show that this parameter is independent of the test specimen geometry

[14, 15]. The effect of fibre percentage has also been studied [4] and research has shown fibres to improve the toughness index by about 50% incorporating 0.1% to 0.5% by weight of PP fibres [14]. Studies on 19mm fibrillated fibres indicate that fibres can enhance the energy absorption and toughness of concrete under compression tests [16].

3 EXPERIMENTAL PROGRAM

Different concrete mix designs containing two types of fibrillated and monofilament PP fibres based on characteristics reviews, with diverse percentage volumes were prepared and tested to instigate this project. The tests conducted in this project are static mechanical properties tests to evaluate the behaviour of each mix. These mixes include replacement of 30% fly ash with cement and incorporating 10% SB latex as a fixed additive. In order to have a reference for our final mixes, 100% plain concrete with no fly ash was also prepared to compare the performance of the mix designs. To evaluate the performance of the fibres in the mix, from the results of the FRPMC mixes, 3 mixes which had either higher mechanical properties or showed higher performance with regards to flexural behaviour are examined.

3.1.Testing

Compressive strength testing is carried out after 7, 28 and 56 days of ageing. A universal testing machine applying axial loads on 100×200 mm cylinders was used.

Flexural strength testing (4-point bending test) – after 14 and 28 days of ageing for computing the modulus of rupture (MOR) was carried out. A universal testing machine was used to test 100×100×350 mm prisms under flexure.

Linear variable differential transformer (LVDT)s were installed to monitor the deflection of the samples under loading condition. In this project, for the flexural strength testing, AS 1012.11— (1985) set up has been used to determine the flexural behaviour of the concrete specimens. ASTM C 1609 [17] has also been used to help calculate and measure specific characteristics of concrete under flexure.

In this test the loading rate was applied constantly for all mixes according to ASTM C1609 in order to avoid any misleading values between the reference concrete and modified mix specimens. According to mentioned standard, for beam size of 100×100×350mm for net deflection up to L/900 (0.38 mm in this case) the loading rate is 0.025 to 0.075 mm/min and for deflections beyond the mentioned value, the loading rate should be 0.05 to 0.2 mm/min. Depth and width of each specimen were measured in 3 sections to work out the average depth and width of the prism length was also measured. Some fluctuations on the deflection measurements were observed during the tests which are discussed in literature and proved not to have a significant influence on the values [18].

3.2.Materials

19 mm fibrillated and 18 mm monofilament PP fibres have been added to the mix by 0.25%, 0.5% and 1% volume fraction of the whole mix. These mixes also include the addition of 30% fly ash (FA) as partial replacement of Portland cement (PC), 10% SB latex and utilisation of manufactured coarse and fine sands to replace natural coarse and fine sand, respectively, to aim for producing a ‘greener’ concrete. Water ratio to cementitious material of the mix is fixed at 0.35 and a target slump of 80±20 is set. Water used for concrete mix is drinking grade tap water.

3.3.Mix Design

Mix design of concrete is fixed in this project, the amount of raw material used is constant and the water to cementitious material proportion is also constant and equal to 35%. In the mixes, PC has been partially replaced with 30% FA and 10% SB latex was added to all the preliminary mixes. It is worth mentioning that all FRC mixes containing SB latex have the same amount of 10% of the additional material inside. This value is also kept constant in order to not introduce more parameters to affect the comparative results of

Table 1: Mix design and poroportioning

Mix ID	PC (kg/m³)	FA (kg/m³)	Fine Aggregate (kg/m³)	10mm Coarse Aggregate (kg/m³)	20mm Coarse Aggregate (kg/m³)	Fibre (V_f) (%)	Water (kg/m³)	SB latex (kg/m³)
C	430.0	0.0	635.0	390.0	700.0	0.0	150.5	0.0
CF	301.0	129.0	635.0	390.0	700.0	0.0	150.5	0.0
CL	430.0	0.0	635.0	390.0	700.0	0.0	150.5	43.0
CFL	301.0	129.0	635.0	390.0	700.0	0.0	150.5	43.0
PM0.25L	301.0	129.0	635.0	390.0	700.0	0.25	150.5	43.0
PF0.25L	301.0	129.0	635.0	390.0	700.0	0.25	150.5	43.0
PM0.5L	301.0	129.0	635.0	390.0	700.0	0.5	150.5	43.0
PF0.5L	301.0	129.0	635.0	390.0	700.0	0.5	150.5	43.0
PM1L	301.0	129.0	635.0	390.0	700.0	1.0	150.5	43.0
PF1L	301.0	129.0	635.0	390.0	700.0	1.0	150.5	43.0
PM0.25	301.0	129.0	635.0	390.0	700.0	0.25	150.5	0.0
PM1	301.0	129.0	635.0	390.0	700.0	1.0	150.5	0.0
PF1	301.0	129.0	635.0	390.0	700.0	1.0	150.5	0.0

PP FRC additions. The amount of SB latex added is by mass of cementitious material.
FRC mix designs are detailed in Table 1. Mixes which showed higher performance with regards to the mechanical properties in the first phase of this project were also tested without polymer. These FRCs are also listed in Table1. Selection has been from among the lower percentage and higher percentage and also the two different types of PP fibres.

Incorporating SB latex with PP fibres does not affect the efficiency of PP fibres in FRPMC regarding the compressive strength, significantly.

Table 2: Compressive strength results

Mix ID	7days	28days	56days
C	61.0	73.0	76.4
CF	46.0	57.5	70.3
CL	47.5	56.5	60.7
CFL	31.5	40.0	49.9
PM0.25L	31.0	36.5	52.2
PF0.25L	30.0	39.0	52.2
PM0.5L	25.5	31.5	37.0
PF0.5L	26.5	34.0	38.0
PM1L	17.5	23.0	25.0
PF1L	27.0	37.5	48.0
PM0.25	38.0	66.5	72.1
PM1	37.5	43.5	49.0
PF1	38.5	58.0	65.6

4 RESULTS AND DISSCUSION

4.1.Compressive Strength

The results show that by adding SB latex by 10% as a polymer additive to the mixes, compressive strength of concrete decreases. By adding lower percentages of fibre to the mix the mechanical properties increase. From among the fibre percentages used in this project, 0.25% helps with enhancement of compressive strength. The improvement of the compressive strength is approximately 3% to 5%. Between the two types of fibre used in this study, monofilament fibres help more to enhance or maintain the compressive strength in lower percentages whereas fibrillated fibres are more effective to maintain the ultimate compressive strength in general.

4.2.Modulus of Rupture

Figure 1 shows the results of the MOR test after 14 and 28 days. Concretes containing no FA seem to have a higher MOR than the concretes with FA and adding SBR Latex to the mixes, have no significant effect on the MOR.

By comparing the results of FRCs with their reference concrete (CF) (Figure 2), it is observed that by adding fibre to the mixes, the modulus of rupture is positively affected and a higher value can be achieved. FRPMCs, results (Figure 2) show that 0.25% of both monofilament and fibrillated PP fibre improve the MOR and by increasing the percentage of the fibre in the mix, this value decreases. This

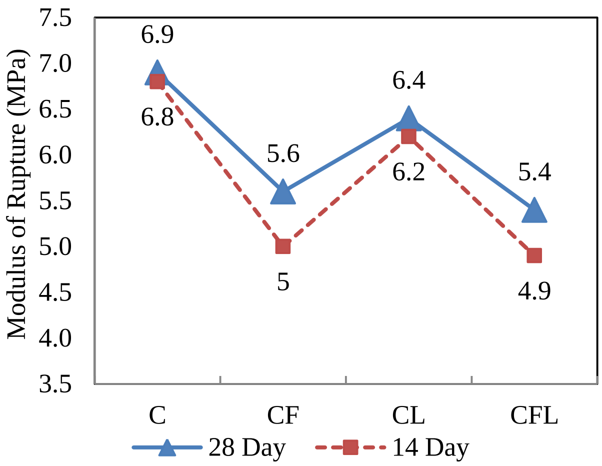

Figure 1: PMC, MOR comparative results

trend is the same trend observed in FRC except that although in FRC the value of the MOR decreases, it is still higher than the reference concrete even at 1% volume fraction.

So far, there are no specific standardised formulas available for FRC or FRPMC design calculation and equations are mostly available to calculate conventional concrete behaviour. Therefore, formulas for conventional concrete have been used to evaluate FRC and FRPMC's characteristics. In Australian standards "AS 3600", the following formula has been presented to measure concrete tensile strength from compressive strength and also MOR test:

$$f'_{ct.f} = 0.6\sqrt{f'_c} \quad (1)$$

$$f'_{ct} = 0.36\sqrt{f'_c} \quad (2)$$

$$f_{ct} = 0.6 f_{ct.f} \quad (3)$$

Where, f'_c is characteristic compressive strength of concrete at 28 days, f_{ct} is the uniaxial tensile strength, $f_{ct.f}$ is the flexural tensile strength, $f'_{ct.f}$ is the characteristic flexural tensile strength of concrete and f'_{ct} represents the characteristic uniaxial tensile strength of concrete. Moreover, for theoretical calculations, only 28 day results are presented due to the fact that design considerations are generally based on these values. Using the above equations, calculations have been done to check if the results of these formulas can be comparable to those of experimental results.

To interpret this data and compare the experimental results with those derived from theoretical formulas, statistical methods have been used. Comparing the experimental flexural strength with the theoretical flexural strength and also tensile strength calculated from the flexural and compressive strength for each mix, the results are presented in Table 3. Column I and IV are the experimental results of compressive strength and flexural strength, respectively. Column II shows the calculated characteristic uniaxial tensile strength from the compressive strength (Column II).

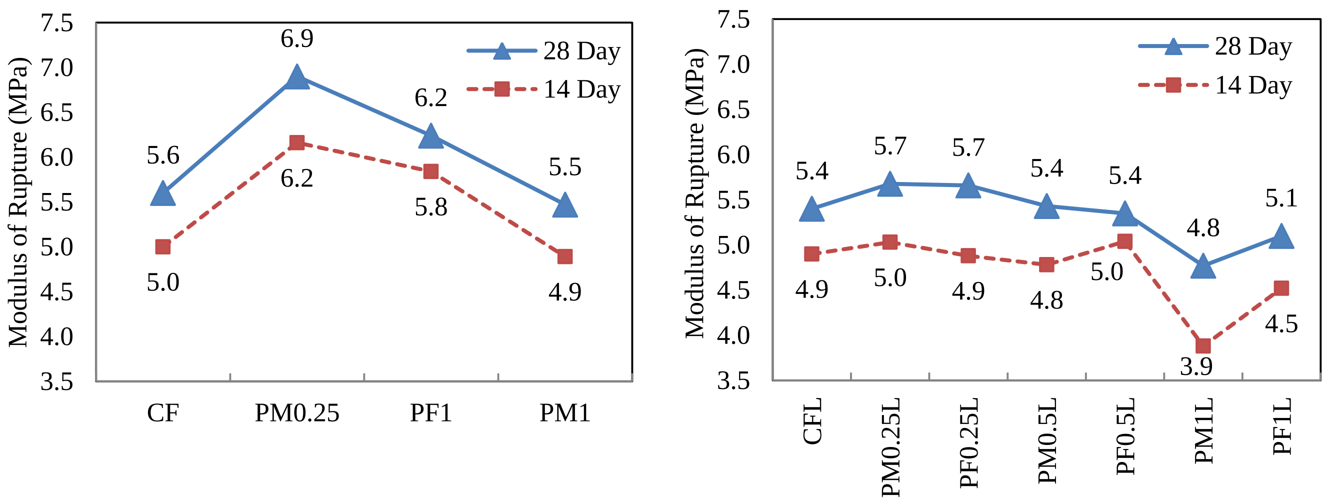

Figure 2: FRC and FRPMC, MOR comparative results

Table 3: Flexural strength Theoretical and Experimental Results

Mix	I	II	III	IV	V
PM 0.25%L	36.5	3.1	5.1	5.8	3.5
PF 0.25%L	39.0	3.2	5.3	5.9	3.6
PM 0.5%L	31.5	2.8	4.7	5.6	3.3
PF 0.5%L	34.0	2.9	4.9	5.5	3.2
PM 1%L	23.0	2.4	4.0	4.7	2.8
PF 1%L	37.5	3.1	5.2	4.7	2.8
PM 0.25%	66.5	4.1	6.8	7.1	4.2
PF 1%	57.9	3.8	6.4	6.5	3.7

Column III shows the characteristic flexural tensile strength of concrete mixes calculated using compressive strength (column II) and column V shows the results of the uniaxial tensile strength calculated from the experimental flexural strength (column IV).

Comparing the theoretical results with the experimental ones, it is observed that the flexural strength of FRC and FRPMC with the characteristics used in this project (except for 1% fibrillated fibre in FRPMC) can be calculated using the equations available in the standard considering the underestimation of the theoretical results comparing to the experimental ones.

In ASTM, there is a standard available regarding FRC which is used bellow to calculate properties and behaviour of unconventional concrete. According to ASTM C1609 [17], assuming the linear elastic behaviour up to the first peak, the first peak deflection of the FRC in 4-point bending testing can be calculated from below equation:

$$\delta_1 = \frac{23P_1L^3}{1296EI}\left[1 + \frac{216d^2(1+\nu)}{115L^2}\right] \qquad (4)$$

Where:"P_1" is the first peak load, "L" is the span length, "E" is the estimated modulus of elasticity in MPa, "I" is the cross sectional moment of inertia, "d" is the average depth of the specimen at fracture and "ν" is the poison's ratio. ASTM publication on concrete testing [19] permits using this equation for the normal concrete as well, therefore in order to be able to compare the data calculations and plotting for the conventional concrete can also been tried to evaluate the behaviour of the FRC, FRPMC and conventional concrete.

First peak point on the load deflection curve is where the slope is zero and the load is at the local maximum. Using this point and using the formula presented by ASTM C1609, the first peak strength can be calculated (There are small fluctuations in the curve which is due to noise or mechanical vibration which according to the standard is natural but needs to be monitored and not confused with the actual values):

$$f = \frac{PL}{bd^2} \qquad (5)$$

In this standard other characteristics have been required to be calculated to evaluate the behaviour of FRC. The residual load values corresponding to net deflection of 1/600 and 1/150 of span lengths help finding the residual strength values and also corresponding toughness. Below figure is extracted from the standard which shows the readings from the load deflection curves.

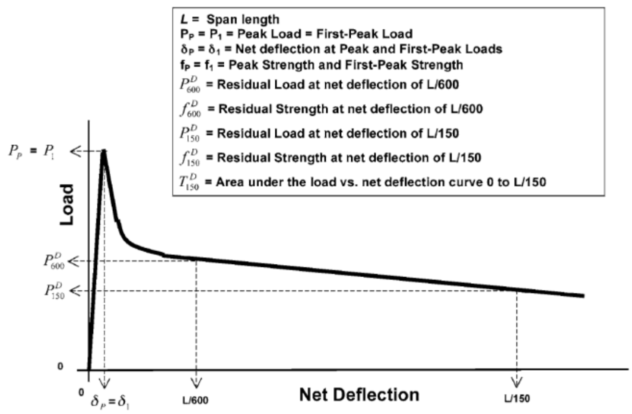

Figure 3: Example of parameter calculations for first-peak load equal to peak load [17]

For FRPMCs and FRCs these values are calculated. The total area under the load deflection curve up to the net deflection of 1/150 of the span length is the toughness which will be presented in Joules. Using the first peak strength, the equivalent flexural strength to the toughness is calculated from below equation:

$$R^D_{T,150} = \frac{150.T^D_{150}}{f_1.b.d^2}.100\% \qquad (6)$$

As test prisms are 100mm × 100mm × 350mm with span length of 300mm, therefore, L / 150 = 2mm and L / 600 = 0.5mm. Readings from the graphs are respectful of these values. For specimens with lower percentage of fibres, weaker or no post peak behaviour has been observed, whereas in larger percentages, FRC and FRPMC show satisfactory behaviour after peak load. This behaviour is more pronounced in mixes containing fibrillated PP fibres. These calculated results are used and presented in next section to evaluate the flexural toughness. Calculations are derived from those mixes with acceptable post peak behaviour. Due to very weak post peak behaviour of the conventional concrete, none of the calculations in this standard can be applicable to them with the data captured in this project. The conventional concrete did not reach the L/150 and L/600 deflections necessary to measure and calculate the related residual strength of the concrete.

4.3.Flexural Toughness

In some literature [20], toughness is considered as the area under the load deflection curve. This area can be an indication of the energy absorbed under flexural loading. In this study, 28 day flexural toughness of FRC and FRPMCs are calculated and presented relative to their reference mixes. This can give an indication of how this value has changed. Table 4 represents the relative flexural toughness values. These values are calculated by the following formula:

$$Relative\ Toughness = \frac{Flexural\ toughness\ of\ modified\ mix}{Flexural\ toughness\ of\ refernce\ mix} \quad (7)$$

Table 4: Relative flexural toughness

FRPMC		FRC	
Mix ID	Relative Toughness	Mix ID	Relative Toughness
CFL	1.0	CF	1.0
PM0.25L	1.3	PM0.25	2.2
PF0.25L	1.1	PM1	4.4
PM0.5L	2.6	PF1	5.9
PF0.5L	2.1		
PM1L	1.7		
PF1L	2.0		

From the above calculations it is observed that the changes in flexural toughness is almost in the same range at similar percentages of fibrilated and monofillament PP fibres in FRPMCs. The optimum value goes to mixes containing 0.5% PP fibre. Lower percentages of fibres in the mix do not have asignificant effect on flexural toughness capacity of this specific FRPMC. This result can be due to the presence of SB latex which has a good energy absorption charcteristic. From the results of the control concrete and refrence mixes, the following observations were gathered. Increase in flexural toughness when FA is added is only 10% larger, which indicates that FA has almost no significat effect. When SB latex is introduced to the mix, this value is improved by 70%, which points out the effect of this material in improving the energy absorption of the concrete mix.

When SB latex is taken out and only PP fibres are introduced to the mix, flexural toughness of concrete-fibre composite significantly increases. From the results, it is observed that at 0.25% , fibres tend to improve this property by about 2 times. When 1% of PP fibre is added, the value improved by more than 4 times when monofillamant fibre is used and in case of fibrilated fibre by about 6 times. The reason this high value could not be achieved by monofilament fibre can be due to the fact that this mix also has lower mechanical properties comparing to the refrence mixes.

FRC and FRPMCs could also reach the desired deflection to calculate the residual strength according to ASTM C 1609 and from among these mixes, FRC containing 1% fibrillated PP could reach L/150 net deflection.

The mentioned mix design has shown deflection both up to L/600 and almost L/150 which is the full behaviour explained in ASTM C 1609 whereas other FRC and FRPMC's could not reach L/150 deflection. Due to the good behaviour, 1% PP FRC mix could gain a much higher deflection comparing to all other mixes before it fails.

Further investigations are worth conducting on the FRC to improve standard specifications to consider this behaviour of the concrete material. Additionally, ASTM C 1550 (standard test method for flexural toughness of fibre reinforced concrete using centrally loaded round panels) may be used to calculate the toughness when needed but a standard calculation for toughness gathered from 3 or 4 point loading test are more commonly used .

It is reported that by adding fibre to the mix the toughness index (toughness) increases [14]. The toughness results of this project are also in harmony with the reports of literature. With regards to ASTM C1609, 1% fibrillated FRC results are calculated taking into account six test samples from two sets of mixes. The area under the full curve up to L/150 has been calculated, the results of which show toughness of following values:

$$(T_{150}^{D})_{PF1} = 16\,J$$

Equivalent flexural strength ratio of these values is calculated from below equation:

$$(R_{150}^{D})_{PF1} = 3.5\%$$

In different literature, it has been discussed that current formulations may not be sufficient or easily used for different situations [14, 18, 21, 22]. Above calculations can be an introduction to a wider range of experiments and future work on the specific mix designs. Table 5, shows specific values calculated for 1% fibrillated FRC using ASTM C1609.

Table 5: ASTM calculations for toughness and residual strength of PF1%

	Max. stress (MPa)	Δ at peak stress (mm)	Max. Δ (mm)	P^{D}_{150} (kN)	P^{D}_{600} (kN)	f^{D}_{150} (MPa)	f^{D}_{600} (MPa)
PF1%	6.10	0.508	2.01	9.0	20.0	2.70	6.00
	6.53	0.722	2.05	11.3	15.3	3.36	4.59
	6.70	0.508	2.03	6.0	10.2	1.80	3.06
	6.20	0.496	1.96	4.21	18.1	1.26	5.43
	6.65	0.650	1.92	7.43	11.0	2.23	3.30
	6.48	0.521	2.10	10.1	20.1	3.03	6.03

12 CONCLUSIONS

The results of this research show that by adding SB latex by 10% as a polymer additive to the mixes the mechanical properties of concrete decreases. By adding PP fibres in to the mix promising results can be gained in different percentages. According to the achieved results some general comments can be made.

1. 0.25% of both PP fibre types, help with the tensile strength of FRPMCs.
2. With percentage increase of fibres, MOR decreases.
3. Both types of fibres have shown approximately similar performance regarding the flexural behaviour of the concrete.
4. FA has no significant effect on long term tensile characteristics of concrete.
5. SB latex addition of 10%, improves the MOR by 14%.
6. Using FA with Latex in concrete tends to decrease the MOR.
7. Where higher percentages of fibre are used, especially at 1%, considerable post peak behaviour is observed.
8. Use of 10% SB latex and PP fibres together and alone in the concrete matrix, helps improve the energy absorption capacity and flexural toughness of concrete composite.

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