

BarChip Technical Note



Durability and Long Term Performance of Fibre Reinforced Concrete

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BarChip Inc.
The Synthetic Fibre Experts

Introduction

Durability of concrete structures is a major consideration for engineers and asset owners who have to justify public spending and therefore the viability and longevity of assets. It would follow that a more durable asset with a longer design life and less maintenance would be more cost effective and more desirable.

Existing construction and research shows that there are significant issues with the use of steel reinforced concrete, which can lead to a significant performance loss over time, resulting in situations where the designed concrete structure could no longer achieve its targeted design life. These performance issues relate to:

- Corrosion of steel rebars or fibres caused by the aggressive media entering cracks in the concrete;
- A phenomenon known as embrittlement, which decreases the performance of steel fibre reinforced concrete with time as concrete ages.

Remedial works of the concrete structure well before the specified design life will yield additional cost to the owner due to loss of revenue and the cost of the works to rehabilitate the structure.

The benefit of the long term durability of BarChip macro synthetic fibre reinforced concrete in contrast to the high rate of corrosion of steel bar and/or fibre in cracked concrete and being immune to embrittlement is a key performance indicator for the construction market.

Corrosion of Steel Reinforcement

One of the main factors affecting the durability of concrete structures is corrosion of steel reinforcement.

It is accepted that the high alkalinity of cement paste, combined with concrete cover to reinforcement provides a natural passivation against corrosion, however this assertion relies on the assumption that concrete will be unaffected by carbonation or cracking. Further, there could be of a higher risk than normal, such as for water and utility tunnels, subsea tunnels or construction in areas like the Middle East where the ground environment is generally more aggressive.

Consider for example that in the USA, a study conducted by the Federal Highway Agencies (FHWA) showed that the direct cost of corrosion was estimated at USD 276 billion (Virmani et al. 2002). About USD 120 billion was spent annually on the maintenance of aging and deteriorating infrastructure which includes 583,000 bridges in need of corrosion remediation works.

In 2016, the National Association of Corrosion Engineers (NACE) released a comprehensive report estimating the annual global cost of corrosion at 2.5 trillion dollars, with the cost in the USA increasing to USD 451 billion (Koch et al. 2016), outlining the





significant extent to which corrosion impacts on concrete infrastructure.

Regardless of preventative efforts (which are substantial) steel reinforcement in concrete is still likely to suffer from corrosion. The prominent reasons for this are;

- Cracking of concrete;
- Carbonation and neutralization of the protective concrete cover;
- Ingress of chlorides or other chemicals into concrete over time, reducing alkalinity and promoting steel corrosion;
- Combinations of the above.

In cracked concrete, the corrosion of reinforcement as a result of these factors can lead to a loss of performance over as little as seven months (Bernard 2004). This is primarily due to a loss of steel section caused from corrosion which leads to “corrosion induced brittle failure” (Kosa and Naaman, 1990).

Corrosion is less likely to occur in uncracked concrete, however embrittlement, also known as late age post-crack strength loss, has been seen to reduce the post crack performance of SFRC by as much as 50% (Bernard, 2015b).



Image 1: Cracking in concrete leads to ingress of corrosive materials, resulting in rapid corrosion of steel reinforcement.

Durability of Fibre Reinforced Concrete: Corrosion

1

1970's: Researchers identify that cracking in concrete leads to rapid corrosion of steel reinforcement.

With the introduction of steel fibres in the 1970's a considerable amount of research was conducted on its durability and resistance to corrosion. Like conventional steel reinforcement, it was shown that in uncracked concrete steel fibre reinforcement showed little deterioration. Fibres embedded within the first few millimetres of the surface paste were corroded, leaving extensive surface rust marks, however volume expansion was not sufficient to cause cracking and the structural integrity would be maintained.

At the same time, research published in the early 1970's showed that the performance of steel fibre reinforced concrete (SFRC) was significantly affected by corrosion (Aufmuth et al. 1974, Morse and Williamson 1977). Further to these reports, Halvorsen et al. (1976) reported that crack widths as small as 0.05mm in steel fibre reinforced concrete are susceptible to corrosion, and concluded that there was no maximum allowable crack width at which corrosion of steel fibre reinforced concrete does not occur.

2

1990's: Kosa and Naaman show that;

1. Corrosion leads to a reduction in fibre diameter, resulting in a large performance loss.
2. Synthetic fibres do not suffer from corrosion.

Kosa and Naaman (1990) conducted exposure tests on over 1,200 fibre reinforced concrete specimens subjected to cyclic exposure conditions. Results showed that;

- **Steel fibre corrosion resulted in a reduction in fibre diameter**, which was primarily responsible for losses in toughness.
- Standard specimens exposed for 6 months showed a reduction in the average minimum fibre diameter of 5-11%, which increased to 12-29% after 10 months.
- It was observed that a reduction of about 30% in minimum fibre diameter led to a reduction in toughness of 40-50%.

Researchers also noted that the effect of corrosion on the minimum fibre diameter gradually changes the type of failure of the composite from typical ductile fibre pull out to fibre rupture or "**corrosion induced brittle failure**" (Kosa and Naaman, 1990).

This research is of particular significance to FRC for tunnel linings, as it highlights the effects of carbonation, which is a substantial concern for tunnels that will be subjected to large amounts of vehicle emissions.

Also highlighted in this research is the significance of achieving adequate compaction, and in turn low

permeability, as it is demonstrated that the specimens with high permeability suffered larger diameter reductions than those with low permeability.

Kosa et al. (1991) continued their work by comparing the durability of four representative fibre reinforced cement composites subjected to increasing levels of exposure in sodium chloride solution, one of which was a polypropylene (PP) synthetic fibre. This was one of the earliest comparative studies of steel and PP fibres. Confirming the previous study, results showed that;

- After 6 months' exposure, standard specimens showed a reduction of 5-20% in modified peak stress and toughness, increasing to 8-27% reduction after 10 months.
- Although all specimens saturated over 6 months suffered severe corrosion ranging from 5-70% of fibre diameter, no corrosion induced cracking was seen on the specimen surface prior to loading.

This suggests that surface appearance is no indication of the performance of the specimen. By comparison, "Polypropylene fibre reinforced specimens exposed to similar corrosion conditions as steel fibre reinforced samples did not exhibit any significant reduction in peak stress and toughness" (Kosa et al. 1991).

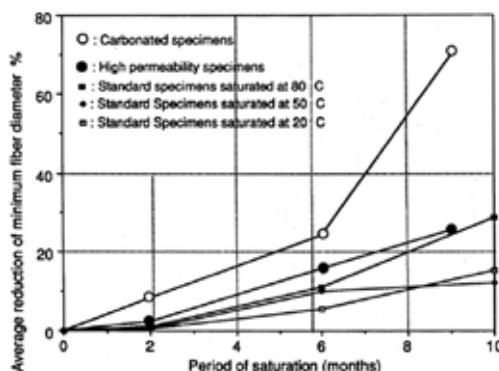


Figure 1: Relationship between the average reduction of minimum fibre diameter and saturation period for the flexural specimens (Kosa and Naaman, 1990).

“...it is not realistic to expect a service life of 100 years...in aggressive environments with steel fibre”

A long term study over 18 years by Hannant (1999) confirmed that polypropylene fibre reinforced composites retain their ductility and strength over long time without significant changes. Specimens made of thin mortar with layers of fibrillated PP films were exposed to different storage conditions: under water, laboratory air and naturally weathered. The results of this study showed that;

- Strength and toughness of the composite was maintained regardless of exposure condition;
- Young's tensile modulus of uncracked naturally weathered and water stored specimens are similar after 18 years, i.e. there was no frost-thaw damage to the PP reinforcement. Pre-cracked

weathered specimens showed the same value as water stored specimens due to autogenous healing;

- Bond strength between PP and matrix was relatively unaffected by exposure condition or time up to 18 years, i.e. the failure mode of the composite does not change with time.

Concluding, the working mode (or failure mode) does not change with age as there is no significant change in bond between PP and cementitious matrix. Thus, the composite retains strength and toughness with time. This is in contrast to steel fibre reinforced concrete, where embrittlement effects change the mode of failure and lead to significant performance loss with age (see page 8, below).

3

1999: Long term durability studies by Hannant confirm that PP fibre retains performance in alkali environment.

In the 2000's research was undertaken to test the durability of FRC in real world service environments. Nordström (2000, 2001) conducted exposure tests of steel fibre reinforced shotcrete (SFRC) specimens in actual road tunnels subject to splashing water from traffic.

Nordström confirmed previous research that corrosion of steel fibres resulted in a decrease in fibre diameter at the crack opening and that corrosion increased as crack width increased.

This localized corrosion at cracks was noticed to greatly reduce the post crack performance of the fibre reinforced shotcrete.

The same author recently published an evaluation of cracked steel fibre reinforced shotcrete after 17 years with field exposures (Nordström 2016). The report concludes that it is not realistic to expect a service life of 100 years with a retained load-bearing capacity particularly in aggressive environments with steel fibres.

4

2000's: Nordström confirms previous laboratory research in a real world setting and shows that loss of fibre section is directly related to crack width.

2016: Concludes that SFRC cannot retain load bearing capacity in aggressive environments.

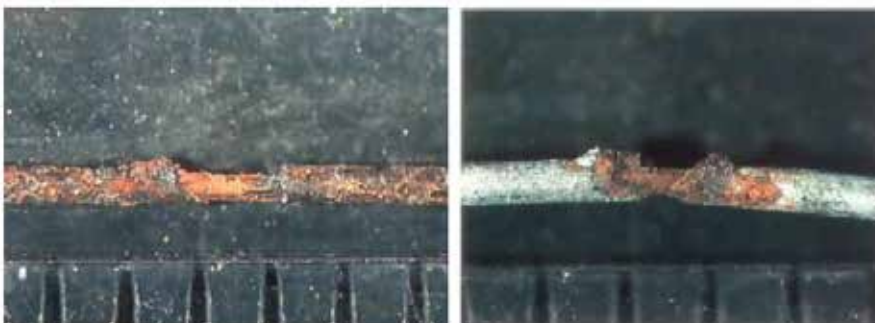


Image 2: Loss of fibre diameter as a result of corrosion at the cracks (Nordström, 2001)

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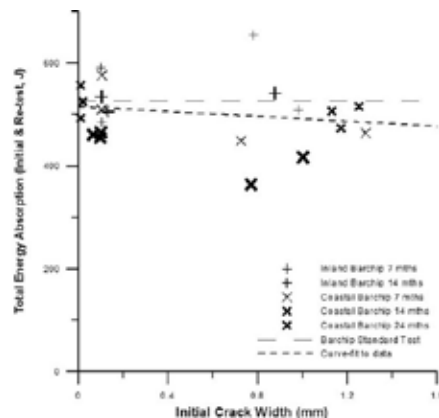
2000's: Bernard confirms;

1. Crack widths greater than 0.1 mm leads to significant corrosion
2. Corrosion of steel fibres results in a brittle, snapping failure
3. Macro synthetic fibre do not suffer from corrosion

Figure 2: Post crack performance of BarChip macro synthetic fibre reinforced shotcrete is not affected by exposure or corrosion, however steel fibre reinforced shotcrete suffers a substantial loss in performance after just 7 months (Bernard, 2004).

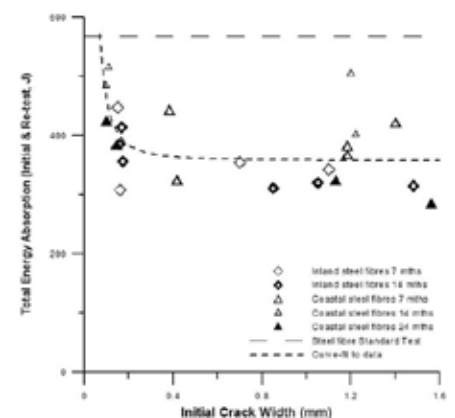
The effect of crack width on the durability of fibre reinforced shotcrete was also examined by Bernard (2004). Exposure testing was conducted on macro synthetic fibre reinforced shotcrete and steel fibre reinforced shotcrete at coastal and inland sites over a two-year period. Testing demonstrated that;

- Steel fibre reinforced shotcrete at both the inland and coastal locations suffered from corrosion, suggesting that the supply of oxygen can have a significant effect due to the presence of chloride ions;
- Crack widths greater than 0.1 mm



in steel fibre reinforced shotcrete specimens led to substantial rates of deterioration;

- Like Kosa and Naaman (1990), **Bernard also noted that corrosion induced brittle failure was evident.** Over the time of exposure, the failure mechanism of steel fibre reinforced shotcrete changed from a ductile pull out to a brittle failure mode at the site of corrosion; and
- By contrast, macro synthetic fibre reinforced shotcrete specimens showed no signs of performance loss over two years at either exposure site.



6

2010's: Research by Kaufmann;

1. Confirms that macro synthetic fibres do not suffer from corrosion.
2. Identifies that synthetic fibres of low material quality can suffer from brittle failure.

Recent studies also confirm this previous research work. Kaufmann (2014) conducted tests on pre-cracked steel fibre and macro synthetic fibre reinforced shotcrete specimens, which were subject to cyclic exposure, with the aim of simulating various tunnel environments. Kaufmann found that;

- After one-year exposure, corrosion caused both the maximum load and rupture energy of steel fibre specimens to be reduced compared with the non-exposed (uncracked) specimens (EFNARC panels);
- The average decrease in peak load for steel fibre sets exposed to a sodium chloride solution was 47%, while the average decrease at 25mm energy absorption was 52%;
- Polymer fibres were shown

to withstand aggressive environments and in most cases no significant drop in load bearing capacity was observed; and

- Corrosion of steel fibres resulted in a "**corrosion induced brittle failure**" of the specimens.

Kaufmann further recorded, for perhaps the first time in literature, the differences in mechanical performance of different macro synthetic fibre types. Kaufmann showed that;

- Polymer fibres of low material quality may suffer damage such as splitting during the application process.
- Shotcrete reinforced with polymer fibres of poor mechanical properties and quality could suffer from embrittlement effects.

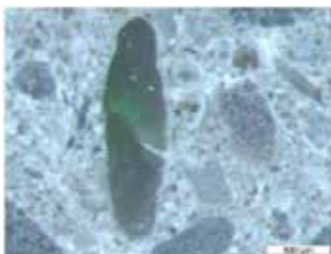


Image 3: Poor quality synthetic fibres can suffer from mechanical failure and damage such as fissioning (top) and splitting (bottom) during shotcreting operations (Kaufmann 2014).



Corrosion of Steel Fibres



Crack Formation in Fibre Reinforced Shotcrete



In-Situ Corrosion of Steel Reinforcement

Presented here is just a sample of the numerous research papers demonstrating the effects of corrosion on the durability of FRC. Evidence supports the conclusion that while corrosion of steel fibre reinforcement is expected in cracked concrete, quality macro synthetic fibres do not suffer performance loss resulting from corrosion.

Evidence from Kaufmann (2014) suggests that macro synthetic fibres of poor material quality may also suffer from embrittlement and from impact damage during application, but that high performance, quality macro synthetic fibres will not. This confirms that only high quality macro synthetic fibre specifically designed for concrete reinforcement should be used.

The British Tunnelling Society's Guideline on Tunnelling states that macro synthetic fibre should have a minimum tensile strength of 500 MPa and a Modulus of Elasticity greater than 10 GPa (British Tunnelling Society, 2010).

“...corrosion of steel fibres resulted in a corrosion induced brittle failure...”

Embrittlement

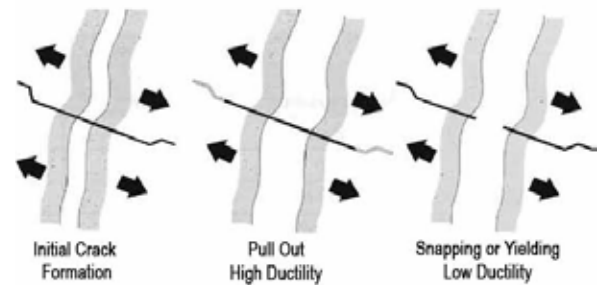


Figure 3: Post-crack failure mechanisms for fibre reinforced concrete reinforced with hooked-end steel fibres (Bernard, 2008).

The term ‘Embrittlement’ of fibre reinforced concrete stands for the loss of ductile performance due to a significant change in its failure mode as the concrete naturally gains strength with age.

Research into the long term performance of steel fibre reinforced concrete has revealed that, as concrete ages and its strength increases, embrittlement can occur (Bernard, 2008). This phenomenon occurs as the increasing concrete strength and paste hardness causes the failure mechanism of the steel fibre reinforced concrete to change from a ductile pull out failure to a brittle failure mode caused by fracturing of fibres, as depicted in Figure 3.

This failure mechanism changes because the bond strength between the concrete and the fibre exceeds the capacity of the fibre’s tensile strength, whereas the bond strength should always allow the fibre to pull out of the concrete in a ductile manner.

A typical shotcrete mix incorporates pozzolanic binders, which increases the late age strength gain of shotcrete, and consequently, the performance of steel fibre reinforced shotcrete reduces with age. Most shotcrete used for tunnel linings requires silica fume and/or fly ash for workability, cohesiveness and durability reasons, meaning that late age strength gain is thus inherent.

The effect of embrittlement is not only related to shotcrete. It is encountered in any concrete where the mix design incorporates pozzolanic binders and late age strength gain occurs. Many segmental tunnels are designed for high durability against chemical attack using up to 70% ground granulated blast furnace slag as binder, for instance in Singapore’s MRT. Post-hardening or late age strength gain, and hence embrittlement, is the logical consequence.

It is widely assumed that steam curing of tunnel segments precludes post hardening of the concrete matrix. However, little data on this is available as testing at later ages is uncommon. In contrast, King and Hebert (2008) report a 28% increase in compressive strength from 28 to only 56 days of age of the self-compacting concrete for the steam cured San Vicente Pipeline tunnel segments.

Numerous research papers have been written about the effects of late age strength gain on the performance of steel fibre reinforced shotcrete. Banthia and Trottier (1995), Farstad (1999), Bernard and Hanke (2002) and DiNoia

and Rieder (2004), all concluded that as concrete strength increased over time, the failure mechanism of steel fibre reinforced shotcrete changed from ductile pull out to brittle failure.

Figure 4 shows a significant change to brittle behaviour with age for the steel fibre reinforced specimens, where in contrast the macro synthetic fibres yield an increase in post-crack performance and energy absorption capacity (toughness). Further study by Bernard (2008) confirms these findings with panel tests carried out to three years of age. This research indicates that the effect of embrittlement on ductility was more significant than corrosion

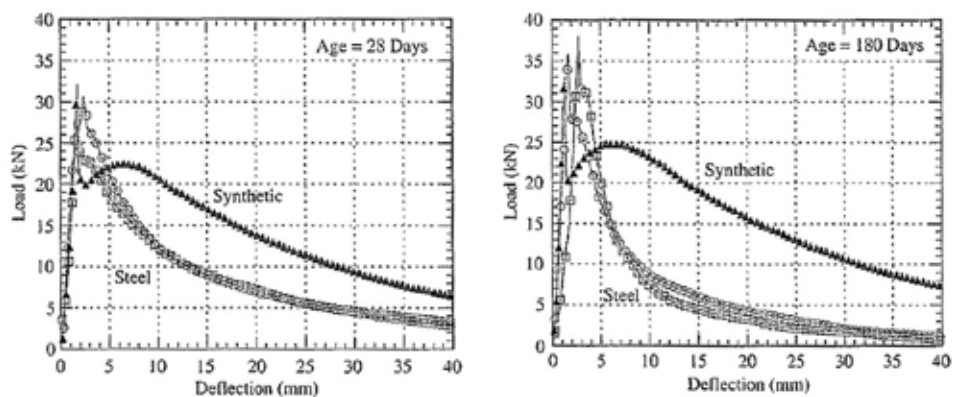


Figure 4: DiNoia and Rieder (2004) – “As age increases from 7 to 180 days, the drop-off in load bearing capacity as a function of deflection occurs more rapidly with increasing age... At 180 days, the drop-off in load bearing capacity is very dramatic (for steel fibre reinforced shotcrete)”.

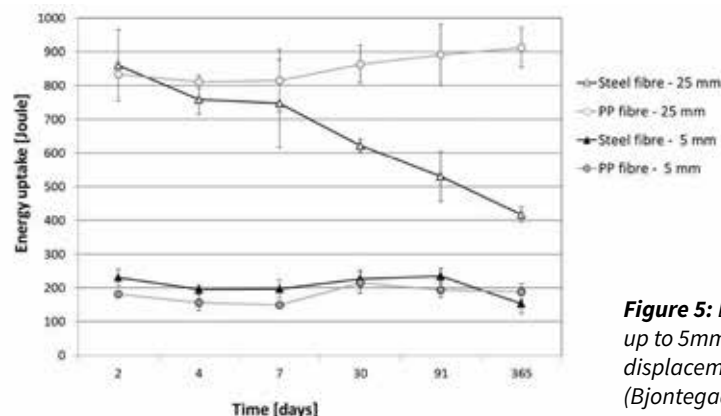


Figure 5: Energy uptake up to 5mm and 25mm displacement vs. time (Bjontegaard et al., 2014)

“If you have high strength concrete and regular fibres, the fibres snap.”

and that standard 28 days testing for quality control could not guarantee satisfactory performance at later ages.

These findings are corroborated by more recent research by Bjøntegaard et al. (2014), who showed that the average ductility (energy absorption capacity) of SFRS panels decreased from 621 Joules at 30 days to 530 Joules at 91 days (-15%) and to 417 Joules after one year (-33%). On the contrary, MSFRS panels yield an increase from 863 J at 30 days to 912 J after one year. The shotcrete had a cube strength of 50MPa at seven days and post hardening developed a cube strength of 90 MPa after one year, producing 80% strength gain.

Recently it has been proposed that higher strength steel fibres are able to overcome the effects of embrittlement. The steel fibre industry stated in an interview with Tunnelling Journal “It’s a high Carbon wire, very, very strong and expensive but it’s what you need with high strength concrete. ***If you have high strength concrete and regular fibres, the fibres snap.***” (Smith 2013). Conversely, this raises the question why the client should pay even more for steel fibres when they wouldn’t face this problem using high quality macro synthetic fibres.

Research recently published by Bernard (2014 and 2015a) shows that embrittlement will occur in nominal concrete strengths as low as 40 MPa and indicates that high carbon steel fibre is not immune to it. It has been confirmed that the behaviour of hooked-end steel fibres commonly used in FRC intended for tunnel structures can change with time from a high-energy pull-out mode to a low-energy rupture mode (Bernard 2014). The change to a rupture-based post-crack mode of behaviour is associated with a substantial fall in residual strength at maximum crack widths exceeding about 2.0 mm in an ASTM C 1609 beam test, yielding residual performance loss of up to 50%.

It is thus advisable that designers also request testing at later age, e.g.

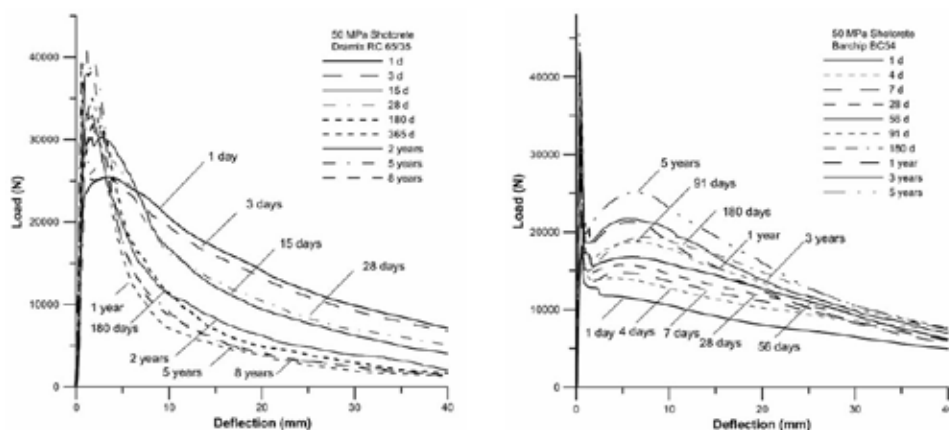


Figure 6: Testing by Bernard (2015a) showing an increase in steel fibre performance at low deflections with age but a dramatic decrease at larger deflections (left), compared with macro synthetic fibres which increase in performance across all deflections with age (right).

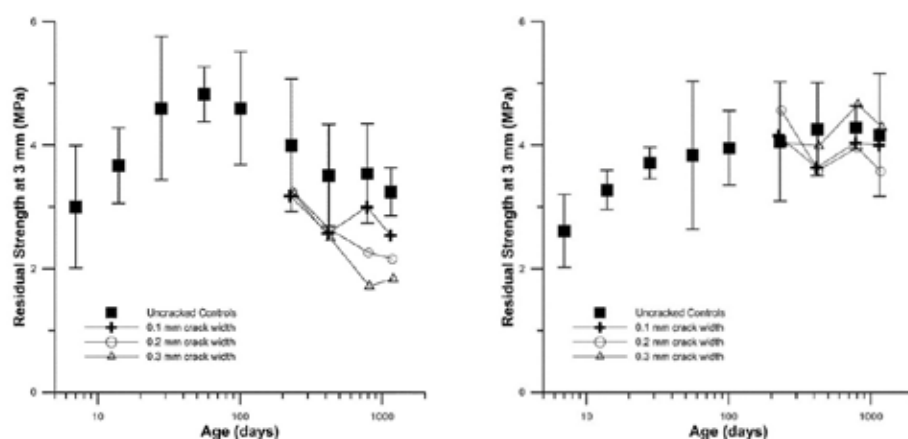


Figure 7: Residual strength results at different ages up to three years for ASTM C 1609 beams reinforced with 40kg/m³ Dramix RC-65/60-BN (left) and 8kg/m³ BarChip 54 (right) (Bernard, 2015b)

a minimum of 90 days of age, to better understand the long-term performance of the fibre reinforced concrete.

Further research by Bernard (2015b) examined how embrittlement and corrosion may combine to degrade the performance of steel FRC over time. The tests revealed that crack widths as small as 0.10 mm resulted in corrosion of the steel fibres, which again raises the question of acceptable crack width limits for SFRC.

Crack widths of just 0.30 mm resulted in a performance loss of 60% over a period of three years of exposure due to

the combined effect of embrittlement and corrosion. In contrast, the results indicate that cracks of up to 0.30 mm maximum width can exist in macro synthetic FRC members without any detrimental effect on post-crack structural performance (Figure 7).

Neither corrosion nor embrittlement occur in high quality macro synthetic fibre reinforced concrete, so the long-term performance remains close to or better than the 28 day measured performance, even for crack widths up to 0.30 mm in aggressive environments.

Conclusions

These research studies, along with others, provide a number of key insights into the durability and long-term performance of fibre reinforced concrete, which are:

1. High quality polypropylene macro synthetic fibres, such as BarChip, do not suffer from the effects of corrosion and maintain performance regardless of known exposure conditions, even in large crack widths;
2. Uncracked steel fibre reinforced concrete specimens are largely unaffected by corrosion, however once cracks are formed, performance deterioration as a result of corrosion is rapid;
3. Steel fibre corrosion results in a loss of fibre diameter at the crack opening. The rate and amount of corrosion increases as the crack width increases;
4. Crack widths greater than 0.10 mm lead to significant rates of deterioration of steel fibre as a result of corrosion, because the crack width affects the time of corrosion initiation;
5. Corrosion of steel fibre reinforcement results in a significant change of the failure mode, changing from a ductile pull out failure to a brittle snapping failure, causing rapid loss of toughness. This is referred to as **corrosion induced brittle failure**;
6. Embrittlement of steel fibre reinforced concrete occurs due to late-age strength gain, causing the bond between the concrete matrix and the fibre to exceed the fibres tensile strength, changing the failure mechanism from a ductile pull out to a brittle failure caused by rupturing of the fibres. This is referred to as **embrittlement induced failure**;
7. Embrittlement has been shown to occur as early as 30 days of age and in concrete with nominal strength as low as 40 MPa, and has been shown to reduce post-crack performance by as much as 50%;
8. High quality macro synthetic fibres, such as BarChip, are not affected by late age concrete strength gain. In contrast they show improved performance with age. However, one study indicates that low quality synthetic fibres may be affected by embrittlement effects;
9. BarChip fibres can be used as an alternative to steel reinforcements with significant associated benefits such as improved durability, reduced costs and increased sustainability;
10. BarChip fibre is a much more environmentally friendly and sustainable reinforcement option, as the carbon footprint for BarChip fibre is significantly lower than that of steel reinforcement.



Nearly all concrete cracks, regardless of design or preventative measures



BarChip macro synthetic fibres will never suffer from the effects of corrosion



The effects of embrittlement on long term performance can be even more severe than corrosion

BarChip
Synthetic Reinforcing Fibre

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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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