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Mechanical properties of a large scale synthetic fibre reinforced concrete ground slab

Amir M. Alani [*], Derrick Beckett

Department of Civil Engineering, University of Greenwich, United Kingdom

HIGHLIGHTS

- ▶ A large scale synthetic fibre reinforced concrete slab was constructed and tested.
- ▶ The slab was subjected to point load at five different positions.
- ▶ Deformations (deflections) at five points were measured and reported.
- ▶ Results are comparable to steel fibre reinforced concrete slab tested earlier.

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ABSTRACT

The existing design code for Concrete Industrial Ground Floors, TR34, by the Concrete Society states that "*Macro synthetic fibres provide some post-cracking or residual moment capacity but with significantly lower performance than steel fibres. They are not known to be used in industrial floor construction*". This paper presents results of an ongoing investigation undertaken by the authors concerning the mechanical and physical properties of fibre reinforced concrete ground slabs at an industrial scale. This paper focuses and presents results concerning the punching shear failure of a 6.00 m × 6.00 m × 0.15 m synthetic fibre reinforced ground supported slab. The paper demonstrates clearly the methodology adopted and the infrastructure used throughout this investigation. The presented results show clearly that the punching shear failure values obtained in this investigation are comparable to values reported for the steel fibre slabs under similar conditions. This work could potentially question the validity of the above statement in TR34. The significance of this research also is in the size of the slab investigated, as there is very limited work, if any, reported within the literature.

1. Introduction

Concrete ground slabs are an essential component of many building structures. Whether they are residential or commercial buildings the behaviour of the ground slabs is affected by the properties and strength of slabs, withstanding loads and forces, choice of materials and also by the properties and characters of soil underneath. The introduction of fibre as one of the main constituents of structural concrete material is not a new concept. However, there is much needed information and knowledge about the mechanical, physical as well as chemical properties and characteristics of fibre rich concrete. No doubt the availability of reliable details of the above characteristics will assist engineers, researchers and concrete technologists in designing concrete structures in a more viable and sustainable manner. Within this context, there is great interest in developing and designing reliable, strong and sustainable fibre reinforced concrete ground slabs to overcome premature failure.

Cengiz and Turanli [1], experimentally investigated and evaluated performance characteristics such as toughness, flexural ductility, energy absorption and load capacity on steel mesh (SM), steel fibre (SF) and high-performance polypropylene fibre (HPPF) reinforced shotcrete panels. It is reported that HPPF can greatly improve the flexural ductility, toughness and load carrying capacity of the brittle matrix in comparison to SM and SF. It is also reported that if fibres are used in "proper" amounts, the hybrid fibre system is more efficient than the mono fibre system from a performance point of view. The addition of HPPF to shotcrete enhances toughness, flexural ductility, load carrying capacity and energy absorption.

In recent years, a unique and dedicated ground slab test rig facility was constructed at the University of Greenwich with a

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[*] Corresponding author. Tel.: +44 1634 883293; fax: +44 1634 883153.
E-mail address: m.alani@gre.ac.uk (A.M. Alani).

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Fig. 1. Ground slab facilities at the University of Greenwich – 2nd test series in progress.

Table 1
Properties of barchip as specified by the manufacturer.

Characteristics	Material properties
Base resin	Modified olefin
Length	48 mm
Tensile strength	640 MPa
Surface texture	Continuously embossed
No. of fibres	59,500 per kg
Specific gravity	0.90–0.92
Young's modulus	10 GPa
Melting point	159–179 °C
Ignition point	Greater than 450°

capability of load testing ground slabs with plan dimensions of up to 12.0 × 6.0 m (72 m^2), Fig. 1. The rig was designed to sustain a single concentrated load of up to 1000 kN (100 tonnes) applied to a contact area of 100 × 100 mm to simulate the maximum racking loads currently in use. Initially, the rig was used to test slabs of dimensions 3.0 × 3.0 × 0.15 m but, as a result of excessive edge and corner lifting, it was decided in 2010 to increase the slab plan size to 6.0 × 6.0 × 0.15 m in order to overcome the limitations of the smaller slab size. The test programme was commenced in April/May 2010 and includes:

1. A slab reinforced with steel fibres at a dose of 40 kg/m^3.
2. A slab reinforced with synthetic fibres at a dose of 7 kg/m^3.
3. A plain concrete slab with no reinforcement.
4. A fabric reinforced slab with an A142 mesh, bar diameter 6 mm, bar spacing 200 mm and cross sectional area per metre width 142 mm^2. The mesh to be located 50 mm from the slab soffit.

The results of the first test have been presented separately elsewhere, Ref. [2]. However, this paper presents the results of the second series of tests stated above. Inevitably the results of the second phase tests have been compared with the first phase tests and presented in this paper too.

It is widely accepted within the community that test results and/or case study results concerning large scale concrete ground slabs would be of significant value, with the possibility that the yielded results may influence exiting design codes and practices. To this effect, the current research programme was undertaken with the aim of reporting on the mechanical behaviour of a 6.0 × 6.0 m fibre reinforced concrete ground slab under static step loading conditions.

In March 2010, the first phase of a new set of slab tests with 6.0 × 6.0 × 0.15 m dimensions was started. One of the main objectives of constructing a 6.0 m × 6.0 m ground slab was to investigate the limitations of the smaller slabs reported previously [3,4], starting with steel fibre reinforcement. The slab was subjected to central, edge and corner loading during the first test [2]. As emphasised earlier, this paper concentrates on the results obtained during the second phase tests concerning a 6 m × 6 m synthetic fibre reinforced concrete ground slab.

2. Methodology and procedures

2.1. Fibre materials

The selection of synthetic fibres was done as per the current market trend and the conclusions of a literature survey. The polypropylene synthetic fibres were found to be the most sustainable and desirable. The concrete mix was designed as per the requirement for the test. The component of the concrete was as per British standards supplied in the form of ready mix concrete by Hanson UK.

The synthetic fibres were supplied by Elasto Plastic Concrete (EPC), barchip "Shogun" categorised as barchip48 with the following material properties (Table 1).

The selected macro synthetic fibre was Class II macro fibres as stated in BS EN 14889 as shown in Fig. 2.

2.2. Properties of concrete mix

The concrete used for this study was ready mixed concrete (RMC) supplied by Hanson UK, Heidelberg Cement Group (with Ordinary Portland Cement, fine and coarse aggregate). The strength class of concrete (C32/40) was in accordance with Table 9.1 of TR34.2003 [7] with a maximum water/cement ratio of 0.55. Table 2 illustrates the details of the concrete mixed.

Note: GGBS = Pulverised blast furnace ash.

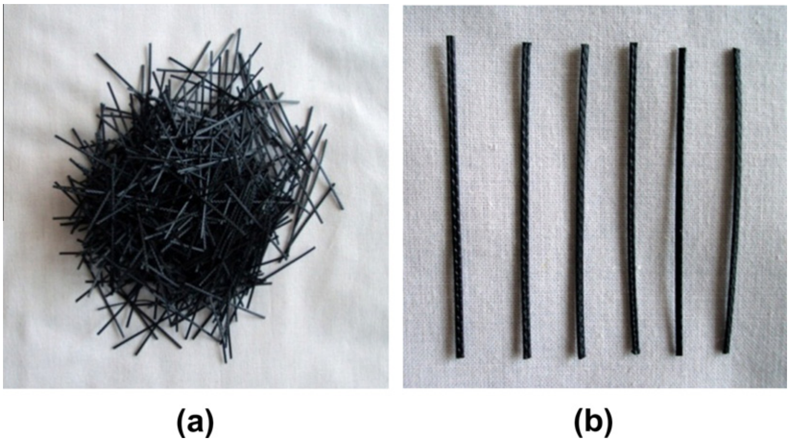


Fig. 2. Macro synthetic fibres.

Table 2
Details of the design mix as supplied by the manufacturer Hanson UK.

S No.	Materials	Quantities			Error
		Target	Actual	Error	
1	10/20 mm Gravel	4479 kg	4490 kg	11.00 kg	0.24
2	4/10 mm Gravel	2308 kg	2315 kg	7.00 kg	0.30
3	Sand	4987 kg	4985 kg	−2.00 kg	−0.04
4	Cement	915 kg	914 kg	−1.00 kg	−0.11
5	GGBS	915 kg	914 kg	−1.00 kg	−0.11
6	Water reducing agent	6.59 L	6.6 L	0.01 L	0.15
7	Total water	573 L	524 L	−49.00 L	−9.35

The barchips (synthetic fibre) were added to the concrete on site at the rate of 7 kg/m^3 and mixed thoroughly (see Fig. 3).

2.3. Fresh concrete testing schedule

- *Slump test:* Three slump tests were carried out for the workability of the concrete mix during the concrete placing.
- *Compressive strength test:* This test was carried out on standard cubes as well as standard cylinders. The test was conducted at 7, 14 and 28 days with 3 cubes at a time and at 7 and 28 days with 3 cylinders at a time.
- *Splitting tensile strength test:* This test was conducted on 3 standard cylinders at 28 days for the tensile strength of concrete.
- *Flexural strength test:* This test was conducted on 9 standard beams with a notch at mid span of the beam at 28 days. A three point loading test was undertaken for determination of flexural strength, Fig. 4.

2.4. Ground conditions

Prior to the load test, it was necessary to establish the soil stiffness – the modulus of subgrade reaction (kN/mm^3). After an initial investigation and CBR testing by "Costain Geotechnical Services", it was deemed that the ground conditions were too stiff to achieve adequate flexure of the slab. In light of this, contractors re-engineered the ground. This involved excavating the existing ground, turning it over and reinstating the soil. The aim of this exercise was to modify the soil compaction level to give more compressible conditions. Then the ground conditions were re-evaluated using a plate equivalent CBR test (in line with BS 1377: Part 9: 1990: C.L. 4.1 [5]). In summary the modulus of sub-grade reaction (k), modified for plate diameter, varied from 44 to 55 MPa/m.

Fig. 5 depicts the ground work undertaken to achieve the required CBR value.

2.5. Placing concrete

After slowly adding the fibre to the delivered ready mix concrete on site, the concrete was placed carefully in the designated formwork in steps according to normal practice. It was placed in equal quantities at different locations within the formwork and then was spread manually by trained technicians. Vibrating pokers were used to ascertain the extraction of the entrapped air within the concrete mix. A laser level was employed in order to achieve a uniform surface throughout (Figs. 6 and 7). Three slump tests were carried out at different stages of the concrete pouring process.

Fig. 3. Ready mixed concrete supplied by Hanson UK.

Fig. 4. Three point load (flexural strength) test underway.

Fig. 5. Completed ground work for the required CBR value.

Fig. 6. Placing concrete at different stages.

Fig. 7. Placing concrete at different stages.

2.6. Test procedure

The load tests (performed by Adam 4000 series Load Cells) were supplemented by an acoustic crack detector (performed by Acoustic Transducers) and the equipment was supplied by Physical Acoustics Incorporated. The load tests were as below with the load applied by jacking against reaction beams and the load transfer to the concrete was via a 100 × 100 mm steel plate intended to simulate the racking loads. The loading plate was sandwiched between a similar plywood spreader plate to counteract any uneven surface on the concrete and a 200 × 200 mm steel plate on which were placed 4 transducers. The load cell and the acoustic crack detector are detailed in Fig. 8.

Figs. 9 and 10 depict the layout of the 5 loading positions together with the displacement transducers and acoustic sensors respectively.

3. Test results

3.1. Properties of fresh concrete

As described earlier the slump test was carried out during the casting of the slab at three different stages of placing concrete. The average value of 55 mm slump was recorded during casting the concrete slab.

Tables 3–5 depict the results of tests that were carried out relating to the properties of the fresh concrete. These tests were carried out within the context of quality control of the concrete used for the 6 m × 6 m slab and the theoretical calculations (Punching Loads) later. Fig. 11 depicts samples tested for splitting tensile strength of the concrete at 28 days.

Fig. 12 is a schematic diagram of the flexural strength tests carried out in this investigation.

The results of the flexural strength test are shown in Fig. 13 and Table 3. Nine beams were tested and the maximum average load value of 13.35 kN with an average R_{e3} (%) value of 34.89 were obtained.

Three samples of beams were also investigated for crack widths manually using a dial gauge micrometer. Fig. 14 depicts the plotted graph of the applied load up to failure point against crack width. Maximum crack width values of 300 μm approximately were measured for all three tested beam samples.

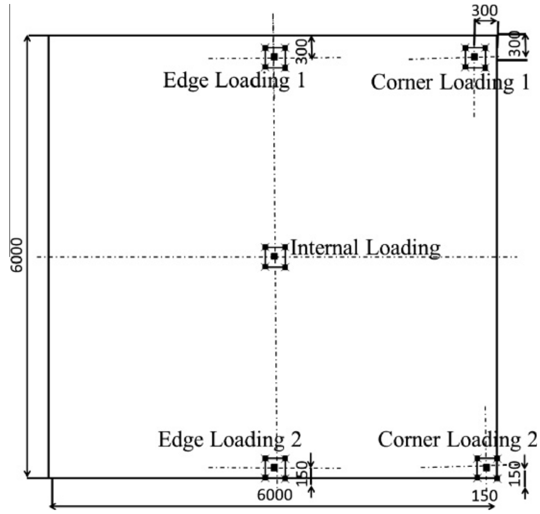
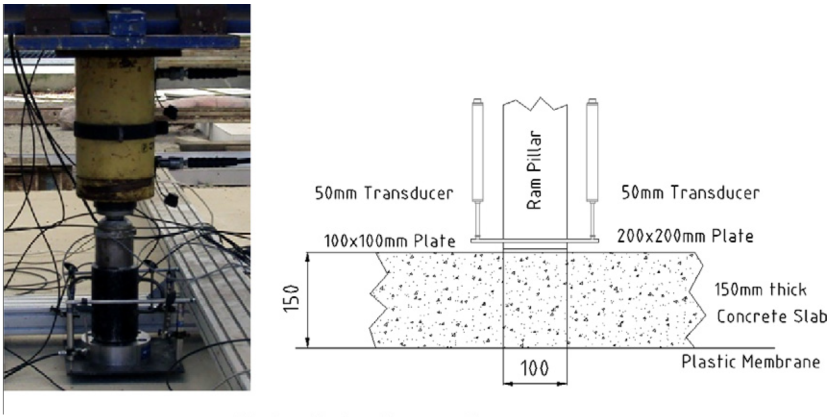


Fig. 9. Loading locations on the 6.0 m × 6.0 m × 0.15 m slab.

3.2. Slab tests

Five different sets of tests were carried out at five different loading points as follow:

- Slab centre point.
- Slab edge (load plate centred 150 mm from slab edge).



Hydraulic loading ram layout

Acoustic sensors Strain gauge transducer

Fig. 8. The layout of the load transducers and acoustic sensors under test conditions.

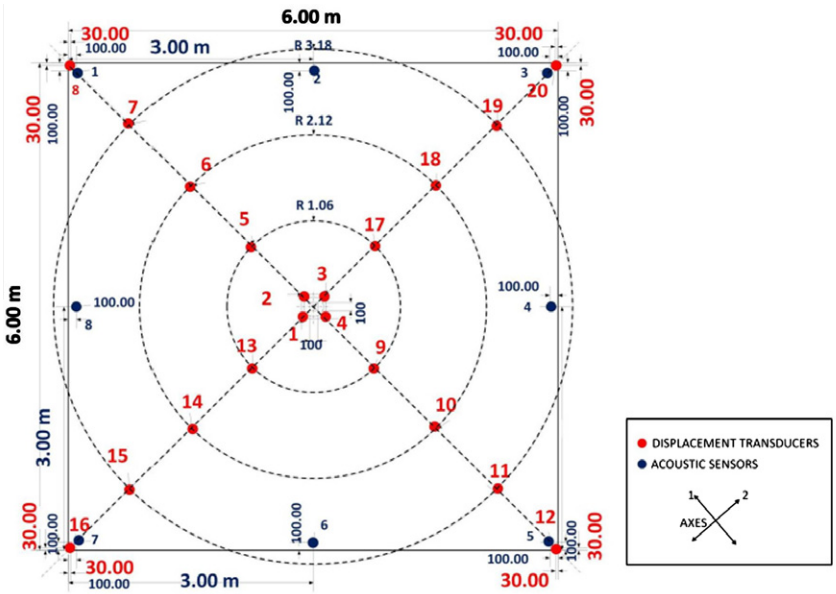


Fig. 10. Layout of the displacement transducers and the acoustic sensors positions for central loading test.

Fig. 11. Tested samples for splitting tensile strength at 28 days.

- Slab edge (load plate centred 300 mm from slab edge).
- Slab corner (load plate centred 150 mm from slab corner).
- Slab corner (load plate centred 300 mm from slab corner).

As explained earlier prior to the load test, it was necessary to establish the soil stiffness – the modulus of subgrade reaction (kN/mm^3). As a result of this exercise, an average CBR value of 8.325 was obtained. From (TR34.2003), Fig. 6 (CBR vkN/mm^3), the modulus of subgrade reaction was taken as $k = 0.05$ N/mm^3. Hence the value of $k = 0.05$ N/mm^3 was adopted for this investigation. For theoretical calculation purposes, the concrete was specified as grade C32/40 in accordance with Table 9.1 of TR34.2003, the compressive strength of the concrete was taken as $f_{cu} = 40$ N/mm^2 (cube) with the modulus of elasticity as $E_{cm} = 33.5$ kN/mm^2.

For all five load positions, the value of Poisson's ratio was taken as $v = 0.2$ (see TR34.2003). The value of R_{e3} (the equivalent flexural strength – a measure of the ductility of the composite material) was taken as $R_{e3} = 0.349$ (average for all load positions).

The slab was cast on 12th April 2011 and the average of the 28 day cube tests was $f_{cu} = 41.83$ N/mm^2. A notched beam test

Table 3
Compressive strength test results for 7 kg/m^3 polypropylene FRC specimens.

Sample no.	Sample description	Age tested (days)	Average density (kg/m^3)	Average peak load at failure (kN)	Average compressive strength (MPa)
1, 2 & 3	Cubes	7	2324.27	701.00	31.15
4, 5 & 6	Cubes	14	2348.62	848.33	37.70
7, 8 & 9	Cubes	28	2319.57	941.33	41.83
1, 2 & 3	Cylinders	7	2302.50	437.10	24.73
4, 5 & 6	Cylinders	28	2313.80	568.20	32.15

Table 4
Splitting tensile strength test results at 28 days.

S. no.	Description	Diameter of cylinder (mm)	Length of cylinder (mm)	Weight of cylinder (mm)	Cylinder density (kg/m^3)	Ultimate load (KN)	Splitting strength (MPa)	Average splitting strength (MPa)
1	Cylinder 1–7	150	300	12.265	2313.523	241.1	13.64	13.30
2	Cylinder 1–8	150	300	12.265	2313.523	224.8	12.72	
3	Cylinder 1–9	150	300	12.280	2316.353	239.4	13.54	

Table 5
Summary of flexural strength test results.

Sample	Description	Equivalent flexural strength, R_{e3} (%)	Average R_{e3} (%)
1	Beam 1–1	35	34.89
2	Beam 1–2	23	
3	Beam 1–3	34	
4	Beam 1–4	44	
5	Beam 1–5	32	
6	Beam 1–6	32	
7	Beam 1–7	37	
8	Beam 1–8	39	
9	Beam 1–9	38	

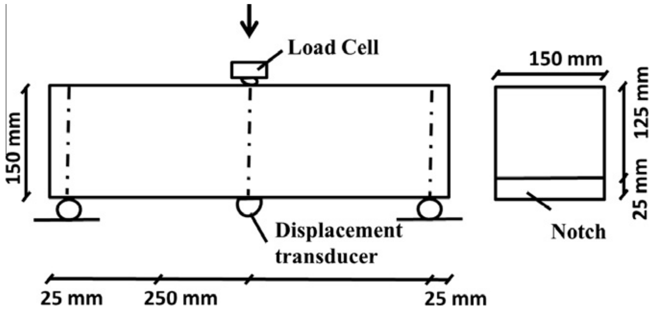


Fig. 12. Schematic diagram of the flexural strength testing setup according to EN 14651:2005 [6].

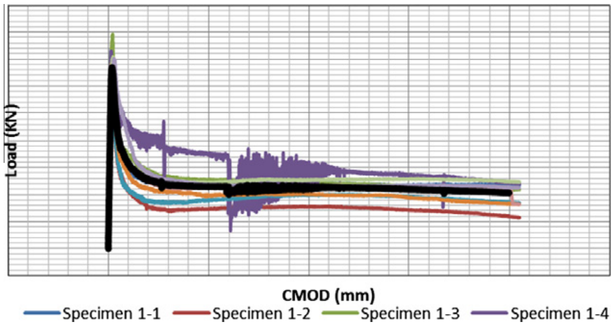


Fig. 13. Graph of load against CMOD.

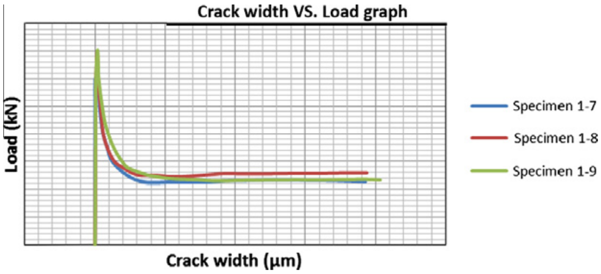


Fig. 14. Graph of crack width vs. Load.

was adopted for obtaining the R_{e3} value of 0.37 (average of 8 tests omitting the highest and lowest values). Loading for location No. 1 (centre of slab) commenced on 11th May 2011 and results of the five load tests were obtained by 24th May 2011.

The test results are summarised in Table 6 below. The difference between the load at first crack (kN) and the load at failure for the five tests has been shown.

Table 6
Summary of results for slab tests 1–5 with comments on crack formation.

Test description	First crack recorded		Ultimate failure		Comments
	Load (kN)	Average deflection (mm)	Load (kN)	Average deflection (mm)	
1. Central/internal loading	–	–	490	6.0	No evidence of punching on top of slab, no cracking visible. Punching type failure was observed at 490 kN
2. Edge – load plate centred 150 mm from slab edge	190	3.8	427	16.0	Cracks were observed immediately beneath the loading point at 190 kN followed by radial/circumferential cracks at 290 and 320 kN propagating towards edges as load increased
3. Edge – load plate centred 300 mm from slab edge	180	3.0	500	15.0	Cracks were observed immediately beneath the loading point at 180 kN followed by radial/circumferential cracks at 360 and 430 kN propagating towards edges as load increased
4. Corner – load plate centred 150 mm from slab corner	60	3.3	240	16.5	Radial/circumferential cracks were observed at 60 kN followed by tension crack at 140 beneath the loading point. Radial/circumferential cracks continued to appear up to 200 kN
5. Corner – load plate centred 300 mm from slab corner	190	3.8	373	16.0	Radial/circumferential cracks were observed at 165 kN followed by tension cracks at 190 beneath the loading point. Radial cracks developed at 290 kN propagating towards the centre

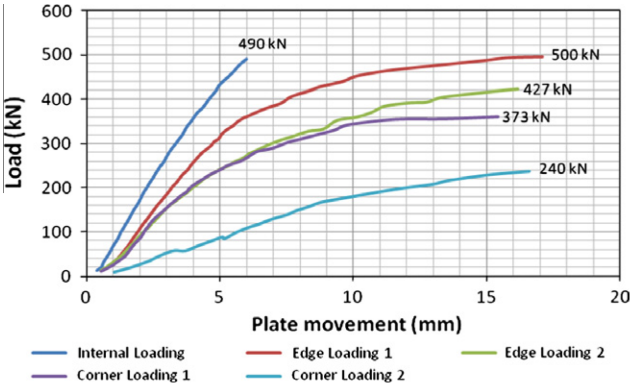


Fig. 15. Load against deflection (plate movement) at five different points on the slab.

Fig. 15 illustrates the applied incremental loading against the deflection patterns formed.

The following Figs. 16–19 illustrate the pattern of settlement due to point load at different positions of the synthetic fibre reinforced concrete ground slab. The depicted results show the pattern of settlement/deflection in two different axes (see Fig. 9 for axis details).

Table 7 below presents results of two separate investigations that were carried out by the authors for comparison purposes. The first set of test results for steel fibre has been discussed elsewhere (a paper is available on line in the Magazine of Concrete Research). This table shows the theoretical and test values for punching shear failure of two different fibre reinforced concrete ground supported slabs (steel and synthetic fibre) which have been tested under similar loading mechanisms including the ground conditions in terms of CBR value.

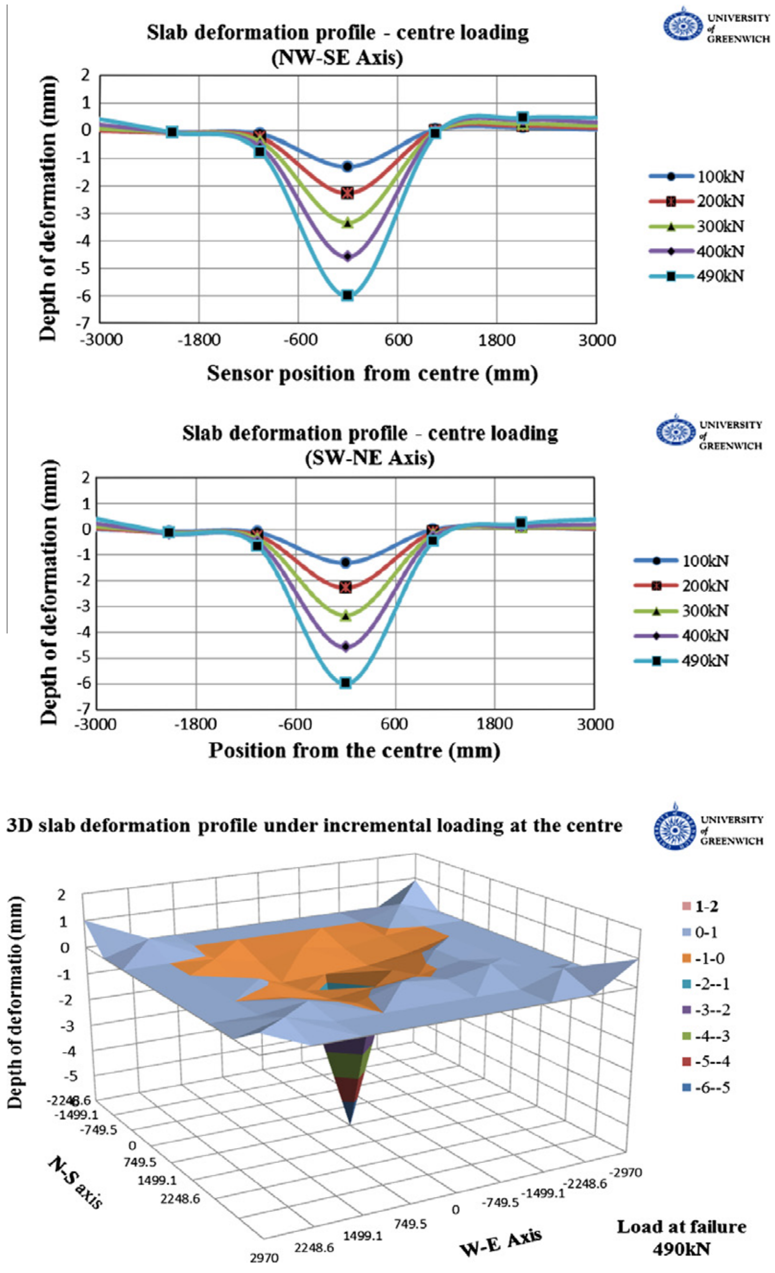


Fig. 16. Deflection pattern under incremental loading conditions at centre position of the ground slab.

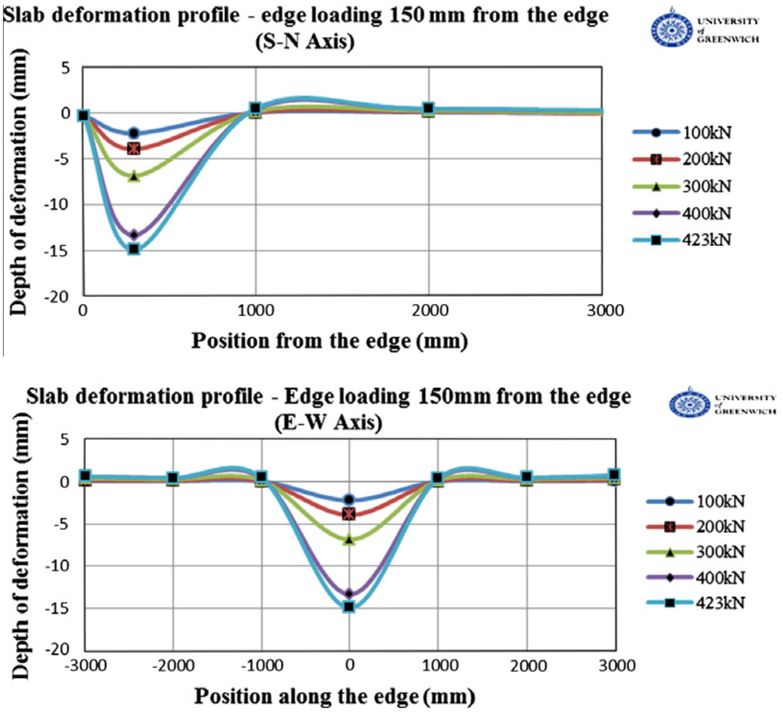


Fig. 17. Deflection pattern under incremental loading conditions at the edge position (150 mm from the edge).

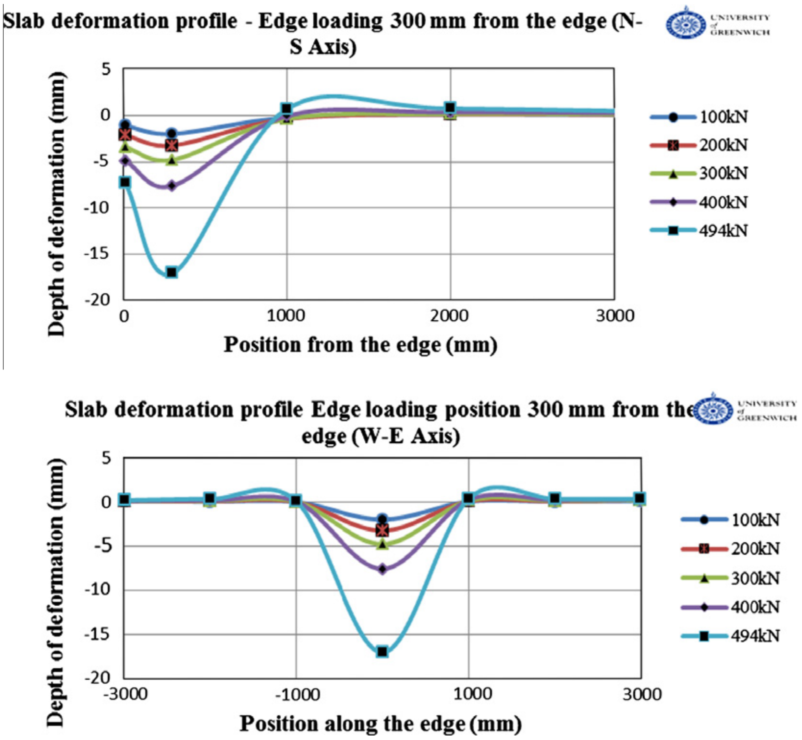


Fig. 18. Deflection pattern under incremental loading conditions at the edge position (300 mm from the edge).

The TR34.2003 (under review) was used to calculate the presented theoretical values based on equations 9.28–9.33 for punching shear. It can clearly be seen that the theoretical values differ significantly from the calculated test values. Astonishingly, synthetic fibre results show higher shear punching failure values than the steel fibre. No doubt these findings demand further investigation which the authors endeavour to address.

4. Summary of results

Comparison of the results for steel fibre and synthetic fibre in terms of punching shear values, Table 7, demonstrates that the ground supported slab reinforced with synthetic fibre has produced higher values at failure than the steel fibre reinforced slab. This applies to all five point tests carried out in this investigation, Fig. 9.

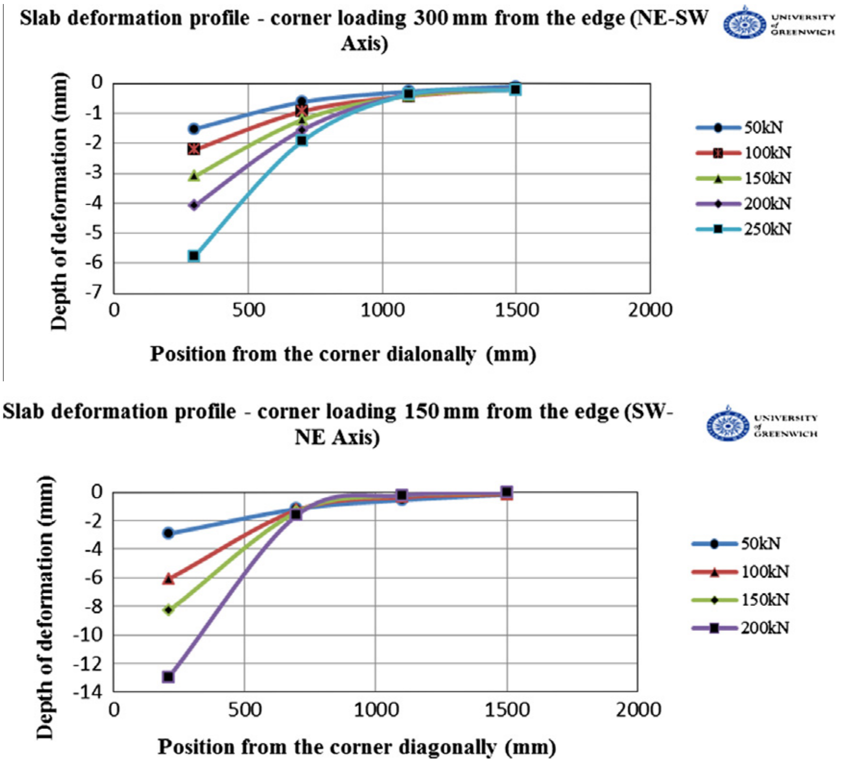


Fig. 19. Deflection pattern under incremental loading conditions at the corner position (150 mm and 300 mm).

Table 7
Punching shear load values at failure for steel and synthetic fibre reinforced ground slabs.

Test description	Steel fibre slab punching shear load (kN)		Synthetic fibre slab punching shear load (kN)	
	Theoretical values	Test values	Theoretical values	Test values
1 – Central/internal loading	387	480	387	490
2 – Edge/load plate centred 150 mm from slab edge	290	350	290	427
3 – Edge/load plate centred 300 mm from slab edge	290	443	290	500
4 – Corner/load plate centred 150 mm from slab corner	194	187	194	240
5 – Corner/load plate centred 300 mm from slab corner	193	310	193	373

Observations concerning the plate movements (deflections) measured at failure have been reported in Table 6. Remarkably, no visible cracks were observed at load position 1 (centre of the slab) at failure. The same observations also were made in the case of the steel fibre slab tested previously [2]. Crack development and propagation of the slab due to the adopted step loading conditions have also been detailed in Table 6.

The theoretical and test values with respect to punching shear load up to the failure point, for both steel and synthetic fibre slabs, have been presented in Table 7. In calculating the theoretical values the estimated values for flexure have been taken from Meyerhof's work, equations (9.10a)–(9.12b) [8].

The theoretical punching shear values have been estimated using clauses 9.11.1 and 9.11.2 of TR34.2003 and it should be noted that both TR34.2003 and TR65 [9] state that shear capacity enhancement is NOT permitted with the use of synthetic fibres.

The results shown in Table 7 demonstrate clearly that the theoretical values are significantly lower than the test values in both cases (steel and synthetic fibres) at all five test positions.

5. Conclusions

The results of this investigation demonstrate that the use of synthetic fibres at a dose of 7 kg/m^3 compares favourably with hook ended steel fibres at a dose of 40 kg/m^3. These results can be considered significant as they challenge common belief and practice within the sector. For example the TR34.2003 (under review) document states that, *"Macro synthetic fibres provide some post-cracking or residual moment capacity but with significantly lower performance than steel fibres. They are not known to be used in industrial floor construction"*. The results reported in this paper can be considered as reliable as all the necessary measures had been put in place in accordance with normal test practice within the discipline. The same testing conditions were applied to the synthetic fibre slab as to the previously reported steel fibre slab including the ground conditions, testing facilities and infrastructure.

The results of this research also clearly demonstrate the significance of tests at grand scale, particularly within the concerning domain (ground supported slabs). As discussed earlier, the results were conclusive in overcoming the limitations of a 3.0 × 3.0 m slab with regard to lifting of the corners and edges that were observed and reported in the earlier works. The theoretical values reported in Table 7 are significantly lower than the achieved test values. One explanation for this is that the theoretical values are based on equations suggested in TR34 which are not dedicated equations for synthetic fibre concrete. This reinforces the significance of findings in this research which can be considered potentially for modification of the suggested equations.

It is important to emphasise the significance of the process of adding fibre to the ready mix prior to placing the concrete. In order to prevent any balling of the synthetic fibre to form, it is essential to add the fibre at a very slow rate and at intervals while the concrete mixer is in motion.

It should be noted that the barchip "Shogun" synthetic fibres have a melting point of 150–165 °C. This may be a cause for concern to floor construction purposes.

Acknowledgements

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References

[1] Cengiz O, Turanli L. Comparative evaluation of steel mesh, steel fibre and high-performance polypropylene fibre reinforced shotcrete in panel test. Cem Concr Res 2004;34(8):1357–64.

[2] Alani AM, Beckett D, Khosrowshahi F. Investigation of the mechanical behaviour of a steel fibre re-inforced concrete ground slab. Mag Concr Res 2012(5). http://dx.doi.org/10.1680/macr.11.0007.

[3] Beckett D. Strength & serviceability design of concrete industrial ground floors. In: Teknische Akadamie Esslingen, 5th international colloquium, January 21–23 2003. Industrial floors 03, vol. 2; 2003. p. 601.

[4] Beckett D. Concrete ground slab test facilities at the university of Greenwich: an update. In: Teknische Akademie Esslingen, 6th international colloquium, January 16–18 2007. Industrial floors 07, vol. 2; 2007. p. 707.

[5] British Standards Institution. BS 1377: Part 1: 1990. Methods of tests for soils for civil engineering purposes – general requirements and sample preparation.

[6] British Standards Institution. BSEN 14651:2005+A1:2007. Test method for metallic fibre concrete. Measuring the flexural tensile strength (limit of proportionality (LOP), residual).

[7] The Concrete Society. Technical report 34. Concrete industrial ground floor slabs – a guide to their design and construction. 3rd ed. 2003.

[8] Meyerhof GGW. Load carrying capacity of concrete pavements. J Soil Mech Found Div. In: Proceedings of the American Society of Civil Engineers (ASCE), vol. 88. June 1962. p. 89–166.

[9] Concrete Society Technical Report No. 65. Guidance on the use of macro-synthetic-fibre-reinforced concrete. Report of a concrete society working group, April 2007.