Cement and Concrete Research xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: www.elsevier.com/locate/cemconres

The effect of mixing on the performance of macro synthetic fibre reinforced concrete

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ARTICLE INFO

Keywords:
Fibre reinforced concrete
Macro synthetic fibres
Concrete mixing
Fibre deterioration
Single fibre pull-out
Residual flexural tensile strength
Mixing time
Mixer type

ABSTRACT

Concrete suffers from brittle failure due to its low tensile strength. This drawback can be compensated for by adding reinforcement bars and/or steel fibres, and more recently, macro synthetic fibres. When mixing concrete with these fibres the aggregates could damage the fibres. This paper presents work done on the effect of mixing on the performance of macro synthetic fibre reinforced concrete. Single-fibre pull-out tests were conducted on various fibres in both the original and mixed state. Furthermore, flexural tests were performed to investigate the influence of mixing time and mixer type on the performance. It can be concluded that mixing is beneficial for flat type fibres, but the performance of crimped or embossed fibres remains the same. Furthermore, longer mixing times (> 10 min) in a pan mixer are detrimental to the performance, while the performance in a tilting drum mixer remains unchanged even after a mixing time of 60 min.

1. Introduction

Even though concrete is globally the most widely utilised building material, it still has certain shortcomings. These include low tensile strength in comparison to compressive strength, as well as its brittle failure in uni-axial or flexural tension. This results in structural design models not including the tensile strength of concrete [1,2]. In order to compensate for this, high tensile strength steel reinforcing bars are typically included. However, due to disadvantages regarding steel reinforcing, such as durability issues in corrosive environments [3–5] and being labour and time-intensive, fibre reinforced concrete (FRC) has been developed as a partial alternative [6–8].

FRC is becoming more widely used in the civil engineering field due to its favourable mechanical properties [6–9]. In particular, fibres increase the toughness of concrete, i.e. providing concrete with a significant residual tensile strength in the cracked phase, due to fibres bridging across crack surfaces [10–12]. Recently, more work is also done on the tensile creep of cracked FRC sections as this creep can increase deflections of structures where fibres are used as the primary reinforcement [13–16]. For most structural applications of FRC, steel is preferred as a material for fibre reinforcement, however, macro synthetic fibres have been developed and successfully introduced to the construction industry [17–19]. The use of macro synthetic fibres in concrete slabs-on-grade has become one of its primary applications [20]. However, the addition of fibres to concrete slabs-on-grade is only beneficial if a yield-line design approach is followed [21,22].

Properties of synthetic fibres are crucial to their performance in cement-based composites such as concrete. As the fibre contents are relatively low (normally < 1% by volume), fibres should possess strength characteristics exceeding that of the surrounding cement matrix as well as have a high aspect ratio [23,24]. Due to fibres working in tension, lateral fibre contraction occurs as a result of longitudinal fibre elongation, ultimately breaking the bond between the fibre and the surrounding concrete matrix. Mechanical interlock can be used to increase the bond characteristics between the fibres and the surrounding matrix. Synthetic fibres have shown to perform worse than steel fibres in the tensile creep of cracked sections [15,25], however, this is only a problem with high, long term loading of a cracked section, which is typically not the case for slabs-on-grade.

Previous research [26] to determine an optimal fibre shape using single-fibre pull-out tests on different existing macro-synthetic fibre geometries, concluded that crimped fibre geometries produce the most promising results. More recent studies [27,28] indicated that the type of fibre deterioration and the degree of deterioration experienced during mixing of fresh FRC is dependent on the parent material, production technology, fibre coating, size and the surface of the fibre. The study also established that the tensile strength of macro-polymer fibres decrease as mixing time increases and that the post-cracking flexural performance of FRC decreases as the mixing time increases for the same fibre type and dosage. Finally, the study concluded that the degree of mechanical deterioration of fibres and the number of deteriorated fibres increase as the mixing time increases.

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http://dx.doi.org/10.1016/j.cemconres.2017.10.010
Received 20 May 2017; Received in revised form 25 August 2017; Accepted 18 October 2017

To the authors' knowledge no work has been published on the effect of mixing on the single-fibre pull-out behaviour of macro synthetic fibre reinforced concrete. In this paper an in depth study is done on the effect of damage caused by mixing on the single-fibre pull-out behaviour of macro synthetic fibres as well as the effect of the mixing time and type of mixer on the flexural behaviour of macro synthetic fibre reinforced concrete.

2. Methodology and experimental framework

In order to investigate the effect of mixing on the performance of macro synthetic fibre reinforced concrete, single-fibre pull-out tests and flexural tests were performed. The single fibre pull-out tests were conducted to compare the single-fibre performance of different macro synthetic fibres with various geometries in their virgin and mixed fibre state. Flexural tests were conducted to investigate the flexural performance of macro synthetic fibre reinforced concrete for one macro synthetic fibre type by taking account of different mixing times and two different mixer types.

2.1. Materials

A concrete mix yielding a compressive cube strength of 38.2 MPa was used for all single fibre pull-out tests. A CEM II/A-L 52.5 N Portland composite cement was used as binder with a natural pit sand (locally known as Malmesbury sand) and Greywacke crushed stone as coarse aggregate with a nominal size of 13 mm. The mix proportions and constituents are shown in the left-hand side of Table 1.

In order to facilitate the manual insertion process of the macro synthetic fibres, the fresh concrete was sieved (2.36 mm sieve) directly after mixing in order to retain a mortar. For fibres with 50 mm length three insertion depths were chosen (with denotations in brackets), i.e. 12.5 (L12.5), 25 (L25) and 37.5 mm (L37.5). Fibres with lengths other than 50 mm were also additionally embedded one half of the respective fibre length (LH).

The fibres used were either embedded in a virgin state, referring to the original condition as received by the suppliers, or in a mixed state. Mixed fibres were subjected to 5 min of mixing in a rotating pan mixer, followed by a rinsing process using water to firstly separate the fibres from the concrete and then remove any form of debris or surface deposits on the fibres. The fibre characteristics, as given by the suppliers, are listed in Table 2. All the fibres in Table 2 were used for the single fibre pull-out tests, except the CHRYSO fibre which was used for the flexural tests investigating the mixing time and mixer type.

For the flexural performance evaluation of macro synthetic fibre reinforced concrete after prolonged periods of mixing, a different mix design was used to be more representative of concrete mixes typically implemented for industrial flooring applications. A CEM II/A-L 52.5 N Portland composite cement was used as binder with a water/binder ratio of 0.55. The fine aggregate comprised of a 60:40 ratio by mass between a dune and crusher sand while the coarse aggregate was a Greywacke crushed stone with a nominal size of 19 mm. The mix design is shown on the right-hand side of Table 1.

Table 1
Concrete mix proportions and constituents.

Single-fibre pull-out test		Three point flexural test	
Constituent	Mass [kg/m^3]	Constituent	Mass [kg/m^3]
CEM II/A-L 52.5 N	319	CEM II/A-L 52.5 N	309
Potable water	204	Potable water	170
13 mm Greywacke Stone	996	19 mm Greywacke Stone	1088
Natural pit sand	873	Dune sand	512
		Greywacke crusher sand	356
		Fibre	4.0
		Plasticiser (CPO134)	2.3
		Superplasticiser (CFR)	max 5.15

A water reducing agent (plasticiser) with trade name CHRYSO Plast Omega 134 (CPO134), which is a hybrid PCE/Lignosulphonate, was added to provide suitable workability. Due to the mixing process, especially for prolonged mixing times, a slump revival admixture with tradename CHRYSO Fluid Rescue (CFR), which is a modified phosphonate polymer, was incorporated. CFR is a high range water reducing agent (superplasticiser) and results in plastic conditions being maintained for an extended time period. The dosage of the slump revival admixture was adjusted for each mixing time as required. The target slump was a value between 50 and 160 mm, workable enough to ensure good compaction. The slump readings were always taken just before the specimens were cast.

For investigating the flexural performance of macro synthetic fibre reinforced concrete, only one macro synthetic fibre type was considered at a constant fibre content of 4.0 kg/m^3 corresponding to a volume fraction (V_f) of 0.43%. This polypropylene fibre, an experimental fibre by CHRYSO, was supplied in a collated, fibrillated form, with a twisted profile and a rectangular cross-section. Table 2 provides the properties of the fibre, as obtained from the supplier.

2.2. Single-fibre pull-out test

Single fibre pull-out tests were conducted to evaluate the interfacial bond achieved by different macro synthetic fibres with various geometries and surface deformations, as well as the effect of damage on the fibre surface caused by mixing.

A 100 mm cube mould was used by inserting a wooden cross to divide the mould into four samples with dimensions of 39 × 39 × 100 mm^3 each. One sample is shown in Fig. 1a). After filling the voids with a sieved mortar, the fibres were carefully inserted to the correct length and re-vibrated slightly to ensure good packing around the fibre. Samples were placed in water at 25 °C at around 24 h after casting and then cured until an age of 28 days.

The concrete sample was held in place at the bottom of the Zwick Z250 universal testing machine by pneumatic operated steel grips. The fibre portion protruding from the mortar matrix was gripped using a clamp consisting of a steel plate fastened to the gripping device, as shown in Fig. 1b) and c). The fibre was gripped as close as possible to the mortar surface in order to eliminate any elastic fibre elongation of the free length. The load cell used has a capacity of 500 N while two 50 mm spring Linear Variable Differential Transformers (LVDTs) were used to measure the actual fibre pull-out displacement. The tests were controlled by the crosshead displacement at a rate of 0.2 mm/s. The rate does influence the pull-out behaviour [14], therefore it is important that all tests are done at the same rate to enable objective comparison between the different fibres.

All the fibres in Table 2 except the CHRYSO fibre were tested using the single fibre pull-out tests. Eight fibres were tested of each fibre type in the virgin state while twelve fibres of each were tested in the mixed state. More fibres in the mixed state were tested to account for potential variability in the test results caused by the additional surface roughening.

2.3. Flexural tests

To investigate the effect of mixing time on the performance of macro synthetic fibre reinforced concrete, flexural tests were performed according to EN 14651 [29]. The adopted flexural test setup is shown in Fig. 2. The setup consists of two supporting rollers, 500 mm apart and one loading roller located at mid-span. A load cell of 250 kN was used together with a crack opening displacement extensometer, which was used to measure the crack mouth opening displacement (CMOD). The extensometer was mounted along the longitudinal axis at mid-width of each test specimen using two knife edges glued to the bottom surface.

Table 2
Fibre properties.

Commercial fibre name	Label	Length [mm]	Modulus of elasticity [GPa]	Equivalent diameter [mm]	Cross section	Surface deformity
Geotex 500 range[a]	C1	50	1.62–2.70	0.74	Round	Crimped
Geotex 600 range[a]	F1	50	1.80–3.0	0.64	Flat	Corrugated (both sides)
Fibsol Macrosol F[a]	F2	50	1.60–2.67	0.60	Flat	Corrugated (one side)
EPC BarChip48[b]	E1	48	10	0.71	Irregular	Embossed
EPC BarChip54[b]	E2	54	10	0.85	Irregular	Embossed
EPC BarChip MQ58[b]	EB1	58	> 7	0.68	Irregular	Embossed/bundled
CHRYSO experimental fibre	CF	50	5.0	0.69	Rectangular	Twisted

[a] Polypropylene.
[b] Modified Olefin.

A closed loop control was used by controlling the CMOD rate at 0.05 mm/min until a CMOD of 0.1 mm was reached and then at 0.2 mm/min until the test was stopped at a CMOD of 4.2 mm as prescribed in the EN 14651 code [29]. From the response, the limit of proportionality (LOP), which corresponds to the maximum stress between a CMOD of 0 and 0.05 mm, as well as the residual flexural tensile strengths (f_{R1} to f_{R4}) at a CMOD of 0.5 mm, 1.5 mm, 2.5 mm, and 3.5 mm were determined, respectively as prescribed according to the EN 14651 code [29].

Five mixing times, 5, 10, 20, 30 and 60 min, were considered to investigate the effect of mixing time on the flexural performance. The mixing time commenced after the last fibres were added to the concrete. The effect of the mixing process was also investigated by implementing the aforementioned mixing times using two different mixers, namely a pan mixer and a tilting-drum mixer as shown in Fig. 3a) and b) respectively.

All specimens had dimensions of 150 × 150 × 700 mm^3 and were demoulded after around 24 h and were then cured until an age of 28 days in temperature controlled water of 25 °C. All specimens were removed not less than three days before testing, to notch the beams at mid span as prescribed by EN 14651 [29]. After notching the specimens were re-immersed into the curing tanks until the day of testing. Each set of tests consisted of six beam specimens.

3. Single fibre pull-out results

To compare the macro synthetic fibre performance on a single-fibre level, the single fibre pull-out test results are discussed in terms of the interfacial bond stress (τ) or elastic bond, using the uniform bond approach, given by:

$$\tau = \frac{F_{peak}}{\pi d_{eq} l_e} \tag{1}$$

with F_{peak} the peak pull-out force required to de-bond the embedded fibre and d_{eq} and l_e the equivalent diameter and embedment length, respectively. It is acknowledged that this approach is not appropriate if the results are to be used in a micro-mechanical model. This is due to the relatively low Young's modulus of the fibres. A higher Young's modulus would result in a rigid pull-out where the shear stress is more evenly spread out. However, the purpose of these calculations is however to compare different fibres in both the virgin and mixed state, so therefore it is useful in the context of this paper.

The interfacial bond stresses (Eq. (1)) achieved by the different macro synthetic fibres are shown in Fig. 4. The individual averages and coefficients of variations are given in Table 3. Firstly, it is noted that almost all the fibres showed a bond decrease with an increase in embedment length. This is expected, due to the relatively low Young's modulus and the model used Eq. (1). In this case the full fibre is not activated when the pull-out starts, but only a section close to the surface. Therefore it seems that the bond is reducing with an increasing embedment length when the resistance is divided by the whole embedment length. Four plots are provided for Fibre EB1, three virgin values and one mixed as shown in Fig. 4f). Fibre EB1 consists of a bundle of three fibres, i.e. two smaller fibres on the side with a larger fibre in the centre. The three virgin results are the combined fibre, the centre fibre and a side fibre. After mixing however, the built-up fibre splits into its individual components, making it impossible to distinguish between the large and small cross-sectional fibres after washing them out of the concrete. Only one result is given for the mixed Fibre EB1 for which an additional equivalent diameter was calculated according to a weighted average of the individual fibre components.

A substantial increase in bond strength of > 100% can be seen for Fibres F1 and F2, both flat fibres, when comparing mixed to virgin fibres. However, it is interesting to note that this effect diminishes when the embedment length is increased. The reason for this increase of bond strength with mixing is due to the fibre surface damage caused while mixing (with the aggregates) which results in a better bond. The diminishing effect at longer embedment lengths, however, is not so clear. One reason could be that the anchorage mechanism changes from adhesion to a mechanical bond the longer the embedment length. That means for longer embedment lengths the surface roughening becomes irrelevant.

a) b) c)


Fig. 1. Single fibre pull-out tests, a) test sample, b) test setup and c) the clamping mechanism.

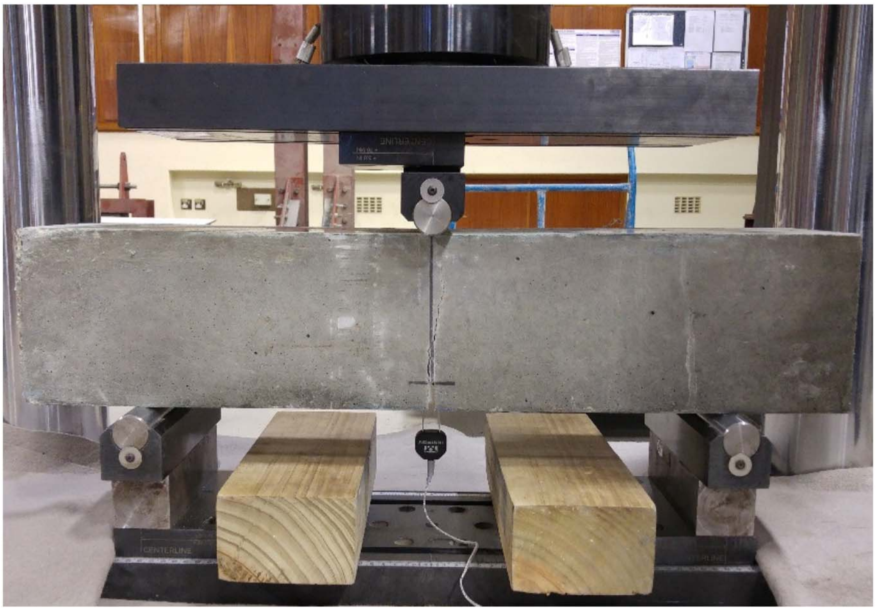

Fig. 2. Three point flexural test setup.

Except for the flat fibres, all the other fibres showed no increase of the bond after mixing the fibres, even for short embedment lengths. This makes sense as, due to the surface deformities of the fibres, mechanical interlock is the primary bond mechanism which is not influenced by the mixing damage.

The uniform bond approach only evaluates the peak resistance load and neglects the post peak region which also contributes to the flexural behaviour of macro synthetic fibre reinforced concrete. Another approach of evaluating the result is to plot the bond stress calculated using the actual length of the fibre still embedded in the matrix. The following equation can be used:

$$\tau_i = \frac{F_i}{\pi d_{eq} (l_e - l_i)} \quad (2)$$

with F_i and l_i the load and pulled-out fibre length at a specific instance during the single fibre pull-out response respectively, and l_e the initial fibre embedment length.

This is demonstrated for Fibre E2 in Fig. 5 tested in a virgin state. This gives a better understanding of the resistance of the fibre during the pull-out process.

The unrealistically high interfacial bond stress in the vicinity of complete pull-out is attributed to the nature of Eq. (2). This is caused by a division of a value nearing zero, as l_i approaches l_e, and the pull-out length measured which is longer than the actual embedment length as the fibre elongates during the tests. As an alternative, a more objective approach can be used by calculating the average bond (τ_{avg}) over a realistic length of pull-out. It is proposed that the average bond should be calculated up to a pull-out displacement of 50% of the embedded length. This can be expressed as:

$$\tau_{avg} = \frac{F_{avg\ l/2}}{\pi\ d_{eq}\ 0.75\ l_e} \quad (3)$$

with $F_{avg\ l/2}$ the average load during the single fibre pull-out response between up to a pull-out displacement of half the embedment length. Fig. 6 depicts the average bond stress for virgin and mixed fibres tested.

Even though this approach is an improvement, the results still show higher bond stresses for lower embedment lengths. Using this average approach the following can be concluded:

- The performance of the crimped Fibre C1 reduced after mixing.
- For flat Fibres F1 and F2 the performance increased after mixing for all embedment lengths.
- The embossed Fibre E1 showed a reduction in performance after mixing.
- The performance of the embossed Fibre E2 remained similar after mixing.

These conclusions indicate that mixing is not always advantageous for the fibre performance and their performance can be reduced with mixing. This, however, will depend on the type of fibre.

Fig. 3. a) Pan mixer and b) tilting-drum mixer.

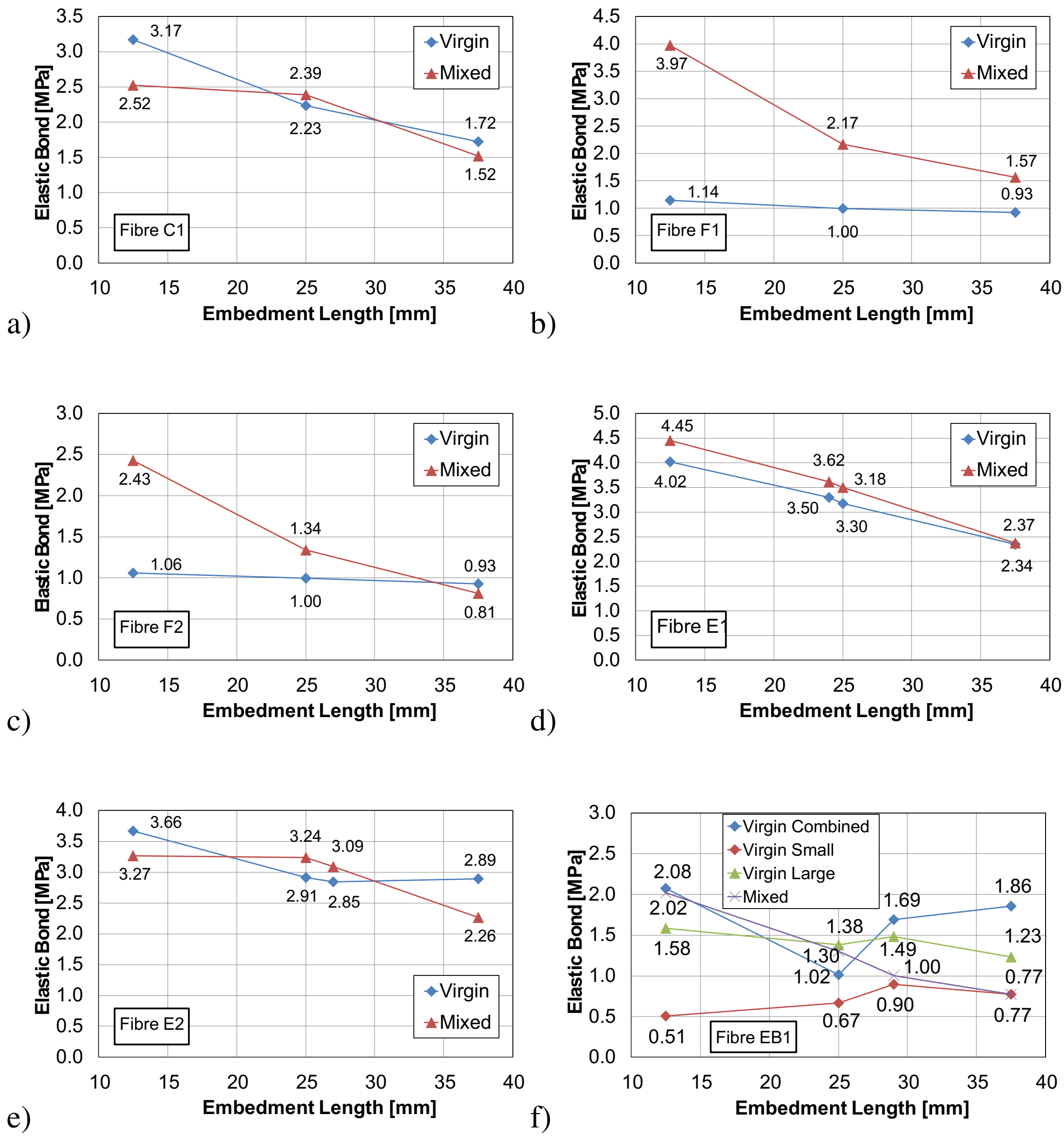

Fig. 4. Interfacial bond stress for various embedment lengths with the fibre type clearly indicated on each graph.

3.1. Scanning electron microscopy

Scanning electron microscopy (SEM) was used as a surface analysis tool to investigate the different macro synthetic fibres, in the virgin and mixed state, before and after pull-out. The SEM images provide useful information regarding the improvement of the bond between the fibre and the surrounding mortar matrix. Generally when better fibre-matrix interaction is achieved the more severe the fibre surface scrapings are.

As an example, SEM images of macro synthetic Fibres C1 and F1 are provided in Fig. 7.

Fig. 7e) and f) show the effect of premixing on the surface of macro synthetic fibres. In contrast to the virgin fibre state, depicted in Fig. 7a) and b), severe surface roughening can be recognised which is believed to be caused by the interaction with the aggregates during mixing. It can further be concluded that for the flat fibres, the improved fibre pull-out bond after mixing is due to the severe surface damage. The round crimped Fibre C1 also showed surface damage after mixing, but not as pronounced as with the flat Fibre F1. Fig. 7g) and h) shows that the mixed fibres after being pulled-out have significantly more damage shown in Fig. 7c) and d) than the fibres that were pulled-out in the virgin state.

It can be concluded that all the synthetic fibres tested did show significant damage to the fibres during mixing. Based on the single fibre pull-out tests it is clear that this damage due to mixing increases the bond of flat fibres, but only for short embedment lengths. Crimped and embossed fibres were less influenced, but in the cases where there was an influence, the performance reduces. For the fibre which consisted of three parts (Fibre EB1), the results are not as clear as the fibre split into three parts during mixing.

4. Flexural test results

The results of the flexural tests were used to investigate the effect of mixing time and mixing process on the flexural performance of macro synthetic fibre reinforced concrete. The results are presented in terms of the limit of proportionality (LOP), which corresponds to the maximum stress measured between a crack mouth opening displacement (CMOD) of 0 and 0.05 mm, and the residual flexural tensile strengths (f_{R1}, f_{R2}, f_{R3}, f_{R4}) at CMODs of 0.5 mm ($CMOD_1$), 1.5 mm ($CMOD_2$), 2.5 mm ($CMOD_3$), and 3.5 mm ($CMOD_4$), respectively.

The following expression was implemented to determine the LOP:

$$f_{LOP} = \frac{3}{2}\left(\frac{F_L\, l}{b h_{sp}^2}\right) \tag{4}$$

Table 3
The bond results of all the single fibre pull-out tests together with their coefficient of variations.

Fibre	Embedment length [mm]	Virgin bond [MPa]	Virgin CoV	Mixed bond [MPa]	Mixed CoV
C1	12.5	3.17	0.25	2.52	0.22
C1	25	2.23	0.10	2.39	0.10
C1	37.5	1.72	0.05	1.52	0.14
F1	12.5	1.14	0.24	3.97	0.20
F1	25	1.00	0.09	2.17	0.09
F1	37.5	0.93	0.06	1.57	0.11
F2	12.5	1.06	0.2	2.43	0.36
F2	25	0.89	0.18	1.34	0.14
F2	37.5	0.84	0.27	0.81	0.14
E1	12.5	4.02	0.17	4.45	0.14
E1	24	3.30	0.08	3.62	0.05
E1	25	3.18	0.04	3.50	0.08
E1	37.5	2.34	0.11	2.37	0.08
E2	12.5	3.66	0.12	3.27	0.19
E2	25	2.91	0.14	3.24	0.12
E2	27	2.85	0.10	3.09	0.14
E2	37.5	2.89	0.07	2.26	0.19
EB1	12.5	2.08	0.11	2.02	0.18
EB1	25	1.02	0.30	1.30	0.20
EB1	29	1.69	0.07	1.00	0.13
EB1	37.5	1.86	0.11	0.77	0.14
EB1	Small/12.5	0.51	0.24		
EB1	Small/25	0.67	0.26		
EB1	Small/29	0.90	0.06		
EB1	Small/37.5	0.77	0.16		
EB1	Large/12.5	1.58	0.39		
EB1	Large/25	1.38	0.07		
EB1	Large/29	1.49	0.04		
EB1	Large/37.5	1.23	0.06		

with F_L the maximum load achieved within a CMOD of 0 and 0.05 mm, l the span length, b the width of the specimen and h_{sp} the distance between the tip of the notch and the top of the specimen.

To determine the residual flexural tensile strengths, the following expression was implemented:

$$f_{Ri} = \frac{3}{2}\left(\frac{F_i l}{b h_{sp}^2}\right) \tag{5}$$

with F_i the load corresponding to a CMOD equal to CMOD_i (i = 1,2,3,4).

4.1. The effect of mixing on the LOP

The LOP achieved by the macro synthetic fibre reinforced concrete using Fibre CF for the various mixing times, and the two different mixers, are provided in Fig. 8a). It is important to note that each data point represents the average of each test set which consists of six beams. The effect of the mixing time on the compressive strength is given in Fig. 8b).

Fig. 8a) depicts an increasing trend for the LOP for both mixer types, corresponding to an increase in mixing time. The compressive strengths also increased with an increase in mixing time as shown in Fig. 8b). The increasing trend can be attributed to a combination of the following three reasons. Firstly, the longer the mixing time the more superplasticiser was added which resulted in better distribution of the cement particles, thus increasing the strength. Secondly, during mixing, some water would have evaporated from the concrete, thus reducing the water cement ratio and, in turn, increasing the strength. Lastly, due to the continued mixing, the entrained air could have been reduced, thus also increasing the strength.

4.2. The effect of mixing on f_R values

The effect of mixing time on the residual flexural tensile strengths (f_{R1}, f_{R2}, f_{R3}, f_{R4}), for both mixer types, is illustrated in Fig. 9. From Fig. 9a) it is clear that the effect of mixing time on f_{R1} is negligible for a pan mixer. However, referring to f_{R2}–f_{R4}, it is evident that an increase in mixing time has a significant decreasing effect. Note that an initial increase in f_{R1}–f_{R4} is experienced for a mixing time between 5 and 10 min, where after the performance decreases, indicating an optimal mixing time of 10 min. It was expected that an increase in mixing time would ensure better fibre distribution and increase fibre surface damage, enhancing the bond between the synthetic fibre and the cement matrix, ultimately improving the residual flexural tensile performance of macro synthetic fibre reinforced concrete. However, for prolonged mixing times exceeding 10 min, the Fibre CF started deteriorating, reducing its tensile capacity, and ultimately decreasing the residual strength to as low as 30% of the strength after 10 min of mixing.

Fig. 9b) illustrates the relationship between mixing time and residual flexural tensile strengths (f_{R1}, f_{R2}, f_{R3}, f_{R4}) for a tilting-drum mixer. The averages and the coefficients of variations are shown in Table 4. A tilting-drum mixer was considered to simulate the mixing process experienced in a ready-mix truck. From Fig. 9b) it is clear that the effect of mixing time on f_{R1}–f_{R4} is negligible. It can be concluded that the mixing process for a tilting-drum mixer does not enhance, nor decrease, the residual flexural tensile performance of macro synthetic fibre reinforced concrete.

4.3. Scanning electron microscopy

As for the single-fibre investigations, scanning electron microscopy (SEM) was used as a surface analysis tool to investigate the effect of mixing time and mixing process on the fibre. Individual SEM images of the Fibre CF were taken in the following conditions:

- Virgin fibre state
- Mixed fibre state - 5, 10, 20, 30, 60 min mixing time (pan mixer)
- Mixed fibre state - 60 min mixing time (tilting-drum mixer)

The SEM images of the fibre in the aforementioned conditions are presented in Fig. 10.

Fig. 10a) depicts the surface of the Fibre CF in its virgin state in the absence of any surface roughening. The extent of the fibre surface damage caused by an increase in mixing time (pan mixer) is illustrated in Fig. 10b) to f). The extent of the surface damage is characterised by significant surface roughening, fine scrapings and a decrease in fibre

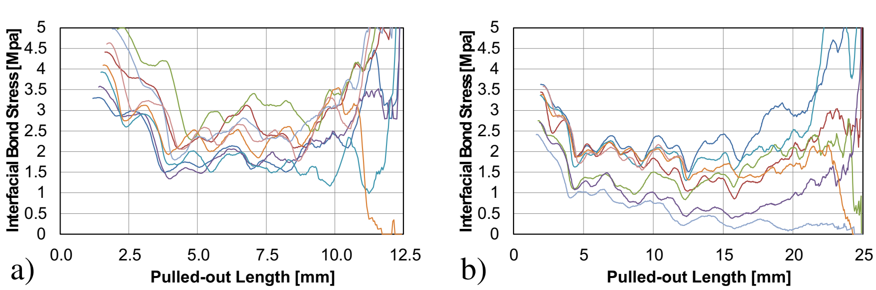

Fig. 5. Interfacial bond stress distribution across virgin Fibre E2 at an embedment of a) 12.5 mm, and b) 25 mm.

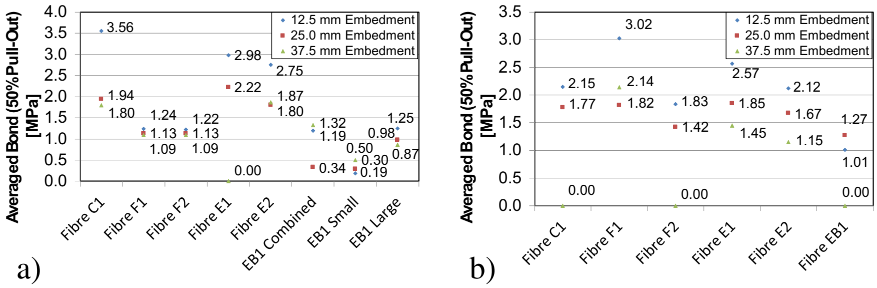

Fig. 6. Average interfacial bond stress of a) virgin and b) mixed fibres.

width for an increase in mixing time. In addition, it was found that after 60 min in the pan mixer the fibres broke into smaller pieces of around 5 to 15 mm in length. The fibre was effectively transformed from a long to short fibre and resulted in a significantly reduced performance.

Fig. 10g) shows the effect of a 60 min mixing time for a tilting-drum mixer. It is evident that the fibre damage is less susceptible to the mixing process of a drum mixer compared to the pan mixer. It should also be noted the fibre is significantly wider after 60 min in the drum mixer compared to the pan mixer. This can be attributed to its lower energy exerted on the concrete, thus decreasing the effect of fibre damage due to aggregates. This supports the negligible effect of an increase in mixing time on the residual flexural performance for a tilting-

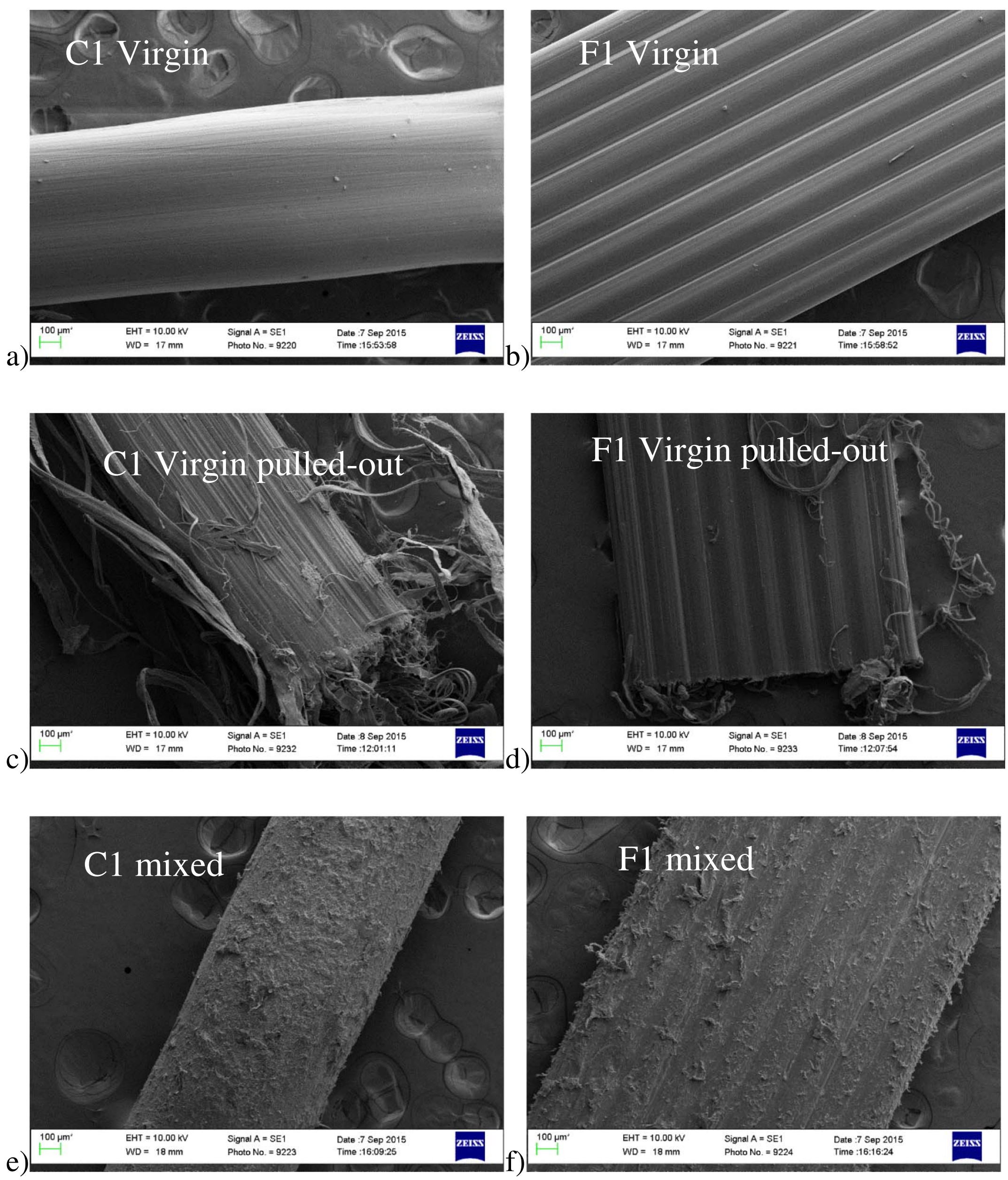

Fig. 7. a–b) Virgin, c–d) virgin pulled-out, e–f) mixed and g–h) mixed pulled-out fibres.

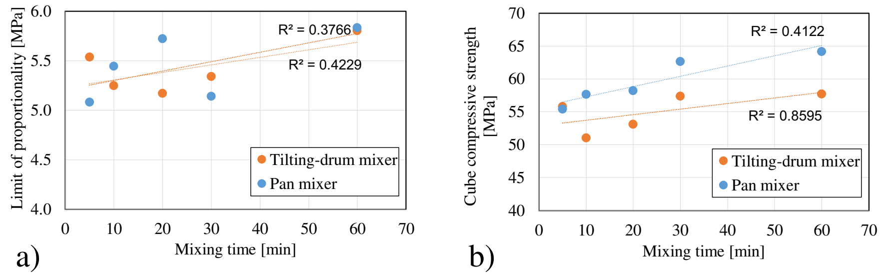

Fig. 8. Effect of mixing time on the LOP, a), and b), the effect on the compressive strength.

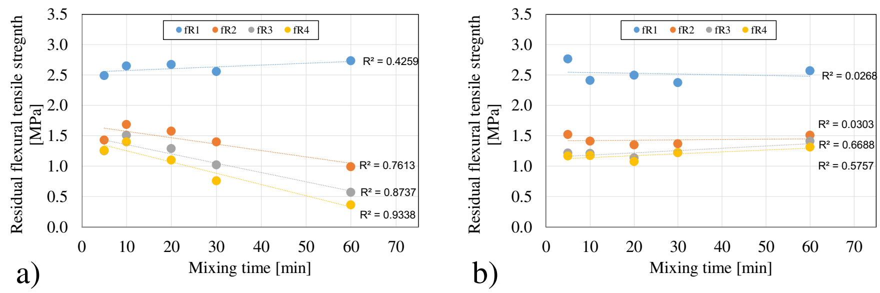

Fig. 9. Effect of mixing time on the residual flexural tensile strength of macro synthetic fibre reinforced concrete for a) a pan mixer and b) tilting-drum mixer.

Table 4
The f_{R1} to f_{R4} values of the mixing time tests together with their coefficients of variations.

Mixer type	Mixing time	fr1	COV	fr2	COV	fr3	COV	fr4	COV
Pan	5	2.49	0.11	1.43	0.21	1.25	0.24	1.26	0.26
	10	2.65	0.12	1.68	0.22	1.51	0.28	1.40	0.29
	20	2.67	0.16	1.58	0.12	1.29	0.13	1.10	0.15
	30	2.56	0.10	1.40	0.07	1.02	0.09	0.76	0.10
	60	2.73	0.11	0.99	0.14	0.57	0.21	0.36	0.31
Drum	5	2.76	0.16	1.52	0.14	1.22	0.21	1.17	0.22
	10	2.41	0.11	1.41	0.13	1.21	0.16	1.17	0.15
	20	2.5	0.08	1.35	0.21	1.13	0.21	1.07	0.23
	30	2.37	0.09	1.37	0.11	1.22	0.11	1.22	0.12
	60	2.57	0.13	1.5	0.17	1.41	0.19	1.31	0.19

drum mixer as shown in Fig. 9b).

4.4. Statistical significance

A simple regression analysis was completed to statistically investigate the significance of mixing time on the residual flexural tensile strengths (f_{R1}, f_{R2}, f_{R3}, f_{R4}) for the two considered mixer types.

A regression analysis is a statistical technique that can be implemented to analyse the relationship between a single dependent variable (f_{R1}, f_{R2}, f_{R3}, or f_{R4}) and one independent variable (mixing time). Interpreting the statistical significance of the independent variable requires a specified acceptable level of statistical error. The most common approach is to specify an α-value (Type I error) which is the probability of rejecting the null hypothesis. By specifying an α-value, an acceptable limit for error is set and indicates the probability that significance exists. For the purpose of this study, an α-value equal to 0.05 was implemented, suggesting that a p-value ≤ 0.05 indicates a significant influence on the considered dependent variable.

Table 5 shows the statistical significance of mixing time, for both considered mixer types, on the residual flexural tensile strengths of macro synthetic fibre reinforced concrete. p-Values ≤ 0.05 indicate a statistical significance.

It is clear that mixing time, considering a pan mixer, has a statistically significant influence on the residual flexural tensile strengths of macro synthetic fibre reinforced concrete, excluding f_{R1} (p-value = 0.33146). The exception of f_{R1} can be explained by the effect of the mixing on the fibre. As explained earlier, the prolonged mixing in a pan mixer results in the fibres breaking into smaller and shorter fibres. These smaller fibres can effectively bridge a 0.5 mm crack, therefore the f_{R1} values are not decreasing with longer mixing time. For larger crack widths the longer mixing times do negatively influence the residual stress.

For the tilting drum mixer, however, the mixing time is shown not to have a statistically significant influence on the performance of macro synthetic fibre reinforced concrete. Combined with the evidence shown in Fig. 10g), it is clear that the drum mixer does not damage the fibres beyond a point where the performance is negatively influenced. It is believed that a tilting drum mixer represents a typical ready-mix truck, which should therefore not be a problem for macro synthetic fibre reinforced concrete. However, when pan mixers are used, e.g. in a precast factory, the mixing time should be no longer than what is needed to distribute the fibres evenly in the concrete. This is also only valid for this one type of fibre and it is recommended that every fibre type is checked that the performance is not negatively influenced before it is used.

5. Conclusions

A study about the resulting damage on macro synthetic fibres due to mixing is presented in this paper. This included single fibre pull-out tests and flexural tests of macro synthetic fibre reinforced concrete. The following conclusions can be drawn from this work:

Single-fibre performance

- Embossed fibre geometries provide the highest resistance against pull-out, followed by flat fibres, while the crimped fibres show the worst performance.
- The calculated bond obtained during the single-fibre pull-out tests show that the bond strength of mixed flat fibres are significantly increased compared to the virgin fibres. However, this is only the case for shorter embedment lengths. For longer embedment lengths there is no advantage if the fibre is first mixed.

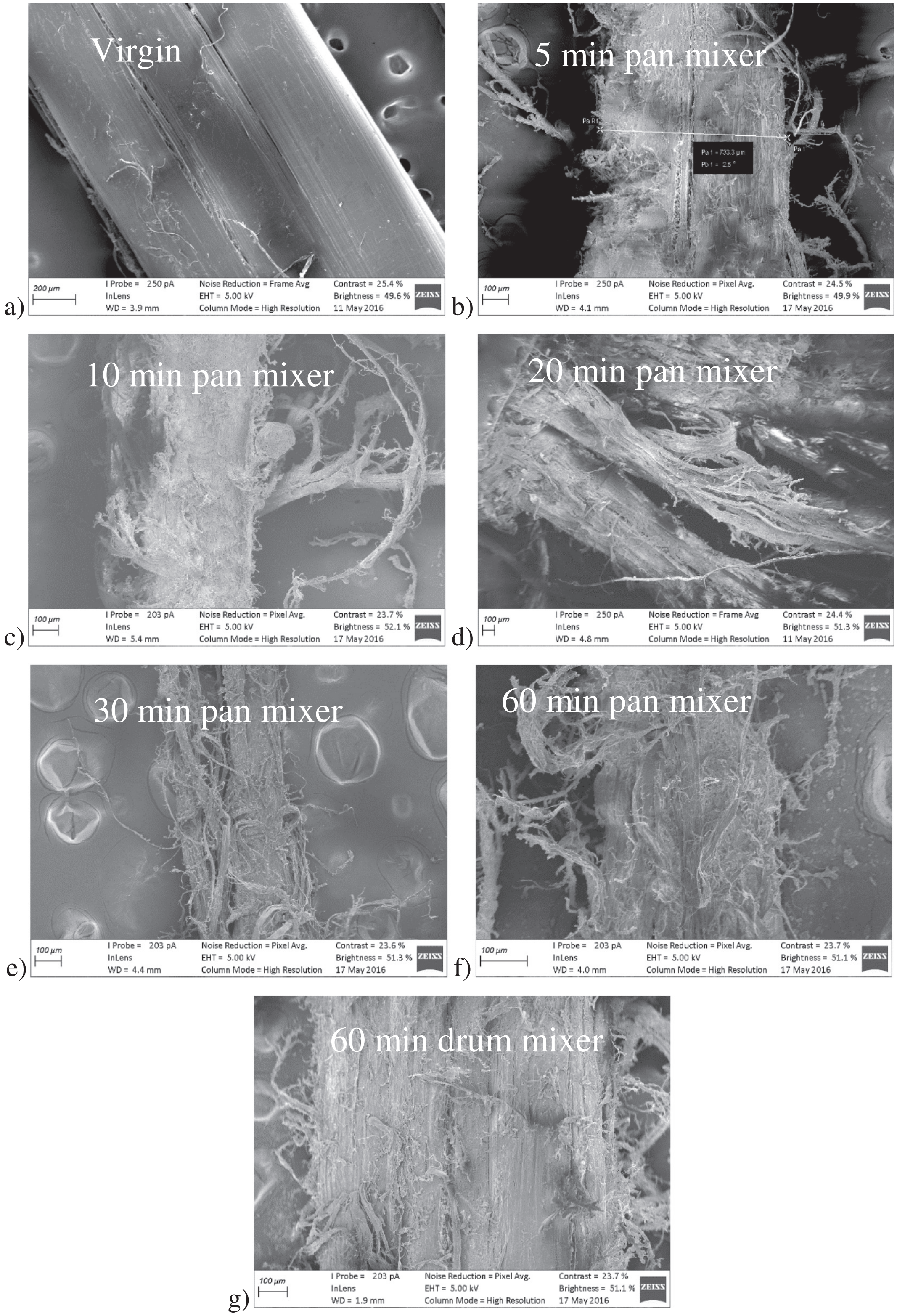

Fig. 10. a) Virgin fibre, mixed in the pan mixer for b) 5 min, c) 10 min, d) 20 min, e) 30 min, f) 60 min, and g) 60 min in tilting drum mixer.

- A new approach of expressing the single-fibre pull-out results is presented. This is based on the average actual pull-out resistance up to half the embedment length. This is believed to be a better approach as the post peak behaviour of the single fibre pull-out behaviour is also included in the calculation.
- Using this new approach it was shown that the performance of flat

Table 5
Statistical significance of mixing time.

Mixer type	Significance (*p*-values)			
	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Pan	0.331460	0.000155	0.000001	0.000000
Tilting-drum	0.705133	0.763739	0.071457	0.138193

fibres is increased after mixing while crimped and embossed fibres show less bond after mixing.

Effect of mixing time and mixer type

- The effect of mixing time and mixer type on residual flexural tensile strength (f_{R1}), corresponding to a CMOD of 0.5 mm, is negligible.
- The extent of the influence of mixing time on the residual flexural tensile strengths (f_{R2}–f_{R4}) is dependent on the mixer type. It is established that, considering a tilting-drum mixer, mixing time has a negligible effect on the performance. However, for a pan mixer, a significant decrease in f_{R2}–f_{R4} occurs for prolonged mixing times exceeding 10 min.

It can be concluded that mixing has a non-negligible role in the performance of macro synthetic fibre reinforced concrete. Prolonged mixing can increase the performance, but too much mixing, however, does however reduce the performance. The optimal mixing time depends on the mixer type as well as the type of fibre. It is recommended that trials are done using the same mixing method and time as would be used for the intended application, and not use a typical laboratory mixer to determine the f_{R1} to f_{R4} values of macro synthetic fibre reinforced concrete for a specific application.

Acknowledgments

The authors are grateful to Geotex, Elasto plastic concrete, and CHRYSO for supplying the macro-synthetic fibres. The authors also acknowledge the financial support by Pretoria Portland Cement and Geotex for the financial support for the single fibre pull-out work and CHRYSO for the financial support of the flexural tests section.

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