# Reinforcement of Concrete and Shotcrete using Bi-Component Polyolefin Fibres

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**Synopsis:** Steel fibres have for many years been a classic fibre reinforcement material for concrete applications, primarily due to the high tensile strength and E-Modulus. However, these fibres have some significant disadvantages: They may corrode, which can lead to structural defects or ugly rust traces, they are stiff which leads to mixing and dosing problems or high equipment abrasion and they are heavy which leads to high transport costs. Furthermore steel production is a high energy demanding process. Low modulus fibres, such as polyolefin based fibres, generally are thought to be less suitable for concrete reinforcement. It can be proven that novel fibre technologies may overcome this drawback. Co-extrusion processes allow economic production of novel Bi-Component fibres. The core of such fibres can be optimised according to mechanical performance demands and the sheath can be optimised leading to an excellent bond to the cement matrix. Polyolefin based Bi-Component fibres used for the mechanical reinforcement of concrete have been developed and the reinforcing potential has been demonstrated by practical field tests, where concrete slabs were manufactured and tested using classical four-point bending tests. First test results of field shotcrete applications are also presented in this paper.

**Keywords:** Bi-Component, fibres, polyolefin, steel, concrete, shotcrete, reinforcement, polypropylene, polyethylene, pull-out

## 1. Introduction

Cement and concrete are relatively strong when subjected to compressive forces, but are not able to take much stress or strain in tension. Therefore methods of improving the tensile properties were investigated many decades back. The obvious method to improve the tensile properties is to incorporate fibres. This was certainly not a new idea as fibre reinforcement of brittle materials dates back many centuries. Possibly one of the most popular fibre reinforced cement products has been asbestos cement. In the late 1970's replacement for asbestos fibres were sought. This was because of the health issues related to asbestos fibres. The asbestos cement industry devoted much research into asbestos replacement materials and many fibre types were investigated. To name just a few: Cellulose, Glass, Kevlar, Carbon, Polyethylene, Polypropylene, Polyacril nitril, Polyvinyl alcohol and Steel.
The asbestos cement industry uses Polyvinyl alcohol combined with Cellulose, as one of the solutions and Cellulose only for autoclaved products. Steel fibres were not used at the very beginning of the research program since the fibres protruded from the thin surface of the composite. As fibre cement is a product, which needs good handling properties, the protruding steel fibres caused damage to the hands of the people erecting the product. The choice of steel fibres was clearly taken from the concrete industry, which in the mid 1970's was successful using steel fibres to improve the tensile properties of concrete. Polypropylene was also looked at in the mid 1980's as asbestos replacement fibres, but was not pursued as the E-Modulus was too low and strain to failure too high. However, 10 years later, much progress had been made with Polypropylene Fibres to improve the E-Modulus and tensile strength. The fibres used on the Hatschek machine in the fibre cement industry are relatively thin (roughly 10 to 25 µm) in diameter where as for concrete applications steel fibres tend to be greater than 150 µm. Low modulus Polypropylene fibres have been used in the ready mix concrete applications for reducing early shrinkage cracking. This fibre also has a small diameter (approx. 20 µm) but does not supply much post 28 day strength properties. With the successful research on improving Polypropylene fibres for the fibre cement industry, researches then started looking at thicker and stiffer Polypropylene fibres as a possible alternative to steel fibres in the concrete industry. The advantage of Polypropylene in concrete slabs is that it does not rust like steel and if it is used correctly, it can supply ductility as well. The problems which had to be overcome for the concrete applications was mixing and flow properties. Therefore when research was started at the Empa on Bi-Component Polyolefin not only the fibre properties were investigated but also the practical aspects of how to mix and distribute the fibres successfully in the

concrete. This paper describes the research programm conducted by Empa on the development of Bi-Component Polyolefin fibres, which covers the choice of a fibre type based on the interfacial bond, design of the optimum core and sheath combination, including surface plasma treatment. The most successful fibre was chosen from the varied tests performed and field test were conducted in order to test their performance in a real environment.

## 2. Bi-Component Fibre Studies

The development of a fibre for the improvement of the post-peak behaviour of concrete includes at first the production of fibres with high tensile capacity and modulus of elasticity. The fibre shall be able to bear in the concrete a high load under tension. Additionally a high modulus of elasticity is necessary so that the cross section is not reduced significantly under load (Poisson contraction) and the bond with the cementitious matrix remains strong. An application of the Bi-Component strategy is a combination, of a core consisting of a high-modulus polymer with a sheath consisting of low-modulus polymer. The main problem with this approach is that high stretch of the filaments are not possible as then a separation of core and sheath is likely to occur. This would lead to low tensile strength of the fibres. Additionally, the relatively weak sheath material would have to guarantee a good bond to the cementitious matrix. Within the scope of this paper, focus was laid on compatible materials based on polyolefin polymer combinations. It is well known, that for thermo-plastic raw materials the following parameters are decisive in order to reach high tenacity at low elongation and high elastic modulus: The polymers must have a low MFR (Meld Flow rate) and a narrow molecular weight distribution. The melt flow rate is a measure for the amount of polymer that flows per time unit through a defined nozzle at a certain temperature and pressure. Furthermore the stretch degree of the filament (after the extrusion) must be chosen as high as possible. It is also known, that fibres with diameters of 0.15 up to 2 mm under mechanical loading tend to fibrillate, which could result in premature debonding in a cementitious matrix. Polymers with a higher melt flow rate MFR and a broader molecular weight distribution show a much more tolerant behaviour during stretching process. This means that the degree of stretching generally is higher. A further positive effect on the fibre properties is reached by the addition of different mineral particles (1, 2, 3, 4) and nano particles (5, 6, 7). Better production conditions are obtained when using a Bi-Component technology. The core polymer may be optimised by designing a high tensile strength and a low elongation at break. For this purpose a Bi-Component fibre with a core consisting of a low MFR polymer and narrow molecular weight distribution and a sheath consisting of a polymer with a higher MFR and a broader molecular weight distribution were manufactured. The stretch process (after extrusion) of such a fibre is optimised regarding mechanical properties, meanwhile the sheath bears high reserves in order to fix the fibre and prevent defibrillation under mechanical loading. In such a fibre the core is optimised regarding best mechanical properties and the sheath provides the best bond to the cementitious matrix.

In laboratory tests it was confirmed that through the addition of 5 to 25 mass-% of fine minerals with a particle diameter <0.01 mm into the polymer, the high strengths values were maintained and the elongation could be reduced. Additionally the modulus of elasticity of the fibres was increased. At the same time the addition of mineral particles lead to a lower Poisson contraction when loaded, which is positive considering the pull-out behaviour.

In this section a comparison has been made between high density Polyethylene fibres (HDPE) and Polypropylene Fibres (PP). The fibres were manufactured with varied diameters and E-Moduli. In addition varied fillers such as micro-glass beads, nano particles and fly ash were co-extruded in the sheath and the core as well. Due to the fact that the number of variables were very large, the choice of the particular variable had to be designed carefully and 12 tailor made fibres were produced for the suitability in concrete applications. The 12 fibre types manufactured are listed in Table 1.

In order to assess the suitability for concrete applications one of the most important tests were performed: i.e. the classic fibre pull-out test well known to fibre reinforced cementitious composites. In cement and concrete applications this is of prime importance, as the load applied to the composite material is transferred via the interfacial bond between the fibre and the matrix.

**Table 1 Varied Bi-Component fibres manufactured**

| Fibre Code | Core / sheath | Diameter µm | Tensile Strength MPa | Elongation at failure % | E-Modulus G Pa |
|---|---|---|---|---|---|
| E | PP / PP + micro glass | 510 | 351 | 15.2 | 4.3 |
| I | HDPE / PP + nano particles | 500 | 496 | 11.8 | 8.9 |
| F | PP + micro glass / PP | 401 | 501 | 10.3 | 5.8 |
| J | HDPE / PP + fly ash | 500 | 510 | 10.2 | 6.9 |
| K | HDPE / PP + fly ash | 500 | 492 | 8.2 | 6.4 |
| L | PP / PP + nano particles | 500 | 625 | 10.4 | 10.4 |
| M | PP / PP | 500 | 598 | 12.0 | 8.4 |
| D | HDPE / PP | 397 | 534 | 15.1 | 8.4 |
| C | HDPE / PP | 388 | 448 | 10.9 | 6.6 |
| A | HDPE 100 % | 350 | 532 | 13.6 | 1.1 |
| H | HDPE / PP | 500 | 532 | 10.2 | 8.7 |
| G | HDPE / PP | 350 | 555 | 9.9 | 9.4 |

The fibre-matrix bond can be measured in many different ways. Typically a single fibre is embedded to a depth L into a mortar or concrete and is pulled out. The resulting load and displacement is measured (8). Relatively large scatter may arise. For this reason, in the described test more than one fibre was embedded in the same manner to a depth L into a mortar. A self compacting mortar with maximal grain size of 4 mm was used in these tests. On the opposite side the fibres were embedded in a block with a much longer embedded length. This provided preferential pull-out to occur at the shorter embedded length matrix block.

After hydration at a certain age both blocks were clamped and then pulled apart with a defined speed (5 mm/min). Simultaneously the resulting load and the displacement were registered. The resulting fibre-matrix bond strength (load per embedded fibre surface area) is calculated, according to standard methods as given in formula 1 below:

$$\tau = \frac{F_{max}}{N 2 \pi r L} \qquad (1)$$

$\tau$ : bond strength (MPa)
N: number of fibres
L: embedded length
r: fibre radius

From these test results it is very evident, that fillers incorporated in the sheath, such as micro-glass, nano particles and fly ash, play a very decisive role in the bond between the fibre and the matrix (Fibres E, I, J, K and L). One exception is where micro glass was incorporated in the core. Here, the mechanism is possibly due to reduced Poisson's contraction. All the other Bi-Component fibres where PP was used as the sheath, the interfacial bond was lower (Fibres M, D, C, H, G). This was also the case for the mono-component HPPE (Fibre A)

The result of these pull-out tests are given in Fig. 1.

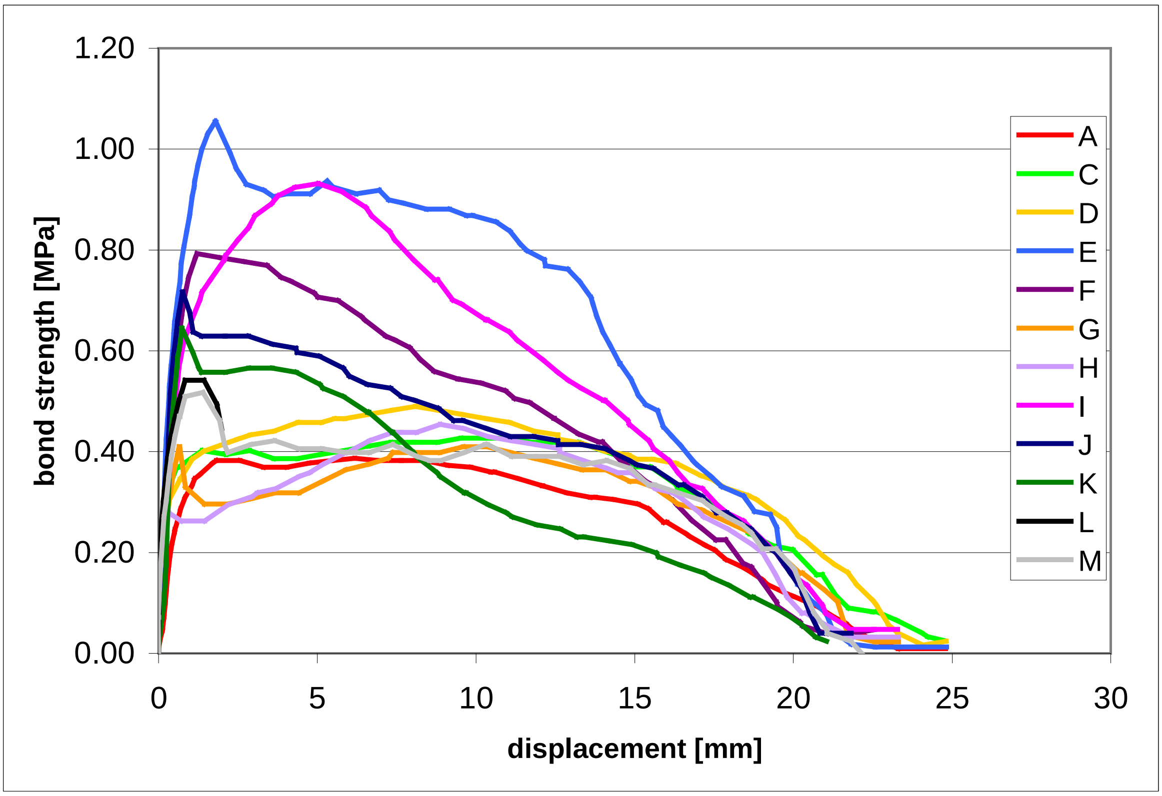



**Fig. 1 Fibre pull-out test – fibre-matrix bond strength (load per embedded fibre surface)**

## 3. Influence of plasma treatment on the fibre-matrix bond strength

The purpose of surface treatment of polymer-based materials is to increase surface wet-ability through electrical discharge. The low surface energy of polymer-based substrates often leads to poor adhesion. To obtain optimum adhesion, it is necessary to increase the surface energy of the substrate to just above that of the material to be applied. Surface treatment with Plasma results in improved surface adhesion properties. The increase in the surface wet-ability is brought about through an electrical discharge. The electrical surface treatment system consists of a high frequency generator, a high voltage transformer and treating electrodes. This system generates the discharge desired for the surface treatment. The plasma treatment with varied process gases can lead to the formation of hydrophilic OH-groups on the fibre surface, which enhance the fibre-matrix bond (9). Victor Li et al have used this technique for improving the bond between Polyethylene fibres and cement and claim to have found an improvement in the interfacial bond. This treatment was also tried on varied fibre types D, E and F, i.e. see:

Fig. 2 Core HDPE / Sheath PP

Fig. 3 Core PP / Sheath PP and micro glass

Fig. 4 Core PP and micro glass / Sheath PP

The improvements for fibre types were significant and certainly confirmed the findings of Victor Li and other researches in this field. However, considering the improvement achieved and the cost of using plasma treatment, it is not considered to be the most economically viable way of improving the fibre-matrix bond. Also the long term stability is questionable.

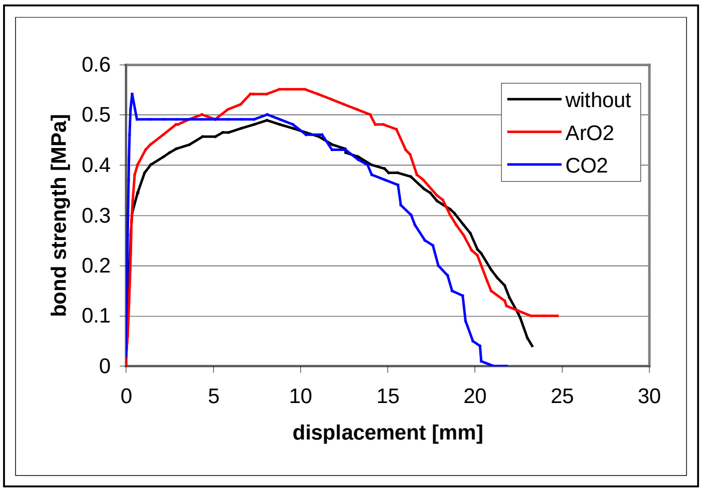



**Fig. 2 Influence of a plasma treatment (different process gases) on the fibre-matrix bond strength of a Bi-Component Fibre (Core HDPE/Sheath PP)**

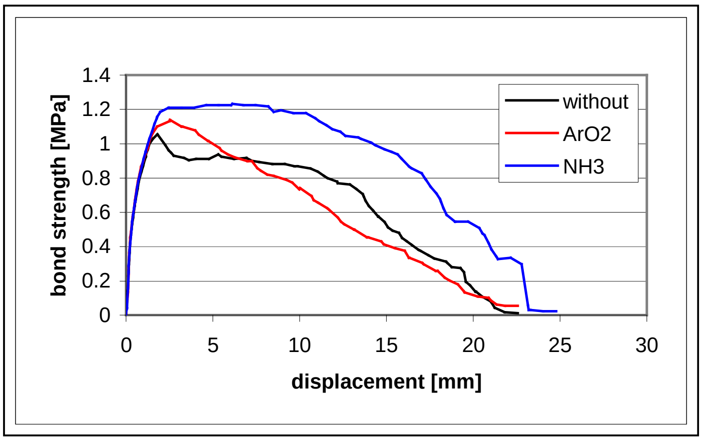



**Fig. 3 Influence of a plasma treatment (different process gases) on the fibre-matrix bond strength of a Bi-Component Fibre (Core PP/Sheath PP and micro glass)**

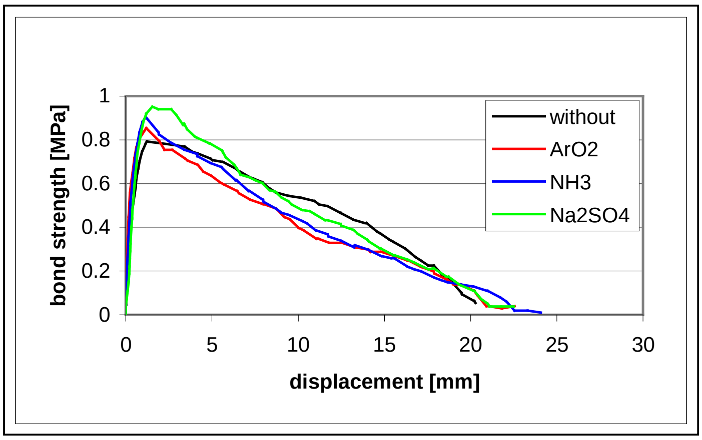



**Fig. 4 Influence of a plasma treatment (different process gases) on the fibre-matrix bond strength of a Bi-Component Fibre (Core PP and micro glass/Sheath PP)**

# 4. Influence of Mechanical treatment to the fibre surface in order to improve the interfacial bond

It was shown in the previous section that fibres with the micro-glass particles in the sheath, provided the highest interfacial bond of all the fibre types tested. This can be related to the rough surface finish on the fibre, which will increase the frictional bond during pull-out. It was also shown in the previous section of this paper that plasma treatment improved the interfacial bond, but with marginal improvements. Therefore the strategy of mechanical surface treatments were considered to possibly be more efficient.
Fibres can be twisted like a Sisal fibre rope to improve the surface finish or by manipulating the surface artificially providing a rough structure (embossing) to the fibres. Using a simple manual embossment method it was demonstrated that bond strength could be improved by 50 %. This was applied to a Bi-Component fibre and led to the manufacture of Bi-Component fibres using a semi-industrial embossment apparatus. The fibres were manufactured on this equipment and the positive results are given in Fig. 5. These results have been taken form a patent which was filed in September 2006 (10), as a result of the work done at Empa Switzerland. A typical example of an embossed fibre is shown in Fig. 6.

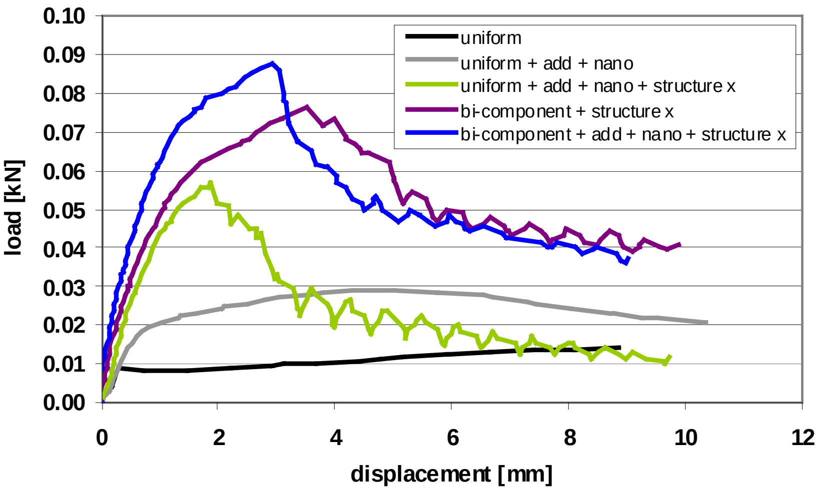



**Fig. 5 Improvement of matrix-fibre bond for Mono-Component and Bi-Component fibres**

Interpretation of the legend in Figure 5:

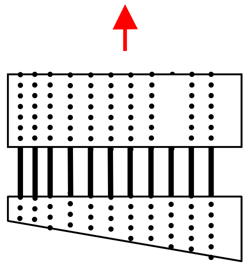
- black: uniform refers to fibres without structure
- gray: fibres without structure but with additives and nano particles
- green: fibres with additives, nano particles and embossment
- purple: Bi-Component fibres with embossment
- blue: Bi-Component with additives, nano particles and embossment

**Fig. 6 Embossed fibres (Structure X)**

From the results given in Fig. 5 it is clear that for the same fibre type (mono-component) the fibre-matrix bond can be improved with additives and nanoparticles, but an even more significant improvement may be found by adding an embossing structure to the fibre. It is also shown that a Bi-Component fibre with the same structure is significantly better again and by simply changing the surface with a structure and including nanoparticles and additives, a very significant improvement in the interfacial bond can be measured.

## 5. Critical Fibre length

In order to optimise the use of Bi-Component fibres in concrete applications, it is necessary to determine the critical fibre length. This value is important as the fibres need to be utilized to their full potential with regard to tensile strength and E-Modulus. Also depending on the application, composite materials can be designed to provide high strength with low toughness or low strength with high toughness properties. Therefore it is important to establish not only the interfacial bond strength, but also critical fibre length, which is the length where the fibre will fracture and not pull-out when the composite is subjected to external loads. It should however be pointed out that the critical fibre length is used for design criteria for the product performance when it is relative fresh (28 days) and also predictions are made for long term aging performance as well. Invariably the interfacial bond in concrete materials improves with aging due to carbonation and therefore the critical fibre length will be reduced as the product becomes older with time. It goes without saying that the fibre mechanical properties and the matrix (cement / concrete) is part of the design criteria as well as this has an obvious influence on the interfacial bond and critical fibre length. The critical fibre length is determined using the classic approach. For this purpose, tension test arrangement is chosen similar to pull-out test procedures, but this time the embedded length is not the same for all fibres. In this test, fibres with an embedded length shorter than the critical length, are pulled-out meanwhile for longer fibres the tensile strength of the fibres is exceeded so that they break apart (see Fig. 7).



$$\tau = \frac{r_f \sigma_f}{2L_c} \qquad (2)$$

$r_f$ = radius

$\sigma_f$ = tensile strength

$L_c$ = critical fibre length

**Fig. 7 Fibre pull-out test arrangement for the determination of critical fibre length**

The critical fibre length for concrete applications using this test for Bi-Component fibres, was measured at 50 mm and for shotcrete application at 38 mm.

## 6. Field tests using Bi-Component fibres

In order to optimise the design of the Bi-Component fibres for concrete applications, laboratory tests were performed on concrete slabs manufactured, using realistic mix designs. These results were subsequently analysed and recommendations were made for field tests. These tests were performed at an independent laboratory. The tests were separated into two applications: 1) Concrete slabs and 2) Spray technology used for tunnel lining. A comparison was made with steel fibres in order to establish the reinforcing potential of the newly developed Bi-Component fibre compared with a conventional system, which is very well established (more than 20 years). This field study was conducted on a typical concrete mix and shotcrete mix respectively used in industry.

| Mix for concrete | Kg / m3 | Mix for shotcrete | Kg / m3 |
|---|---|---|---|
| Cement | 290 | Cement | 400 |
| Fly ash | 60 | Fly ash | 50 |
| Sand 0/1 | 466 | Sand 0/1 | 116 |
| Sand 0/4 | 291 | Sand 0/4 | 958 |
| Aggregate 4/8 | 175 | Aggregate 4/8 | 600 |
| Aggregate 8/16 | 446 | Accelerator | 29.25 |
| Aggregate 16/32 | 563 | Plastizer | 6.3 |
| Plastizer | 4.9 | | |

The steel fibre used for concrete application was Dramix 80/60 (30kg/m3) and the Synthetic fibre used was Fibrofor L 1 50 (4.5 kg/m3), a special Bi-Component fibre with HDPE core and PP sheath with aggregate, nano particles and embossed finish (length 50 mm). For shotcrete applications a steel fibre Dramix 65/35 was used to compare with the Fibrofor L 38. In this case 6 kg/m3 was used for Fibrofor L 38 and 35 kg/m3 was used for Dramix 65/35. It should be pointed out that both tests were performed using the conditions applied in the field and no optimisation programs were conducted. The results should be considered therefore in the light of first-off tests in order to generally assess the capabilities of Fibrofor fibres. Concrete slabs were made with both fibre types and tested according to Swiss standard tests. The test results for concrete application are given in Fig. 8 below:

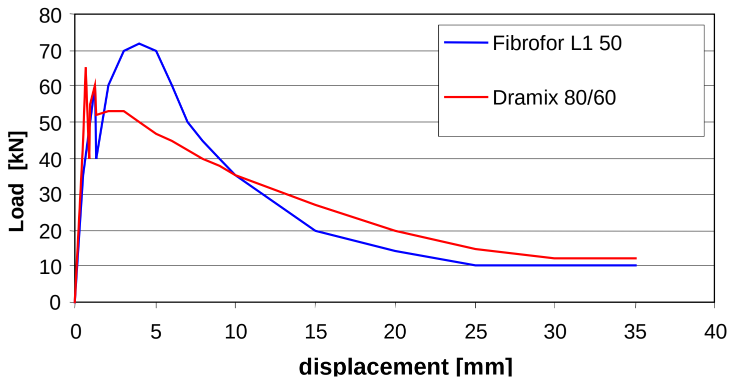



**Fig. 8 Field Tests for Concrete Applications**

Here it is evident that in this particular test the Fibrofor fibres certainly show a good reinforcing potential for concrete application. It should however be pointed out that some of the fibres fractured. This indicated that there is still a lot of potential for optimisation using Fibrofor fibres. Possible options are:

- Change in the concrete mix design
- Optimise the critical fibre length
- Design of the embossment depth according to the concrete mix used

With regard to the shotcrete application, standard procedures were used and an industrial telescope spray equipment was applied. This equipment is standard equipment used in the mining industry for spray application up to 8 m. The mix was designed according to the specification of Empa. Concrete slabs were made by spraying the material into a wooden box, which had the same dimension as the concrete slabs produced for concrete application. Similar bending tests were carried out on these specimens as well (according to Swiss standard specifications; “Swiss Standard SIA 162/6 Testing of Steel fibre concrete 1999”). The application of this mix was very successful. The flow properties and rebound properties of the Fibrofor fibres indicated excellent use of plastic fibres for shotcrete applications. Also the mechanical property tests showed high ductility. In the shotcrete slab tests, however, the fracture surface showed that the majority of the fibres had fractured. The fibre length chosen for this test was 38 mm. This indicated that an even shorter fibre length can be used. This will also be a great advantage with regard to rebound, as it is required that as little rebound as possible should take place in order to utilize the full potential of the reinforcing fibre.

## 7. Summary

It has been reported in this paper that Bi-Component Synthetic (Polyolefin) fibres can be co-extruded to produce varied combinations of sheath and core. The core can be modified to improve the E-Modulus and tensile strength of the fibre and the sheath can be co-extruded using nano particles, glass beads and fly ash. Using the above mentioned additives to the sheath, improvements to the interfacial bond were achieved. It was also shown that the interfacial bond could be improved using plasma treatment to the surface of the fibre. The most successful way of improving the surface bond characteristics of the fibre was using the embossing technique. This mechanical surface treatment resulted in the most efficient interfacial bond strength. Bi-component fibres were manufactured with and without fillers added to the sheath and the best combination was found to be an embossed Bi-Component fibre with additives and nano particles in the sheath. The critical fibre length was determined for this fibre type and produced on a semi-industrial machine. Sufficient fibres were produced for laboratory tests and field tests. The results from the field tests for concrete and shotcrete applications indicated that Bi-Component Polyolefin fibres can be used successfully as an alternative to steel fibres. The field tests should be regarded as preliminary tests as there is a large potential for optimisation when using Bi-Component fibres.

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