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Comparative evaluation of the time-dependent deformations of cracked steel fibre and synthetic macro-fibre reinforced concrete in tension

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Furthermore, to understand the mechanisms responsible for the time-dependent deformation of specimens, investigations were performed at the single fibre level through a time-dependent fibre pull-out test and fibre creep tests. All tests were carried out in a climate-controlled room. Results showed that the creep is a function of applied load, and significantly more creep was recorded for synthetic macro FRY in relation to steel macro FRC. While creep fracture did not occur for the steel macro FRC specimens even at high loads, it did occur for synthetic macro FRC. For synthetic macro FRC, creep mechanisms were identified to be fibre creep and complete fibre pull-out, while fibre pull-out was observed for steel macro FRC.

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Comparative evaluation of the time-dependant deformations of cracked steel fibre and synthetic macro fibre reinforced concrete in tension

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This study investigated the tensile creep responses of steel and synthetic macro FRC under sustained loads for 8 months. Specimens for the investigation were prisms of 100 × 100 × 500 mm³ with specially designed steel anchors for supporting the specimens on the creep frames. All specimens were notched and cracked before been subjected to varying creep loads. The creep loads varied between 30 to 85% of the residual strength, obtained from uniaxial tensile tests performed on similar specimens. Creep for the test period was measured in terms of crack width opening. Furthermore, to understand the mechanisms responsible for the time-dependent deformation of specimens, investigations were performed at the single fibre level through a time-dependent fibre pull-out test and fibre creep tests. All tests were carried out in a climate controlled room. Results showed that the creep is a function of applied load, and significantly more creep was recorded for synthetic macro FRC in relation to steel macro FRC. While creep fracture did not occur for the steel macro FRC specimens even at high loads, it did occur for synthetic macro FRC. For synthetic macro FRC, creep mechanisms were identified to be fibre creep and complete fibre pull-out, while fibre pull-out was observed for steel macro FRC.

Key words: Creep, macro fibre, fibre reinforced concrete, time-dependent behaviour, uniaxial tensile creep

INTRODUCTION

Creep is defined as time-dependent deformation (strain, deflection, crack width widening) under sustained load. Much has been reported over the years on the time-dependent behaviour of concrete when under sustained load, and in the unloaded state, which is known as shrinkage. Furthermore, models predicting this time-dependent response of concrete have been developed and reported extensively in literature (Bažant & Prasannan 1989; Bažant et al 1991; Bažant & Kim 1992; Bažant 2001; Brooks 2005; fib Model Code 2010). Concrete structures are subjected to sustained loading from the dead weight of the structures throughout their lifetime. If adequate consideration in the design stage is not made for creep, sustained loading on the structures could have significant long-term damaging effects. These could result in structural failure and serviceability issues such as cracking, excessive deflection in beams, buckling of columns, and loss of prestress in prestressed concrete structures.

With the increasing use of short discrete macro fibres in slabs-on-grade, shotcrete, precast elements and marine structures, attention needs to be focused on the creep of fibre reinforced concrete (FRC). This is because the creep behaviour of FRC differs from that of conventional concrete. Fibres are known to control crack propagation in concrete (i.e. toughen the concrete). While significant improvements in the mechanical properties of FRC have been reported over conventional concrete in the short-term (Zollo 1997; Brandt 2008; Buratti et al 2011, Simões et al 2017), much remains to be known about its long-term response under sustained loads. Soon after the initiation of a crack, the activity of the fibre is triggered to control further propagation of the crack by its bridging action. Under a time-dependent sustained load, particularly for a cracked section, it becomes a concern if the bridging activity of the fibres can be maintained.

The two most commonly used types of macro fibres in concrete structures are steel and synthetic fibres. Like steel reinforcing bars, creep in steel fibres is negligible, while synthetic macro fibres have been reported to undergo significant creep under sustained loading (Muliana 2014, Babafemi & Boshoff 2015). When synthetic macro fibres are exclusively used as reinforcement for concrete, a higher level of creep can be envisaged compared to steel and steel fibre reinforced concretes. This is due to the low elastic modulus of synthetic fibres compared to steel fibres, and the poor bonding they have with the cement matrix due to their hydrophobic nature. However, the use of synthetic fibres in shotcrete and concrete floor-on-grade applications is on the increase lately. The advantages of the fibres, when compared to steel fibres, include low density (lightweight), resistance to chemicals, economy, and non-deterioration in concrete, which could be responsible for the increase in usage.

Though a number of studies have considered the creep of different types of fibre reinforced cementitious composites (Bissonnette & Pigeon 1995; Bissonnette et al 2007; Garas et al 2009), yet, this are still few compared to creep of conventional concrete. Moreover, the creep responses were not considered in the cracked state. Fibres are only active in the cracked state to control crack widening which simulates an in-service condition. If a true understanding of the time-dependent behaviour of FRC is to be obtained, specimens tested should be cracked before subjecting them to sustained loading. Though studies on the creep of FRC in the cracked state has been increasing recently (Tan & Saha 2005; Boshoff et al 2009; Zerbino & Barragán 2012; Garacia-Taengua et al 2014; Zhao et al 2014; Boshoff 2014; Abrishambaf et al 2015; Babafemi & Boshoff 2015), the majority of these works are focused on the flexural creep. Therefore, more studies are still required leading to better understanding of this subject. This would further lead towards developing a structural design model that incorporates the creep of cracked macro FRC, which does not exist at the moment.

In this paper, a comparative study of the creep responses of steel and synthetic macro FRC under varying levels of sustained uniaxial tensile load are presented. The results have been published elsewhere (Babafemi and Boshoff, 2015, Nieuwoudt 2016) and was the result of two different PhD studies. The approach of these two studies are however similar. The purpose of this paper is to present the results together and so highlighting the differences and similarities of the time-

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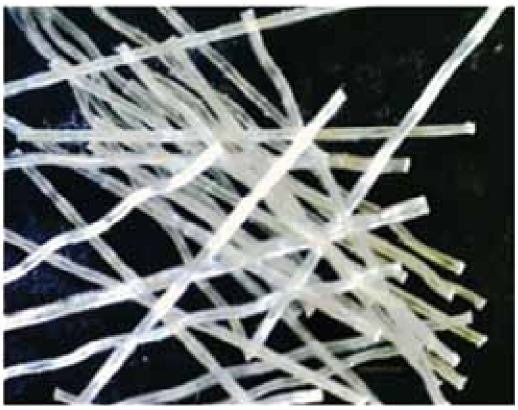

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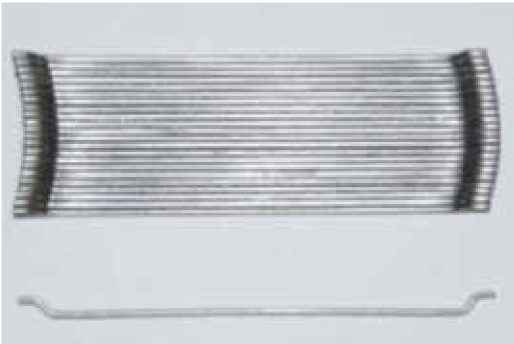


Figure 1: (a) Macro PP and (b) steel fibres

dependant behaviour in uni-axial tension of cracked FRC containing steel and synthetic fibres, which has not been done before. To simulate in-service conditions after crack initiation, all creep specimens were tested in the cracked state. Further understanding of the mechanisms responsible for the time-dependent crack widening of specimens subjected to sustained loads was pursued and is reported.

MATERIALS AND METHODS

Fibres and properties

Steel and synthetic polypropylene (PP) fibres were used for the investigation of the creep of cracked macro FRC (one type for each). To enhance bonding with the matrix, the macro PP fibre has a slightly crimped configuration and an X-shaped cross-section (see Figure 1a), whereas the steel fibre is the hooked-end DRAMIX 3D65/60-BG shown in Figure 1b. The properties of the fibres as provided by the manufacturers are presented in Table 1.

Table 1: Properties of steel and synthetic fibres as supplied by the manufacturers

Properties	PP fibre	DRAMIX 3D65/60-BG
Relative Density	0.88-0.92	7.85
Modulus of elasticity (GPa)	4.3	210
Elongation at yield (%)	15 to 25	-
Tensile strength (MPa)	400	1160
Melting point (°C)	150-170	-
Length (lf) [mm]	40	60
Nominal diameter (df) [mm]	0.8	0.9
Aspect ratio (lf/df)	50	67

Concrete mix design

The following materials were used in the preparation of the concrete mixture: CEM I 52.5N with a relative density (RD) of 3.14, crushed Greywacke stone with a RD of 2.80, natural sand (locally known as Malmesbury sand) with RD of 2.62, and superplasticiser (Dynamon SP1) conforming to the requirements of EN 934-2:2009+A1:2012. The superplasticiser was added to adjust the rheology of the mix. The fine aggregate, passing a 4.75 mm sieve, had a fineness modulus of 2.3, while the coarse aggregate passed through a 6 mm sieve size but was retained on a 4.75 mm sieve. Mindful of the effect of fibres on workability, the mixture was designed to have high workability. Sand, cement and stone were added dry, mixed before the addition of water and superplasticiser; thereafter, the fibres were added and mixed for a further 2 min. It should be noted that only one concrete mixture was designed and used. PP and steel fibres were used at 1 and 0.5% (by volume), respectively, while the volume of superplasticiser was 0.2 and 0.5% (by weight of binder) for PP and steel FRC, respectively. The superplasticiser content for the steel FRC mixture was increased because the steel fibres reduced the workability more than the PP fibres. Also note that the batch of sand and cement were different for the PP and steel FRC. Both of these influenced the strength of PP compared steel FRC. The details of the concrete mix are presented in Table 2.

Table 2: Material composition of steel and synthetic FRC

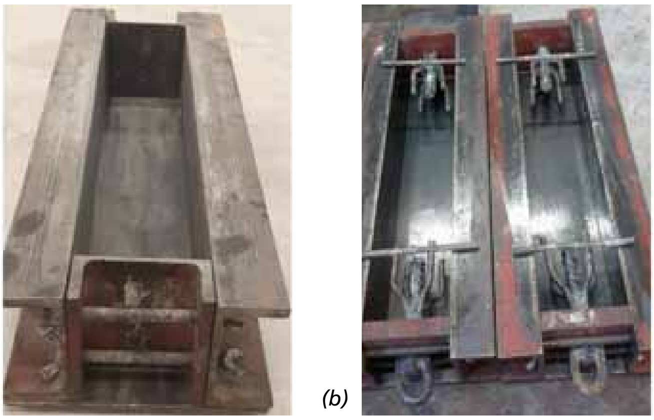
Materials (kg/m^3)	PPFRC	Steel FRC
Cement	395	395
Stone	800	800
Sand	990	990
Water	190	190
Fibre	9.1	39.25
Superplasticizer	0.79	1.975

The slump value was measured before and after the addition of fibres following standard procedure [SANS 5862-1]. Prior to the addition of fibres, the slump values were 160 and 230 mm for the PPFRC and SFRC mixes, respectively, while this reduced to 100 and 130 mm, respectively, after the fibres were added. Evidently, the addition of fibres generally reduces the workability of concrete mixes.

Specimen preparation

The specimens were designed in such a way that it would be possible to position them in the test machine with relative ease. To accomplish this, a steel mould, 100 × 100 × 500 mm^3 was re-designed to incorporate specially designed steel hooks. The original and the finished moulds with the steel hooks in place, ready for receiving fresh concrete mix, are shown in Figure 2 (a,b).

The fabricated steel hooks had eye-like loops welded to them as anchors (Figure 2b) for the application of uniaxial tensile loads. The closed steel end of the original mould was removed and a wooden block (100 × 100 × 200 mm3) was inserted. The wooden block had a central hole of 18 mm in diameter. The block was halved to allow for the positioning of the hook into the mould, while the other half was placed over it and secured with the screws of the steel moulds at both ends. To eliminate eccentricity of the hooks at the ends of the mould (to eliminate internal moment during testing), another wooden block was used to vertically align the central studs at each hook (Figure 3). A levelling instrument was used to check the side and top alignment of



(a) (b)

Figure 2: a) Original steel mould b) the finished mould

the central stud of the hooks. After the alignment was established, the hooks were kept in that position by winding a wire around the central stud, and connected to a crossbar placed across the mould (Figure 2b). The whole setup was properly tightened and the temporary wooden blocks removed.

Figure 3: Alignment of hooks using spirit level

After all the moulds had been prepared, they were placed on a vibrating table and casting was done in two layers. The fresh fibre concrete mixture was placed in the middle of the mould and, under vibration, flowed to fill up the hooks without distorting their positioning. The surface of the moulds were properly finished and demoulding occurred after 24 h. All the specimens were cured by complete immersion in water at a temperature of 23 °C for a further 27 days and tested at an age of 28 days. Prior to testing, all specimens were notched peripherally with a 3 mm thick diamond blade at the middle of the specimens to a depth of 10 mm, giving an effective specimen area of 6400 mm^3 at the notched portion.

The compressive strength of the concrete mixtures was tested following the procedure outlined in SANS 5863 using 100 mm cube specimens. The test was performed at a loading rate of 0.3 MPa/s using a Contest Materials Testing Machine with a capacity of 2000 kN.

Uniaxial tensile test

The tensile properties of concrete were determined using a uniaxial test. This test was performed in a Zwick Z250 Universal Testing Machine with a capacity of 250 kN. The welded eye-like loop to the embedded steel hook was used as a link to support the specimen in the test machine (Figure 4) which resulted in boundary conditions that are free to rotate.

Prior to placing the specimen in the test machine, two (LVDTs) for measuring the crack width over the notched area had been installed on aluminium frames attached to the concrete specimens as shown

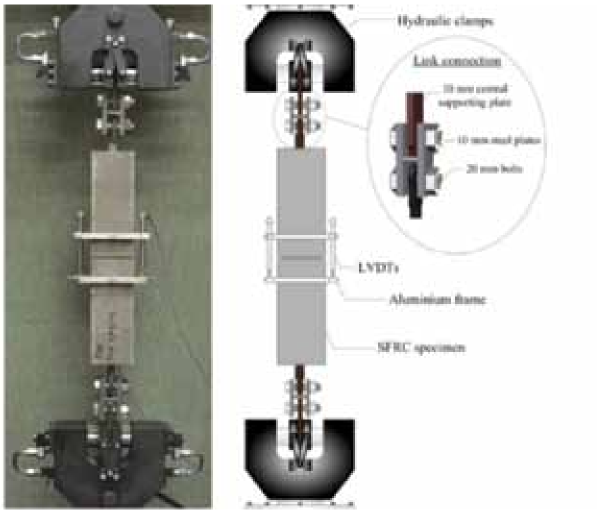


Figure 4: Uniaxial tensile test setup (Nieuwoudt, 2016)

in Figure 4. The gauge length of the detachable aluminium frames was 120 mm. Six specimens were tested for the steel macro FRC, and three for the synthetic macro FRC specimens. All specimens were tested at a loading rate of 0.01 mm/s by the speed of the crosshead of the test machine. The readings were recorded with an electronic data acquisition system supplied with the testing system.

Uniaxial tensile creep test

The time-dependent crack mouth opening was investigated using the uniaxial tensile creep test. All specimens for the creep tests were pre-cracked in the Zwick Z250 material testing machine to an average residual crack width of 0.5 mm, and unloaded at the same rate before being taken to the creep frame where the creep loads were applied at different stress levels of the post-crack uniaxial tensile strength. It should be mentioned that the test machine was not a closed-loop system, and due to its low stiffness, the pre-cracked widths varied per specimen upon cracking and unloading, with steel FRC specimens showing more scatter. All tests were carried out in a climate-controlled room at a temperature of 23±1 °C and relative humidity of 65±5%. The synthetic macro FRC specimens were loaded at 30, 40, 50, 60 and 70% of the average residual tensile load, whereas steel macro FRC specimens were loaded at 30, 50, 70 and 85%. The creep frames were designed to take two specimens in series as shown in Figure 5.

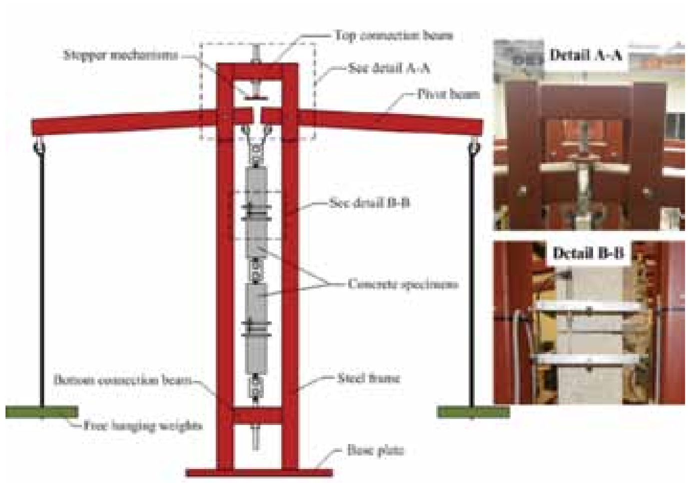


Figure 5: Schematic representation of the uniaxial creep frame showing specimens in series (Nieuwoudt, 2016)

Prior to subjecting the specimens to sustained loading, each frame had been calibrated for each applied load level. During the creep test, crack mouth opening displacement (CMOD) was automatically measured for the test period (8 months) using the two LVDTs connected to a HBM Spider8 data acquisition system. The gauge length for the creep tests was 70 mm. The actual creep measured in terms of CMOD was obtained by subtracting the drying shrinkage from the measured deformation over the gauge length. The displacement reading obtained from the creep test (total creep) included crack widening (due to fibre pull-out), material creep strain, and drying shrinkage strain. Since the load level of the specimens were always less than 2.5 MPa, the expected creep strain in the material over the gauge length is significantly less than the drying shrinkage and time-dependant crack opening. Therefore the material creep over the gauge length can be disregarded.

Drying shrinkage test

The creep specimens were tested unsealed in the controlled environment, hence, a number of phenomena were occurring at the same time. These included basic creep, drying creep, drying shrinkage and the time-dependent crack widening. While it is difficult to separate the basic and drying creep from the total creep occurring (Boshoff, 2007), the drying shrinkage could be separated. Therefore, two load-free specimens of the same size and under the same test environment as the creep specimens were simultaneously tested for drying shrinkage. The drying shrinkage was measured using two 10 mm LVDTs attached to aluminium frames screwed to the concrete specimens. To have a larger area, the LVDTs were extended to have a gauge length of 300 mm over the specimens as shown in Figure 6. The shrinkage strains measured on the beams were used to determine the shrinkage occurring over the gauge length of the creep tests and subtracted to determine the crack widening.

Figure 6: Drying shrinkage test specimens

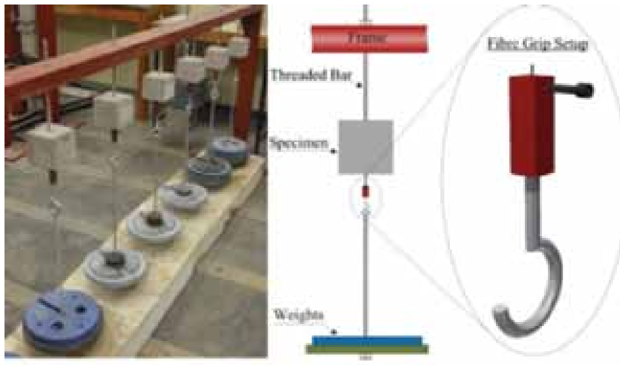
Investigation of creep mechanisms

An attempt was made to understand the mechanisms responsible for the time-dependent crack widening of the cracked macro FRC under sustained loads. For both types of macro fibres, time-dependent pull-out tests were undertaken as described in the next section. Furthermore, since synthetic macro fibres are known to undergo creep under sustained load unlike their steel counterpart, an investigation was performed to quantify this creep.

Time-dependent pull-out test

The time-dependent pull-out creep for both type of fibres was investigated using the same concrete mixture but without fibres. Only a single fibre was inserted at the mid-point of the cross-sectional

(a)



(b)

Figure 7: Time-dependent fibre pull-out test setup showing steel fibre gripping device (a) and synthetic fibre gripping device (b) (Nieuwoudt, 2016; Babafemi & Boshoff, 2015)

area of the 100 mm cube specimens used. Steel and synthetic macro fibres were inserted to embedment lengths of 15 mm and 25 mm, respectively. The embedment length of the steel fibre is not critical as basically the full load is taken by the hooked-end, thus the embedment length does not play a role. The embedment length of the synthetic fibre is taken as slightly more than half the fibre's length to ensure sufficient bond, but also sufficient fibre outside of the concrete to grip. After curing the specimens for 27 days, 10 mm threaded bars were inserted and glued into the drilled holes made on the opposite side of the embedded fibres. This ensured that the threaded bars stayed perpendicular to the concrete surface. For the hooked end steel fibres, the hooks on the one end were cut off to have it straight for the purpose of gripping, while the hooked end was inserted into the concrete. A simple gripping system was developed to effectively grip the steel fibres and prevent any slippage (Figure 7a). In the case of the synthetic fibres, hand drill chucks were used which prevented any damage to the fibres (Figure 7b). All tests were performed in the same climate controlled room as the uniaxial tensile creep specimens.

After preparation of the specimens, they were placed in position on the supporting steel frame shown in Figure 7a, and steel weights applied. Sustained loads of 50, 70 and 85% were applied in the case of the steel fibres, while that of the synthetic fibres were 50, 60, 70 and 80%. It should be noted that these sustained loads were based on the average maximum pull-out loads obtained from single fibre pull-out tests conducted on the steel and synthetic macro fibres at embedment lengths of 15 and 25 mm, respectively.

The pull-out displacement over time was measured optically by taking digital images with a microscope that contains a 3.1 Mega-pixel EC3 Leica camera. For each of the specimens, a reference image was taken and scaled, while pull-out on other images at different time periods were based on the reference images in each case.

Synthetic macro fibre creep test

The creep setup was similar to that discussed in the previous section, except that the single synthetic macro fibre was gripped at both ends by hand drill chucks, and the sustained load applied (Figure 8).

One single fibre was tested at 30% of the average tensile capacity (143 MPa) determined using a loading rate of 0.5 mm/s. The creep of the fibre was also measured optically following the same procedure described in the previous section.

Figure 8: Test setup for creep of synthetic macro fibre (Babafemi & Boshoff, 2015)

RESULTS AND DISCUSSION

Compressive strength results

The 28-day compressive strength results for the control and fibre concretes are shown in Table 3. Thirty cubes from eight batches were tested for the plain concrete, while sixteen were tested for the FRCs.

Table 3: Average compressive strengths and densities of specimens

Concrete type	Compressive strength (MPa)	CoV of compressive strength [%]	Density (kg/m³)
Synthetic macro FRC	40.19	3.42	2218
Plain concrete	43.80	4.21	2420
Steel macro FRC	60.22	2.74	2371
Plain concrete	54.35	4.50	2315

The results presented in Table 3 reflect an increase (10.8%) in the compressive strength when steel macro fibres were added to the control specimens as against a decrease for the synthetic macro FRC (8.2%). While it is understandable that the addition of fibres at certain high dosages creates more void and inhomogeneity in the concrete matrix, leading to reduced compressive strength (Richardson, 2006; Emdadi et al 2013), some other researchers have reported increase in strength (Yazici *et al* 2007; Holschemacher *et al* 2010; Bencardino, 2014). It is evident that there is no harmonised position in literature on the effect of fibres on the compressive strength of concrete. This is because the effect depends on a number of factors which has to do with the properties of the fibres, dosage of fibre and the concrete mixture used. However, it is important that the compressive strength test of samples be undertaken for any operation where FRC is to be used. The increase in the compressive strength of the control mix used for steel FRC over that of synthetic FRC is due to the change in the cement and fine aggregate batch used for the synthetic FRC. This would not have any effect on the creep performance of cracked specimens, since the stress levels were based on the residual tensile stresses.

It should be mentioned that it is a general opinion that fibres in concrete improve the toughness in compression. Hence, for the specimens tested in this research, while the specimens with fibres held the concrete together at failure, the chips of the control specimens spalled off during the test.

Uniaxial tension strength test results

The uniaxial tensile responses of the steel and synthetic macro FRC are reported in Fig. 9. The results are presented as stress versus crack width opening (σ-w) relationship.

The crack width opening was obtained after subtracting the mean displacement at the peak tensile strength of the specimens, and the linear elastic response was neglected. The LOP (limit of proportionality, also known as the cracking strength) of the steel FRC specimens is higher than that of the synthetic FRC specimens. This can be directly linked to the concrete strength, where the steel FRC had a higher compressive strength, thus resulting in a higher LOP. This was due to a change of batch of cement and sand. Added fibres at these relative low volumes plays an insignificant role in the LOP. (Li and Maalej, 1996; Richardson *et al* 2010). The LOP showed a relative large scatter, especially the steel FRC samples, and can be attributed to the type of tests, namely a hinged-hinged direct tensile test. This does not influence the creep tests presented in this paper as all the samples were pre-cracked and the post-peak stress was used as the reference load.

Beyond the LOP, it was observed that for both types of FRC, significant crack opening and drop in stress occurred before the fibres were fully engaged to control the crack widening. The drop in stress is due to the brittle nature of concrete, which is even more pronounced under uniaxial tensile load. However, this significant crack widening at ultimate strength could be minimised if a test machine with higher stiffness and a servo-controlled closed loop control is used. Mean residual stresses when the fibres started to control the crack width opening are indicated as points B in Figure 9.

It is clear that due to the higher stiffness of the steel fibres, they are more effective in controlling the drop in stress and the crack width at which it occurs. Due to the lower stiffness of the synthetic fibres, they have to stretch significantly before they are activated to control

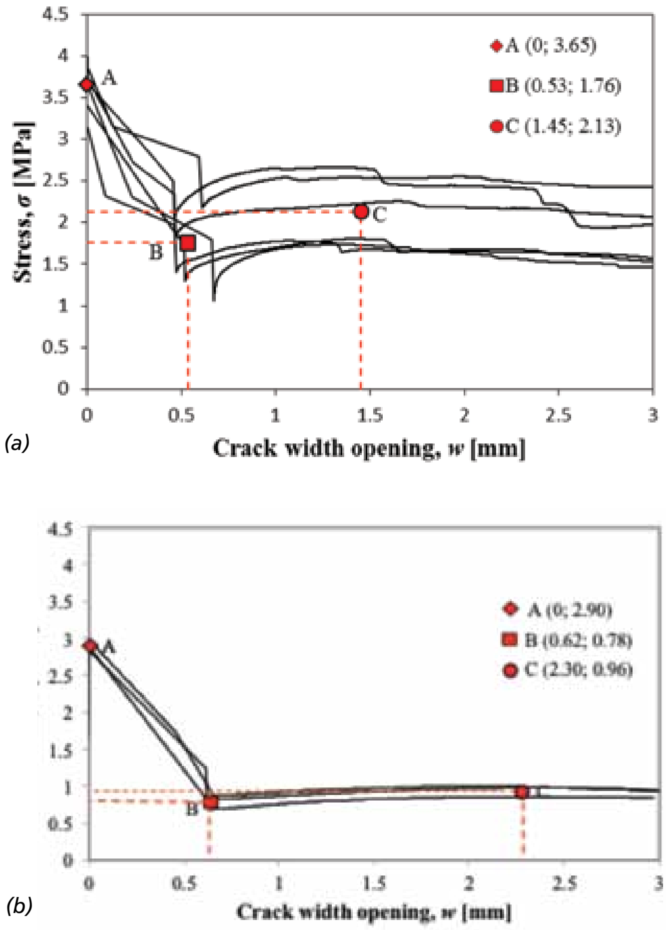


Figure 9: Uniaxial tensile test response (a) steel macro FRC (Nieuwoudt, 2016) (b) synthetic macro FRC (Babafemi & Boshoff, 2015)

crack widening; hence, the lower residual stress and larger crack width opening at B. Also, while the maximum post-crack stress was reached at a crack width of 1.45 mm for the steel FRC, this occurred at 2.3 mm for the synthetic FRC (point C in Figure 9) due to the lower stiffness of the synthetic fibres. Significant higher residual tensile strength of 147% over that of synthetic FRC is obtained at a crack width of 0.5 mm, and 133% at 1.5 mm. However, in both fibre specimens, significant toughness is displayed in the post-cracking region indicating high energy absorption, though more pronounced with the steel FRC. This is due to the hooked ends of the fibres which require more energy to straighten during pull-out.

As can be observed in Figure 9, the steel FRC showed more scatter in uniaxial tension response than the synthetic FRC. Even though too few samples were tested to make this a firm conclusion, similar results were also reported for specimens subjected to flexure (Buratti et al 2011). Fibre type and distribution do play a significant role in the scatter of results as reported by Burratti et al (2011). An observed phenomenon during test was out-of-plane propagation of cracks in some specimens. Other research works have also reported similar observation (Barragan, *et al* 2003; Dupont, 2003). This phenomenon could be attributed to the heterogeneous nature of fibre reinforced concrete.

Uniaxial tension creep results

For the synthetic macro FRC specimens, due to consistency of the post crack residual stresses for the three specimens tested in tension, loads applied to creep specimens were based on the average residual tensile stress shown at point B (Figure 9b). However, the steel macro FRC specimens were predicated upon the residual strength of each specimen after unloading (due to the scatter). Each specimen was pre-cracked and then unloaded. The crack occurred abruptly during the crack formation phase and as soon as the crack was initiated, the load was removed which caused an irrecoverable Crack Mouth Opening Displacement ($CMOD_{irr}$). Presented in Table 4 are the residual strength ($σ_r$) and $CMOD_{irr}$ of each specimen determined) for each specimen.

The average results of the tests conducted over a period of 240 days for both fibre concretes are presented in Figure 10a & b.

Table 4: Properties of cracked steel macro FRC specimens (Nieuwoudt, 2016)

Required stress level	Specimen no.	$σ_r$ [MPa]	$Choi_r$ [mm]	$σ_{sus}^{Required}$ [MPa]	$σ_{sus}^{Actual}$ [MPa]
30%	1	1.87	0.404	0.56	0.58
	2	2.02	0.547	0.61	0.70
	3	1.99	0.549	0.60	0.58
50%	1	2.08	0.433	1.04	1.04
	2	1.59	0.451	0.79	0.70
	3	2.68	0.429	1.34	1.28
70%	1	1.76	0.441	1.23	1.28
	2	2.08	0.518	1.46	1.51
	3	2.25	0.468	1.58	1.51
85%	1	2.23	0.376	1.89	1.89
	2	2.72	0.333	2.31	2.38
	3	2.89	0.765	2.45	2.38

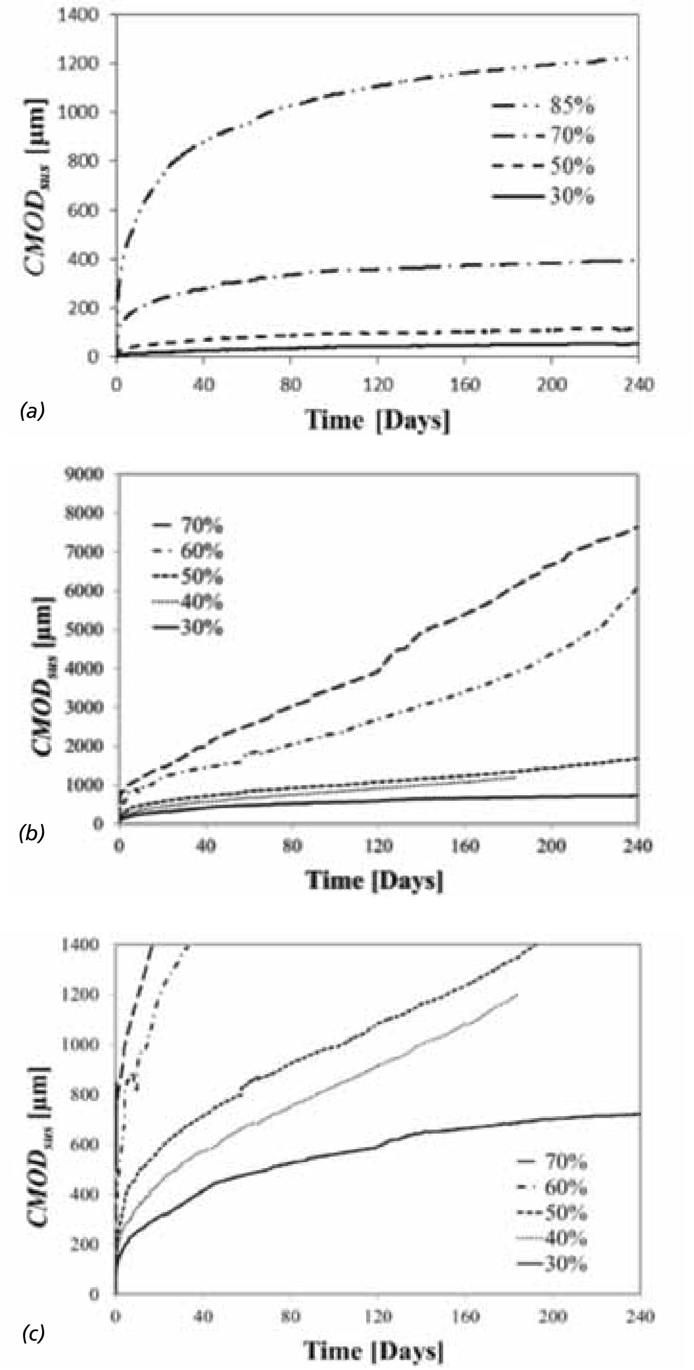


Figure 10: Average creep of cracked FRC (a) steel macro FRC (Nieuwoudt, 2016) (b) synthetic macro FRC (Babafemi & Boshoff, 2015) (c) the same as (b), but using a smaller scale.

It should be borne in mind that the average creep presented in Figure 10 is the actual creep deformation due to the sustained loads ($CMOD_{sus}$) after deduction of the drying shrinkage obtained over the same test period as previously mentioned. The instantaneous response 1 minute after the creep load was applied ($CMOD_{inst}$) was also subtracted. This was deducted as it is seen as the instantaneous crack widening which is not due to the sustaining of the load, thus not due to creep.

The results presented in Figure 10 show clearly that the creep of FRC is dependent on the applied sustained load (stress level); the creep ($CMOD_{sus}$) increases as the sustained load increases, and increases with time at a decreasing rate. It should be mentioned that the results of the average creep at 30, 40 and 50% stress levels for the synthetic FRC (Figure 10b) are averages of four specimens, two specimens were tested at 60 and 70%.

Examination of the creep response of the cracked synthetic macro FRC in comparison to the steel FRC under sustained load leaves no doubt that they are significantly higher. The CMODsus of cracked synthetic macro FRC at a 50% stress level compares to that of steel FRC at 85% stress level after 240 days (about 1200 μm). However, creep fracture occurred in one specimen at 70% stress level only after 10 h. One specimen of those loaded at 60% stress level had to be unloaded after reaching a creep of 10 mm (the limit of the LVDTs) after 15 days. These two stress levels show are therefore not able to be sustained for cracked synthetic macro FRC. On the other hand, none of the cracked steel FRC specimens fractured over the period tested. However, in both fibre concrete types, significant creep can be observed over the measure period; hence, the creep of FRC should be a major consideration when using FRC.

For both types of FRC, the creep seems to be linear up to 50% stress level. Beyond this level, a non-linear response is evident as shown in Figure 11. The non-linear increase beyond 50% stress level is thought to be the result of the non-linear increase in the instantaneous pull-out, pull-out creep of the fibres and fibre creep in the case of synthetic fibres.

CREEP MECHANISMS

Time-dependent fibre pull-out test results

For both types of macro fibres, the time-dependent pull-out responses are presented in Figure 12. The steel fibre responses at different sustained loads were labelled A while the synthetic was labelled B at the different sustained loads as shown in Figure 12 (a & b).

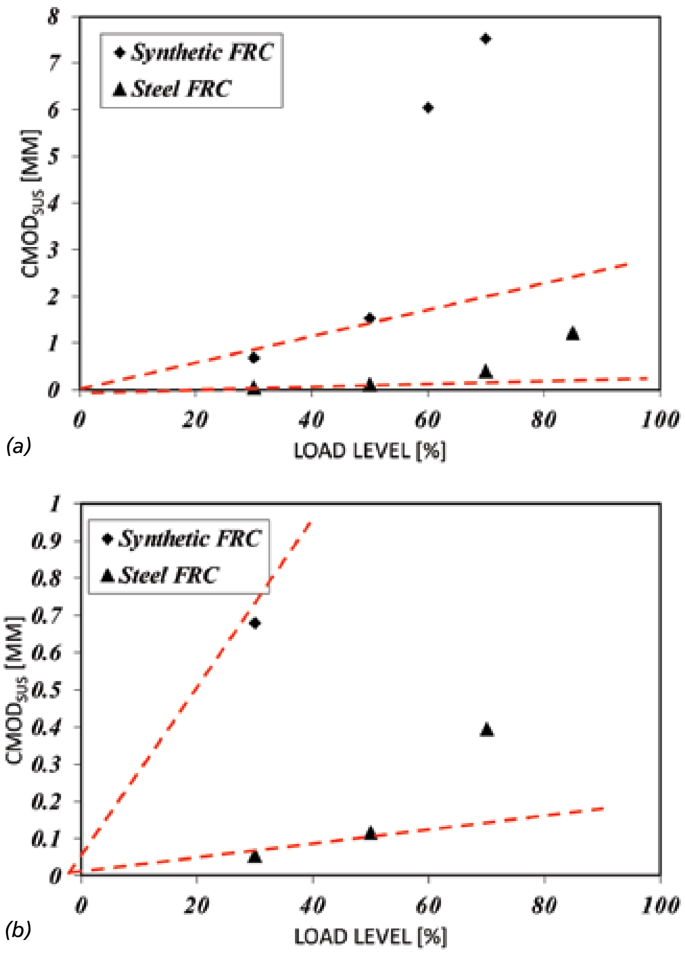


Figure 11: a) 240-day CMODsus at different load levels with a different y-axis for b) to show the behaviour of the steel FRC.

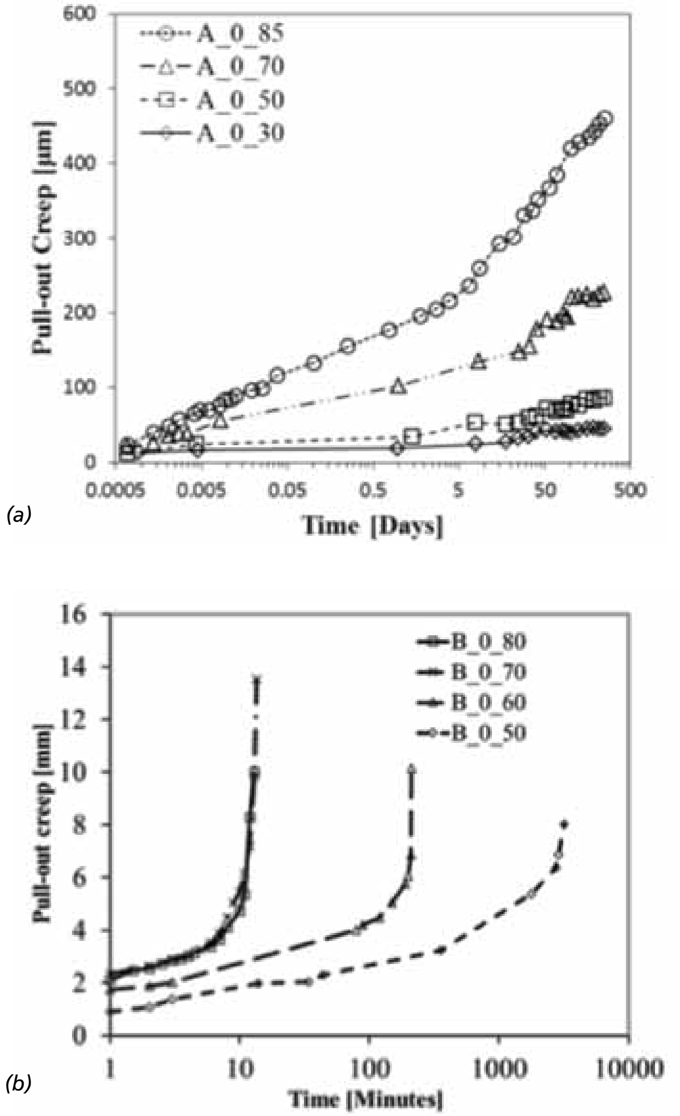


Figure 12: Time-dependent pull-out of macro fibres, a) Steel and b) Synthetic fibres

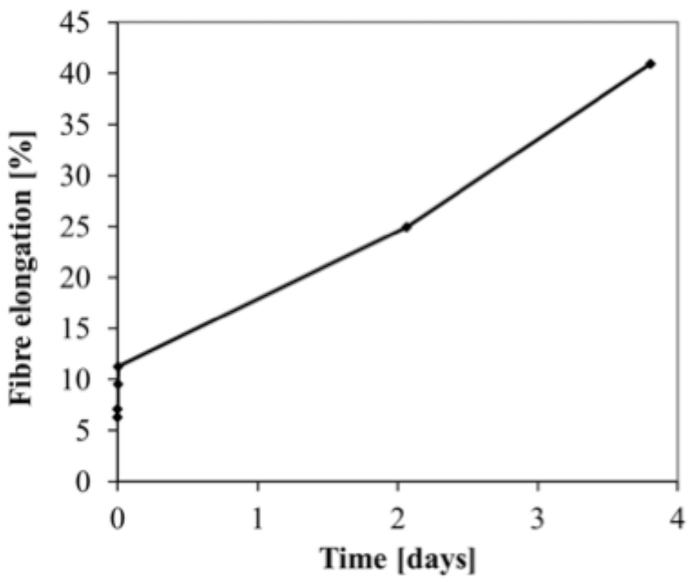


Figure 13: Creep of single macro synthetic fibre (Babafemi & Boshoff, 2015)

As evident in the macro-level investigation (uniaxial tensile creep specimens), the time-dependent pull-out creep of single fibres is dependent on the magnitude of the applied creep load. Significantly lower pull-out creep occurred with the steel fibres at comparable load level than their synthetic fibre counterpart. It is significant to mention that all the synthetic fibres pulled out completely from the matrix after just more than two days, while at 250 days, none of the steel fibres had pulled out at the various applied creep loads. This confirms a better creep performance with steel fibres than synthetic fibres as previously observed in Figure 10. Synthetic fibres are known to have poor bonding with the cement matrix and also have very poor stiffness.

The failure mechanism of the synthetic fibres under sustained loads can be adjudged to be due to fibre lengthening (Poisson's effect) and then complete pull-out. On the other hand, with the steel fibres, because of the hooked end, the tensile creep load is transferred to the surrounding matrix as compressive load around the hook. This can lead to micro-cracking around this point as the hooked end straightens and gradually pulls out under the sustained creep load (Nieuwoudt & Boshoff, 2016).

Fibre creep test results

As previously mentioned, the single fibre creep test was undertaken to understand the contribution of the synthetic fibre to the time-dependent creep behaviour at the macro level. The result of a single fibres subjected to 30% of the tensile capacity of the fibre is presented in Figure 13.

The result shows that the fibre creep can have a significant contribution to the creep of cracked synthetic macro FRC. Just before 4 days under sustained tensile load, and at such a low stress level, fibre creep was about 42%. It should be noted that this elongation is dependent on the stiffness of the fibre which in this case is 4.3 MPa (see Table 1). MacKay & Trottier (2004) reported creep occurring for a fibrillating synthetic fibre at 40%. However, for some new type of synthetic macro fibre with elastic modulus of 10 GPa, significantly lower creep is expected.

CONCLUSIONS

This research investigated the creep responses of cracked steel and synthetic fibre reinforced concrete beams under varying sustained uniaxial tensile loadings. The mechanisms responsible for the time-dependent crack width opening were also investigated at the single fibre level and for the time-dependent pull-out creep and fibre creep tests. The following conclusions can be deduced.

- The compressive strength of concrete with the inclusion of fibres could increase or decrease depending on the type of fibres (steel or synthetic) and other associated fibre properties. Hence, compressive strength should be checked for any type of fibre mix.
- Steel macro FRC showed better residual strength properties and crack control ability than synthetic macro FRC in the post-cracking region in a uniaxial tension test. At a crack width of 0.5 mm, steel FRC showed improved residual strength of about 147% over that of synthetic FRC at the same width.
- Creep of FRC is a function of the applied creep load. Steel FRC showed far lower creep compared to synthetic FRC. The creep of cracked steel FRC at 85% appears only comparable to those of synthetic FRC at 50% after 8 months of sustained loading. While creep fracture occurred at 60 and 70% stress levels for synthetic FRC, no fracture occurred for steel FRC even at a high stress level of 85%.
- Fibre creep and pull-out have been identified as the mechanisms responsible for the time-dependent creep of cracked synthetic FRC while only fibre pull-out occurred for the steel FRC.
- Significant creep has been measured for both steel and synthetic macro FRC over a period of 8 months. Therefore, the creep of FRC should be taken into account in their use for structural purposes. ▲

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