Post crack flexural toughness in steel fabric and fibre reinforced concrete beams

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ABSTRACT

The purpose of the paper is to provide independent research and evaluate manufacturers' claims that structural polypropylene fibres provide satisfactory crack control reinforcement and compare the test results from macro synthetic polypropylene fibres against steel fabric reinforced concrete, extensively used as a crack control medium in concrete ground bearing floor/hardstanding slabs where tensile forces are likely to occur. Three concrete beam types were produced, plain, steel reinforced and fibre reinforced, and a comparative study was undertaken of post crack flexural toughness. The procedure used was to manufacture steel A 142 fabric and macro fibre reinforced concrete beams to provide load, deflection data, toughness indices and was compliant with, ASTM C1018 -97, [ASTM, 1997] using a three point loading arrangement. The data was representative of what might occur in a floor slab. The findings of the paper is that A1 42 steel fabric reinforcement as used in slabs was more effective in producing toughness and residual strength when directly compared to the performance of structural polypropylene fibre reinforced concrete. When small post crack forces are encountered within the concrete matrix, polypropylene macro fibres are suitable for crack control. The paper makes direct comparisons between known and widely used crack control using steel fabric, and the use of low modulus polypropylene macro synthetic fibres as a crack control medium.

Keywords: Macro synthetic [type 2] polypropylene fibres, A 142 steel fabric, medium strength concrete, ASTM 1018.

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1.0 INTRODUCTION

Recent modern methods of constructing ground floor slabs have used 38 to 50 mm fibres as a replacement for welded steel fabric as a crack control medium. How the fibres perform depends upon the fibre type e.g. steel, glass fibre, high modulus polyethylene, carbon, aramid, or polypropylene and the fibre dosage per cubic metre of concrete [0.9 to 6 Kg/m^3]. Polypropylene fibres have various forms, these being – synthetic macro [type 2], fibrillated or monofilament all with different length and diameter permutations. The fibre type determines the normal commercial dosage used in concrete applications and the effect upon the finished product with regard to crack control, acting as micro reinforcement in the case of monofilament polypropylene fibres and macro reinforcement for class 2 fibres.

Therefore in any structural concrete, it is essential to provide some sort of reinforcement to mitigate concrete's low tensile strength. The reinforcement provides two functions; the first is for crack control and hence improved durability; the second is to resist tensile forces resulting from applied loads. [I.e. increase load-bearing capacity]. Traditionally crack control reinforcement has been achieved by using A 142 steel fabric reinforcement, which is placed before the concrete is poured.

More recently various attempts have been made to replace these bars with fibres of various shapes, lengths and material composition. The potential benefit of using fibres is that they are small enough to be included in the concrete mix and therefore can remove labour associated with placing traditional reinforcement and provide reinforcement throughout the mix in all directions. The other potential benefit is that; if fibres are spread evenly throughout the concrete, then so should the tensile forces, which would lead to a large number of smaller cracks rather than fewer large cracks.

For a fibre to be successful as reinforcement it must have the following attributes: Be easily spread evenly throughout the mix,

Should have sufficient bond with the concrete to transfer any tensile stresses across the concrete rupture plane,

Should be sufficiently stiff and have a suitable modulus of elasticity so as to limit cracking to acceptable limits,

Provide fracture toughness,

Should be sufficiently durable to provide service throughout the life of the concrete.

With regard to crack control in concrete floor slabs, the traditional use of B-type steel mesh fabrics having a greater area of steel in the longitudinal direction, has decreased. A-type fabrics, with equal areas in each direction are increasingly used, with restrained movement joints at 6 m intervals to form nominally 6 m-square panels, similar to large area construction. This approach is considered to result in a lower risk of cracking than using heavier fabric and more widely spaced joints. Steel fabric has traditionally been considered to have no structural effect, that is, not to increase the load-carrying capacity of a slab [Concrete Society, 2003]. Fibres share the same characteristic of not improving the flexural strength or load bearing capacity.

The acceptable limit [Narayan and Goodchild, 2006] for surface cracking of concrete is limited to 0.3 mm depending upon the degree of exposure and this can be better controlled with many small reinforcement fibres than steel bars at more distant centres, where the concrete between the bars is un-reinforced.

One other reason for contractors choosing macro polypropylene fibres for structural enhancement when compared against other reinforcing mediums was one of cost. Polypropylene when compared to glass fibre is 10 times less expensive by weight and 30 times by volume. [Mu et al, 2002] In terms of structural performance; with the correct choice of fibre, the highest bond strength between fibre and cement is within 40% of type R mild steel [Richardson, 2005]. Other qualities attributable to non-metal fibre reinforcement are; zero reinforcement corrosion, reduction in ion flow [Richardson, 2004], reduced water absorption [Richardson, 2003], and no aging problems.

However the design guide TR 34 [ASTM, 1997] states, 'flexural strength of concrete with fibre additions is unaffected... fibres affect the post crack flexural strength ratio'. To conclude; the designer has the option when using macro polypropylene fibres in reinforced concrete floor slabs, to provide enhanced post crack qualities when compared to un-reinforced concrete and provide a corrosion free reinforcement. This research examines and quantifies the degree of post crack reinforcement with a medium/high strength concrete at a fibre dose of 6 kg/m^3. If mixed monofilament and structural fibres are used together, then positive benefits of lower absorption are provided with macro reinforcement. These qualities will provide enhanced durability and eventually lower life cycle costs.

2.0 SCOPE OF THE RESEARCH

The concrete batching was carried out to a single design mix. Control cube samples were taken from each batch [Figure 2] to establish relative compressive strength between the batches, thus determining relative consistency of the design mix.

Although the significance of the work is largely related to crack control in ground floor slabs, no account has been taken for the effect of the modulus of sub grade reaction [k], which is the relationship between the ground bearing pressure and the deflection. The rationale is that although high direct loads are imposed upon floor slabs, the resultant load on the underside of the floor slab is usually low due to the dispersion of forces through the slab. The beam test to ASTM 1018 was used to determine the forces within the concrete without consideration of the surrounding factors.

3.0 TEST METHODOLOGY AND STANDARDS USED

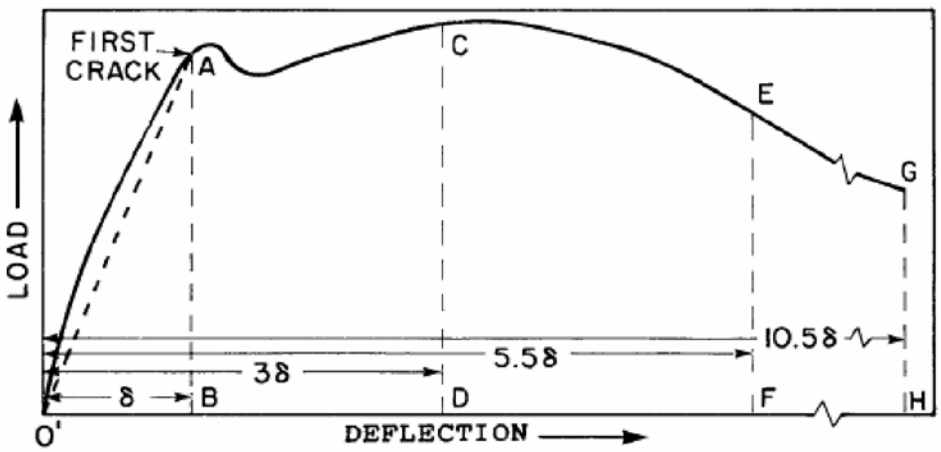
The aim of the test programme was to:

Investigate the flexural strength of concrete beams with regard to their post crack toughness

- performance, crack width and maximum deflection.
- Compare the relative performance of traditional A142 welded steel fabric reinforcement against polypropylene macro [type 2] fibres.

All the experiments were conducted following the American Society for Testing and Materials [ASTM] 1018 standard to determine post crack toughness. For each beam tested a chart was automatically produced using a Denison [DMG 67] constant rate [0.3 mm/minute] loading apparatus [Figure 4], directly linked to computer software showing how flexural strength compared to post crack deflection and what the maximum load was [Figure 1].

Fig 1.0, ASTM 1018 chart showing toughness indices maximum deflection.



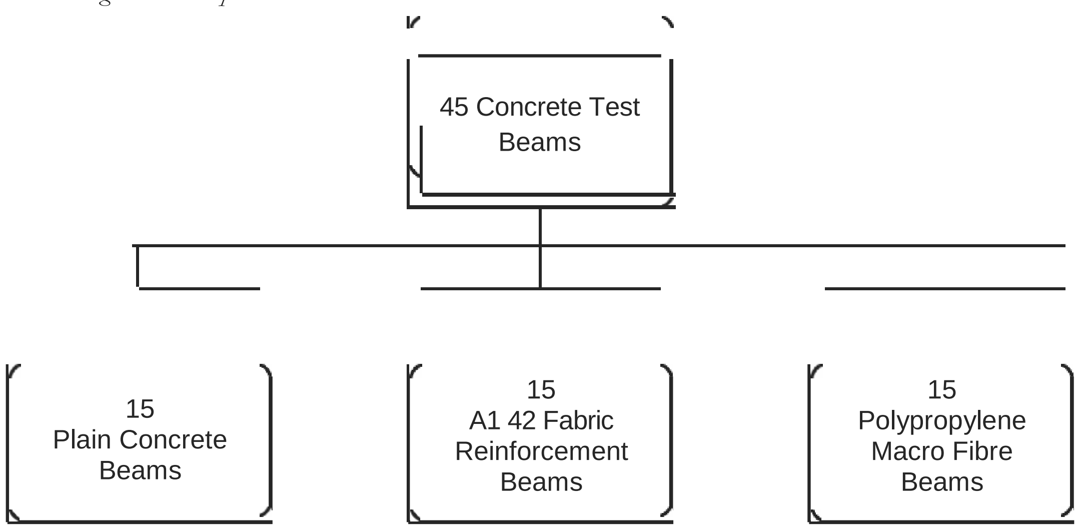
(b) Convex upwards to first crack
FIG. 3 Important Characteristics of the Load-Deflection Curve

3δ = I_5, 5.5δ = I_{10}, 10.5δ = I_{20}.

The first-crack strength characterizes the behaviour of the fibre-reinforced concrete up to the onset of cracking in the matrix, while the toughness indices characterize the toughness thereafter up to specified end-point deflections [ASTM, 1997]. Beams tests were used to evaluate these properties, acting as thin sections through a hardstanding/floor slab.

Due to the large size of the sample cohort, three batches of concrete were made to the design mix, each batch was subject to a slump test and the beams were compacted on a vibrating table.

Fig 2.0, Beam design mix and procedure.



The concrete design mix per m^3 [Figure 2] was 370 Kg of CEM1 cement, 675 Kg of coarse sand, 1008 Kg of 20 mm washed sea dredged gravel, with a water cement ratio of 0.55. Reinforcement was one single layer of steel A 142 fabric or a fibre dose of 6 kg/m3 macro [type 2] polypropylene fibres. Fibre characteristics – specific gravity 0.91, nominal filament diameter 0.9 mm, fibre length 40 mm, and elastic modulus 3500 N/mm^2.

4.0 CONTROL SAMPLE [CUBE TEST – 1 NO PER BATCH]

The need to determine the consistency between batches was felt to be paramount for reliable interpretation of the laboratory beam test results. In this regard control sample cubes were taken and tested for ultimate compressive strength in accordance with BS EN 12390-3:2002.

According to BRE Digest 326 [1987] [BRE, 1987] 'differences in properties occur in all constructional materials. In building and civil engineering much attention is given to the variability of compressive strength of concrete. A standard deviation...is seldom less than 2.5 and not more than 8.5 N/mm^2.' These parameters apply to concrete over 20 N/mm^2 in strength where above this strength 'the standard deviation remains sensibly constant' [BRE, 1987] this test uses concrete above 20 N/mm^2 where strength is the main criterion used for judgement of similarity of the three control batches. The batches were found to be within the Building Research Establishment limits [BRE, 1987].

The compressive strength of the control cubes were 51 N/mm^2, 53 N/mm^2, and 49 N/mm^2, for each respective batch as shown in Figure 2, viewed left to right. The slightly lower compressive strength would be expected due to the addition of polypropylene fibres.

5.0 RESULTS

The test results showed that A142 steel fabric had a greater post crack strength, and greater toughness indices but suddenly failed at significant deflection. Polypropylene macro fibres held the concrete together under extreme deflection following the rupture plane being formed. The load deflection curves were plotted and the toughness indices calculated in accordance with ASTM 1018.

This work has examined the effectiveness of macro structural [type 2] polypropylene fibres when used in concrete, compared against traditional A142 steel fabric reinforcement in terms of crack control and post crack toughness performance. Table 3 when compared to Table 1, shows the varying degree of strain hardening for A142 steel fabric reinforced concrete. Strain hardening [+ 46%] occurs between the first crack and maximum load. Once the maximum load was achieved, the fibre beams conveyed a much reduced post crack load, which was reflected in the lower toughness indices values.

It was found that A142 steel fabric had a greater post crack strength [strain hardening] compared to polypropylene fibres [strain softening]. The fibres gave lower load transfer values with regard to post crack tensile properties. The position of the steel fabric in relation the applied load contributed to the enhanced post crack strength, lower crack widths, decreased deflection [- 42%] and higher toughness indices. The A 142 increase in toughness indices compared to fibre beams were:-

I5 605%

I10 631% I20 675%.

The fibres in the beam specimens held the concrete together under extreme deflection, due to the frictional bond between the concrete and the fibres in the rupture plane. It was generally accepted; the strength of the concrete had little effect on the failure load for the fibres, as this was attributable to the bond between the concrete and the fibre that broke first [Bentur et al, 1997]. The final post crack load was influenced by fibre direction, total number of fibres, fibre type and concrete type [Parviz and Lee, 1990]. Analysis of fibres bridging the rupture plane gave no consistent direct relationship between post crack strength and fibre direction, however embedded length, and orientation were difficult to evaluate with certainty and therefore have been omitted from the findings.

The average density of the concrete was 2367 Kg/m^3 and the mean flexural strength values were:

- Plain beams 5.5 N/mm^{2}A142 beams 5.5 N/mm^{2}Fibre beams 4.5 N/mm^2.
- Details of fibre beam load and deflection values are shown in Figures 3 and 4, showing post
- crack load transfer qualities.

Fig 3.0, Load deflection for polypropylene fibre reinforced concrete beams.

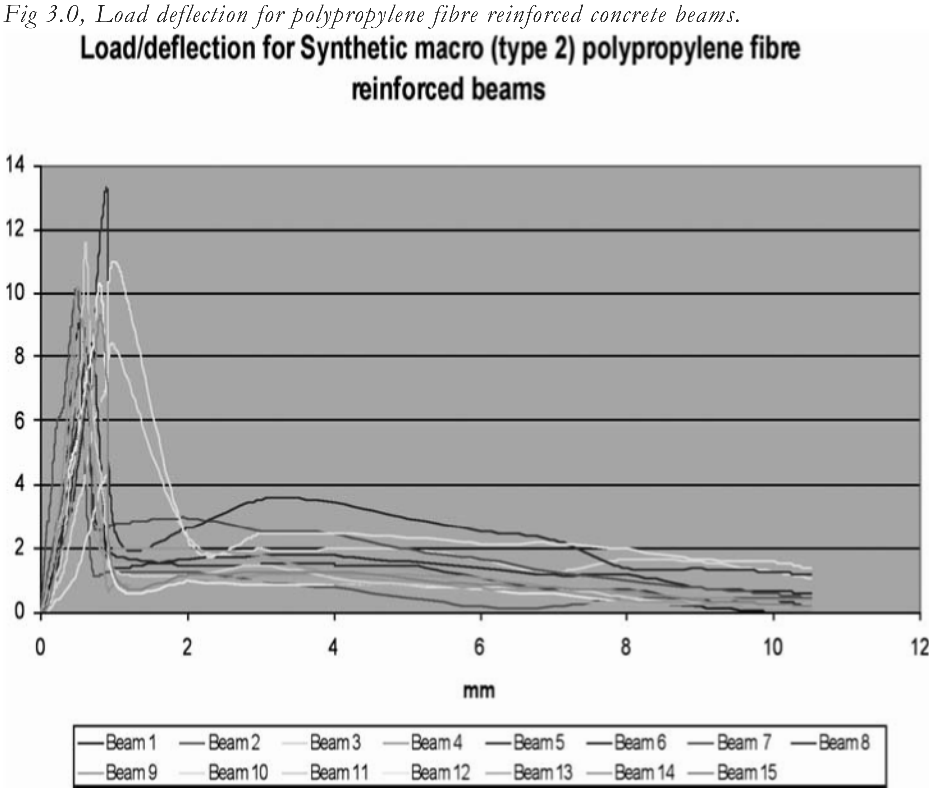
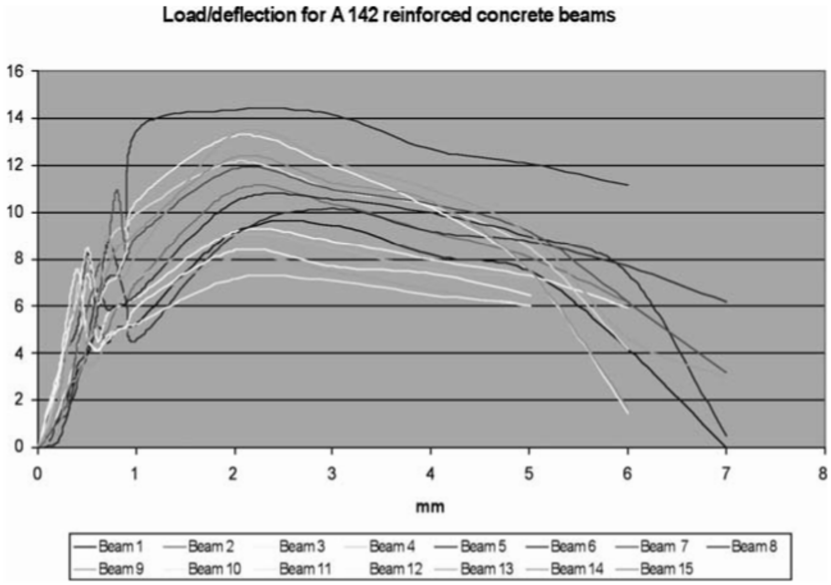
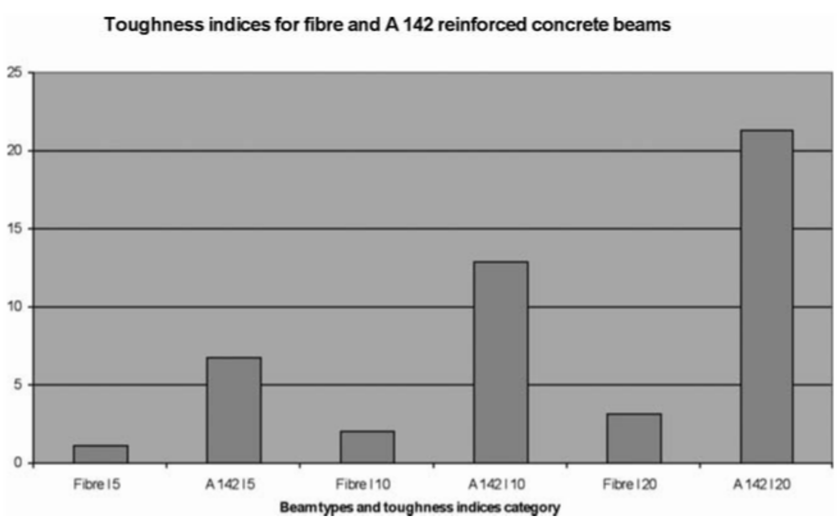


Fig 4.0 Load deflection for polypropylene fibre reinforced concrete beams



Toughness indices results from the three point loading tests are detailed in Figure 5, arranged in ascending values for ease of comparison.

Figure 5 – Toughness Indices I5, I10, I20, for synthetic macro fibre and A 142 reinforced concrete beams



The Denison testing apparatus and linked computer programme [Figure 6] was used for all beam testing and using a crack detection pocket microscope [x 40] the first crack was identified.

Figure 6 – Denison [DMG 67], beam sample and linked computer.

Table 1.0, A142 reinforcement beam – toughness indices.

Ref	Dimensions W x d x l [mm]	First crack load kN	First crack deflection [mm]	I_5 x 3	I_{10} x 5.5	I_{20} x 10.5
1	101 x 101 x 500	5.2	0.4	8.30	18.09	35.40
2	101 x 101 x 500	7.1	0.6	8.19	15.29	20.61
3	100 x 101 x 500	7.2	0.6	6.73	12.42	20.90
4	101 x 101 x 500	6.5	0.6	6.46	13.09	21.73
5	101 x 100 x 500	8.4	0.9	4.68	5.16	13.44
6	101 x 102 x 500	7.2	0.8	8.41	14.56	23.55
7	101 x 102 x 500	10.1	0.9	5.99	10.21	12.63
8	100 x 104 x 500	8.4	0.6	7.46	14.17	19.36
9	101 x 100 x 501	7.4	0.4	4.81	10.25	19.35
10	100 x 100 x 500	6.0	0.45	5.93	11.75	22.32
11	101 x 101 x 501	8.5	0.55	8.12	14.85	22.69
12	100 x 100 x 501	7.7	0.4	4.42	10.01	19.39
13	101 x 100 x 501	6.1	0.4	7.05	14.50	27.75
14	100 x 101 x 501	9.0	0.75	7.77	13.23	18.34
15	100 x 101 x 500	7.8	0.6	8.30	15.62	22.42
Total		**112.6**	**8.95**	**102.62**	**193.20**	**319.88**
Mean		**7.51**	**0.60**	**6.84**	**12.88**	**21.33**

Table 2.0, Macro synthetic fibre reinforced beam – toughness indices.

Ref	**Dimensions W x d x l [mm]**	**First crack load kN**	**First crack deflection [mm]**	**I_5 x 3**	**I_{10} x 5.5**	**I_{20} x 10.5**
F1	101 x 100 x 500	9.02	0.5	1.2	2.26	3.86
F2	101 x 101 x 500	10.06	0.5	0.77	1.97	2.56
F3	100 x 101 x 500	8.36	0.9	2.11	3.7	5.60
F4	101 x 101 x 500	8.09	0.5	1.27	2.32	3.71
F5	101 x 101 x 500	7.86	0.7	1.3	2.25	3.27
F6	101 x 102 x 500	8.4	0.6	1.21	2.29	3.99
F7	101 x 102 x 500	8.79	0.6	1.91	3.27	5.43
F8	100 x 101 x 500	13.17	0.6	1.37	2.39	3.38
F9	101 x 100 x 500	10.23	0.6	0.59	1.13	1.91
F10	100 x 100 x 500	11.01	0.8	1.42	2.46	3.64
F11	101 x 101 x 500	11.64	0.8	0.67	1.19	1.87
F12	100 x 100 x 500	10.33	0.6	0.58	1.02	1.4
F13	101 x 100 x 500	9.64	0.8	0.81	1.33	1.95
F14	100 x 101 x 500	9.3	0.8	0.93	1.75	2.99
F15	100 x 101 x 500	9.32	0.8	0.77	1.25	1.79
Total		**145.22**	**10.1**	**16.91**	**30.58**	**47.35**
Mean		**9.68**	**0.67**	**1.13**	**2.04**	**3.16**

Table 3 – Deflection at I20 – comparison A142 and Fibre beams.

	Macro Fibre beams		A 142 reinforced beams		
Ref	**Final deflection at I_{20} [mm]**	**Max load kN**	**Final deflection at I_{20} [mm]**	**Max load kN**	**Position of steel [d] mm**
1	10.13	9.02	6.93	10.66	60
2	13.08	10.06	6.20	11.26	61
3	10.06	8.36	6.38	9.39	53
4	9.41	8.09	5.48	12.43	71
5	9.21	7.86	6.88	10.11	60
6	9.41	8.4	6.08	10.84	60
7	10.33	8.79	5.93	11.76	60
8	13.10	13.17	4.50	14.44	80
9	10.06	10.23	6.98	8.11	55
10	11.05	11.01	7.98	7.34	48
11	11.69	11.64	5.03	13.68	80
12	10.32	10.33	6.68	8.46	59
13	9.62	9.64	6.75	9.13	60
14	10.21	9.3	5.43	13.42	80
15	10.23	9.32	4.98	12.87	75
Mean	**10.53**	**9.68**	**6.15**	**10.93**	**64.13**

6.0 CONCLUSION

The use of synthetic macro [type 2] polypropylene fibres as a secondary reinforcement has the potential to be used in situations where the forces encountered are small, to provide crack control by distributing and absorbing tensile stresses which may occur as a result of shrinkage and temperature movements. If significant forces within hardstanding or floor slabs were to be encountered, then steel fabric reinforcement has the ability to provide greater toughness, lower deflection and reduced crack widths.

The use of fibres in concrete hardstanding or floor slabs has benefits to flooring companies, as fibres avoid the difficulty of placing steel fabric whilst running wheeled floor laying equipment over the fabric to lay the slab. Polypropylene fibre reinforcement is not subject to corrosion and can be used in severe exposure conditions such as marine environments, thus assisting designers in making informed choices as to whether or not synthetic macro fibres may be a suitable replacement for steel fabric.

7.0 REFERENCES

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