

Development of high strength self-compacting fibre reinforced concrete for prefabricated concrete industry

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Abstract. Prefabricated construction is an emerging industry in Australia and considered a key mechanism to boost productivity in the construction industry. The use of fibre reinforced concrete has a huge potential in the prefabricated industry as the concrete can be delivered straight to the precast mould, eliminating in many cases the steel reinforcement, thus increasing production quotas and cost savings. Such results can be further improved by utilising self-compacting concrete reinforced with fibres. Although the use of steel fibres as reinforcement is now well established, in the precast industry thin walls and shape of the moulds can be a limitation to steel fibre as well as work health and safety concerns for handling. Under such conditions, the use of polymeric fibres can be extremely beneficial, reducing labour hours and placement time as well as improving safety. This paper reports the development of high strength self-compacting fibre reinforced concrete for application in prefabricated concrete industry, exploring the effect of Forta-Ferro and ReoShore fibres on concrete fresh and mechanical properties.

1 Introduction

Recent developments in precast concrete manufacturing has created a high demand for new concrete types with enhanced properties, both at early and late ages, and fibre reinforced concrete plays an important role in this scenario. Macro high modulus fibres, especially steel fibres, are already used for replacing rebars in non-structural applications and have a huge potential in the precast industry eliminating in several cases the need of steel reinforcement and improving the production efficiency, reducing the time and labour cost related to installation of steel rebar, and thereby enabling the production of thin precast elements. Steel fibres have various beneficial effects on the mechanical performance of concrete and the use of it has spread out in different applications such as industrial pavements, precast structural elements, tunnel lining, etc. [1]. In addition, guidelines, specifications and test methods for steel-fibre reinforced concrete are well established [2-5]. In Australia, the national standard for the design of concrete bridges was reviewed and the new release AS 5100.5 [6] now includes design procedures for steel fibre reinforced concrete in a comprehensive way. However, the limitations of steel fibres in terms of unfavourable effect on concrete rheology [7] and reduced workability, difficulty in finishing, hazards in handling, and corrosion of fibres cannot be disregarded. In addition, the stiff steel fibres may be problematic to be used in thin precast

elements of different shapes and therefore there is a crescent demand for alternative fibres that can effectively be used in fibre reinforced concrete.

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Micro synthetic (polymer) fibres are mainly used to reduce the cracking due to shrinkage and are not as effective in improving the structural properties and post-cracking behaviour of concrete with a small volume addition. Macro-synthetic fibres have been recently made available and can be suitable alternatives to steel fibres in some applications, although fibres of one type cannot offer all the improved properties due to the limitations of each type. For example, micro-fibres can be beneficial to arrest the micro-cracks and delay but are not effective in bridging macro-cracks whereas macro-fibres can bridge the larger cracks and thereby improve the post-cracking performance of concrete. Optimised combinations (hybridisation) of two or more types of fibres in concrete can develop better engineering properties than using only one type of fibre and can be achieved combining fibres with different shapes,

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dimensions, tensile strength, Young's modulus, ductility, and bond properties to cementitious matrices [8].

Forta-Ferro fibres are a recently-developed blend of synthetic fibres, designed as a cheaper, non-corrosive and easier-to-finish replacement for steel fibres. The product is a blend of two types of fibres: (i) fibrillated polypropylene fibres to reduce and control shrinkage and temperature cracking, and (ii) very heavy-duty twisted-bundle monofilament fibre made of a strong synthetic copolymer, to increase load-transfer and post-crack performance. ReoShore is a high-performance monofilament structural fibre made of 100% virgin polypropylene. The fibre is 45 mm, which is shorter than Forta-Ferro, and has higher stiffness when compared to Forta-Ferro, which may improve concrete toughness and crack control. The fibres used together are expected to complement each other by combining the beneficial effect of stronger and stiffer fibres in the first phase of crack opening to improve the flexural strength whereas the softer fibres in the later phase to improve the residual flexural performance.

Self-consolidating concrete (SCC) has fresh concrete properties with high flowing ability without segregation and thereby compacted by the self-weight without any vibration or added compacting effort [9]. These properties of SCC are highly beneficial in terms of reduction of labour cost to compact the concrete with vibration. This is especially true for the use of SCC in the casting of structural elements with congested reinforcement and in manufacturing of thin precast elements. The addition of fibres can further improve the mechanical performance of SCC.

Forta-Ferro is already used in a range of commercial precast products produced by Aus Pits in Australia. Aus Pits is an experienced pre-cast concrete manufacturing company, specialising in the supply of custom designed products including pits for storm water, drainage and connections for electrical, communications and data networks. Deakin University was engaged by Aus Pits for a R&D project to extend the existing range of fibre reinforced concrete products beyond the current limits by improving concrete properties.

This paper presents an experimental investigation conducted to develop high strength self-compacting fibre reinforced concrete for application in prefabricated concrete industry, using Forta-Ferro and ReoShore 45 fibres as reinforcement. This is an ongoing research project with the industry partner and the paper only highlights the material testing phase of the project.

2 Experimental program

Four batches of self-consolidating concrete were used in the research, where three different dosages of Forta-Ferro fibres (Fig. 1-a) were incorporated in three batches and a hybrid combination of Forta-Ferro and ReoShore 45 (Fig. 1-b) fibres (hybrid fibres) was added to the fourth batch of concrete. All mixes were produced in a ready mix concrete plant (Local Mix, Geelong, Australia), using a standard concrete mixer truck. To mimic a real scale production, for each batch of concrete

4 m³ of concrete was produced. Detailed properties of the two fibres are presented in Table 1 and the concrete batch identifications with the corresponding fibre dosages are given in Table 2. Mix proportions of the concrete batches are not included in this paper for confidentiality reasons. Fresh properties were assessed through slump flow test as per AS 1012.3.5 [10]. Compressive strength, indirect tensile strength and modulus of elasticity of concrete were assessed as per AS 1012.9 [11], AS 1012.10 [12] and AS 1012.17 [13]. To investigate the flexural strength and the post-cracking flexural behaviour, four beams were fabricated for each batch for the 28-day test. The tests were conducted following the BS EN 14651 [2]. The flexural strength f_{ctf} and the equivalent flexural strength ratio $R_{e,3}$ were calculated for each beam.

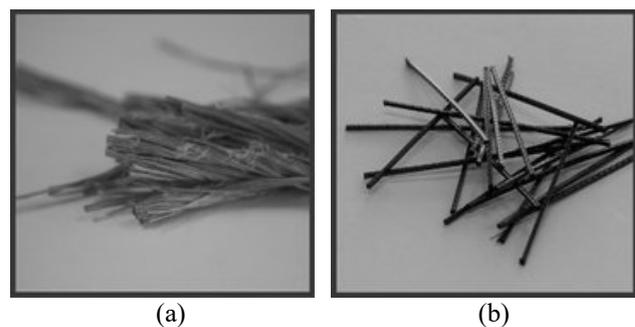


Figure 1. (a) Forta-Ferro and (b) ReoShore 45 fibres

Table 1. Fibre properties as per manufacturer's specification

Fibre type	Forta-Ferro	ReoShore 45
Length (mm)	54	45
Tensile strength (MPa)	570-660	750-850
Fibre form	Blend of twisted bundle of monofilament and fibrillated network	Monofilament
Acid/Alkali resistance	Excellent	Excellent
Absorption	Nil	Nil

Table 2. Concrete batches

Batch Description	Specification
FF-LD	Forta-Ferro – Low dosage
FF-MD	Forta-Ferro – Medium dosage
FF-HD	Forta-Ferro – High dosage
FF-LD/RS-LD	Forta-Ferro – Low dosage + RheoShore 45 – Low dosage

3 Results

3.1 Fresh properties

All mixes were designed to flow on the test apparatus in the range of 510 to 590 mm (diameter), with ideal flow of 560 mm in 4 seconds. Figure 2 shows a fibre reinforced self-compacting concrete produced in this work during the execution of the flow test. Visual observations during the test also offer additional information about bleeding capacity and segregation potential. All mixes accepted as self-compacting concrete flowing beyond the minimum flow range, except for the the mix with the highest dosage of Forta-Ferro fibres, FF-HD. Although the mix presented good fibre dispersion and enough paste, the higher dosage of fibres reduced the fluidity of the mix and required longer mixing time to obtain a reasonable mix workability. However the desirable fresh properties were not achieved in that particular mix.



Figure 2. Flow test of one of the mixes produced in this project giving evidence on the self-compacting properties of the material

3.2 Compressive strength, tensile strength and modulus of elasticity

The 28-day test results for compressive strength, split tensile strength and modulus of elasticity are summarised in Table 3 and the comparison of the results for four concrete batches are plotted in Fig. 3 and 4. Results revealed that batch FF-LD where low dosage of Forta-Ferro fibres were added to standard 60 MPa mix showed the highest compressive strength and modulus of elasticity on 28 days. The characteristic compressive strength calculated from the 28 day-compressive strength following AS3600 ensures that the batch meets the requirement of 60 MPa high strength concrete grade. The mix with the highest dosage of Forta-Ferro fibres, FF-HD exhibited the lowest compressive and split tensile strength, and modulus of elasticity among the four batches of concrete. The characteristic compressive strength of this batch is 47 MPa, which lies in the range of normal class concrete as per AS 1379 (2007). Hence, the mix does not meet the criteria for being a high strength concrete. The poor performance of this batch of concrete can be attributed to the poor fresh property

observed during casting. It is therefore likely that the mix was not self-compacted properly (since no additional compaction was applied), which led to the reduced strength. Further rheological adjustments would be necessary to make this mix suitable for the current fabrication process. Batch FF-LD/RS-LD showed slightly lower compressive strength and modulus of elasticity compared to FF-MD, however the compressive strength meets the requirement of high strength concrete - grade 60 MPa.

Table 3. Summary of 28-day test results

Batch Description	Mean Compressive strength f_{cm} (MPa)	Split tensile strength $f_{ct,sp}$ (MPa)	Modulus of elasticity E_c (MPa)
FF-LD	69.6	3.89	34,153
FF-MD	69.6	5.00	32,687
FF-HD	52.7	2.28	28,968
FF-LD/RS-LD	67.0	3.87	32,866

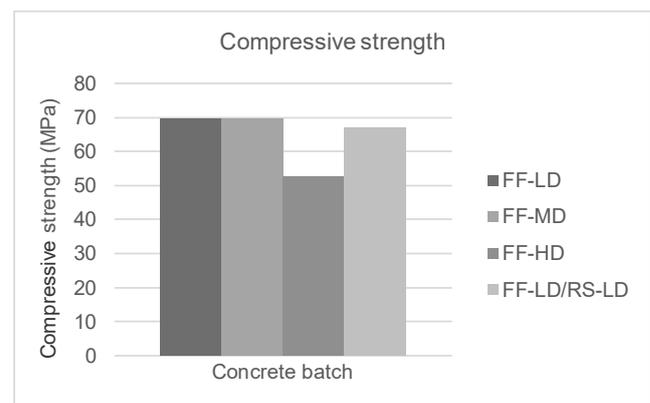


Figure 3. Compressive properties of four batches of fibre-reinforced concrete

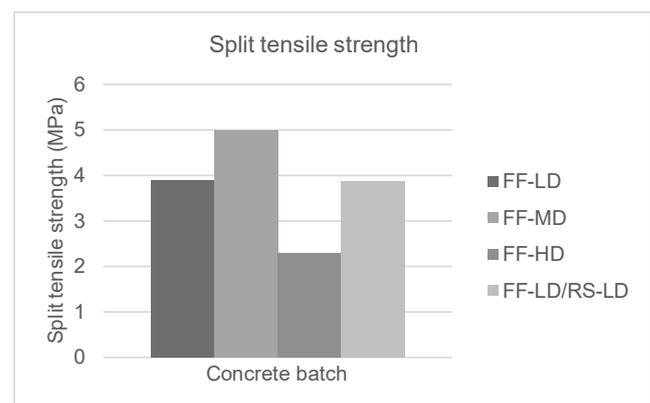


Figure 4. Tensile properties of four batches of fibre-reinforced concrete

3.3 Flexural strength and equivalent flexural strength

The flexural strength determined from the notched beam testing under three-point bending and $R_{e,3}$ values for all four concrete batches are summarised in Fig. 5 and 6. The crack mouth opening was measured with CMOD transducer conforming to BS EN 14651 [2]. These results were calculated from the load-CMOD plots (Fig. 7).

The increase in fibre dosage from low dosage in FF-LD to high dosage in FF-HD did not improve the flexural strength of concrete, however, residual flexural strength was increased significantly from 36% to 79%, which is clearly indicative of the effectiveness of fibres in post-cracking behaviour of concrete. The slight reduction of flexural strength of FF-HD when compared to FF-LD, can be explained by the inadequate fresh properties of FF-HD. FF-HD might not have achieved proper compaction which reduced the flexural strength, similar to the observation from compressive and split tensile strength.

On the other hand, batch FF-MD and FF-LD/RS-LD showed significant improvement of flexural strength compared to FF-LD and FF-HD, being 19 and 25% higher than FF-LD. The higher flexural strength of the two batches justify not only the effect of fibres but also the adequacy of the mix design to achieve appropriate rheology of self-compacting concrete. Comparatively higher flexural strength in FF-LD/RS-LD than FF-MD can be correlated with the efficiency of hybrid fibres, resulting in the overall improvement of the stress-transfer mechanism.

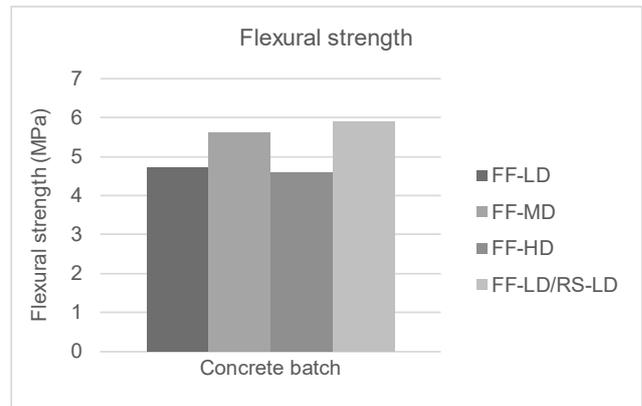


Figure 5. Comparison of flexural strength

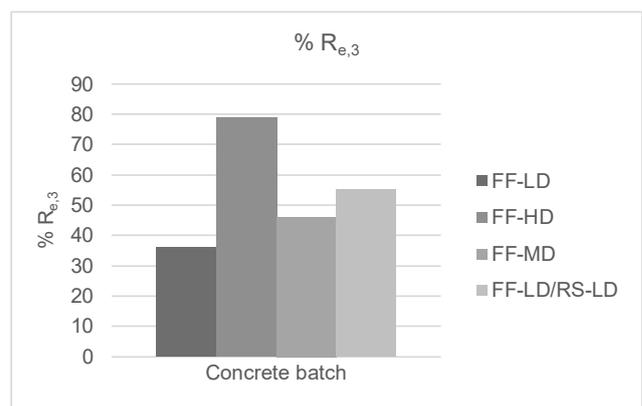


Figure 6. Comparison of residual flexural performance

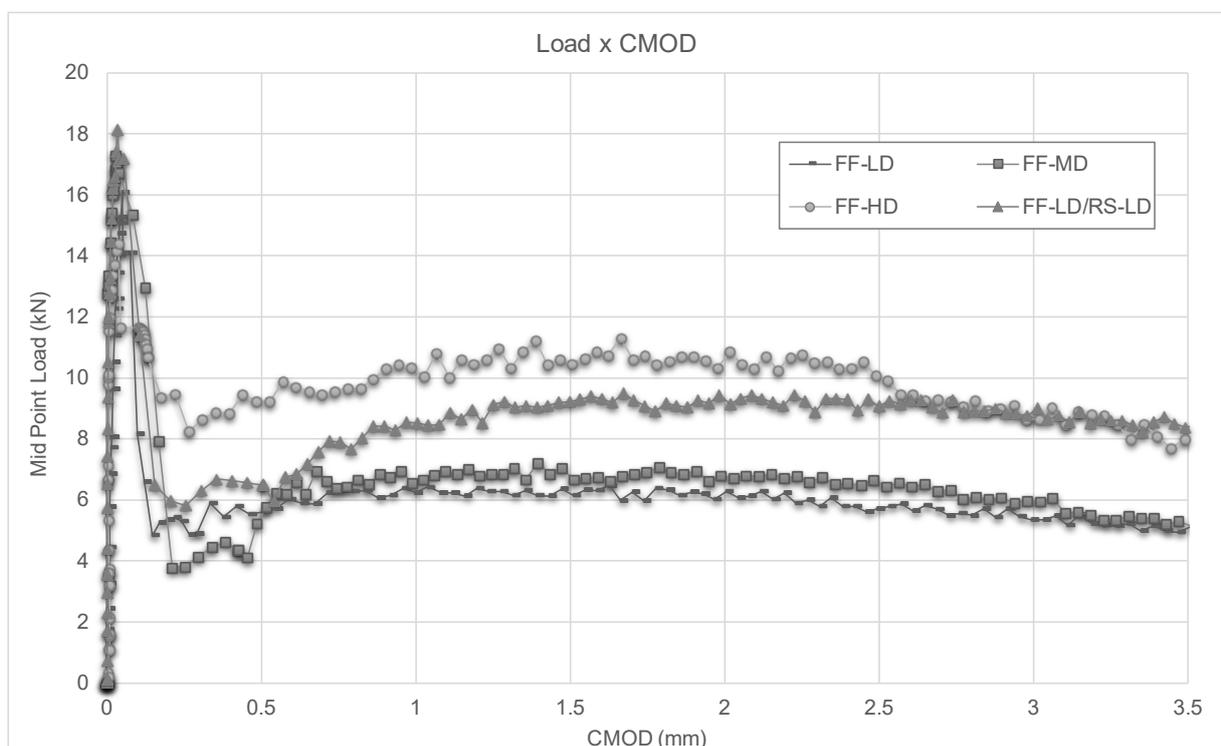


Figure 7. Load vs. CMOD plots of four batches of fibre-reinforced concrete

Regarding the flexural performance, the technical report 'TR63' by Concrete Society [3] states that the flexural strength and ductility of a concrete beam is only predicted to increase if $Re,3$ is greater than 0.5. The equivalent flexural strength ratio $Re,3$ of FF-MD and FF-LD/RS-LD were 0.46 and 0.55, respectively, which are much higher than that of FF-LD and justify much better residual flexural performance of these two batches. However, the values are significantly lower than batch FF-HD ($Re,3 = 0.76$) due to comparatively lower dosage of fibres used in these two batches. Considering this criterion, it is expected that both FF-HD and FF-LD/RS-LD mixes would improve the flexural performance of the fibre-reinforced pits (the target application of the mixes) eliminating the conventional steel reinforcement. However, much lower compressive strength and unacceptable fresh properties of FF-HD hinder its suitability for target application.

4 Conclusions

This paper investigated fresh and mechanical properties of four different fibre-reinforced high strength self-compacting fiber reinforced concrete batches fabricated using three different dosages of Forta-Ferro fibres and a hybrid combination of Forta-Ferro and ReoShore fibres, in order to identify suitable mix(es) for the production of pre-cast components, as a part of a collaborative research project between Deakin University and Aus Pits. Considering overall performance, the hybrid mix FF-LD/RS-LD (low dosage of Forta Ferro + low dosage of RheoShore fibres) seems to be the most suitable mix design out of the four for the intended application. The hybrid mix not only met the criteria for compressive, tensile and flexural strength but also showed significantly improved post-cracking flexural behaviour representing improved ductility. This feature is highly desirable in the design of concrete structures and can be beneficial in the construction of precast concrete products of thin sections by replacing the conventional rebar and thereby reducing the construction time and labour cost.

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