SYNTHETIC MACRO FIBRES – AN INNOVATION IN FIBRE REINFORCEMENT

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INTRODUCTION

Polypropylene micro fibres have been used in cement based building materials for many years. During the last 5 years or so, recent developments in synthetic fibres for concrete have lead to the introduction of a new type of fibre for concrete - synthetic macro fibres. These fibres impart a post crack or "residual" flexural strength to the hardened concrete in a similar way to that achieved by steel fibres. This paper will focus on the principal aspects of one particular type of synthetic macro fibres and highlight the most typical applications for this type of fibre reinforcement for concrete.

FIBRE REINFORCEMENT FOR CONCRETE

Innovations in construction materials are well documented; fly ash, silica fume, ground granulated blast furnace slag to name but three. In the last couple of years, the well documented rise in steel prices (which is the second most used material behind concrete) has put even more pressure on project managers and engineers to find ways to reduce construction costs. Steel is used in beams, girders, rebars, and mesh or fibres just to name a few.

Steel mesh in slabs is mainly used to control cracking due to either drying shrinkage and/or thermal movements. Correct location of the steel mesh in a slab section to provide optimum drying shrinkage crack control is very labour intensive and time consuming since the mesh needs to be placed in the top third of the slab and hence, needs to be suspended on closely spaced chairs. The concrete sometimes needs to be pumped from the ready mix truck since the suspended steel mesh prevents the truck from discharging the concrete where it is actually needed. It is also very difficult to use laser screeds machines, which consolidate and level the concrete, which are very efficient when large concrete slabs are being poured.

Steel fibre reinforced concrete, where deformed steel fibres are mixed directly into concrete replacing the steel mesh, has been an increase in use over the past few years, primarily because of their ability to replace steel mesh. It has been demonstrated in the past through many tests conducted by Universities [1,2,3,4,5,6] and thousands of completed projects, that steel fibres (when used at a sufficient dosage rate) can provide better or equal crack control than steel mesh reinforcement in applications such as industrial slabs. In addition to controlling drying shrinkage cracking, it has been shown that the flexural capacity of slabs supported on ground also increased. In order to achieve the same benefit with steel mesh, a second layer of mesh would need to be installed but located in the bottom third of the slab.

The addition of steel fibres can, therefore, demonstrate significant savings to the contractor in not having to place steel mesh but there are some potential disadvantages in using steel fibres. Special steel fibre dispensers are required to ensure even distribution throughout the concrete and to avoid fibre balling and nesting. When steel fibre reinforced concrete needs to be pumped, there is a potential for increased mechanical wear on the internal surfaces of the cylinders of the pump, hoses and finishing equipment. Pumping pressures also need to be increased.

Although the high alkalinity of the concrete limits the corrosion of steel fibres within the concrete, steel fibres close to the concrete surface and in cracked concrete sections will start to corrode, particularly if the concrete comes into contact with water, chlorides or acids. This effect will lead to surface staining and in the worst-case scenario (at crack widths of > 0.5 mm) to a loss of crack control capacity [7,8,9]. Another potential problem is related to steel fibres protruding out of the concrete surface, which can be caused by improper concrete placement or by concrete spalling, abrasion or degradation.

SYNTHETIC MACRO FIBRES

Synthetic “macro” fibres, which provide significant amounts of post-cracking toughness or post-cracking flexural strength to the concrete, are a recent innovation in fibre technology for concrete. This is in contrast to the already well accepted polypropylene “micro” fibres, which usually have a fibre diameter in the range of 20 µm to 50 µm and are used to control plastic shrinkage cracking, plastic settlement cracking and in some cases, can provide resistance to freeze/thaw disruptions and explosive spalling in tunnel lining concretes.

Synthetic macro fibres are much easier to handle than steel fibres since the specific gravity of the

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material is typically about 12% of that of steel. They maintain their mechanical properties in alkaline as well as in acidic environments. Typical (equivalent) diameters of synthetic macro fibres ranges from 0.5 to 1 mm, with tensile strengths ranging between 350 to 700 N/mm². The addition dosage rates of these fibres needed to achieve residual flexural strengths of > 1 N/mm² will vary depending on fibre type (i.e. material and fibre dimensions). In common with steel fibre reinforced concrete, increasing the dosage of synthetic macro fibres to achieve a certain toughness performance target will have a negative impact on the workability of the concrete as well as on the ease by which the surface of a floor can be finished. To overcome this impact on workability, the addition of a superplasticising admixture is always recommended ensuring, therefore, that the other parameters of the concrete mix design (i.e. strength, durability etc.) are maintained.

Synthetic macro fibres typically have a relatively low modulus of elasticity (i.e. 3,000 to 5,000 N/mm² or 3 to 5 GPa). The performance of these fibres at small crack openings is inferior to that of deformed steel fibres, which typically have a higher modulus of elasticity (i.e. 180,000 and 210,000 N/mm² or 180 to 210 GPa). Most of the commercially available steel fibres are designed to fail in “fibre-pull-out” mode (i.e. the fibre “pulls out” of the concrete matrix) rather than in “fibre-failure” mode. Where the fibre breaks, therefore, the high modulus of steel is only partly utilized when the concrete starts to crack. This shortcoming does not represent a big problem in many applications such as shotcrete linings for mining tunnels, but it is a significant shortcoming in applications such as civil tunnels or slab on ground floors, where large cracks are not acceptable to the engineer or the client.

AN INNOVATION IN SYNTHETIC MACRO FIBRES

STRUXX® 90/40 synthetic macro fibre is a new innovation in this area of fibre reinforcement for concrete. Developed and patented by W.R. Grace and depicted in Figure 1., this type of synthetic macro fibre was introduced in 2002 throughout the worldwide construction market. The main constituent components of this polymeric fibre type are polypropylene and polyethylene. Its mechanical and geometric properties are significantly different to those of other commercially available synthetic macro fibres. The length of the fibre is 40 mm, an aspect ratio (length divided by the equivalent diameter) of 90 and a specific gravity of 0.92. This ‘flat’ type of fibre has a rectangular cross-section with an average width of 1.40 mm and an average thickness of 0.105 mm. The average tensile strength of the fibre is 620 N/mm² (MPa) with a modulus of elasticity (chord modulus) of 9,500 N/mm² or 9.5 GPa. These properties are significantly different from those mentioned earlier.

Figure 1; STRUX 90/40 synthetic macro fibre

The ‘flat’ fibre design was chosen in part to achieve a large fibre surface area to fibre volume ratio in order to increase the mechanical bond between the fibre and the hardened cement paste. The elastic modulus of the synthetic macro fibre nearly matches the elastic modulus of the cement paste, in which the fibre is embedded, which allows the fibre to transfer stresses across a crack immediately after crack initiation has occurred. Good crack control can, therefore, be achieved in concrete.

Other synthetic macro fibres with either an insufficient bond between the fibre and the cement paste or having a lower elastic modulus initially need to elongate or “stretch” before they are able to transfer significant amounts of stresses across widening cracks. This leads to larger crack openings. This can be observed when measuring the flexural performance (see Figure 2) using a beam test set-up such as described in ASTM C1609-06[10] or JSCE-SF4[11], which is being used for designs of fibre reinforced concrete slab-on-ground in CSTR 34[12].

Figure 2; Flexural stress versus deflection curves measured according to ASTM C1609-06
In the case of the load versus deflection response of concrete specimens reinforced with lower modulus, “crimped” synthetic macro fibre, the stress reduces significantly immediately after the peak flexural stress has occurred. At larger beam deflections, the post-cracking or “residual” flexural strength of the concrete starts to increase again. At an equivalent fibre addition rate, the higher modulus (i.e. 9.5 GPa) of the 40mm long synthetic macro fibre shows a much better response after initial cracking. The response of concrete specimens reinforced with this type of synthetic macro fibre nearly matches the average behaviour of a concrete reinforced with 20 kg per cubic meter of a 50 mm long “crimped” steel fibre with a wire diameter of 1.3 mm. At a beam deflection of approximately 0.25 mm, the high modulus synthetic macro fibre reinforced beams maintain their load carrying capacity until the tests are stopped at a beam deflection of 3 mm.

At larger deflections, the average residual load carrying capacity of concrete reinforced with 4.6 kg/m³ of the high modulus synthetic macro fibre matches the performance of the 50 mm long “crimped” steel fibre added at a dosage of 40 kg/m³. It has to be noted, however, that there are many different types of steel fibres on the market which all perform differently in concrete.

One kilogram of this type of high modulus synthetic macro fibre contains around 185,000 fibres. In comparison, one kilogram of the 50 mm steel fibre (with a wire diameter of 1.3 mm) contains only around 2,000 individual fibres — a ratio of one steel fibre for every 92 synthetic macro fibres. The standard deviation of the post-cracking flexural strength of a fibre reinforced concrete with a high fibre count per volume of concrete is generally lower compared to a fibre reinforced concrete with a low fibre count. The standard deviation is important since the characteristic value (which takes into account the average value), the standard deviation and the number of samples tested are used for design of fibre reinforced concrete. For example in Germany, the DBV (German Concrete Association) steel fibre technical bulletin classifies fibre reinforced concrete in various fibre classes. Figure 3 shows the performance of the 40mm long, high modulus synthetic macro fibre reinforced concrete beams tested according to DIN 1048 part 1 ‘Testing methods for concrete’.

The concrete mix design used for these tests was according to the requirements of the German Institute for Civil Engineering (DIBt) for Fibre products used as concrete additives. If local materials from New Zealand and/or mix designs with a higher fine aggregate content are used to make synthetic macro fibre reinforced concrete, significantly higher residual flexural strength values can sometimes be obtained (see Figure 4.).

Large scale testing of ground supported concrete slabs reinforced with 40mm long, high modulus synthetic macro fibres

Before this type of high modulus synthetic macro fibre was introduced commercially to the North American market, a large scale-testing program was conducted at the University of Illinois. One purpose of the program was to measure and compare the structural response of un-reinforced or “plain” concrete slabs with that of steel fibre, steel mesh and the high modulus synthetic macro fibre reinforced concrete slabs under interior and edge loading conditions. Simply supported, small-scale beam tests had demonstrated in the laboratory that the synthetic macro fibre could significantly increase the post-cracking strength or toughness of concrete thereby matching the performance of concrete beam tests reinforced with steel fibres. The structural benefits of the synthetic macro fibre, however, when added to “plain” concrete, were unknown at that time. Since the high modulus synthetic macro fibre had been specifically developed and optimised for such an
application, the structural benefits had to be investigated.

Large-scale slab tests were also required to determine if the beam toughness results generated in the laboratory could be used to predict the flexural and ultimate capacity of the synthetic macro fibre reinforced slabs in the same manner as previous research had done with steel fibres\(^1\)\(^\text{,2,5}\)\). This type of testing was essential for new fibre types because ground supported slab design codes such as the Technical Report 34 (TR 34) published by the UK Concrete Society\(^1\)\(^\text{,2}\) incorporate beam toughness results such as the equivalent flexural strength ratio, \(R_{e,3}\), to predict the concrete slab’s ultimate capacity and to calculate the required slab thickness.

The slab dimensions selected for this study were 2.2 m x 2.2 m x 0.127 m. The fully supported slabs were tested under monotonic loading conditions in displacement control to better capture the response of the concrete before and after cracking. Load-induced strains were measured using embedded strain gauges, which were placed at various locations before the slabs were cast. The objectives of the strain gauge placement were to measure compressive and tensile stresses at the top and bottom of the slab. Surface deflections of the concrete slabs were measured by an array of Linear Variable Displacement Transducers (LVDTs) as shown in Figure 5, where the fully instrumented slab can be seen before the load is being applied. Detailed information and interpretation of all the test results obtained from these experiments can be found elsewhere\(^1\)\(^4\)\(^,\)\(^5\)\(^,\)\(^6\)\) - only a brief summary and conclusions will be presented in this article.

The ultimate load carrying capacity of the plain concrete slab is improved significantly with the addition of the high modulus synthetic macro fibre. Compared to un-reinforced concrete, the flexural capacity under centre load conditions increased by 25% for a concrete slab reinforced with the synthetic macro fibre at a dosage of 3.0 kg/m\(^3\) and 32% for a slab reinforced with the synthetic macro fibre at a dosage of 4.4 kg/m\(^3\) (see Figure 6). Concrete reinforced with the synthetic macro fibre also outperformed steel fabric reinforced concrete where the cross sectional area of the steel mesh, \(A_s\), was 123 mm\(^2\)/m.

The equivalent flexural strength ratio \(R_{e,3}\) indicated a similar increase in the flexural and ultimate capacity of the fibre reinforced concrete slabs over the un-reinforced concrete slab. The addition of the high modulus synthetic macro fibre to the concrete slab helped to keep the slab in contact with the ground after flexural cracking had been reached thus enabling a better re-distribution of load. Embedded strain gauges further confirmed that the load carrying capacity of the fibre reinforced concrete slabs was distributed over a larger area before flexural cracking and thus allowed for a higher flexural and ultimate capacity relative to the plain and steel mesh reinforced concrete slabs.
The slabs reinforced with the high modulus synthetic macro fibre and with the steel fibre had overall similar fracture behaviour. The load-deflection curves also indicated that the structural ductility of the synthetic macro fibre reinforced slab and steel fibre reinforced slab was similar. The synthetic macro fibres, as well as steel fibres, did not increase the tensile capacity of the concrete slabs, which was consistent with findings from previously published reports.

The findings from this study confirmed that the post-cracking flexural strength measured on a relatively small beams could be used to predict the structural performance of the synthetic macro fibre reinforced ground supported concrete slabs as well as steel fibre reinforced ground supported concrete slabs. Since this study has been completed, many hundreds of ground-supported slabs, reinforced with the high modulus synthetic macro fibres in lieu of conventional steel mesh or steel fibres, have been successfully completed.

**APPLICATIONS FOR 40mm LONG, HIGH MODULUS SYNTHETIC MACRO FIBRES**

The primary application of the high modulus synthetic macro fibre has been the reinforcement of ground-supported concrete. In more than 100,000m² of finished floors, steel mesh has been replaced with various amounts of the synthetic macro fibre depending on the local requirements. In the case of ready mixed concrete production, it is important to provide a fibre that can be easily added to the concrete with minimal impact on the normal operation. The geometry (i.e. length, width etc.) of the high modulus synthetic macro fibre was also selected such that it would readily disperse in the plastic concrete and would not adversely affect the finishing characteristics at normal volume fractions (i.e. fibre dosage), which range from 0.25 to 0.75% (i.e. 2.3 to 6.9 kg per cubic meter of concrete).

The fibre can be added to the empty ready mixed truck prior to loading the concrete constituents or pre-mixed concrete, therefore minimising the time the truck has to spend in the concrete plant. After the concrete constituents have been added, the synthetic macro fibres are then mixed for at least five minutes at maximum mixing speed allowing the fibres to disperse throughout the load of concrete. Due to the mixing action with the plastic concrete, the surface of the fibre is slightly abraded which increases the strength of the bond between the fibre and the hardened cement paste. It is important to note that the addition of the synthetic macro fibre will have a negative impact on the workability of the concrete due to the relatively high fibre surface area. As previously mentioned, the workability can be restored by adding additional water reducing admixture or, preferably, a superplasticising admixture.

The fibre reinforced concrete can be easily pumped, if required. Figure 8 shows the pumping and placing of concrete reinforced with the synthetic macro fibre added at a high dosage of 5.3 kg/m³ for a composite steel deck floor construction where more than 1,200m³ of concrete were successfully pumped up to 7 storeys with ease. Experience shows that the pump pressure remained low, even for higher fibre addition rates since the fibres are very flexible and offer minimum resistance in shear due to concrete flow. The flexibility of the fibre also makes the finishing process of the concrete surface easier. Vibrating screeds are recommended to level the concrete and bring enough paste to the surface to embed the fibres.

Figure 8; Pumping concrete reinforced with the high modulus synthetic macro fibre

For larger areas of floor construction, a laser screed machine can be used to compact and level the concrete. See Figure 9.

Figure 9; Compaction using a laser screed

The high modulus synthetic macro fibre reinforced concrete is bull-floated to bring up additional paste for the final finishing process. For indoor slabs, the concrete is generally finished using a power trowel leading to near “fibre free” surfaces seen in Figure 10.
For outdoor applications, a broom finish or "panned" finish is normally applied (see Figure 11). In this case, some of the synthetic macro fibres are expected to be seen on the surface of the concrete pavement which will not cause any harm to the environment, since they will quickly wear off due to abrasion. The synthetic macro fibre close to the surface will provide the plastic shrinkage crack control needed for these applications.

In the UK, a new sea defence wall has been constructed along 3.2 km of Blackpool's shoreline and is rapidly becoming a benchmark project for marine defence authorities.[21,22] This type of high modulus synthetic macro fibre technology was used to reinforce much of the concrete that is being installed along the length of Blackpool's promenade seen in Figure 12. It is probably the first time in the world that this technology has been employed for major precast concrete elements in marine coastal defences. The omission of steel reinforcement cages has proved to be a significant benefit in terms of cost and time. Using the synthetic macro fibre also eliminated the logistical issues of transporting and storing tonnes of steel mesh on site. Pouring the concrete into precast moulds off site, without the problems surrounding the placement of steel cages, has also speeded up that side of the operation.

CONCLUSIONS

An innovative high performance, high modulus synthetic macro fibre is being increasingly used throughout the world in the construction of floors, pavements and other applications, primarily to replace steel mesh reinforcement and steel fibre reinforcement. Extensive testing and field experience have shown that the high modulus synthetic macro fibre can be used in lieu of steel mesh or steel fibres in most of the cases.

In addition to the control of cracking caused by either plastic shrinkage, drying shrinkage and/or thermal contractions, the flexural capacity of ground-supported slabs is increased by adding this type of synthetic macro fibre to the concrete. This type of fibre addition to concrete can allow either an increase in the allowable loading of the slab or a decrease in the slab thickness while maintaining the required level of flexural capacity. The synthetic macro fibre can be easily added to concrete production processes. The fibre disperses quickly and efficiently throughout the concrete. Concretes reinforced with the synthetic macro fibre can be placed and finished in the same way as conventional methods. Since the synthetic macro fibre does not corrode and does not create any safety hazard, this technology is an innovative solution to problems related to concrete steel reinforcement in general.
REFERENCES


