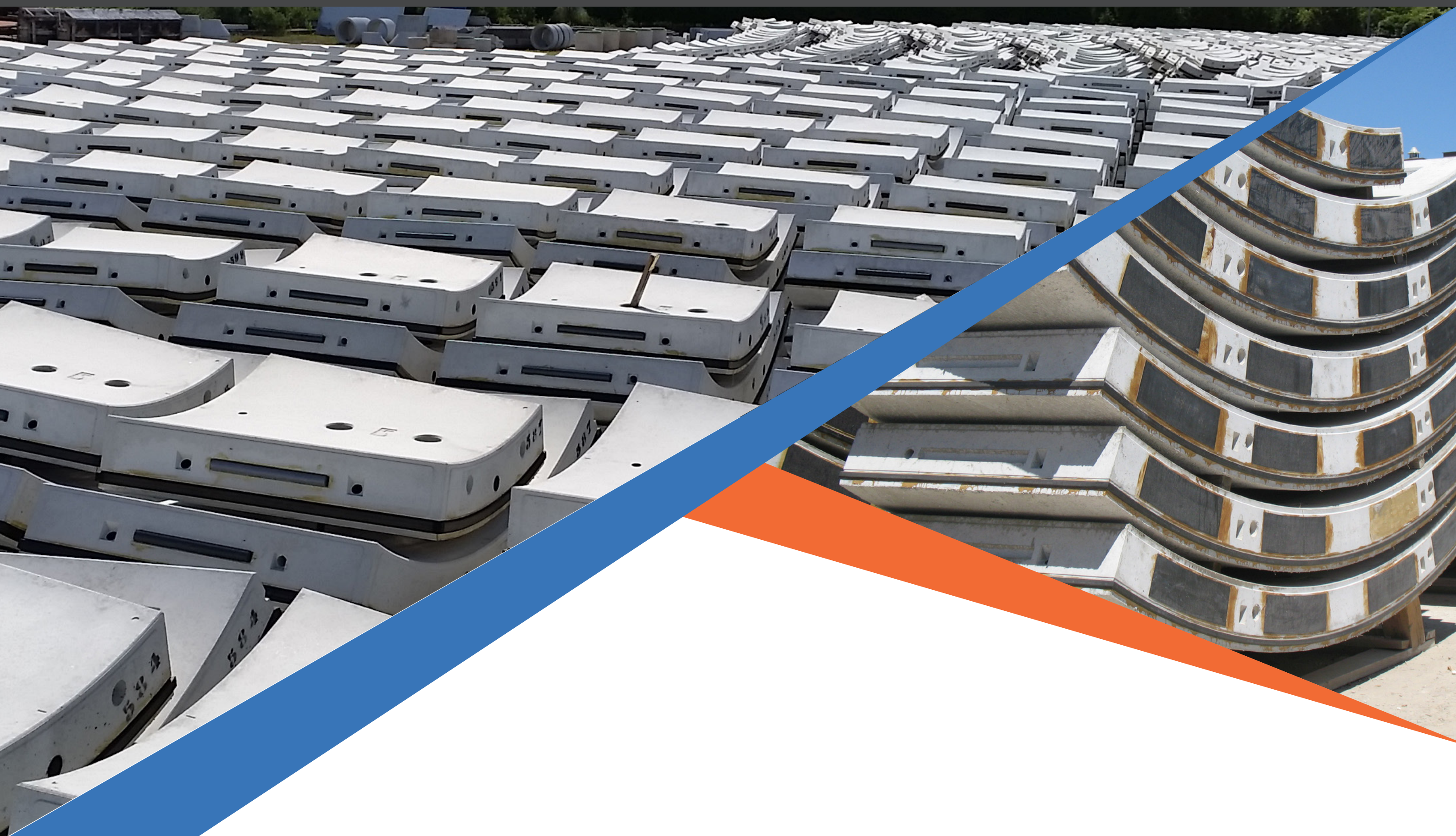
BarChip Technical Note



BarChip Inc.
The Synthetic Fibre Experts

Model Code 2010 and the Design of Concrete Structures using BarChip Macro Synthetic Fibre

Revision No. 1: April 2018

What is Model Code 2010?

The *fib Model Code 2010* for concrete structures is a comprehensive recommendation for the design of reinforced and prestressed concrete. It is intended to be a basis for future codes for concrete structures, e.g. the next generation of Eurocode 2 (EC2).

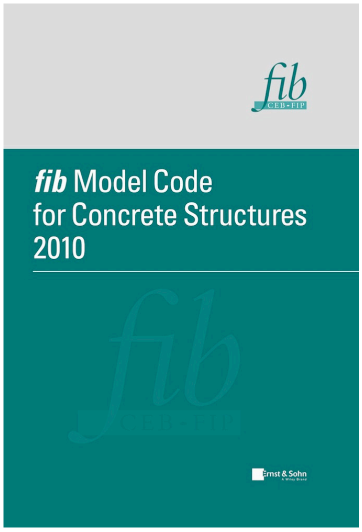
It also presents new developments with regard to concrete structures, structural materials and new ideas in order to achieve optimum structural and sustainable behaviour. The latest edition, Model Code 2010 Final Draft (MC2010), published in March 2012 as fib bulletins 65 and 66, incorporates fibres as reinforcement in the chapters on materials and structural verification.

The rules in MC2010 are based mostly on experience gained with steel fibre reinforced concrete. Thus, it is perceived within the marketplace as the go to design guide for steel fibre reinforced concrete. However, it can also be used to design concrete structures using macro synthetic or other types of fibres.

MC2010 enables designers to have a reference code that sets out the performance criteria for FRC structures, but it must be remembered that there are a number of other design codes and guidelines available to designers that may better suit the promotion of macro synthetic fibres.

The fibre relevant chapters of MC2010 are:

- 5.6 *Fibres/Fibre Reinforced Concrete,* covering the material's aspects and design values
- 7.7 *Verification of safety and serviceability of FRC structures*, covering structural design aspects



Essentially MC2010 details how the designers:

- **Conduct an appropriate test;**
- **Evaluate the test results; and**
- **Apply test results to a structural design.**

Image 1: *MC2010 is not intended to be applied to slab on grade or shotcrete applications.*

To which applications does Model Code 2010 apply?

MC2010 is intended to be applied to any structural reinforced or prestressed concrete elements. However, it is ***not*** intended to be applied to:

- Temporary shotcrete linings;
- Slabs on grade; and
- Applications in which the addition of fibres aims for increased resistance to plastic shrinkage, abrasion or impact.

For fibre reinforced concrete the precast segmental lining industry is the key market where this Code may be used.

How designers reacted to Model Code 2010.

Many designers around the world (predominantly Europeans) are using MC2010 as the basis for their structural designs, especially for the design of fibre reinforced precast tunnel segments. However, there is a perception that synthetic fibre reinforcement cannot be used when designing with MC2010. This perception is based on a belief that;

- *Macro synthetic fibres do not meet the **material property requirements** stipulated in MC2010*
- *Macro synthetic fibres do not meet the **performance requirements** stipulated in MC2010*

However, BarChip fibre can meet the material property requirments and meets the performance requirements, and is therefore suitable for use with MC2010. These two statements will be addressed in the following.

"BarChip fibre can meet the material property requirements and meets the performance requirements, and is therefore suitable for use with MC2010"

Material Property Requirements of Model Code 2010

MC2010 is open to all fibre materials as long as their behaviour is independent of time. It lists the types of fibres that can be used in concrete reinforcement, which include steel, polymer, carbon, glass or natural material fibres. The reference throughout the document is only to "*Fibres*". So in general BarChip macro synthetic fibres are covered by the scope of MC2010.

The following are two important caveats to the above points, which may deter the use of macro synthetic fibres by designers.

MC2010 states:

1. *"Fibre materials with a Young's Modulus which is significantly affected by time and/or thermo-hygrometrical phenomenon are not covered by the Model Code."*
2. *"In case of organic or natural fibres, post cracking long-term behaviour can be affected by an additional creep of the fibres themselves."*

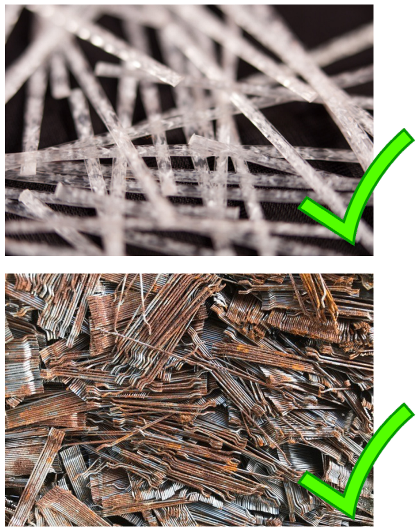


Image 2: *The ITAtech FRC segment design guideline equally applies the material and design rules of MC2010 to both steel and macro synthetic fibres*

Point 1 - Thermo-hygrometrical phenomenon

Point 1. *Thermo-hygrometrical phenomenon* means that the material properties can change both over time and due to temperature or humidity. This, in any case, is a general standard requirement for concrete reinforcing materials. However, this paragraph is open ended in terms of what "*significantly*" actually means. Irrespective of this BarChip has proven itself in many applications and tests to show that it is ***not*** significantly affected by time or humidity. This is because polypropylene is inert and durable.

- When specifying macro synthetic fibres as reinforcement TR65 states *"macro synthetic fibres will not be significantly affected by moisture and will not be attacked by chlorides when used in marine structures or those subjected to de-icing salts" (TR 65 2007).*
- ASTM C1116 states that *"Fibres such as polyolefins (polypropylene and polyethylene) … have been shown to be durable in concrete." (ASTM C 1116 2010).*

See also BarChip Technical Note, *'Durability and long-term Performance of FRC'.*

As a polymer, BarChip naturally performs differently at variable temperatures. However, BarChip has proven its performance in thermo-critical environments, such as in shotcrete linings of deep mines, where no failure has ever been reported. This shows that even when exposed to higher temperatures, the composite material will perform as designed and the isolated thermal properties of BarChip fibre become subordinate.

The only critical condition regarding performance loss of polymer fibres could be a sudden strong increase in temperature, e.g. during the course of a tunnel fire. However, this extreme condition does not apply to any other application of BarChip fibre. Again, the performance of the fibre reinforced composite is not only dependent on the fibre behaviour, but will be affected by a number of factors including the concrete mix design, compressive strength, member thickness, age, etc.

Given this, if a fibre reinforced concrete product meets the specified performance requirements over time, then its fibre material ***is suitable for use with MC2010.***

Image 3: *Proven in-service performance across a wide temperature range.*

Point 2 - Isolated tensile creep

Point 2: The critical point addressed here is the isolated tensile creep of polymer fibres. However, this isolated behaviour can only happen in statically determined systems (e.g. standard beams like ASTM C1609 or EN 14651) where one single crack would open and eventually lead to failure.

In reality this never happens, because all structures are built with redundancy, i.e. they are highly statically indeterminate, so that moments and stresses can be redistributed in order to avoid the aforementioned strain localization and failure.

Thus, the isolated tensile creep properties of the polymer fibres (or any other fibre material e.g. steel fibres) become subordinate within the concrete composite in a regular hyperstatic system, such as a tunnel lining. Segmental linings are usually designed to remain under hoop thrust, so that tensile creep can't happen. In contrast, potential cracks from temporary load cases could close with time due to compressive creep of the concrete.

Also, recent research by Prof. Ian Gilbert showed that the fibres reduce time-dependent in-service deformations and significantly reduce maximum crack widths when used in combination with conventional reinforcing bars in statically determined beams (Gilbert and Bernard 2015). This again shows that the isolated properties of the fibre material become ancillary in real structural applications.

Apart from creep deformation under sustained loading, MC2010 also addresses the long term behaviour of cracked FRC, specifically whether "*long term performance is affected by creep/creep rupture*" in chapter 5.6.2.

Research has shown that creep rupture is very abrupt for SFRC, similar to plain concrete, whereas for MSFRC it is much more benign, giving more warning signs such as a growing crack width prior to failure (Bernard 2014).

The results revealed that hooked-end steel FRS can fail in bending in less than one hour when subjected to a sustained load of more than 70% of static capacity when initial crack widths exceed 2.5 mm.

See also BarChip Technical Note, '*Creep Behaviour of FRC*' for further information.

Image 4: *A segmental tunnel lining is designed to be in compression, meaning isolated tensile creep of fibre reinforcement is not a factor.*

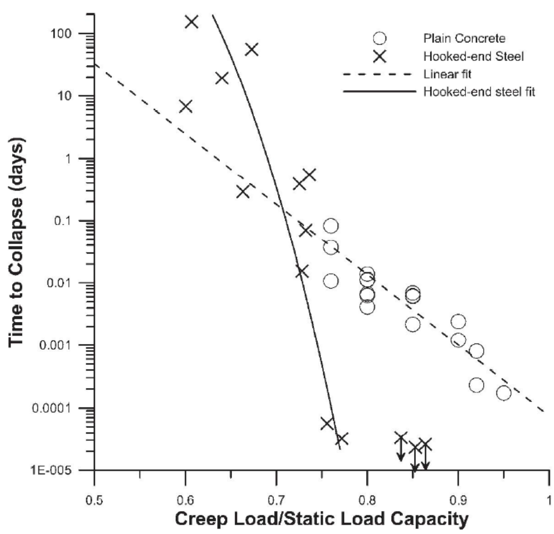


Image 5: *Time to collapse plotted as a function of load ratio for plain concrete specimens tested by Zhou and hooked-end steel FRS panels [4]*

Performance Requirements of Model Code 2010

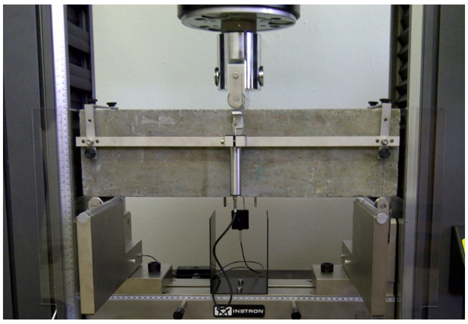


Image 6: *EN 14651 Notched Beam Test*

The performance of FRC is obtained by testing notched beams according to EN 14651. Residual flexural strength values are obtained at different stages of crack mouth opening (CMOD).

For structural design the important values are:

- f_{R1} at 0.5 mm CMOD. This value represents serviceability limit state (SLS) to control crack widths after reaching the elastic peak stress (LOP); it also yields the strength interval of the performance class.

- f_{R3} at 2.5 mm CMOD. This value represents ultimate limit state (ULS), i.e. load-bearing capacity at maximum allowable strain limit.

MC2010 does not explicitly specify minimum values for f_{R1} and f_{R3}. However, in order to reach the minimum residual strength class ***1a***, the following values must be reached:

- f_{R1k} **≥ 1.0 MPa**

- f_{R3k} **≥ 0.5 MPa**

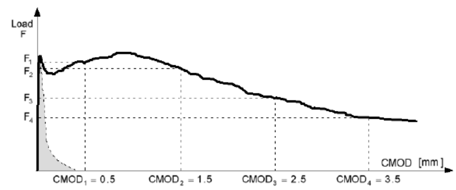


Figure 5.6-6: Typical load F – CMOD curve for plain concrete and FRC

Image 7: *Typical load F - CMOD curve for plain concrete and FRC*

More importantly, MC2010 requires a minimum ductility performance of FRC for structural use. In order to substitute reinforcement entirely or partially at ultimate limit state, two performance requirements are given:

1) f_{R1k} / f_{Lk} **> 0.4**

2) f_{R3k} / f_{R1k} **> 0.5**

These are ductility requirements in order to prevent any brittle failure.

In detail, they mean:

1. Ratio between residual stresses at CMOD 0.5 mm and peak stress (flexural strength) must not be less than 40%. This criterion is predominantly introduced for crack width control and aims to protect any steel reinforcement (bars or fibres), as testing has shown crack widths as low as 0.1mm can result in steel fibre corrosion (Bernard 2015). This criterion on ductility ratio is sometimes more difficult to fulfil with macro synthetic fibre than with steel fibres, due to the drop after peak load, especially at low dosages. However, since corrosion is not an issue for BarChip fibre, the necessity of this specification could be waived.

2. Ratio between residual stresses at CMOD 2.5 mm and 0.5 mm must not be less than 50%. This criterion aims to avoid large performance drops with an increasing crack width, as can happen with short steel fibres. This criterion normally never causes a problem for BarChip fibre.

The Majes-Siguas II project is a water irrigation project in Peru which includes 20 km of segmentally lined tunnel. Project testing at the National University of Engineering, Lima, shows that BarChip 48 meets the performance specifications. Concrete:

f'_c = 60 MPa (f'_c = 20 MPa @ 5 hours)
Fibre Type: BarChip48
Dosage: 7.5 kg/m^3
Test Lab: National University of Engineering, Lima, Peru
Age (Days): 29

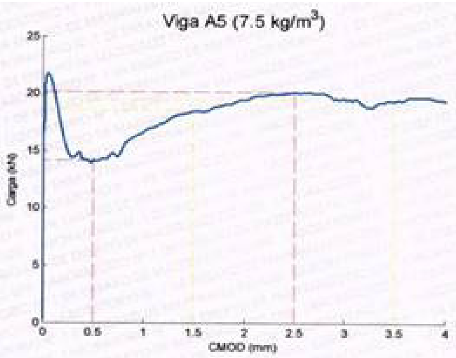


Image 8: *BarChip48 load-CMOD curves for Majes-Siguas II water irrigation tunnel*

Specimen	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
A4	6.42	4.48	5.16	5.82	5.59
A5	6.93	4.51	5.90	6.42	6.18
A6	6.57	4.67	5.18	5.30	5.87
Average	**6.64**	**4.55**	**5.41**	**5.85**	**5.88**
Standard Deviation	0.262	0.102	0.422	0.560	0.295
Coefficient of Variation	3.9 %	2.2 %	7.8 %	9.6 %	5.0 %
Characteristic Value	**6.6**	**4.5**	**5.3**	**5.7**	**5.8**

FRC Classification: 4e

Classification to fib Model Code 2010		
Strength Interval	f_{R1k}	4.0 MPa
Residual Strength Ratio	f_{R3} / f_{R1k}	1.3
f_{R1k} / f_{Lk} = 0.7	0.7 > 0.4	**Pass**
f_{R3k} / f_{R1k} = 1.3	1.3 > 0.5	**Pass**

Satisfies the minimum structural criteria for Ultimate Limit State design (ULS) and allows substitution of conventional reinforcement.

BarChip macro synthetic fibres are capable of meeting both these performance requirements for many applications, and are therefore suitable for use with MC2010.

The above test results show a residual strength ratio of around 130%, which corresponds to class 'e'. This increase in ductility with displacement is highly desirable for a redundant design.

It should be noted that MC2010 does not specify a general tension hardening behaviour of FRC. This is only the case for linear elements without conventional reinforcement and without compressive stress in the section (chapter 7.7.2), e.g. in simply supported beams to avoid failure due to strain localization (single crack).

"BarChip fibre meets the performance requirements stipulated in MC2010"

Further Consideration with regard to Model Code 2010

Model Code 2010 is a model code, not a standard

MC2010 is not yet a standardised Code, so its use in the design of concrete structures is not mandatory, rather it is a recommendation that may or may not be adopted. However, it is highly likely that Eurocode 2 will adopt MC2010 in its next review. During this review, and with more experience gained using macro synthetic fibre, it might be that the adoption of MC2010 into EC2 will drop or at least alter the aforementioned material requirements.

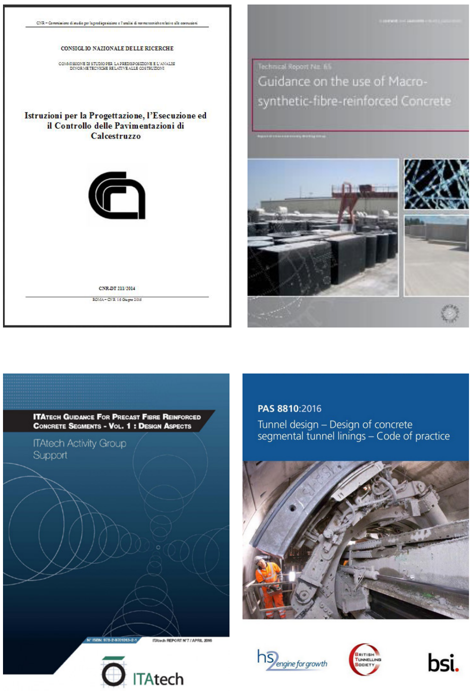


***Image 9:** Alternative design guidelines for design with fibre reinforcement.*

MC2010 comprises new methodologies for structural analysis that the market will embrace:

- ***"Verification assisted by numerical simulations"*** - BarChip can provide highly qualified and specialized Finite Element Analysis that is unique in the market. Thus, our technical development is well in line with emerging design codes.
- ***"Verification assisted by testing"*** - MC2010 gives guidance for the experimental assessment of the response of structural members. Special design problems may be studied experimentally and a combination of testing and numerical verifications can be applied. BarChip invests every year significant part of its profit in R&D, in order to study and prove the performance of BarChip FRC in special applications.

On the other hand, other design guidelines exist that have been successfully used to date and therefore can be used in place of MC2010. All of them reference macro synthetic fibres.

- *Guide for the Design and Construction of Fibre-Reinforced Concrete Structures* CNR-DT 204/2006 (The design rules of this Italian guideline have been adopted to a great extent by MC2010);
- *Guidance for precast fibre reinforced concrete segments – Vol. 1: design aspects.* ITAtech report no. 7, 2016;
- PAS 8810 *Tunnel design – Design of concrete segmental tunnel linings – Code of practice.* The British Standards Institution, UK, 2016;
- *TR65 – Guidance on the use of macro synthetic fibre reinforced concrete, Concrete Society, UK, 2007;*
- *TR34 - Concrete industrial ground floors, 4th edition,* Concrete Society, UK, 2014

Model Code 2010 does not take into account important design factors for service life

MC2010 states that fibres subject to time dependent change are not covered by this guideline. However, there is no reference made to the composite performance with regard to time dependent changes. For instance embrittlement of steel fibre reinforced concrete, which means a significant change in failure mode with age and the associated detrimental performance loss is not mentioned in MC2010.

MC2010 assumes that steel fibres will not corrode if design parameters are met, i.e. the concrete will maintain minimum crack widths and protect the steel fibre. If the concrete does crack, steel fibres will corrode very quickly, especially if water or salts percolate through the crack. Several papers however indicate that corrosion will also occur in carbonated concrete regardless of cracking.

Concrete reinforced with high performance macro synthetic fibres does not suffer embrittlement effects, nor do they corrode. Thus, they are the preferred option in many demanding applications.

See also BarChip Technical Note, '*Durability and long-term Performance of FRC*'.

Conclusions and recommendations

1. BarChip can meet the material and design requirements stipulated in MC2010.
2. The time-dependent behaviour of macro synthetic fibres is irrelevant to most tunnel linings that are designed to remain in compression and thus tensile creep is non-existent.
3. Steel fibre is more effected by embrittlement over time than macro synthetic fibre is by creep in tunnel linings.
4. MC2010 does not address the corrosion of steel fibre reinforcement at crack widths common in an assets service life. Nor does it address the detrimental effect of embrittlement.
5. Other guidelines are available for use.

References

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Gilbert, R. I. and Bernard, E. S. (2015). Time-dependent Analysis of Macro-synthetic FRC Sections with Conventional Bar Reinforcement, proceedings of the World Tunnelling Congress (WTC 2015) in Dubrovnik, Croatia, May 2015

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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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