Mechanical Properties of Macro-Synthetic Fibre Reinforced Concrete under Static loading for Railway Transoms Application

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ABSTRACT

Most researches about railway bridges focus on the sleepers which are essential components within the track infrastructure. Indeed, most of these studies reveal that the existing sleepers made of either timber, steel or prestressed concrete are not entirely adequate for the modern railway operational conditions. Correspondingly, transoms (i.e. considered as large sleepers) used on railway bridges have higher design requirements as compared to traditional sleepers on ballasted track since they directly transfer the high static and dynamic loads from the rails to the bridge girders. These concerns related to the sleeper's material have long been acknowledged by researchers, however their practical replacements with composite alternatives remain fairly limited. Therefore, this research addresses the use of Macro-Synthetic Fibre Reinforced Concrete (MSFRC) as an alternative and sustainable material for transoms in the field of railway bridges. Accordingly, the research presented herein will focus on the mechanical properties of macro-synthetic fibre reinforcement in concrete subjected to various static loadings. More emphasis has been given to the flexural and tensile strength characteristics since their associated stresses induced throughout the railway bridge ties (i.e. transoms) are comparatively higher. In addition, the effects of different fibre volume and aspect ratios will be thoroughly compared and discussed. The outcomes generated by the experimental tests are expected to enhance the durability, workability and flexibility of the concrete sleepers towards a more sustainable Australian railway track infrastructure.

1 INTRODUCTION

As stated throughout several studies, railway sleeper characterises an essential component of the railway track system towards the safety and performance demands (Hameed & Shashikala 2016; Sharma et al. 2017; Shin, Yoo & Yoon 2018). Also commonly known as transoms (i.e. bridge ties), sleepers are the transverse components beneath the rails which primary functions are to maintain the track geometry and redistribute the high applied wheel loads (i.e. vertical, lateral & longitudinal) at tolerable stresses onto the supporting ballast or girders (Kumar & Sambasivarao 2014; Tzanakakis 2013). Currently, there are over 2.5 billion timber sleepers in-service around the world from which 8 million are located throughout the Queensland railway network (Manalo et al. 2010). Nevertheless, with the increase in speed and axle loads of trains as well as the unavailability of high-quality timber throughout the years, engineers implemented the use of steel, concrete and polymer sleepers which offered superior mechanical behaviour (Sadeghi & Barati 2012). Figure 1 below highlights the geometrical characteristics of the wooden, steel and prestressed concrete sleepers typically in service throughout the Australian railway network.

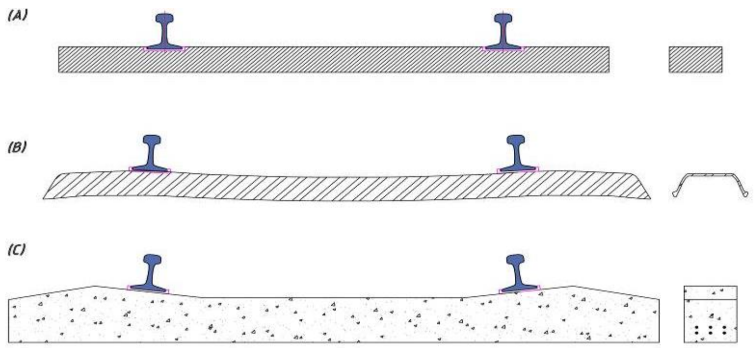

Figure 1 – Existing sleepers: (a) Wooden, (b) Steel, (c) Prestressed concrete

Characteristically, sleepers are designed for a lifetime (i.e. 20 – 60 years) either equal or greater than the expected service life of the rail thus providing an efficient work cycle for the full track system. However, these sleepers are usually susceptible to premature failures resulting from material degradation, corrosion and cracks (shown in Figure 2) which considerably increase the maintenance frequency and cost.

Figure 2 - Failure modes of sleepers (a) Timber, (b) steel, (c) Concrete (Ferdous & Manalo 2014)

In recent years, numerous developments in the field of railway sleepers have emerged, highlighting the sustainable characteristics of composites material as an alternative to traditional timber, steel and prestressed concrete sleepers. Indeed, these composite technologies could be engineered with superior mechanical properties to further reduce the disposal and maintenance cycles of the railway track components to a minimum. Nowadays, these modern composite sleepers are predominantly categorised into two groups wherein which the sleepers are either manufactured entirely from polymer matrices or through the strengthening of existing sleeper materials with embedded fibre reinforcement technology (i.e. fibre reinforced concrete).

Indeed, such incorporation of fibres is predominantly targeted towards the partial or complete substitution of the steel prestressed cables to further improve the design efficiency in terms of weight, adaptability, mechanical properties and corrosion resistance. As a result, FRC provides relatively greater reinforcement towards a more durable and ductile concrete (shown in Figure 3), characteristically suppressing thermal (i.e. freeze-thaw conditions), plastic and drying shrinkage cracks. Other advantages of FRC over conventionally reinforced concrete include: a reduction in weight by approximately 25%, 27% decrease on average in concrete consumption and a 42% diminution in the use of steel reinforcement (Kohoutková & Broukalová 2013).

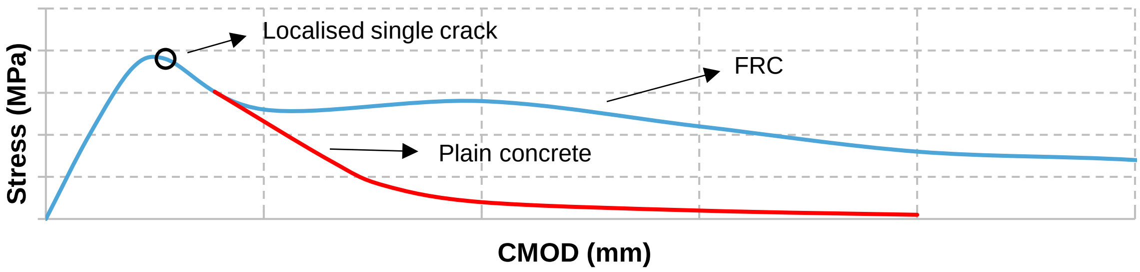

Figure 3 – Flexural behaviour of FRC as compared to plain concrete

However, despite all the aforementioned benefits of FRC, its implementation in specialised industry such as railway remained fairly limited. This is mainly due to the knowledge gap surrounding the optimum fibre dosage for different fibre types (i.e. natural, glass, steel & synthetic) and their respective effects on the strength and durability behaviours of concrete. Therefore, in an effort to continuously provide an innovative solution, the study herein presented will focus on the reinforcing capabilities of macro-synthetic fibres integrated in traditional prestressed concrete sleepers towards efficiently reducing the cost while optimising the strength and failure characteristics. The macro-synthetic fibre reinforcement chosen for the intend of the herein presented study is the polymeric BarChip fibre which characteristically possesses most of the required critical mechanical properties for sleeper application. These include good durability, strength (i.e. residual), corrosion resistance, environmentally friendly and light weight which are all favourable towards the partial or complete substitution of conventional reinforcing steel bars in prestressed concrete sleepers.

2 METHODOLOGY

2.1 Concrete Mix Design

The high strength concrete mix (i.e. M50) herein presented was designed and further adjusted to achieve a characteristic class strength of at least 50 MPa with a water-to-cement (w/c) ratio of approximately 0.39. These class limitations ensure that all of the fifteen batches met the minimum prestressed concrete sleepers' strength, durability and workability requirements as specified in the relevant Australian Standards: AS 1085.14-2012. Table 1 below summarises the concrete mix design implemented towards the investigation of the mechanical behaviour of macro-synthetic fibre reinforced concrete.

Table 1: Design mix as per expected concrete class strength

No.	Component	Dosage (kg/m^3)
1	Builders Cement (30% fly ash)	445.5
2	Blue Metal – 10mm Coarse aggregate	869.8
3	Nepean Paving Sand (Coarse)	510.0
4	Newcastle Sand (Fine)	350.0
5	Total Water	175.2
6	High-Range Water Reducer (HRWR)	4.4 – 5.3
7	Water-to-Cement ratio (w/c) ~ 0.39	

2.2 BarChip Fibres

The BarChip macro-synthetic fibre concrete reinforcement are predominately made from a high performance polypropylene base material, providing structural reinforcement (i.e. class II) in concrete, mortar and grout (BarChip 2018). The macro-synthetic fibres herein investigated are the BarChip 48 and BarChip MQ58 (shown in Figure 4) which compliance with EN 14889-2 have been casted at six different fibre volume ratios ranging from 0.0% (control) to 2.0%. The use of fibres is expected to increase the durability of the concrete while concurrently reducing the carbon-dioxide (CO_2) emissions. Table 2 below summarises the characteristics of the BarChip synthetic fibres studied with their associated structural applications.

Table 2: Physical and Chemical characteristics of the BarChip fibre products (BarChip 2018)

Fibre	Length (mm)	Base Material	Tensile Strength	Young's Modulus	Applications
BarChip 48	48	Virgin Polypropylene	640 MPa	12 GPa	Pavement, Industrial floors & Precast components
BarChip MQ58	58	Bi-Component Polymer		10 GPa	

Figure 4 – (a) BarChip 48, (b) BarChip MQ58, (c) Length Comparison

2.3 Experimental Methodology

For enhanced accuracy and reliability of the experimental results, the concrete manufacturing process was based on controlled laboratory conditions where 105 specimens comprising of cylinders (Ø100 x 200 mm) and beams (150 x 150 x 575 mm) were tested under compression and residual flexural strength tests respectively. Figure 5 below represents the specimen sizes used in accordance with the relevant Australian Standard: AS 1012.8.1-2014 'Method of making and curing concrete – Compression and indirect tensile test specimens', AS1012.9-2014 'Methods of testing concrete – Method 9: Compressive strength tests – Concrete, mortar and grout specimens' and European Standard: EN 14651-2005 'Test method for metallic fibered concrete – Measuring the flexural tensile strength'.

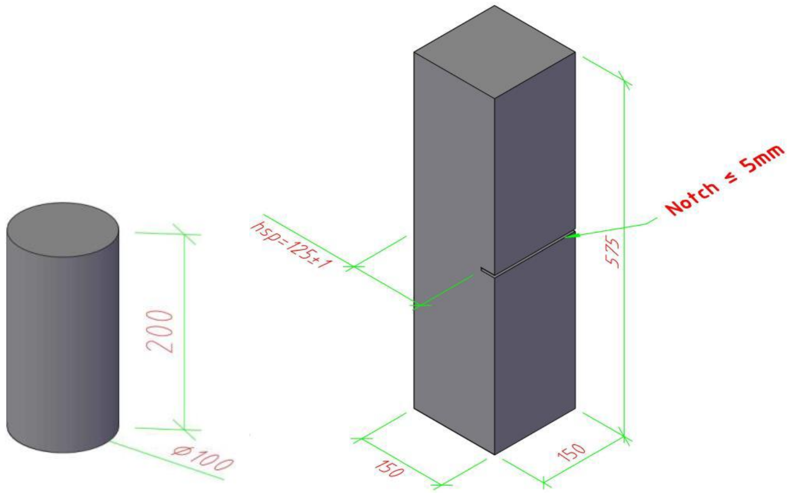

Figure 5 – 3D representation of the specimens tested

The cylinder samples have been tested at 28 days to provide essential understanding of the characteristic compressive strength growth in MSFRC. The specimens were then capped, measured and subsequently loaded in the compression machine as shown in Figure 6-a below.

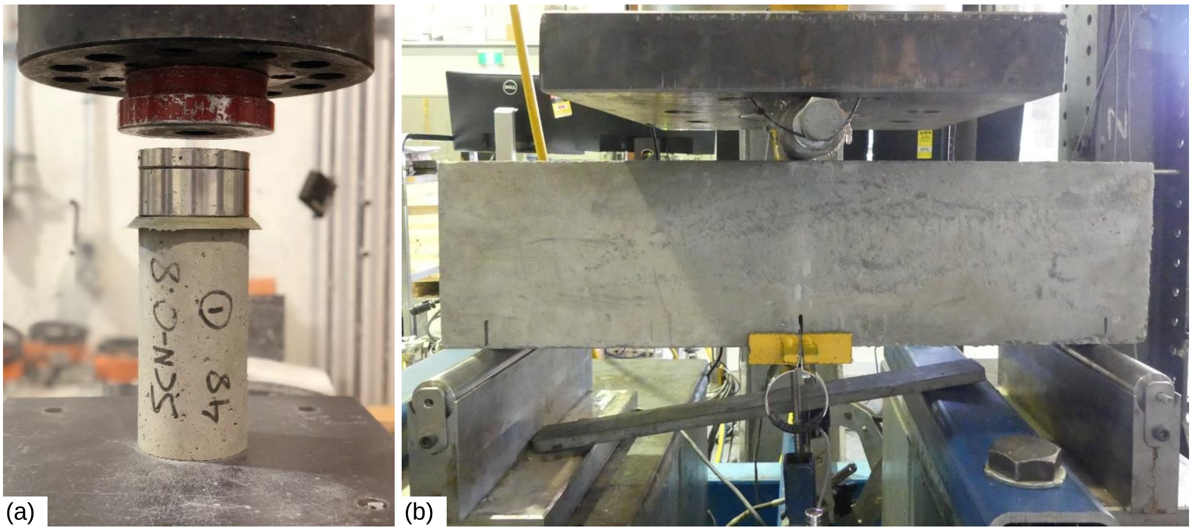

Figure 6 – Test setup and instrumentation (a) Compressive test, (b) flexural test

Similarly, after 28 days, the beam specimens (shown in Figure 6-b) were equipped with crack mouth opening displacement (CMOD) and linear variable differential transformers (LVDT) at mid-span, measuring both the crack width and the vertical displacement respectively. Correspondingly, the flexural strength of the specimens was investigated through a 3-point bending test during which both the pre-cracking (i.e. LOP) and post-cracking (i.e. residual) stages of the macro-synthetic fibre reinforced concrete were determined.

3 EXPERIMENTAL RESULTS

3.1 Overview

The results generated from the experimental tests herein presented, summarises the fundamental mechanical behaviour of the macro-synthetic fibre reinforced concrete in terms of mix slump/spread results, characteristic compressive behaviour and residual (post-cracking) flexural strength. Indeed, these parameters are crucial towards the practical implementation of this innovative sleeper material.

3.2 Mix Spread/Slump Results

The expected spread flow for the MSFRC mix design was between 500 – 750 mm. This prerequisite ensures that both types of fibres (i.e. BarChip 48 & BarChip MQ58) were consistently dispersed throughout their respective specimens, while concurrently achieving a high level of workability towards practical implementations. Figure 7 below presents the spread/slump test results obtained thorough the different batches with increasing fibre content.

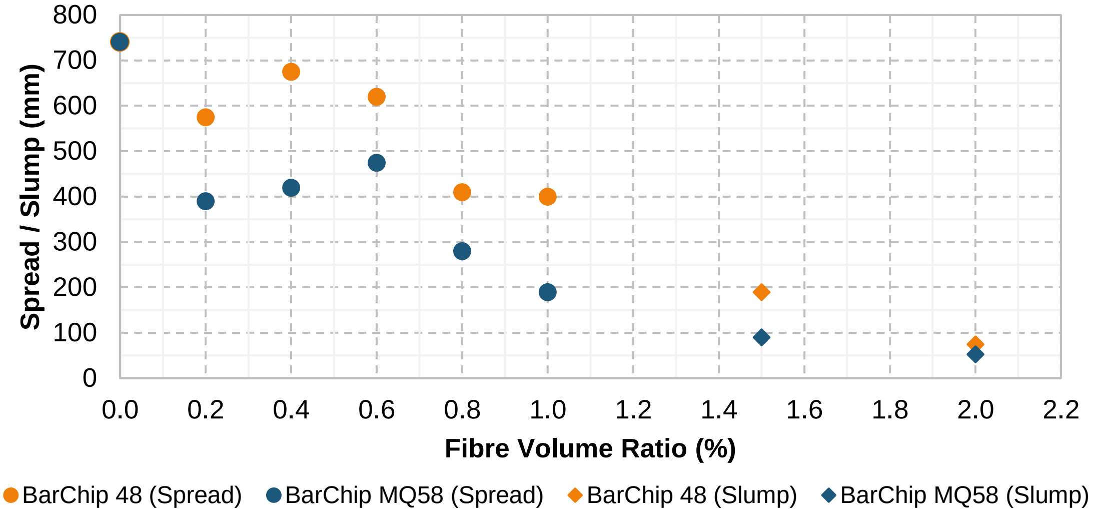

Figure 7 – Mix spread/slump results for BarChip 48 & BarChip MQ58

As expected, the plain concrete mix achieved the design mix requirement with a spread of 740mm. Nevertheless, as the fibre volume fraction were increased (i.e. above 1%), the spread flow for both fibre types were observed to drastically reduce towards an actual slump (shown in Figure 8), as a consequence of fibres balling. In addition, it was observed that BarChip 48 attained moderately higher spread flow as compared to BarChip MQ58 which individual fibre (i.e. bi-component polymer) typically break down in quite a few thinner and more flexible fibres. This behaviour of BarChip MQ58 enables a comparatively higher dispersion rate of the fibres at low volume fraction (i.e. up to 1%), despite reducing the workability of the mix by roughly 38% on average.

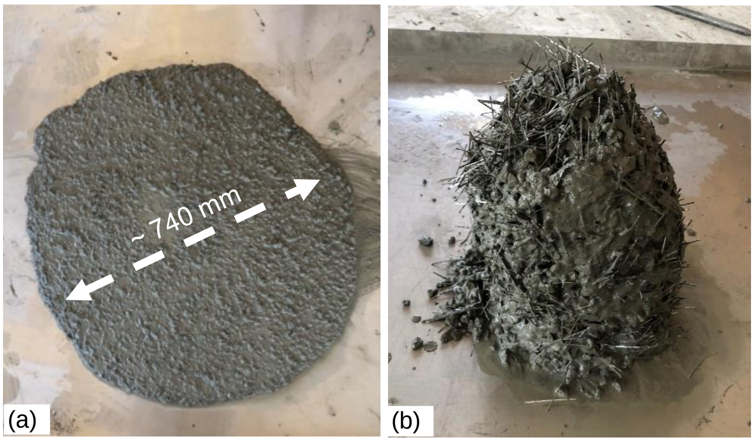

Figure 8 - Slump flow for various fibre volume ratio – (a) Control with 0.0%, (b) 2.0% fibres

3.3 Compressive Strength

At 28 days, the macro-synthetic fibre concrete specimens are expected to have reached 99% of their ultimate compressive strength capacity. As a result, most of the specimens encompassing BarChip 48 and BarChip MQ58 at different fibre volume fractions were observed to exceed the minimum 50 MPa requirement as illustrated in Figure 9 below.

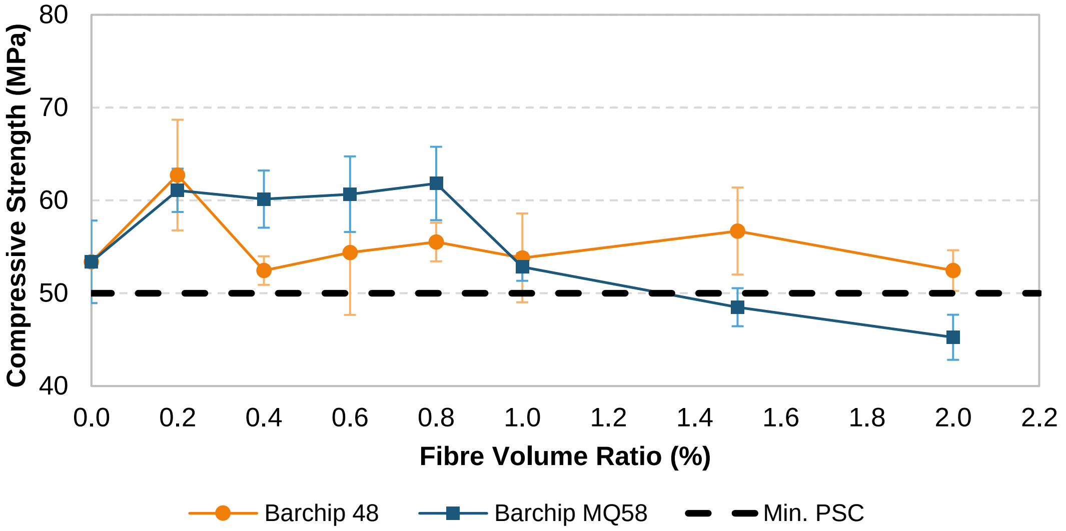

Figure 9 – Compressive strength vs. Fibre volume ratio at 28 days

On average, BarChip 48 specimens were observed to peak at 62.7 MPa (i.e. 0.2% fibres), thus characterising an increase of approximately 18% over plain concrete which ultimate capacity only achieved 53.4 MPa. This particular behaviour of BarChip 48 specimens at 0.2% fibre volume ratio can be justify by the slightly lower spread-flow obtained as previously highlighted. On the other hand, specimens reinforced with BarChip MQ58 (up to 1%) experienced on average a 6.6% increase in compressive strength as compared to BarChip 48. In addition, the ultimate strengths of the MSFRC encompassing BarChip MQ58 fibres were observed to be closely consistent up to 1.0% of fibres, reaching a peak at 0.8% with 61.8 MPa. However, as the fibre volume fraction exceed 1%, the compressive behaviour of the samples is found to significantly decrease due to the balling effect of longer fibres which also involved undesirable air voids and a reduction in workability.

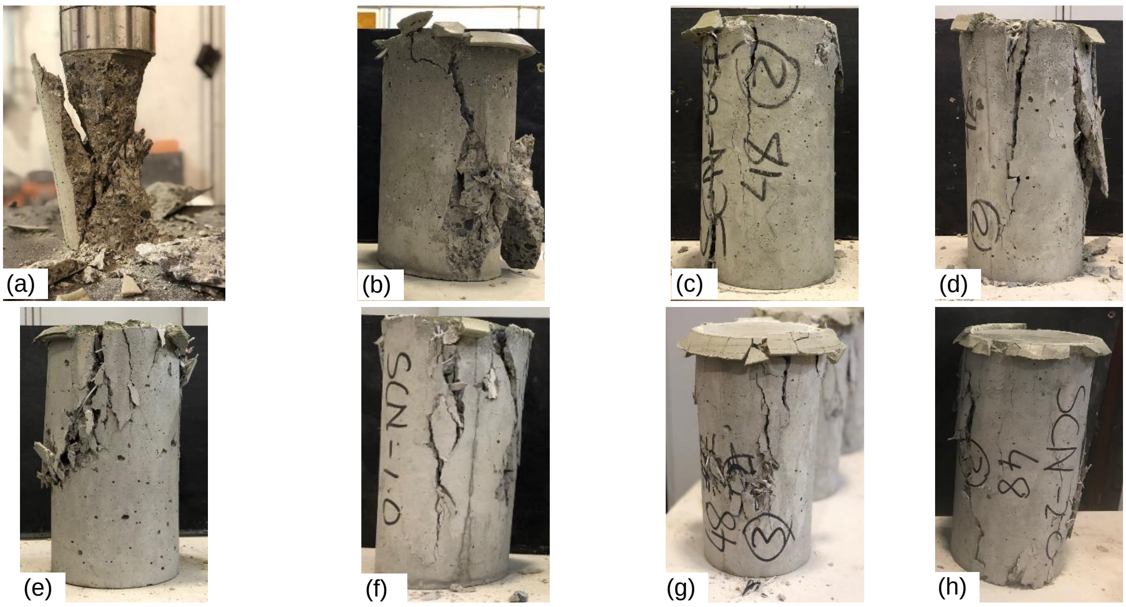

Figure 10 - Failure modes of BarChip 48 specimens under static compression test at 28 days (a) 0.0%, (b) 0.2%, (c) 0.4%, (d) 0.6%, (e) 0.8%, (f) 1.0%, (g) 1.5% & (h) 2.0%

Both BarChip 48 and BarChip MQ58 specimens were able to sustain relatively higher stresses with minimum cracks formation (i.e. splitting/shear failure) as compared to plain concrete (i.e. splitting/conical failure) as shown in Figure 10. This behaviour is mainly justified through the increase of fibres supressing cracks initiation and propagation towards improving the failure mechanisms.

3.4 Residual Flexural Strength

The flexural strength herein presented critically identifies the pre and post-cracking behaviours of concrete with increasing macro-synthetic fibre dosage as represented in Figures 11 and 12 below.

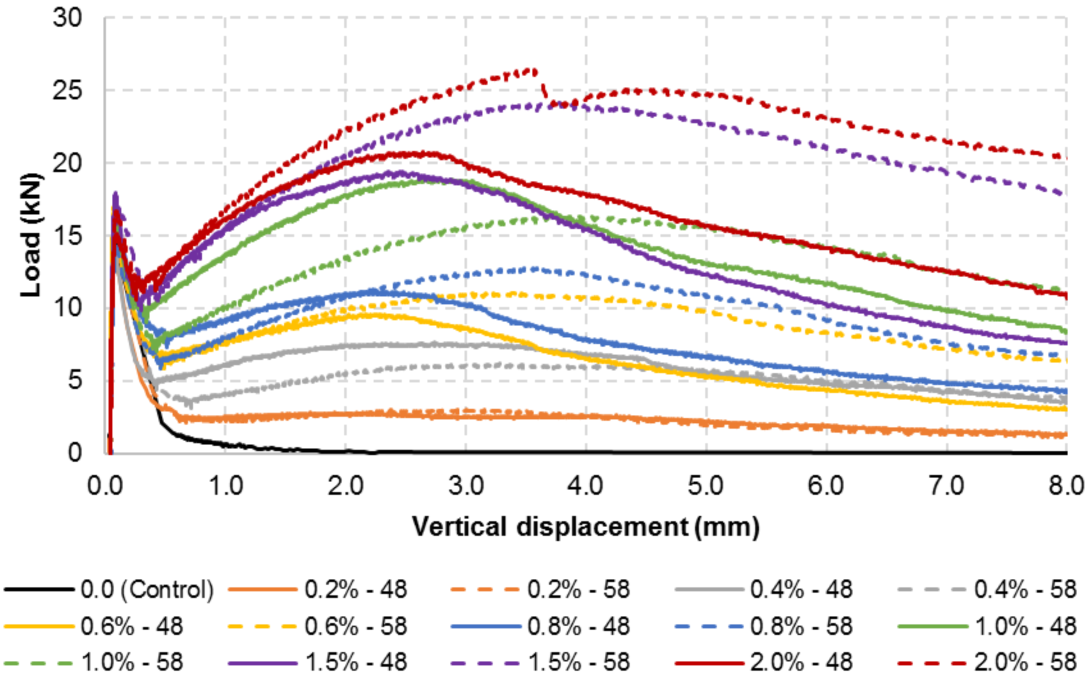

Figure 11 – Load vs. vertical displacement comparison for BarChip 48 & BarChip MQ58

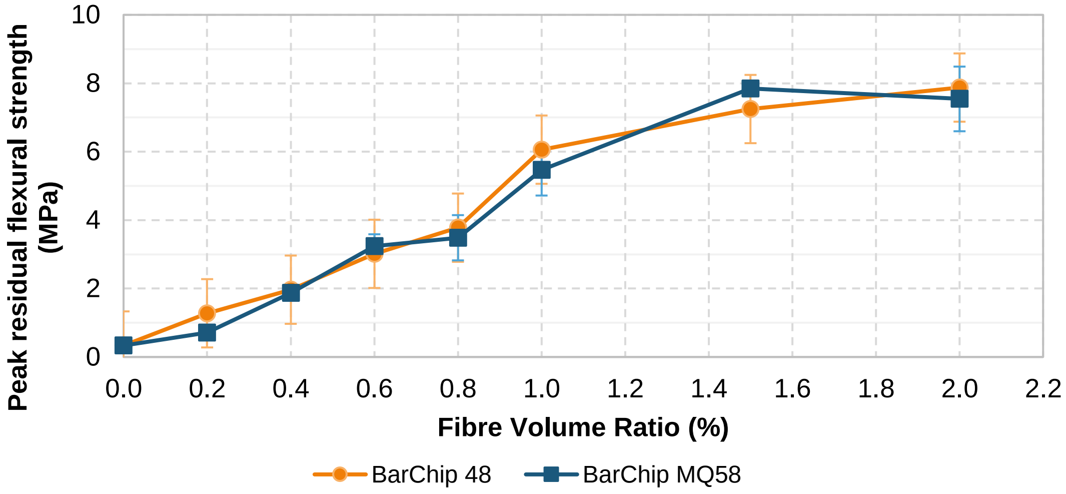

Figure 12 – Post-cracking flexural strength comparison for BarChip 48 & BarChip MQ58

In comparison, the post-cracking behaviour of MSFRC is observed to significantly increase as the fibre volume ratio increases up to 2.0%. Overall, both types of fibres exhibited a positive effect on the residual flexural behaviour of the concrete as summarised in Figure 12 above. For instance, BarChip 48 provided the greatest increase in residual strength at 2.0% (i.e. 7.88MPa) as compared to BarChip MQ58 which peaked at 1.5% with a post-cracking strength of 7.85MPa. This post-cracking behaviour of the MSFRC is justified by the mechanics of crack formation and propagation wherein which the fibres interact with the concrete matrix to stabilise and suppress crack growth.

4 CONCLUSION

This paper discusses three key impacts of macro-synthetic fibre reinforcement on the mechanical properties of concrete. An accurate experimental program has been developed in accordance with the relevant international standards to investigate the workability, compressive strength and residual flexural behaviours of the MSFRC. Accordingly, the specimens reinforced with macro-synthetic fibres (i.e. BarChip 48 & BarChip MQ58) were experimentally tested from which the following conclusions were achieved:

- Workability – Both types of fibre drastically influenced the workability of the concrete mix, implying a reduction of approximately 40% when mixed above a fibre dosage of 1%;
- Compressive strength – The experimental results demonstrated that the fibres provide a bridging effect characteristically reducing the crack propagation towards more a ductile failure mode. However, the addition of both types of fibre did not noticeably influence the ultimate compressive strengths. In fact, beyond 1.5% of fibres adverse effects were observed towards decreasing the compressive strength by 12.5% on average;
- Flexural behaviour – The addition of fibres was observed to have a negligible impact on the ultimate flexural strength (i.e. pre-cracking) of the notched specimens. However, the fibre reinforcement improved the fracture mechanisms towards a more ductile behaviour, characteristically minimising the loss in capacity sustain after the initial cracks. Overall, higher fibre dosages showed better performance in terms of residual flexural strength (i.e. post-cracking), ductility and toughness.

5 REFERENCES

- BarChip 2018, viewed 20 October 2018, <https://barchip.com/product/>.
- Ferdous, W & Manalo, A 2014, 'Failures of mainline railway sleepers and suggested remedies – Review of current practice', *Engineering Failure Analysis*, vol. 44, pp. 17-35.
- Hameed, AS & Shashikala, AP 2016, 'Suitability of rubber concrete for railway sleepers', *Perspectives in Science*, vol. 8, pp. 32-5.
- Kohoutková, A & Broukalová, I 2013, 'Optimization of Fibre Reinforced Concrete Structural Members', *Procedia Engineering*, vol. 65, pp. 100-6.
- Kumar, DK & Sambasivarao, K 2014, 'Static and Dynamic Analysis of Railway Track Sleeper', *International Journal of Engineering Research and General Science*, vol. 2, no. 6.
- Sadeghi, J & Barati, P 2012, 'Comparisons of the mechanical properties of timber, steel and concrete sleepers', *Structure and Infrastructure Engineering*, vol. 8, no. 12, pp. 1151-9.
- Sharma, RC, Palli, S, Sharma, SK & Roy, M 2017, 'Modernization of Railway Track with Composite Sleepers', *International Journal of Vehicle Structures & Systems*, vol. 9, no. 5, pp. 321-9.
- Shin, H-O, Yoo, D-Y & Yoon, Y-S 2018, 'Enhancing the resistance of prestressed concrete sleepers to multiple impacts using steel fibers', *Construction and Building Materials*, vol. 166, pp. 356-72.
- Tzanakakis, K 2013, *The Railway Track and Its Long Term Behaviour*, 1 edn, Springer Tracts on Transportation and Traffic, Springer-Verlag Berlin Heidelberg.

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