

CONCRETE: FRIEND OR FOE?

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ABOUT THE AUTHOR

After completing his BEng degree in Civil Engineering at Stellenbosch University, Prof Boshoff enrolled for an MScEng degree at the same institution. This is where his passion for and love of concrete started. His MScEng enrolment was upgraded to a PhD and he then spent time at TU Kaiserslautern, Germany, under a DAAD scholarship to finish his experimental work. He received the HL Reitz medal for the best postgraduate student in Civil Engineering for his PhD, titled 'The Time-dependent Behaviour of ECC'. After completing a postdoc year at Stellenbosch University he was appointed formally, with teaching, research and supervision responsibilities. Prof Boshoff became head of the division for structural engineering and civil engineering informatics in 2010, a position he still holds. He also started the Unit for Construction Materials, which forms part of the Institute of Structural Engineering of Stellenbosch University.

He has published more than 55 papers in journals and conference proceedings and is the project leader for numerous industry-funded research projects. He is involved in technical committees for both Rilem and *fib*. He has served on the board of the Concrete Society of Southern Africa for more than six years and was president of the society from 2012 to 2014. Recently, Prof Boshoff was awarded the medal for the upcoming researcher of the year by the Faculty of Engineering.

His research interest is in the field of construction materials, but more specifically fibre-reinforced concrete, concrete cracking in the fresh and green state, as well as unconventional and eco-friendly construction materials. In addition, he has made it his life's mission to teach people the difference between cement and concrete.

CONCRETE: FRIEND OR FOE?

INTRODUCTION

Concrete has been part of society for thousands of years. The first known use of a concrete-like material was in 7 000 BCE in what is now Southern Israel, where a concrete floor was cast using quicklime as cement mixed with water and stone (Domone & Illston, 2006). Concrete has progressed from an elementary construction material to a modern material used in almost every structure. A prime example is the Burj Khalifa, at 830 metres the tallest building in the world, with concrete as its main structural material. Even today, concrete is more often than not the construction material of choice.

The reasons for the success of concrete as a construction material are clear: it is cheap, robust and relatively easy to use. The final product is a rock-like structure that typically lasts for decades. It can be prepared by hand with limited skills and still produce a reliable product, but it can also be optimised using expert knowledge of advanced mix designs and, with the aid of modern chemical admixtures, produce a superior product with almost limitless possibilities.

Concrete is typically defined as a construction material made from a mixture of broken stone or gravel, sand, cement and water, which can be spread or poured into moulds and forms a stone-like mass on hardening. The definition of “cement”, however, can be contentious, but it is often assumed that concrete has to contain Portland cement to be called concrete. A patent for this modern-day Portland cement was filed in Britain by Joseph Aspdin (Aspdin, 1884) in 1824. The above definition of concrete also should be expanded to read “binder” instead of “cement”. And a binder should be defined as a combination of materials that, due to a chemical reaction, bind sand and/or stone to a hardened state. This definition would be more appropriate for modern-day concrete.

This definition then also would include ancient concretes, such as quicklime-based concrete or lime/pozzolana concrete, and also more modern concrete alternatives, such as alkali-activated concrete (Wang

et al., 1995) and geopolymers (Majidi, 2009). It would include all materials that can be used in the same way as conventional structural concrete.

However, concrete is almost never used as a stand-alone construction material. It is typically combined with steel reinforcing bars to improve the tensile and flexural capacity of concrete members. Herein also lies a secret to the success of concrete: the thermal coefficient of expansion of concrete and steel is about the same, therefore there is minimum interfacial debonding during normal daily temperature fluctuations. One significant negative aspect of steel is the corrosion when exposed to the environment. However, when steel is exposed to a high-pH environment, the corrosion stops due to a passivation layer of Fe_3O_4 that is created on the surface of the steel, and concrete normally has a pH of more than 12.5, which is sufficient to create this layer. These two aspects – the temperature expansion compatibility and protection against corrosion – make steel reinforcing and concrete a near perfect match.

Anchors and fasteners can be fixed easily to concrete, it is possible to strengthen concrete structures, and concrete can be demolished relatively easily and recycled if needed. Paint adheres easily to concrete surfaces and surfaces can also be modified for architectural effects, for example power floated or exposed aggregate finishes.

Concrete seems like the perfect construction material for modern society. However, there is one large, unavoidable problem: it has a significant negative effect on the environment. It is estimated that cement manufacturing alone contributes to more than 5% of world CO_{2e} emissions (Damtoft et al., 2008) and it is estimated that this will increase to 10 % by 2050 if current trends are sustained (Taylor et al., 2006).

The question thus remains: is concrete a friend or a foe? In this paper the environmental impact of concrete is discussed, as well as possible solutions for reducing the impact. Some research on advanced/unconventional uses of concrete is also reported as possible solutions to reduce the environmental impact.

ENVIRONMENTAL IMPACT OF CONCRETE

When determining the environmental impact of concrete, the contribution of cement is by far the most significant (Van den Heede & De Belie, 2012). The sand and stone (aggregates) and admixtures do have an impact, but this is typically overshadowed by the impact of the cement. The manufacturing process of cement is key to understanding the impact thereof on the environment.

Cement

Cement is manufactured by burning limestone and shale in a rotating kiln and milling the product to a fine, grey powder. A cement plant is typically located at the source of the raw materials and the fuel (typically coal) is transported to the plant.

The manufacturing starts with the grinding of the limestone (CaCO_3) and shale (iron and aluminium oxides), which is then added to a preheater that heats up the material to about 900°C before the material enters a long (typically more than 80 m) inclined kiln, as shown in Figure 1. The material is slowly transported through the kiln towards the source of the heat. About 90% of the calcination takes place in the preheater, while the rest occurs in the kiln up to a temperature of 1100°C . Calcination is the decomposition of limestone to calcium oxide and carbon dioxide, as follows:



It is important to note that this reaction releases large quantities of CO_2 . When the temperature exceeds around 1250°C , the process of clinkering starts, during which the cement is actually formed. The material has to be heated to 1500°C for full clinkering to occur. The product, the clinker, is then mixed with gypsum and milled to a fine powder with particles typically smaller than $80\ \mu\text{m}$. This is then called cement. Cement can be extended/blended by mixing it with other materials, and this is explained in a next section.

It has been estimated that, on average in the year 2000, about 870 g of CO_2 was released for every 1 kg of cement manufactured (Damtoft et al., 2008). This explains the significant impact on the environment. This is further complicated by the fact that about 60% of the CO_2 emission is due to the calcination process, and not the energy required for the kiln. So, even if 100% renewable energy is used for heating the kiln, there still will be 530 g of CO_2 released for every 1 kg of cement manufactured.

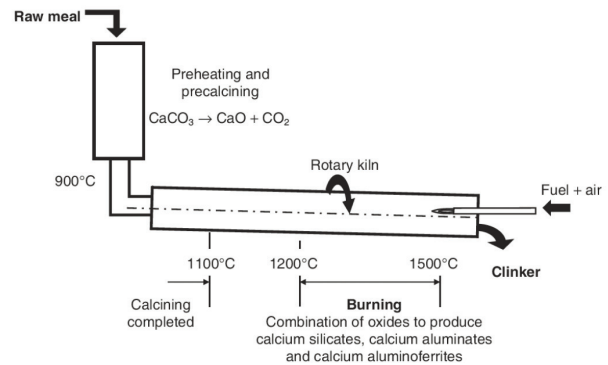


Figure 1. Typical cement-manufacturing kiln (Domone & Illston, 2010)

To put this in perspective, it is estimated that around 4 billion tonnes of cement were produced in 2013, of which 59% was produced in China alone (see Figure 2; CemBureau, 2013). It is interesting to note, however, that cement production in Europe has declined by about 10% since 2001, while cement production in Asia has increased by almost three times over the same period. Cement production in Africa has also increased by more than 2.5 times since 2001. With this growth in cement production, and China already producing such high volumes of cement, the outlook for the reduction of carbon emissions by cement manufacturing is not positive.

It is acknowledged that only carbon emission is considered here and that there are a large number of other environmental impact indicators that also need to be included. However, the so-called carbon footprint does give a good indication of the environmental impact of a construction material.

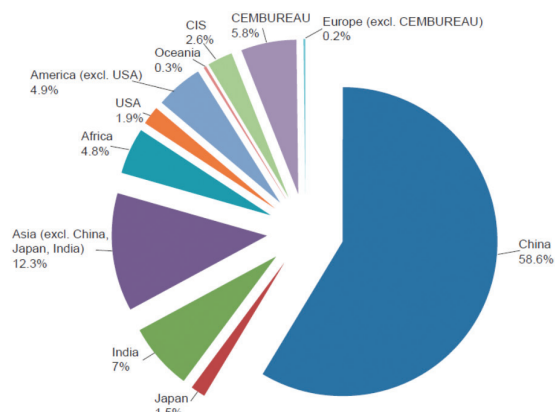


Figure 2. The world cement production by region in 2013 (CemBureau, 2013)

Concrete

Even though cement manufacturing results in a large emission of CO₂, concrete does not consist of 100% cement. Cement is only the binder and therefore only part of the concrete. Figure 3 shows typical constituents by weight for average strength (30 MPa characteristic strength) concrete. It is important to understand that, for a given cement type, the cement content is not solely responsible for the strength of the concrete. Rather, in general terms, the ratio of water to cement determines the strength of the concrete. The higher the ratio (more water to cement), the lower the strength. Thus, lowering the water content will increase the strength and, more importantly, if the water and cement are both reduced at the same ratio, the strength will remain around the same.

The water content is important for the consistency, however, and the concrete would be too “dry” or harsh to work with if the water is reduced. Therefore it is not so easy to reduce the cement content without using additional admixtures or improving the aggregates.

The total scope of CO_{2e} emission for this typical concrete mixture has been calculated as 356 kg CO_{2e}/m³ concrete for typical South African materials (InEnergy, 2010). This is equivalent to 148 g CO_{2e}/kg concrete. This is significantly less than when only cement is considered, although it still is an enormous amount of greenhouse gas emissions, especially if the volume of concrete produced world-wide is taking into account.

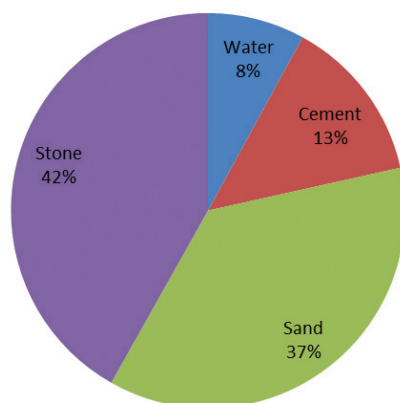


Figure 3. Typical 30 MPa concrete composition by weight.

The impact of concrete on the environment is without a doubt negative. There are solutions to reduce this impact, and many of these solutions are already implemented to some extent. However, they typically are used only where it results in an economic advantage as well. The following section discusses four solutions to reduce the environmental impact of concrete.

SOLUTIONS TO ENVIRONMENTAL IMPACT

There are a number of solutions to reduce the environmental impact of concrete. Firstly, of course, is to replace concrete with a completely new material that is so-called carbon neutral (or even carbon negative), durable, robust and easy to use. There is not a viable alternative to concrete that adheres to these requirements, however, so the focus in the short to medium term should be on reducing the environmental impact of concrete as we know it. There basically are four ways in which this can be done, namely:

- blending or extending cement using supplementary cementitious materials (SCMs), which typically are waste materials;
- optimising concrete mix designs to reduce cement content, typically using water-reducing admixtures or better-graded aggregates;
- improving the durability of concrete, which results in a reduction in the environmental impact if the full life cycle is considered; and
- implementing advanced and/or unconventional uses of concrete.

Blending or extending cement using SCMs has been common practice for some decades already. It significantly reduces the environmental impact of concrete, as part of the cement is replaced by a waste product without any significant reduction in the strength of the combined material, now called binder instead of cement. Fly ash (FA), ash of pulverised coal burned at power stations, and ground granulated blast furnace slag (GGBS), a by-product of the steel-manufacturing process, are typically used. Up to 95% of cement can be replaced by GGBS; however, this will result in a slow-strengthening concrete (Kumar et al., 2004). Typical limits for the replacement of cement are 30% with FA and 50% with GGBS. This can have a significant influence on the greenhouse gas emissions. For typical concrete, as shown in Figure 3, the carbon emissions can be reduced by up to 23% and 36% for FA and GGBS replacement respectively (InEnergy, 2010).

Using SCMs to partially replace cement has a number of benefits, but the two most prominent are the reduction in overall cost of the concrete and the improved durability of concrete containing SCM (Papadakis, 2000). Therefore common cement (actually binder) that can be purchased in 50 kg bags is typically already blended with SCMs to some extent (SANS 50197-1).

Improvements can also be made by optimising the mix design of concrete. If the same strength can be obtained using less binder, the environmental impact can be reduced significantly. In general terms, the strength of concrete is determined by the ratio of water to binder. The less water in relation to binder in the concrete, the higher the strength, but of course only if the same strength class of cement is used. Thus, to be able to reduce the binder content, the water content has to be reduced, but it still will have to produce concrete with the appropriate consistency. This can be done by adding so-called (high-range) water-reducing admixtures. This will allow adequate consistency while reducing the water in the concrete, therefore reducing the amount of binder required for a specific strength of concrete.

The technology of these admixtures has improved significantly over the past decades. The older generation of admixtures (e.g. lignosulphonates) are used regularly today as the concrete becomes more economical due to the relative low cost of the admixture. The saving in binder is typical more than the cost of the required admixture. The more modern admixtures (e.g. polycarboxylate ethers) are more effective and thus can decrease binder content significantly, but do not always result in a more economical concrete due to their high cost. There also is the problem of the codified minimum cement content required to obtain a certain level of durability. Numerous studies have shown, however, that the durability does not necessarily decrease with a reduction in cement content if the water/cement ratio and strength are kept constant (Buenfeld & Okundi, 1998, Dhir et al., 2004, Wasserman et al., 2009).

The third option is to increase the durability, thus leading to a structure with an increased lifespan and in need of less repair work (Alexander et al. 2008). Improved concrete mix designs play an important role, but just as important is the execution of the work on site and the structural design. There is a strong move away from a prescriptive approach to concrete durability to a performance-based approach that can ensure the same or even better durability with less binder (Walraven, 2008).

Lastly, concrete can be used in advanced and/or unconventional ways. These include approaches that typically fall outside the framework of conventional concrete design. Typically the material and the structure have to be designed together to achieve a superior product. Some examples are the very broad field of fibre-reinforced concrete (Brandt, 2008), alkali-activated binders (e.g. geopolymers) (Habert et al., 2011), high to ultra-high strength concrete (Wille et al., 2012) and the structural use of foamed concrete (Jones & McCarthy, 2005).

One simple design example is the reduction of the environmental impact of a bridge by increasing the strength of the concrete. A high-strength concrete of 95 MPa was used for an alternative bridge that falls outside the allowed maximum design strength of concrete (50 MPa) in the South African design codes. The environmental impact of the high-strength concrete per volume unit will be more due to the higher binder content, but less of the material is needed in the structure, thus leading to a more environmental friendly bridge (Habert et al., 2012).

The following sections consider a few of these advanced/unconventional solutions recently researched at Stellenbosch University and highlight some of the advantages, but also the challenges. They are all in the field of fibre-reinforced concrete, namely:

- low volume fibre reinforced concrete (LV-FRC);
- macro fibre reinforced concrete (M-FRC); and
- strain hardening cement-based composites (SHCC).

The reduction in the environmental impact as a result of advanced or unconventional solutions is not always straightforward, especially if the material and its properties are not yet fully understood. The following sections give some background to a few of the many solutions under investigation. The purpose is not to present these three solutions as the ultimate solution to reducing the environmental impact of concrete. Rather, both the advantages and challenges are discussed objectively on the basis of current research.

LOW VOLUME FIBRE REINFORCED CONCRETE (LV-FRC)

The first solution is low volume fibre reinforced concrete (LV-FRC), which is defined as a conventional concrete with a relatively small volume of micro synthetic fibres added, typically between 0.06 and 0.1% by volume. Polypropylene is typically used, but polyester is also effective. Due to this small volume, the mechanical properties of hardened concrete are not influenced. The main advantage, however, is crack control during the first few hours after casting, more specifically, before the final setting time has been reached (Combrinck & Boshoff, 2013).

These cracks are called plastic shrinkage cracks and occur as a result of capillary pressure built up due to water evaporating from within the concrete (Wittmann, 1976). This happens within the first few hours after concrete is cast and consolidated.

The continual evaporation of water from the concrete surface causes water menisci to form between

the particles, which tend to suck the particles together in both the horizontal and vertical directions. When these particles are prevented from moving closer together due to a restraint, the internal capillary pressure becomes negative. This build-up of negative capillary pressure is known to be the main mechanism that causes plastic shrinkage cracking and was first documented by Wittmann (1976). It is a complex process and the different phenomena that contribute to plastic shrinkage cracking, including bleeding, setting and crack growth, are shown in Figure 4.

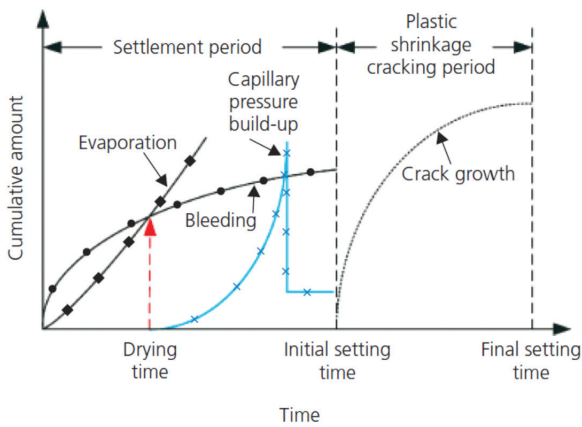


Figure 4. Phenomena and mechanisms contributing to plastic shrinkage cracking (Combrinck & Boshoff, 2013).

These plastic shrinkage cracks can have a severe negative effect on the durability of a concrete member, as they often are directly above the reinforcing steel. This position is dictated by small settlement cracks that occur before plastic shrinkage cracks. Deleterious materials (water, oxygen, chlorides, etc.) thus can reach the reinforcing steel through the crack (Qi et al., 2003).

The addition of micro synthetic fibres has been shown to reduce the risk of plastic shrinkage cracks for a few decades already (Soroushian et al., 1995). However, the quantification of this risk reduction due the addition of the fibres and the mechanism of how the fibres reduce the risk of cracking have not been understood until now.

A model quantifying the severity of plastic shrinkage cracking was published recently (Boshoff & Combrinck, 2013). The significance of the cracking severity calculated was verified using measured crack areas during a large number of tests. This model calculates the cracking severity based on the bleeding volume, evaporation rate

and plastic period, and is shown in Figure 5 together with the experimental chamber used to simulate typical and extreme environmental conditions with different wind speeds. Figure 6 shows the effect of the fibre volume on the cracking severity, clearly showing a significant reduction.

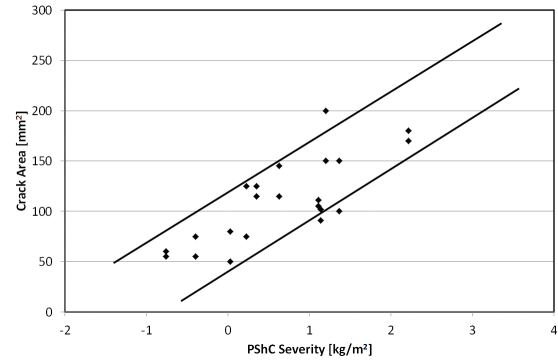


Figure 5. a) Correlation of the calculated severity of plastic shrinkage cracking with the crack area.



Figure 5. b) the environmental chamber used to quantify the plastic shrinkage cracking.

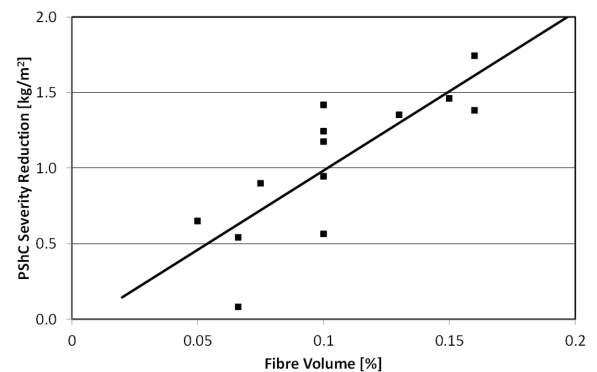


Figure 6. The effect of the fibre volume on the reduction of the risk of plastic shrinkage cracking.

Even though the phenomenon of crack reduction when using LV-FRC is clear, the question remains: why do synthetic micro-fibres reduce plastic shrinkage cracking? To determine this, a number of tensile tests were done on fresh concrete – concrete less than six hours old. This is a complex test, as the material is still semi-liquid, but it does have mechanical properties that can be tested. The setup is based on a mould with two parts that are pulled apart while resting on an air bearing to remove the effect of friction. In this setup, the friction is negligible compared to the tensile force required to “fracture” the fresh concrete. The setup is shown in Figure 7 a).



Figure 7. a) The tensile test setup for fresh concrete.

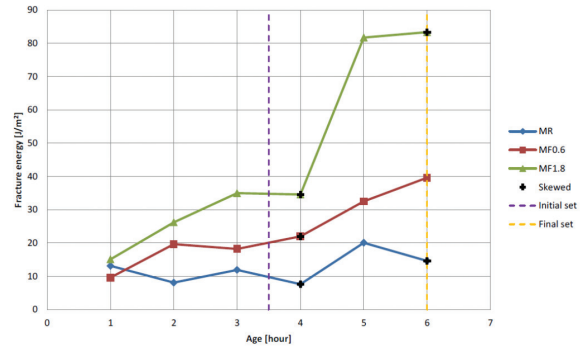


Figure 7. b) the fracture energy at different ages. Note MR is the control, MF0.6 has 0.06% fibres and MF1.8 has 0.18% fibres (Dippenaar, 2015).

A recent study (Dippenaar, 2015) found that a small volume of micro-fibres does not significantly influence the tensile strength or the strain capacity of concrete before cracking, as commonly believed. However, the results did show a clear increase in the tensile fracture energy up to an age of 6 hours, as shown in Figure 7 b). This fracture energy also significantly increases with an increase in fibre content. The addition of fibres, especially the higher additions (0.18 % by volume), showed some multiple cracking during the testing, which also contributed to the higher measured fracture energy. This helps to understand the mechanism by which the fibres actually improve the cracking behaviour.

The next step in this research is to model the cracking behaviour of fresh concrete using the mechanical properties obtained from the tensile tests with the aid of the finite element method. Phenomena that need to be included are the volumetric shrinkage (plastic shrinkage), vertical shrinkage (plastic settlement), the mechanical properties, which change significantly with time, and of course all the boundary conditions and restraints, such as steel reinforcing or formwork. This model will then be able to predict the position and severity of these cracks by using the concrete material properties, ambient temperatures and the layout of the concrete element. The preliminary results of the finite element analyses of plastic settlement combined with plastic shrinkage are shown in Figure 8, with the cracks indicated clearly over the restraints, showing that both plastic settlement and plastic shrinkage cracking occurred.

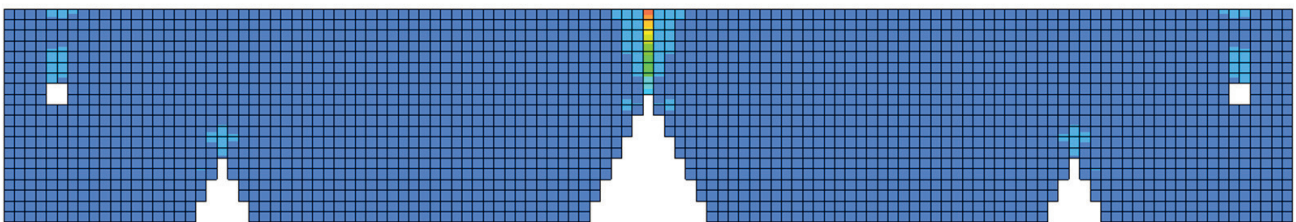


Figure 8. Preliminary finite element modelling results of a section containing reinforcing bars and triangular inserts, showing both plastic settlement and plastic shrinkage cracking.

This work will result in a better understanding of this early-age cracking and can then assist with the specification of LV-FRC and also the dosage required to mitigate these preventable defects in concrete members. This will result in more durable concrete structures, which in turn will result in a less severe environmental impact.

MACRO-FIBRE REINFORCED CONCRETE (MFRC)

Macro-fibres, also known as structural fibres, are fibres with lengths of between 30 mm and 60 mm and effective diameters of between 0.5 mm and 2 mm. They are available in both steel, polypropylene and polyvinyl alcohol, while the last mentioned is not used on a large scale. They also have numerous different geometric irregularities to increase their bond with concrete. Typical fibres are shown in Figure 9.

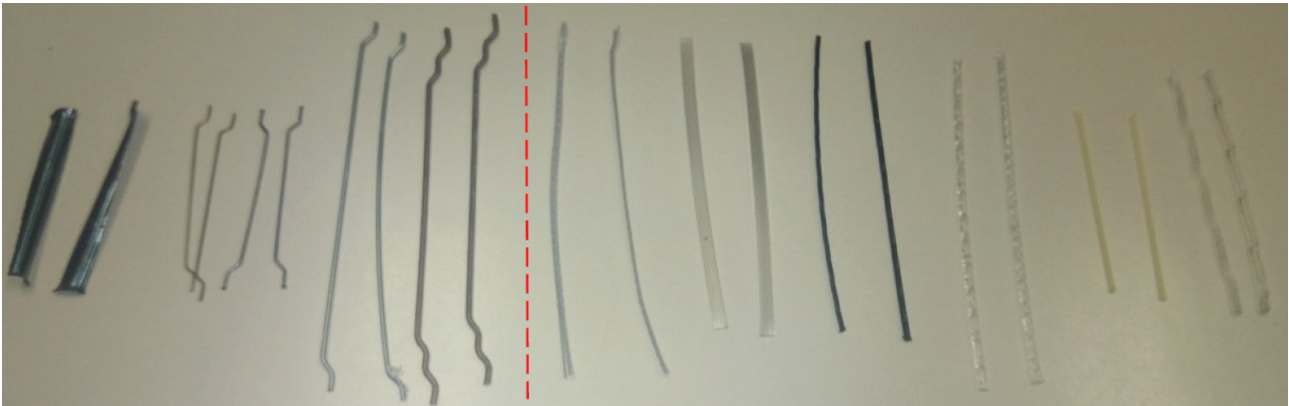


Figure 9. Different shapes of macro-fibres available. All fibres to the left of the dotted line are steel and those to the right are polypropylene, except the third and fourth fibres from the right, which are polyvinyl alcohol.

Macro-fibres are added to concrete at volumes typically less than 1.5%, and more often around 0.5%. These are still relatively low volumes, so these fibres only enhance the concrete behaviour once the concrete has cracked, after which the fibres start to transfer the load over the crack plane. This is similar to the contribution of conventional steel reinforcing, which only becomes significant once concrete has cracked.

The most obvious advantage of macro-fibres in concrete is for concrete industrial floors on grade. The implementation of fibres for floors on grade in South Africa is not straightforward, as these types of floors are typically designed using the elastic Westegaard Theory approach (Marais & Perry, 2000). This approach designs the floor so that no cracking occurs due to loading, not even in extreme loading conditions. As mentioned, fibres only influence the mechanical behaviour of concrete once it is cracked, therefore the advantage of using macro-fibres is not evident when designing using the Westegaard Theory approach.

In contrast to this design approach, the Yield Line Theory approach can be used for designing floors on grade (Concrete Society, 2014). This approach accepts that, in extreme loading conditions, cracking will occur and the ductility that the fibres add to the concrete is then taken into account.

Using the Yield Line Theory design approach together with macro-fibres, the required thickness of concrete floors can be reduced without impairing the performance. This is a significant solution that can be used in the industry to reduce the environmental impact of concrete.

However, there are a few challenges before this solution can work:

- South African engineers have to move to another design approach, viz. the Yield Line Theory opposed to Westegaard Theory;
- quality control tests on MFRC are not straightforward and laboratories are currently not equipped to perform the required tests on macro-fibre reinforced concrete; and
- the tensile creep of cracked MFRC is a concern and requires further investigation.

The tensile creep of MFRC concrete currently is the focus of a number of researchers world-wide and a RILEM Technical Committee, titled “Creep Behaviour in Cracked Sections of Fibre Reinforced Concrete”, has been created to investigate this. However, only three papers have been published on the tensile creep of cracked fibre-reinforced concrete to date (Boshoff & Adendorff, 2013, Boshoff, 2014, Babafemi & Boshoff, 2015), and only the last one is on MFRC, specifically on

polypropylene fibres. These results show that the tensile creep of synthetic MFRC concrete can be significantly increased when subjected to a sustained tensile or flexural load. This could have a detrimental effect on the long-term performance of MFRC.

The quantification and modelling of this time-dependent behaviour is ongoing research. Some results are presented here to give an indication of the challenges currently experienced with the tensile creep of cracked MFRC.

To test the tensile creep of cracked MFRC, concrete specimens typically are notched and pre-cracked before testing in a tensile creep frame as shown in Figure 10 a) (Babafemi and Boshoff, 2015). Single fibres embedded in concrete were also tested under sustained tensile loading, as shown in Figure 10 b). The crack widening for the first-mentioned test was monitored using LVDTs and the single-fibre pull-out tests were quantified using scaled microscope photos. The single-fibre tests provide insight into the creep behaviour on the single fibre level and the performance of different types of fibre can then easily be compared using this test method.



Figure 10. a) The tensile creep test setup.

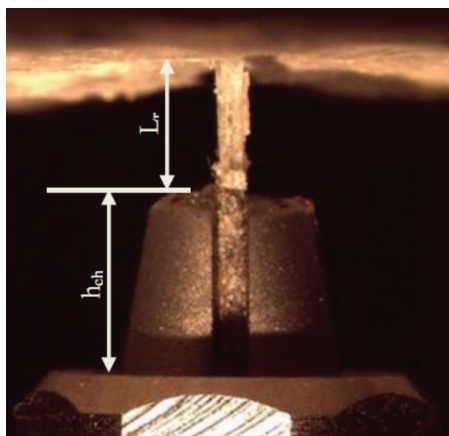


Figure 10. b) the single-fibre pull-out setup (Babafemi & Boshoff, 2015)

This investigation has shown that there is a significant increase in the tensile creep of MFRC once it is cracked. This has been investigated for both steel and polypropylene fibres. Figure 11 shows the crack widening and fibre pull-out displacement of single-fibre tests – both are for polypropylene fibres, while Figure 12 shows unpublished work on the single-fibre time-dependent pull-out for steel fibres. It is alarming to note that, for load levels as low as 50% of the post-peak resistance, the crack widening is more than 1.5 mm after 6 months for the polypropylene fibres. This will be significantly less for steel fibre based on the single-fibre pull-out results of steel fibres shown in Figure 12 a). The damage during the steel fibre creep test occurred in the concrete around the hooked end of the steel fibre, as shown in Figure 12 b) using micro-CT scanning. The damage to the polypropylene fibres occurs mostly in the fibre itself.

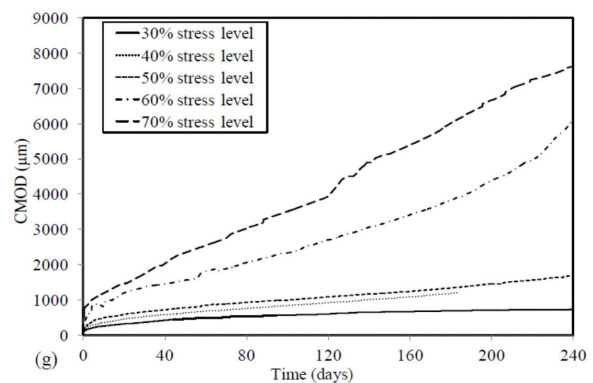


Figure 11. a) The tensile creep of cracked synthetic MFRC.

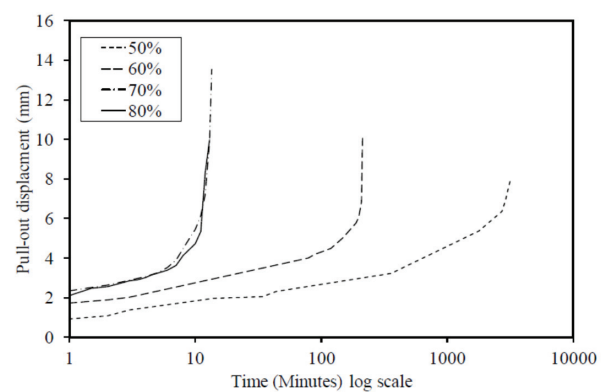


Figure 11. b) the single-fibre pull-out creep results for synthetic fibres.

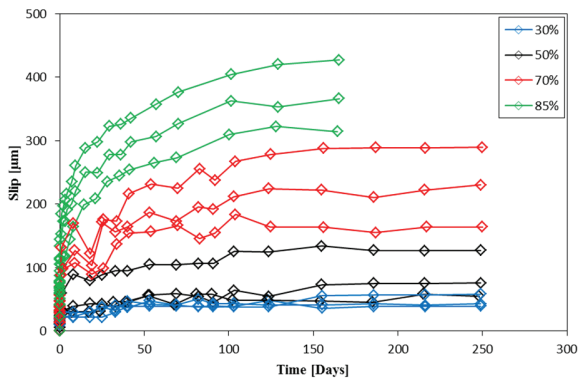


Figure 12. a) Single-fibre pull-out creep tests on steel fibres.

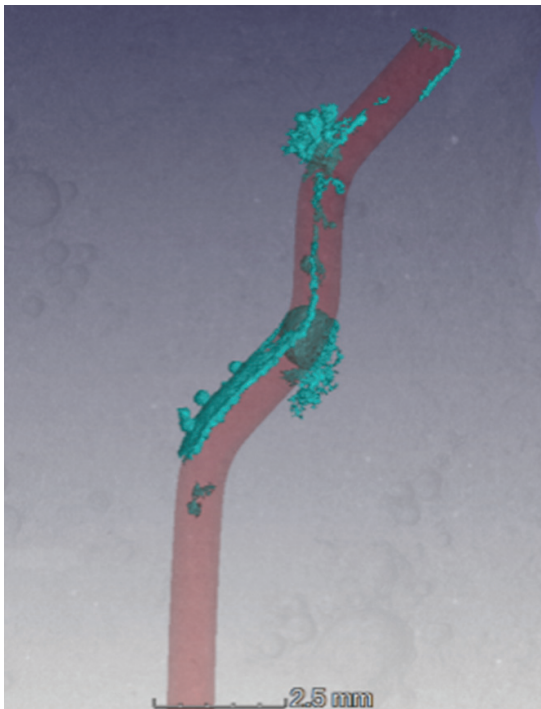


Figure 12. b) micro-CT image showing the damage and debonding around the hooked end of an embedded steel fibre during the test.

These results show that MFRC still poses some challenges, especially the tensile creep behaviour once the material has cracked. However, cracking will only occur under extreme loading conditions, which typically are not sustained for long periods of time. The impact of the increased creep of cracked MFRC does require further investigation, however, as it is believed that the material can be applied within the norms of accepted design approaches without a risk.

STRAIN-HARDENING CEMENT-BASED COMPOSITES (SHCC)

Strain-hardening cement-based composites (SHCC) have been researched and developed since the middle

1990s (Li, 1993) and have been the topic of special edition publications, conference sessions and even entire conferences. The addition of a relative small volume of micro-fibres (2%) transforms concrete, a quasi-brittle material, into a pseudo strain-hardening material (Boshoff & Van Zijl, 2007). The mix design, however does require careful “engineering”, as the fracture energy needs to be sufficiently low to obtain steady-state crack growth. The ductility of this material can be seen in Figure 13 a).

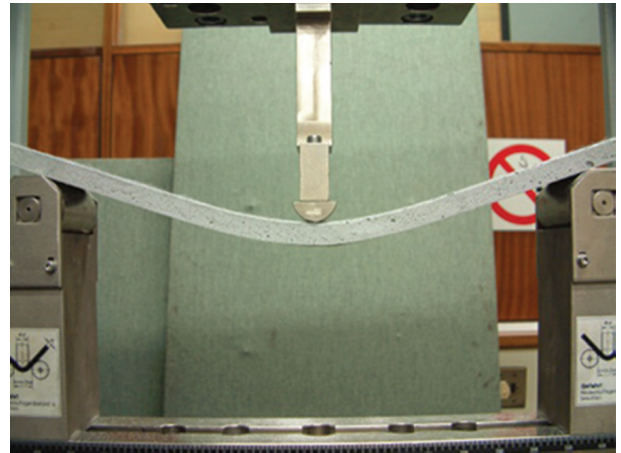


Figure 13. a) The ductility of SHCC

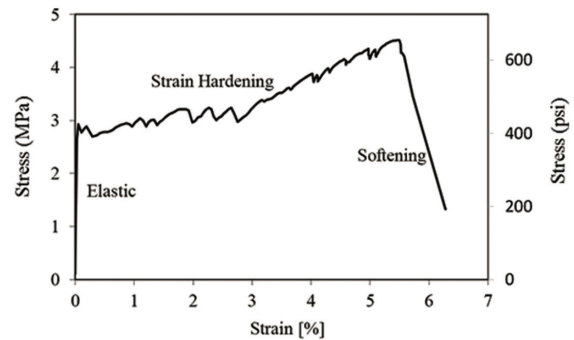


Figure 13. b) the typical stress-strain response (Boshoff, 2014)

A typical stress-strain behaviour is shown in Figure 13 b). Note that the tensile strain capacity of concrete is typically around 0.01%, while SHCC is more than 3%, which is an improvement by more than two orders or magnitude. This is useful for structures that require large energy-absorption capacity, such as structural elements required to resist seismic action, but is also useful as a repair material.

The greatest advantage, however, the cracking behaviour of SHCC. Fine, multiple cracks occur during tensile loading, typically less than 60 µm in width, opposed to single, localised cracks typically found in conventional reinforced concrete. This has a significant durability enhancement potential for concrete structures, as it has been found that the ingress of deleterious materials into cracks with a width of less than 100 µm is typically

insignificant (Wang et al., 1997, Sahmaran et al., 2007). What is clear, however, is that the rate of ingress of deleterious materials is directly linked to the crack width.

For this advantage to be utilised, the durability improvement has to be quantified. Early studies of the cracking behaviour of SHCC focused on the average crack width and spacing to describe the crack pattern (Li et al., 2007, Sahmaran & Li, 2008). It has since been acknowledged that a more comprehensive crack pattern quantification is required to assess the durability, including the statistical distribution of the crack widths. This is because the rate of ingress and the transported volume of deleterious materials are strongly dependent on the crack width.

This dependency on the crack width is not linear, therefore the average crack width cannot be used as an indicator. Therefore a new model has been proposed that takes the crack width distribution into account (Boshoff et al., submitted). A log normal distribution was found to best describe the crack widths, and this distribution is weighed by a so-called crack ingress potential, which is based on experimental data. After integration over the crack width domain, the final answer is multiplied by the crack intensity, which is defined as the number of cracks per metre over 1 000.

The final answer is a single value at a specific tensile strain, called the ingress potential index (IPI). Typical results for strain values up to 0.75% are shown in Figure 14 for both chloride diffusion and water permeation. It is acknowledged that this is just the first step in the quantification of the durability potential of SHCC. This approach must be expanded to include the actual corrosion process of the reinforcing steel that is a result of this ingress of deleterious materials. The corrosion process is most probably also influenced by the crack pattern.

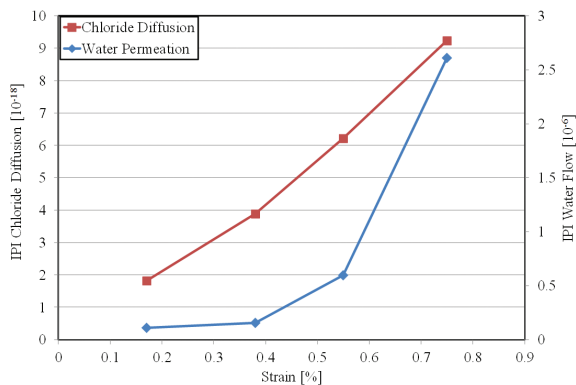


Figure 14. IPI values for both chloride diffusion and water flow up to a tensile strain of 0.75% (Boshoff et al., submitted).

The tensile creep of cracked SHCC is also a problem, however, and it has been found that the average crack width can be increased significantly in size if subjected to a sustained tensile loading (Boshoff & Adendorff, 2013). This was tested for unreinforced SHCC and it is believed the creep will be significantly less when reinforced SHCC is used. However, it requires further investigation.

CONCLUDING REMARKS

The question has been asked whether concrete should be seen as an enemy or an ally. It is clear that concrete has a noticeable negative impact on the environment, both directly and indirectly. What is even clearer is that modern civilisation cannot function without concrete. Concrete, and more specifically cement, has become a key ingredient of economic growth, and cement sales are often used as an indicator thereof. Cement is entrenched in almost every sphere of human settlement and industry.

There is no current technology that offers a solution to replace concrete in a sustainable, robust manner. Advanced and high-level research should continue and even be accelerated, as this could produce long-term solutions to the environmental impact of concrete.

However, there are solutions for the short and medium term (probably defined as the next 40 to 50 years) to reduce the environmental impact of concrete. We simply have to use cement more smartly. The key for the near future lies in the four mentioned aspects, viz. using supplementary cementitious materials (SCMs), optimising mix designs, improving durability and, lastly, using advanced/unconventional applications of concrete.

Firstly, supplementary cementitious materials (SCM) are vital in producing more sustainable concrete structures. Cement must be replaced as much as possible using waste materials such as fly ash and ground granulated blast furnace slag. One hampering aspect of using high large replacements of SCMs is that strength development can be retarded significantly. However, if this can be taken into account in construction projects, the environmental impact can be reduced even further. The limits need to be pushed using SCMs.

The mix design of concrete should be improved. It is acknowledged that mix designs of typical ready-mix suppliers are already optimised economically, although the environmental impact typically is not considered. Cement content can be reduced further using (expensive) super plasticisers, and also using better graded (more expensive) aggregates. Another aspect hindering the reduction of the cement content is the

minimum cement content specification for durability. It is time for the industry to move away from prescriptive durability specifications (e.g. minimum cement content) towards performance-based specifications that will allow the use of concrete using less cement, but still meeting the durability requirements.

Durability should form a more integral part in structural design as well as in the construction itself. The durability of structures can be improved significantly at both the design stage and in construction. Many durability issues are a result of poor workmanship, which could be avoided with proper staff training and supervision.

Lastly, further research is needed in advanced/unconventional applications that reduce the environmental impact of structures. Some examples given here, such as low-volume fibre-reinforced concrete and macro-fibre reinforced concrete, are used in the industry, but the potential is there for significantly more use of these. It is not just the responsibility of researchers to see that these solutions are implemented, but the engineers in industry also have a role and responsibility. Universities should expose future engineers to new technology, but, even better, universities should teach students the skills to investigate, understand and implement new technologies that have not even been developed yet.

The world simply cannot do without concrete. However, it is the responsibility of every person to start using concrete more smartly. Concrete is our friend, but the friendship cannot last indefinitely.

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