BarChip
Technical
Note

Creep of Fibre Reinforced Concrete

Revision No. 1

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BarChip Inc.
The Synthetic Fibre Experts

What is Creep?

Creep is defined as a time-dependent increase in strain of a material in response to a sustained stress. This increase in strain occurs in addition to the elastic strain experienced upon the initial application of stress (Wittman, 1982). Creep of concrete can occur in tension, compression, and shear. Creep of cracked fibre reinforced concrete is generally only considered in tension. Creep most commonly manifests as a time-dependent increase in deflection or crack width and in this regard is considered a serviceability issue (Gilbert and Ranzi, 2011). However, creep can also act to redistribute load from highly stressed areas to lower stressed areas and can thereby diminish the incidence of cracking. Understanding creep and its effects on fibre reinforced concrete is a complex process but can be important when seeking to predict the long-term behaviour of structures (Ghali and Favre, 1994).

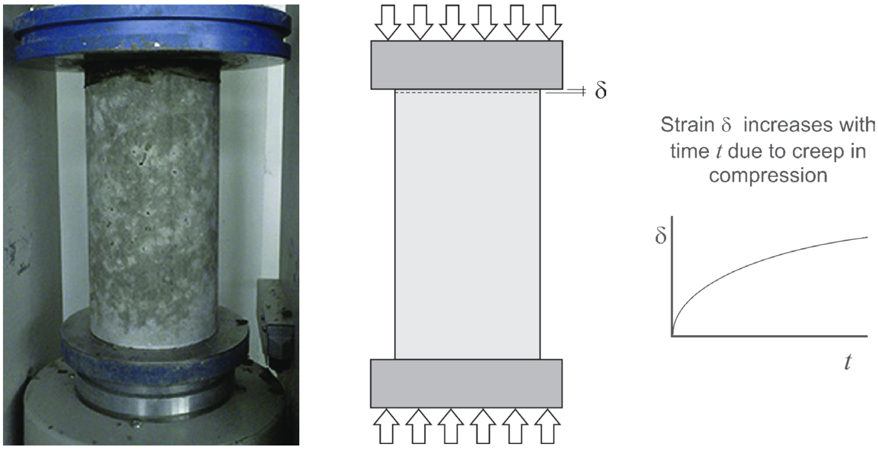


Figure 1. Creep effects in concrete subject to sustained compression.

When loaded in compression, the fibres within FRC are effectively inactive, so the creep of FRC in response to sustained compression is dominated by creep of the concrete matrix. However, when loaded in tension, FRC may crack. If tensile stress across a cracked section is sustained, both the concrete and fibres will exhibit some form of creep (Plizzari and Serna, 2018). Tensile creep of concrete is difficult to characterise but is generally taken to be equal in magnitude to compressive creep of concrete for the same magnitude of applied stress. In contrast, creep of fibres is influenced by many factors as discussed below.

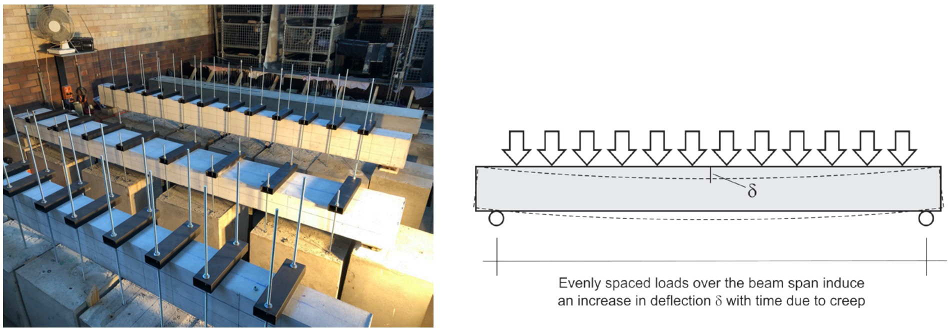
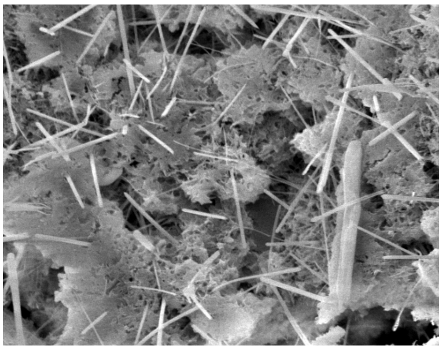


Figure 2. Deflection increases with time due to creep effects in bending (Watts et al, 2021).

What Causes Creep of Concrete?

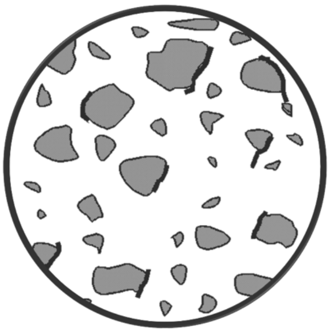
The progressive strain that concrete experiences under a sustained stress is primarily caused by the movement of moisture within calcium silicate hydrate (CSH) crystals in the cement paste within concrete (Mehta and Monteiro, 2013). CSH is a platy crystalline material that constitutes the primary binding phase in hydrated cement paste, formed by chemical reactions between cement particles and water during the hydration process.



CSH crystals within concrete.

The microstructure of CSH crystals significantly contributes to the mechanical properties of concrete and influences creep in several ways. The spacing and arrangement of these crystals also influences the overall porosity of the material. Increased porosity is associated with higher levels of creep because it allows for more movement of moisture within the concrete in response to stress, contributing to time-dependent deformation. The ease of mobility of water within the hydrated cement paste is the critical factor in the long-term deformation of concrete under sustained stress. Factors that influence water permeability in concrete, such as water/binder ratio, cementitious content, and degree of hydration/curing, also influence creep (Popovics, 1992).

Creep in concrete is influenced by factors such as temperature, humidity, and the properties of the concrete mix. Several additional mechanisms contribute to the creep of concrete, including:



Microcrack development in concrete.

Microcracking: Microcracks may develop in the concrete matrix due to various factors such as shrinkage, thermal expansion and contraction, and loading. The presence of these microcracks can influence the magnitude of time-dependent deformations as they evolve and propagate under sustained stress.

Aggregates: The type and characteristics of aggregates used in the concrete mix can influence its creep behaviour. Some types of aggregate, including quartzite and basalt, exhibit very little creep, thus inclusion of these aggregates can reduce the propensity of a mix to suffer creep. Moreover, the relative quantity and grading characteristics of the aggregates within the concrete also play a role in creep (finer aggregates generally promote more creep than coarse aggregates).

Concrete aggregates can influence creep behaviour.

Temperature and Humidity: Elevated temperatures can accelerate the creep process in concrete. Higher temperatures increase the rate of chemical reactions and affect the mobility of water within the concrete. Relative humidity can also impact creep, as changes in moisture content can influence the rate at which moisture is expelled from calcium silicate hydrate crystals and thereby affect creep strains.

Creep of concrete in tension is an important process at early ages because it acts to reduce the frequency of thermal and drying shrinkage cracks. When evaporation occurs from a young hydrating concrete surface, shrinkage stresses arise. If the shrinkage stress exceeds the tensile strength of the concrete it will crack. Tensile creep can relieve the magnitude of shrinkage stresses generated and reduce the likelihood of cracking. This is one reason why proper curing of fresh concrete surfaces is so important to controlling cracking: not only does curing reduce shrinkage stress development but it assists in strength gain and increases the length of time available for creep to dissipate whatever tensile stresses that may arise. Creep of the concrete component of a structure can reduce the incidence of cracking and thereby aids in the satisfaction of serviceability and durability requirements.

Creep of concrete can be of concern to the long-term performance of FRC structures such as tunnel linings and elevated members. Creep tests are conducted to help quantify the long-term deformation characteristics of FRC mixes under anticipated conditions, helping engineers make informed decisions in the design and construction phases. Despite the generally negative portrayal of creep, creep of uncracked concrete in compression and tension helps to relieve the stresses that can generate cracks (Gilbert and Ranzi, 2011). Since cracks commonly lead to an increased rate of deterioration of a structure (ACI 544.5R-10), creep can be useful in the context of preserving the durability of both the concrete and reinforcement in some circumstances.

Creep of Fibres at Cracks

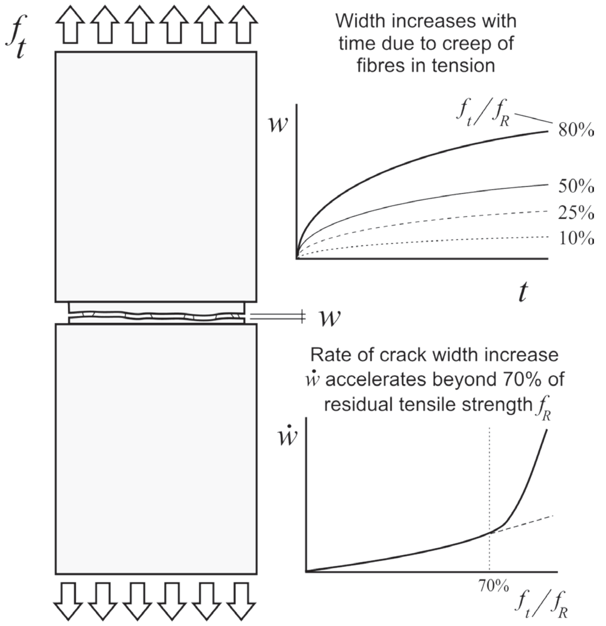


Figure 3. Crack width increase in tension is often proportional to the magnitude of sustained tensile stress ft compared to short-term post-crack residual tensile strength f_R (Boshoff and Nieuwoudt, 2017). For hooked-end steel FRC, the rate of crack width increase will accelerate beyond $f_t/f_R = 0.70$.

The most common manifestation of creep of fibres at cracks is a time-dependent increase in crack width (Gettu et al, 2017). There are two types of tensile creep experienced by a fibre reinforced concrete member, or a hybrid bar and fibre reinforced concrete section, that can lead to a progressive increase in crack width. These are:

- Time-dependent elongation of fibres
- Time-dependent pull-out of fibres

It is generally agreed that steel fibres and reinforcing bars suffer negligible elongation under a sustained tensile load but that macro-synthetic fibres can suffer elongation that must be accounted for when estimating long-term post-crack deflections and crack widths (Babafemi et al, 2018). Creep is an inherent property of the polymers that comprise macro-synthetic fibres, but the magnitude of elongation likely to be experienced by a polymer fibre can vary dramatically depending on chemistry and manufacturing methods (Findley et al, 1976; Turner, 2001).

In contrast, both steel fibres and macro-synthetic fibres can potentially suffer time-dependent pull-out from the concrete matrix (Boshoff and Nieuwoudt, 2017). This type of creep-like behaviour is related to the geometry of the fibre and tends to be more prevalent for fibres with a uniform cross-section (such as tape-based macro-synthetic fibres and cold-drawn steel fibres of straight or hooked-end geometry). The extent of slippage that occurs for a fibre will depend on factors such as the smoothness of the fibre surface, hardness of the cement paste, and magnitude of tensile stress. Crack width increase due to fibre slippage is structurally equivalent to fibre elongation and therefore must be accounted for when assessing long-term serviceability issues such as likely maximum crack width (Gettu et al, 2017).

> *“For this reason, it is a mistake to claim that all macro synthetic fibres exhibit high levels of elongation-based creep...”*

The available experimental evidence for post-crack creep of fibres in concrete seldom distinguishes between elongation and pull-out due to the difficulty of measuring elongation of fibres embedded within concrete. However, single-fibre elongation tests have indicated that elongation is a real phenomenon for some types of macro-synthetic fibre (Vrijdaghs et al, 2018). The extent of elongation suffered in response to sustained tensile stress is influenced by numerous material and manufacturing parameters and therefore cannot be predicted nor generalised. For this reason, it is a mistake to claim that all macro-synthetic fibres exhibit high levels of elongation-based creep (Gettu et al, 2017). Instead, the propensity for a particular type of fibre to suffer elongation under the conditions expected in service must be evaluated by testing.

Time-dependent pull-out of fibres from within a concrete matrix (often occurring in combination with elongation) is relatively easy to measure (Boshoff and Nieuwoudt, 2017). This is usually done by measuring crack width increase with time for a FRC member subject to either direct tension or flexure. Many studies have demonstrated that crack width increase with time will occur for both steel and macro-synthetic FRC and that the rate of crack width increase is generally greater for macro-synthetic fibres than steel fibres (Gossla and Rieder, 2009; Kusterle, 2016). However, most published papers have conducted so-called ‘comparative’ tests using steel FRC mixtures that exhibited higher post-crack tensile strength than competing macro-synthetic FRC mixtures. The sustained stress imposed on the macro-synthetic FRC mixtures was, as a result, greater than was imposed on the steel FRC mixtures. When subject to similar levels of sustained stress, some types of embossed macro-synthetic fibres have been shown to exhibit a similar degree of time-dependent crack width increase with time as hooked-end steel fibres (see Figure 4, Garcia-Taengua et al, 2017).

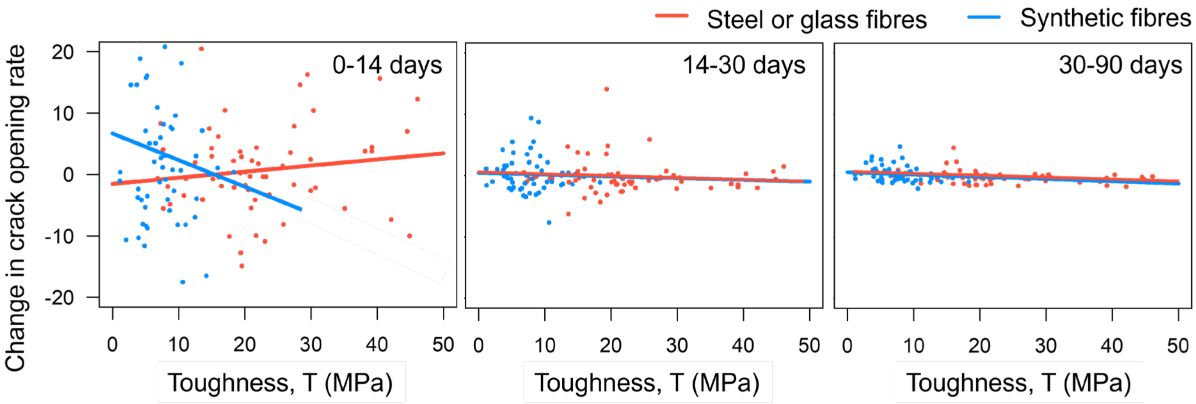


Figure 4. Influence of toughness on relative rate of crack opening in FRC beams, showing similarity in creep performance for steel and macro-synthetic fibres (Garcia-Taengua et al, 2017).

Aspects of FRC Creep Relevant to Structural Performance

There are four aspects of the post-crack creep of fibre reinforced concrete that can be considered in the context of FRC performance in structures. These are:

- Crack width increase,
- Deflection of suspended structures,
- Creep rupture,
- Durability of steel reinforcement.

The first issue is relevant to structures made with either fibres on their own or hybrid structures incorporating fibres and steel reinforcing bars. There are few suspended structures made using fibres on their own, so the second issue is mainly relevant to hybrid structures made with fibres and steel reinforcing bars. Creep rupture is potentially an issue for structures made using fibres as the sole form of reinforcement. The last issue is clearly only relevant to structures containing steel fibres or steel reinforcing bars.

A substantial amount of evidence describing the effects of creep in FRC structures has been published in recent years, as outlined below. Despite this, creep is a challenging phenomenon to account for in structures and generally requires advanced analytical techniques to model successfully (Bazant, 1988).

Crack Width and Deflection Increase due to Creep

Numerous investigations of the creep of FRC have addressed the issue of time-dependent increase in crack width and deflection. The majority have used beams as the basis of assessment, and thus have examined behaviour in response to flexure (Candido et al, 2017; Tošić et al, 2022; Watts et al, 2022), but some have used direct tension specimens (Boshoff and Nieuwoudt, 2017). Several investigations have also based measurements upon the flexural behaviour of panels to model tunnel linings (Larive et al, 2016; Bernard, 2010, 2021). All of these have generally concluded that macro-synthetic FRC experiences greater creep deformation and crack width increase with time than steel FRC, but that there is a wide range in the degree of deflection and crack width increase for macro-synthetic FRC. Moreover, the difference in creep deformation between steel and macro-synthetic FRC varies with age. Behaviour is very similar at young ages (up to 7 days age) but starts to diverge at later ages (Larive et al, 2016).

An important factor that influences time-dependent crack width increase of steel FRC is embrittlement. In concrete of normal strength, most fibres are designed to pull-out in response to a tensile stress at cracks leading to a degree of post-crack ductility. However, when the strength of the concrete is too high, the fibre anchorage strength can exceed the tensile strength leading to rupture instead of pull-out. Thus, the preferred high energy pull-out mode of post-crack fibre behaviour changes to a brittle low-energy mode involving rupture of individual fibres because the resistance to pull-out exceeds the breaking strength of the fibre (Bernard, 2020). This phenomenon primarily affects steel fibres but can also affect some types of macro-synthetic fibre. Steel fibres within an embrittled mix will not slip relative to the surrounding concrete and thus, as long as the tensile strength of the fibres is not exceeded, a member comprised of embrittled FRC will exhibit negligible crack width increase with the passage of time. However, embrittled FRC will also exhibit relatively poor ductility because the energy-absorbing capacity of a ruptured fibre is very low. One can therefore conclude that a steel FRC mixture can either exhibit high resistance to creep (when in an embrittled state) or high ductility (when fibres are able to pull out during crack widening), but not both (Bernard and Amin, 2023). The strength of the concrete matrix must be tailored to the strength and pull-out characteristics of the fibre to obtain one or the other mode of post-crack behaviour.

> ***"One can therefore conclude that a steel FRC mixture can exhibit high resistance to creep or high ductility, but not both."***

In general, crack widths can be expected to increase with time for all types of FRC under the action of a sustained tensile stress. Crack width increase will be limited for embrittled steel FRC and mixes made with fibres that exhibit a geometry resistant to progressive pull-out (such a slit-sheet, enlarged end, or paddle-end fibres). The degree of crack width increase will vary with the magnitude of tensile stress, the dosage rate of fibre, and characteristics of both the concrete matrix and fibres. Performance data required to predict long-term deflections should thus ideally be obtained from tests performed on the fibre reinforced concrete mixture in question.

The majority of research conducted into post-crack creep of FRC over the last 30 years has been carried out using beams. Research on hybrid members comprised of Reinforced Concrete and FRC (RC/FRC) have generally been undertaken using relatively slender simply supported beams of 3-4 metres length and 200-400 mm depth (Candido et al, 2018; Watts et al, 2022; Tošić et al, 2022). In contrast, research on pure FRC mixtures has most commonly involved beams similar to either pre-cracked EN 14651 or ASTM C1609/C1609M prisms (e.g. Kusterle, 2016 ; Llano-Torre et al, 2017 ; Buratti and Mazzotti, 2017). A common beam test configuration, developed under the auspices of RILEM TC 261-CCF, is the three-beam arrangement shown in Figure 5. Three beams are tested concurrently using a similar gravity load imposed using a lever. Deflections and crack widths

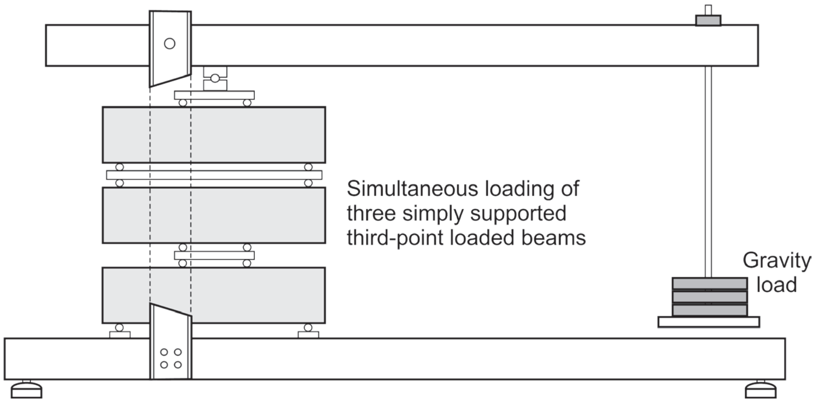


Figure 5. Creep testing of pre-cracked FRC beams using the RILEM TC 261-CCF recommended configuration.

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> ***“This indicates the error in believing that all macro-synthetic fibres exhibit ‘high levels of creep’ and all steel fibres exhibit ‘low levels of creep’.”***

are measured independently as a function of load duration, which is typically imposed for 2-3 years. This compact and relatively low-cost configuration allows numerous FRC mixtures to be assessed concurrently, resulting in economical comparative studies of the influence of a number of fibre and mix parameters on post-crack creep performance (e.g. Monetti et al, 2019; Tošić et al, 2020; Llano-Torre and Serna, 2021).

While the majority of experimental data describing the creep of FRC has been obtained using simply supported beams, this configuration is rarely encountered in design practice. Moreover, it is quite onerous in regard to deflections and crack widths because the lack of structural redundancy provides little opportunity for the type of load re-distribution that commonly occurs in redundant structures such as tunnel linings, slabs, and frames. Creep results obtained in other types of tests, particularly involving panel specimens, is often of greater relevance to structurally redundant applications because they exhibit the type of stress re-distribution typical of most structures.

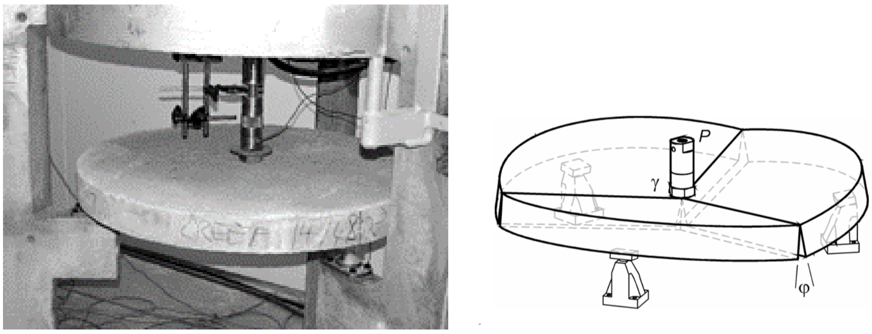


Figure 6. Panel specimen subject to sustained central point loading.

A panel-based experimental set-up and scheme of assessment for creep conducted using ASTM C1550 specimens is shown in Figure 6 (Bernard, 2010). These tests demonstrated that the magnitude of creep deformation experienced after 100 days loading broadly increased with the ratio of imposed long-term load over short-term resistance (Figure 7). The tests also demonstrated that creep deformation can vary by an order of magnitude for different types of macro-synthetic fibre (identified by their commercial names Kyodo, Strux, and HPP), and by a factor of about 5 for different types of steel fibre (Novotex and Dramix), when subject to the same load magnitude. This indicates the error in believing that all macro-synthetic fibres exhibit ‘high levels of creep’ and all steel fibres exhibit ‘low levels of creep’. Research conducted using pre-cracked beams subject to long-term loading

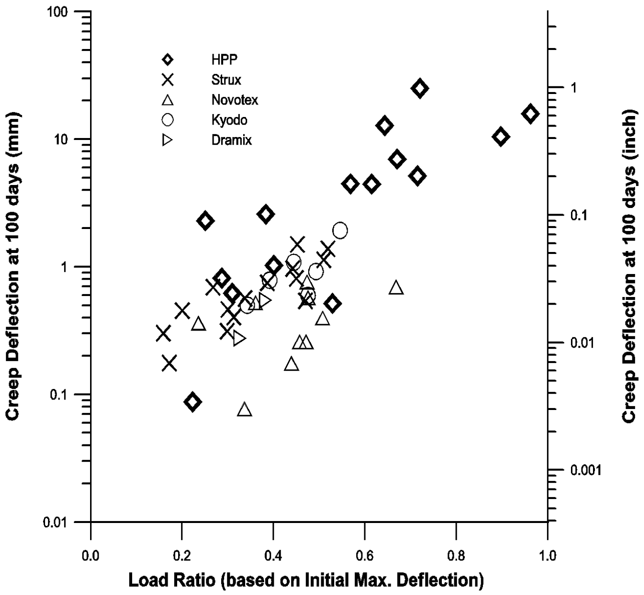


Figure 7. Creep deflection at 100 days expressed as a function of load ratio (based on load capacity at initial maximum deflection).

indicate a similar divergence in the magnitude of creep deformation and crack width increases for different types of steel and macro-synthetic FRC mixtures (Llano-Torre et al, 2017; Nakov et al, 2017).

A second type of panel-based experimental examination of creep behaviour in fibre reinforced shotcrete was used by Larive et al (2016) to assess the creep characteristics of various FRS mixtures at early-ages. The performance of several such mixes is illustrated in Figure 8, where EN14488-5 square panels produced by spraying were subjected to a sustained load for 320 days (with an increase part way through the test). The data indicated that BarChip BC54 macro-synthetic FRS (denoted as BF03) exhibited similar performance to steel FRS (BF02, BF04 and BF06), but absolute performance varied with dosage rate of fibre.

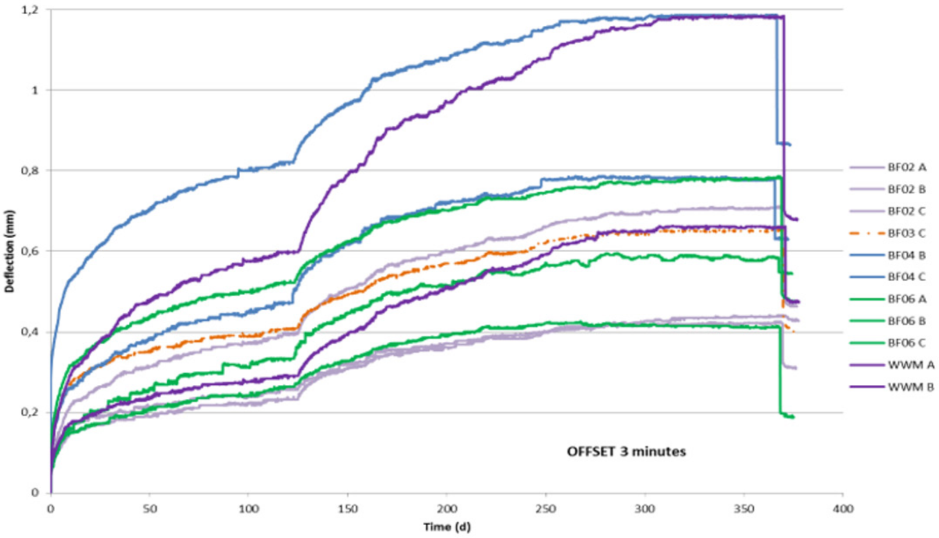
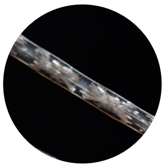
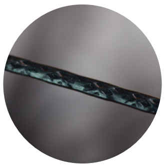


Figure 8. Creep deflections measured under 320 days of sustained loading for EN 14488-5 square panels comprised of fibre reinforced shotcrete. The majority of mixes incorporated steel fibres (BF02, BF04, and BF06) or welded wire mesh (WWM). One mix (BF03) incorporated Barchip BF54 fibres (orange line).





Creep Rupture

An issue that is of particular concern in suspended applications for FRC is the potential for creep rupture. Creep rupture is defined as the time-dependent loss of structural continuity in response to an imposed long-term stress that is lower in magnitude than the short-term breaking stress. For FRC, creep rupture most commonly occurs as a result of time-dependent pull-out of fibres, but occasionally has been observed to arise as a result of tertiary elongation of synthetic fibres (Kurtz and Balaguru, 2000).

Tests on FRC panels by Bernard (2021) indicated that BarChip BC54 fibres exhibited a time to rupture at least two orders of magnitude greater than exhibited by smooth synthetic fibres, especially at small crack widths (Figures 9-10). Moreover, the same investigation demonstrated that non-embrittled hooked-end steel fibres (Dramix RC65/35 3D in 32 MPa shotcrete) experience rapid creep rupture under gravity loads exceeding 75% of the short-term strength determined by closed-loop testing. This result was also confirmed by Kusterle (2016) for Dramix RC65/60 fibres in moderate-strength concrete under gravity loading. Creep rupture at moderate levels of stress (~70% of short-term breaking stress) has also been observed in steel FRC by Zerbino and Barragan (2012) and Llano-Torre et al (2017). This suggests that closed-loop testing (in which run-away fibre slip is prevented by the closed-loop mechanism of the test machine) produces optimistic estimates of load resistance for conditions in which fibre pull-out due to rapid slippage is possible. This type of failure is unlikely to occur for fibres possessing geometric obstructions such as embossments or end-enlargements that physically prevent fibre slip relative to the surrounding cement paste.

Boshoff and Nieuwoudt (2017) also demonstrated through long-term single-fibre pull-out tests and FRC tension member tests involving gravity loading that hooked-end steel fibres experience an acceleration in rate of progressive slip relative to the cement paste when the sustained load exceeds 70% of the short-term residual load resistance. Since most applications involve gravity loading, this suggests that commonly used hooked-end steel FRC should not be subject to a sustained stress, even in the short-term, greater than 75% of post-crack residual capacity indicated by closed-loop testing.

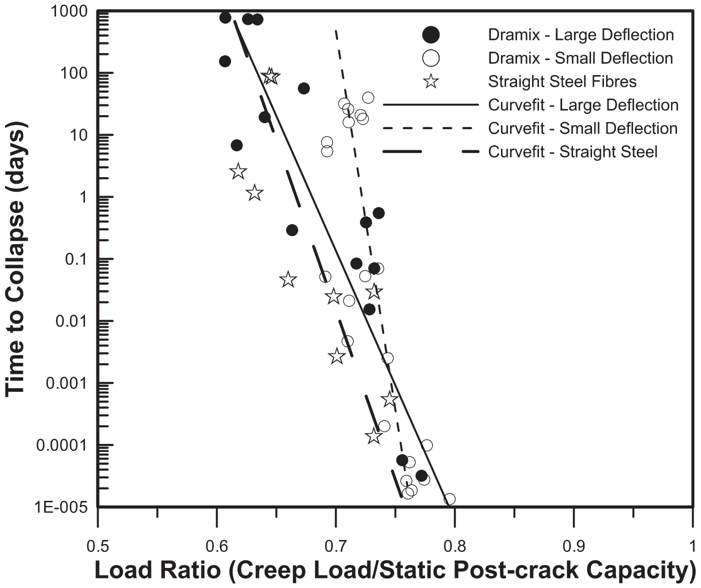


Figure 9. Time-to-collapse plotted against load ratio for specimens dosed with BC54 macro- synthetic fibres.

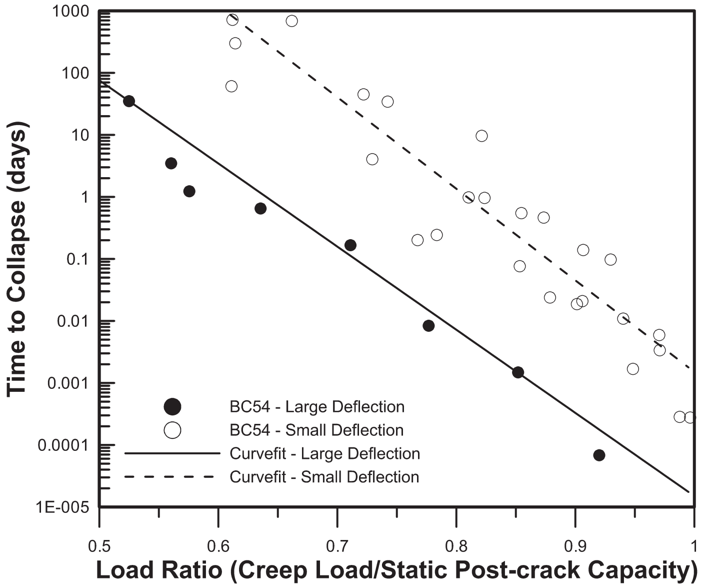


Figure 10. Time-to-collapse plotted against load ratio for specimens dosed with Dramix RC65/35 hooked-end steel fibers and straight steel fibres. The time-to-collapse appears to be relatively unaffected by the magnitude of the initial post-crack deformation.

Relaxation

Relaxation is the process by which a stress existent in a material will dissipate over time under conditions of relatively constant strain. In general, this will only occur if there is an alternative load path within a structure. Relaxation of concrete occurs as a result of the same microscopic moisture transfer mechanism within CSH crystals that is responsible for conventional creep deformation. Relaxation is particularly evident in young concrete and can assist in dissipating tensile stress generated by thermal or drying shrinkage. It also contributes to load re-distribution around points of peak load or stress. Relaxation of the concrete matrix is therefore useful in preventing cracking. Even in the event of cracking, relaxation will act to re-distribute load away from the zone of cracking and lead to a reduction in the magnitude of long-term crack widths (Ghali and Favre, 1994). In tests, loading configurations are selected to cause either creep or relaxation to dominate behaviour in a specimen, but in most redundant structures, creep and relaxation occur concurrently and are difficult to separate.

> ***"...in most redundant structures, creep and relaxation occur concurrently and are difficult to separate."***

In the context of empirical assessment, ‘relaxation’ is a form of ‘inverse creep’ in which the level of stress steadily falls in response to an imposed (usually fixed) strain (Bazant, 1988). This type of testing can be more challenging than conventional creep testing and thus the relaxation of cracked FRC is seldom reported. Nevertheless, relaxation is worth examining because it is relevant to structures such as slender tunnel linings in which the lining is not stiff enough to resist the deformation imposed by the ground (Bernard and Amin, 2023).

Tests of ASTM C1550 FRC panels subject to relaxation have indicated that a combination of tensile relaxation in the fibres and (less significant) compressive relaxation in the concrete compression zones results in dissipation of load within a period of hours for both hooked-end steel fibres and macro-synthetic FRS loaded in flexure (Figures 11 and 12, Bernard and Amin, 2023). However, when the matrix strength is high and the steel fibre reinforced mix is embrittled, the degree of relaxation is much lower, leading to a retention of load resistance (Figure 13).

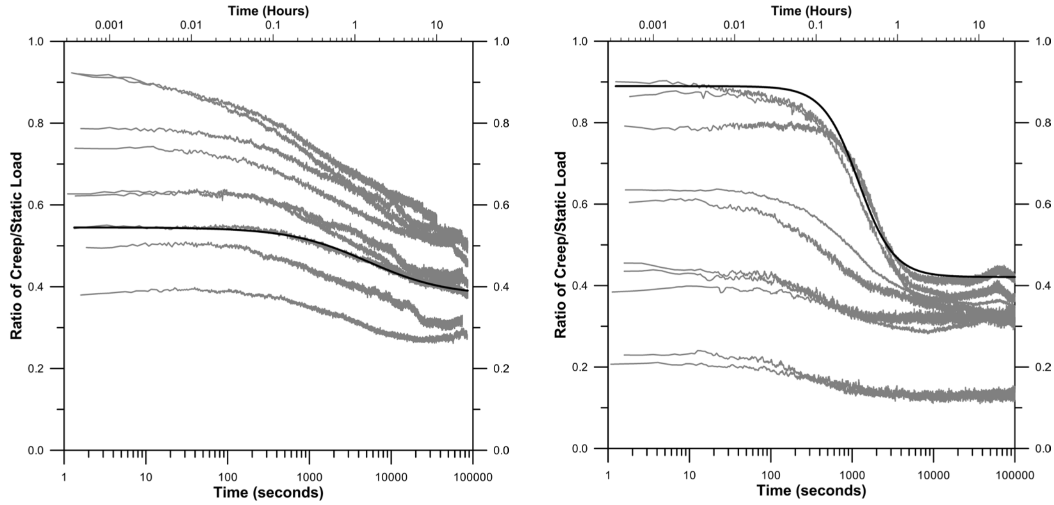


Figure 11. a) BC54 load relaxation data as a function of log$_{10}$(time) with a typical curve fit, and b) relaxation curves for 32 MPa SFRS panels with a curve fit to typical curve.

> ***“This indicates that high-ductility non-embrittled steel FRC exhibits similar performance to high tenacity embossed macro-synthetic FRC in relation to creep response.”***

The significance of progressive fibre pull-out to relaxation is most evident in Figure 12. In 32 MPa shotcrete, Dramix 65/35 3D steel fibres do not suffer embrittlement, so are free to pull-out either in response to short-term loading (in which case they provide high ductility) or sustained loading. The ratio of residual load resistance after 12 hours of loading compared to initial residual resistance during short-term loading (plotted on the vertical axis) is essentially the same for non-embrittled Dramix 3D fibres as BarChip BC54 fibres subject to the same relative magnitude of load (plotted on the horizontal axis). This indicates that high-ductility non-embrittled steel FRC exhibits similar performance to high tenacity embossed macro-synthetic FRC in relation to creep response. Very low creep in the long-term can only be achieved for a pure FRC mixture by deliberately embrittling the mixture so that high fibre anchorage strength prevents progressive pull-out with the passage of time.

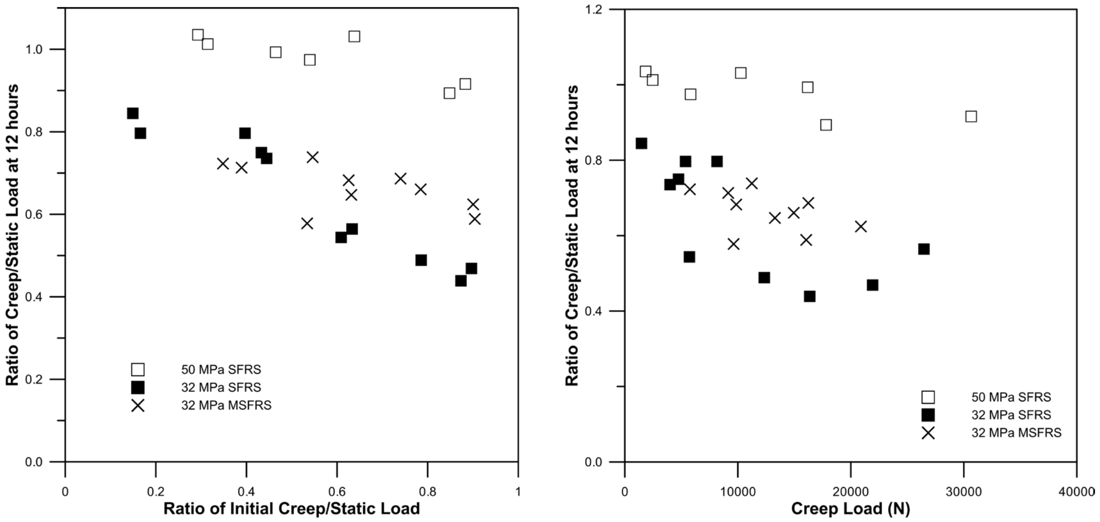


Figure 12. Fall in retained creep load ratios at 12 hours compared to a) initial creep/static ratio, and b) load magnitude.

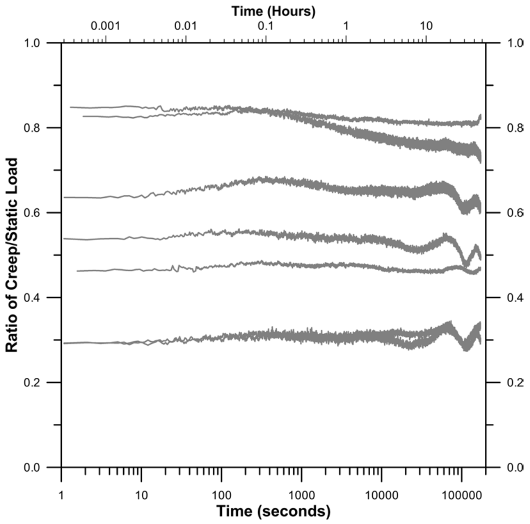


Figure 13. Plot of load ratio as a function of time after commencement of relaxation for all end-hooked steel FRS made with 50 MPa plotted for the first 200,000 seconds (48 hours) of relaxation.

Influence of Fibres on Long-term Crack Widths in Reinforced Concrete/FRC Beams

The majority of experimental research conducted in relation to FRC has involved tests that typically take 10-40 minutes to complete. The results obtained from these tests are commonly taken to describe ‘short-term’ behaviour because material response is too fast to include creep effects. In order to assess creep effects, loading must be imposed for a sustained period of time, typically lasting several days to years depending on the anticipated duration of loading required in design. When data is available describing behaviour over an extended period of time, the material or structural response is described as ‘long term’. Given that loads may be imposed for 30 years or more in some applications, a degree of extrapolation is usually undertaken from experimental data to design. Evidence from long-term tests carried out to date (Kusterle, 2016; Bernard, 2021; Candido et al, 2018) indicates that the majority of deformation and crack width increase for FRC structures appears to occur over a relatively short initial period of loading (typically a few months) and can be extrapolated relatively successfully to longer periods of time.

In the context of flexural cracks in hybrid RC/FRC members, both steel and macro-synthetic fibres have been found to reduce the maximum width of flexural cracks compared to conventional RC beams in the short term (Model Code 2020, 2024). The effect of fibres on short-term flexural crack spacing and widths has been recognized for many years and is now accounted for in several codes (Eurocode 2 Annex L, 2023; AS3600 Chapter 16). Their effect on long-term crack widths has taken longer to be recognized, with only a limited number of experimental results available from long-term laboratory and field measurements of loaded RC/FRC beams (Candido et al, 2018; Watts et al, 2022; Tošić et al, 2022). These results indicate that crack widths increase with the passage of time for both steel and macro-synthetic FRC but the magnitude of increase is dependent on many factors.

There are numerous factors affecting short and long-term crack widths and deflections in RC/FRC members. The reasons for this include the fact that crack spacing (which directly influences crack widths) is determined primarily by short-term post-crack performance and does not change with duration of loading, and both crack widths and deflection are influenced by creep of the concrete in compression which affects steel and macro-synthetic FRC equally. Moreover, most steel fibres will progressively pull-out when subject to sustained tension if the mixture does not exhibit embrittlement (Boshoff and Nieuwoudt, 2017; Bernard and Amin, 2023) and therefore do not differ fundamentally from macro-synthetic fibres. In addition, embossed macro-synthetic fibres have been shown to increase the effective bond strength between concrete and steel bars (by enhancing confinement) both at early and mature ages (Figure 14; Watts et al, 2021). However, the elongation and pull-out characteristics of macro-synthetic fibres varies substantially between different brands.

While test data on long-term crack widths in limited, it is fair to say that long-term crack widths are most effectively controlled using an FRC mixture exhibiting a high level of post-crack performance over the first 0.5 mm of crack width, made with fibres exhibiting a high level of resistance to pull-out and/or elongation. Long-term crack width prediction is not presently included in any published code, but work is currently in progress to include estimation of long-term crack widths for hybrid RC/FRC beams and tension members made with either steel or macro-synthetic fibres in future editions of structural codes.

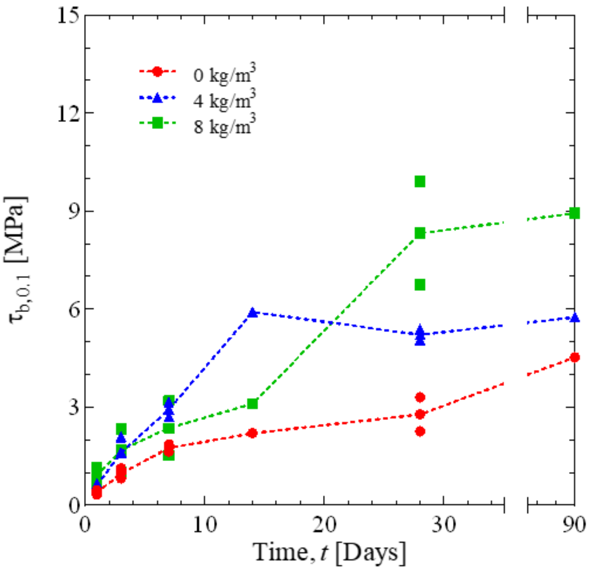


Figure 14. Bond strength development in plain and macro-synthetic FRC containing BarChip BC48 fibres, measured using bar pull-out tests at 1 to 90 days age (Watts et al, 2021).

Crack Widths and Durability of Steel Reinforcement

Steel reinforcing bars and fibres are generally well protected from corrosion if buried at sufficient depth within dense concrete exhibiting low permeability to water and chloride ions. However, if cracks exist in the concrete, oxygen and potentially aggressive ions such as chlorides can gain ready access to the steel reinforcement leading to rapid corrosion. Since steel fibres are typically only 0.5-1.0 mm in diameter and have a very high surface to volume ratio, they can lose structural effectiveness soon after the onset of corrosion. For these reasons, limits are placed on the maximum acceptable width of cracks deemed necessary to protect steel reinforcement from corrosion. Crack width limits will depend on the aggressiveness of the environment (Model Code 2020, 2024) but will generally vary from 0.3-0.4 mm for benign indoor environments to 0.15 mm for aggressive marine and underground environments (AFTES, 2013).

Creep of fibres (either by elongation or slippage) across a crack subject to sustained tension can lead to a progressive increase in crack width with time. In the context of corrosion, this is of greatest concern to steel FRC and hybrid steel RC/FRC members but is also of potential concern to hybrid RC/FRC members containing macro-synthetic fibres and steel bars. Members reinforced with macro-synthetic fibres on their own are not subject to any corrosion concerns and are therefore not subject to a durability-related crack width limit (although they may still be subject to deflection or crack width limits based on permissible water penetration rate). In general, engineers must recognize that crack widths in members subject to sustained tensile stress will increase with time and this must be considered supplemental to short-term crack width predictions when seeking to satisfy total crack width limits.

Cracking in concrete leads to a loss in fibre diameter due to corrosion. A 30% loss can occur in as little as 10 months, resulting in a 50% decrease in performance.

Summary

Creep is a complex time-dependent process that is the product of numerous aspects of material response to load, time, and environment. In particular, creep of concrete in compression is the result of very different processes than creep of cracked FRC in tension. For these reasons, the structural effects of creep cannot be approximated by simple models. It is therefore important to consider creep carefully when seeking to assess the long-term effects of this phenomenon on structural behaviour and durability.

The isolated physical properties of fibres are not necessarily representative of the behaviour of a FRC composite. Differences in fibre material do not play a direct role in determining the response of cracked FRC sections under sustained flexural loads. Rather, they influence the flexural toughness of the composite, which in turn affects the creep response (Garcia-Taengua et al. 2017). Aspects of fibre geometry as well as the properties of the surrounding concrete also play a role in controlling the long-term response to tensile loads. Given the number of parameters that influence creep of FRC in tension, it is naïve to generalise behaviour as being determined by fibre composition or concrete strength alone.

Most creep tests have been undertaken using simply supported beams, but simply supported beams are seldom encountered in design practice. Statically indeterminate structures that experience a re-distribution of load as a result of creep are common in the real world. This type of structure can benefit from load re-distribution in a way that is not apparent in simple non-redundant members. The behaviour of statically redundant test specimens such as panels is therefore likely to be more representative of real-world structural behaviour than simply supported beam tests.

The evidence from multiple investigations indicates that time-dependent pull-out of fibres is the dominant mechanism of crack width increase with time. Moreover, commonly used steel fibres, such as hooked-end fibres, exhibit rates of progressive pull-out that are similar to that exhibited by embossed macro-synthetic fibres. Creep effects must therefore be considered for both steel and macro-synthetic FRC loaded in tension if control of long-term crack widths is important in design. Given the superior corrosion-resistance of macro-synthetic FRC, maximum allowable crack width limits are usually more stringent for steel FRC. When considering both rates of creep, and durability requirements, is it clear that steel and macro-synthetic FRC may be closely matched in terms of competitiveness in many structural applications.


BarChip reinforced jointless floor.


BarChip reinforced shotcrete lining.


BarChip reinforced segmental lining.

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BarChip Inc.

OUR VISION

BarChip has a simple vision - revolutionise the world of concrete reinforcement. For over 100 years the technology of concrete reinforcement has barely changed. We set out to create a new reinforcement for the 21st century. We created BarChip synthetic fibre reinforcement.

OUR PROCESS

We believe that long term business relationships can only be sustained by a commitment to provide the highest quality products and services. We make sure to understand your concrete, know the performance requirements and work with you to get the right design and the right performance outcomes.

YOUR PRODUCT

When you work with BarChip you know that your concrete asset has been reinforced to the latest engineering standards. It will never suffer from corrosion. It will be cheaper and quicker to build. It will be safer and it will keep performing throughout its entire design life.

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