Advanced design methodologies for steel fibre reinforced concrete and new methodology of real time quality control

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Abstract. Steel fibre reinforced concrete has developed over years for the use in structural applications. The material itself has undergone development into higher performing steel fibre types and thus into higher performing steel fibre concretes. Whilst in regards to standards the development went from recommendations into building codes the way of designing – linear elastic design methods or yield line theory – and the way of quality control seemed to remain unchanged from the past. This paper shall emphasize the recent development in a design tool that enables a non-linear design methodology and a new advanced way of real time quality control.

1. Introduction

Steel fibre reinforced concrete (SFRC) is a composite material that provides post crack strength to concrete. With the publication of Model Code 2010 and various national standards, advanced guidelines for the design of SFRC for structural applications are available. During the last decade steel fibres are increasingly being used in structural applications, e.g. rafts, segmental tunnel linings, pre-stressed beams or even elevated slabs. Depending on the actual application, steel fibres may act as the sole reinforcement or may be combined with traditional concrete reinforcement. Typically the plasticity theory is used to work out the capacity of steel fibre reinforced structures. Meanwhile non-linear design methodologies are integrated into software that allows for a very accurate calculation of the material contribution. Due to more optimized design calculations and the increasing use of SFRC in structural applications, quality control has gained additional importance. Beam testing is one possibility for performance verification but is not always preferred due to effort and variation of results. Therefore alternative quality control methods have been developed, based on the combination of initial beam testing and focus on process control. An ideal solution to measure fibre type, amount and distribution over a full truck load with a measuring device will be one main focus of this paper.

2. Material development

Steel fibres increase the ductility of the concrete by bridging cracks and transferring tensile stresses over these cracked zones. Knowing that national codes are under development and the intention to integrate SFRC as structural reinforcing material into Eurocode 2 were trigger to increase physical performance of steel fibres. Many different parameters influence the performance of the steel fibre concrete: the tensile strength of the steel wire, fibre shape, ductility of the wire, the dosage of steel fibres and the concrete quality. The newly developed Dramix® steel fibres, the families 4D and 5D, are especially designed to reinforce structural concrete elements.

The main difference between the 4D/5D family and the 3D family is the significantly increased performance in serviceability limit state (4D) and ultimate limit state (5D). The combination of type of anchorage (more end hooks), stronger wires (up to 2200 MPa) and more ductile wires (up to 7% of elongation) are key in this increased performance. The tensile strength of a steel fibre has to increase in parallel with the strength of its anchorage. Only in this way can the fibre resist the forces acting upon it.

This development of steel fibres has been applied some years back and high performing fibres are used for structural applications.

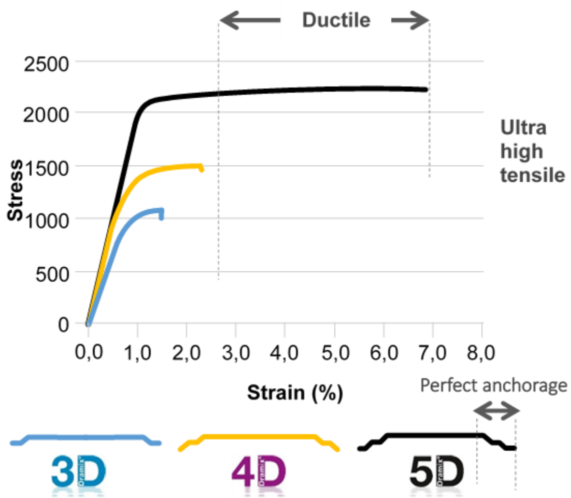

Figure 1. Yield strength and strain capacity of the wire used for the different steel fibre types.

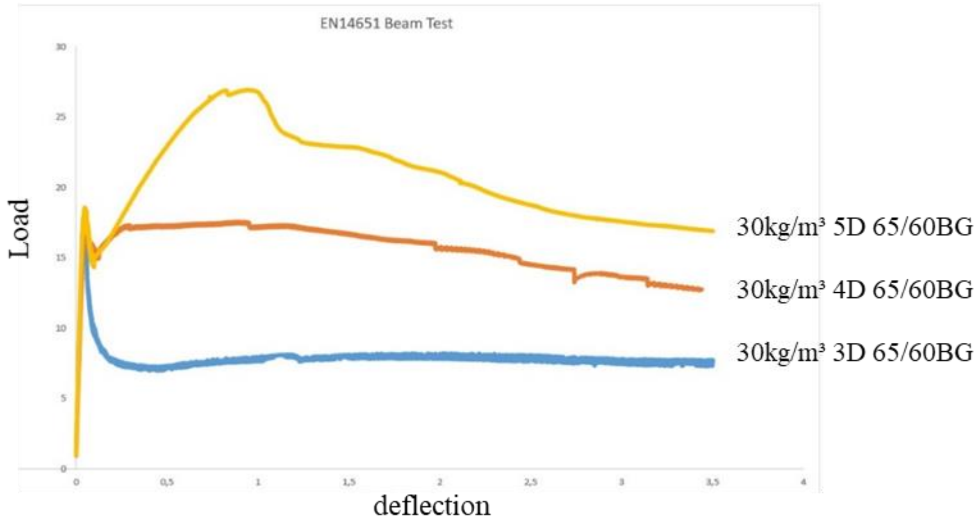

Figure 2. Beam test curves with each 30kg/m³ dosage rate. 3D and 4D steel fibre type with typical strain softening behaviour, 5D steel fibre type with bending hardening behaviour.

3. Development of codes and standards

Steel fibre reinforced concrete has been subject of much research over the last 40 years. In line with the knowledge built up, guidelines and standards developed gradually.

In the early 1980's, the SFRC test standards – JSCE-SF4 and ASTM C1018 – were in place and widely used. The performance was described as "flexural toughness" and represented the energy dissipation. Actually, the EN14651 is the test standard mostly used in Europe, but also widely accepted outside Europe. The performance of the SFRC expressed directly in flexural post crack stresses at specific crack mouth openings.

The first design guideline was published in 1995: "Dramix Design Guideline". This document contained the first basic design rules in order to design concrete structures with steel fibres. This document was a result of a cooperation between N.V. Bekaert S.A., the Belgian universities KULeuven and UGent and the Belgian building research institute WTCB.

A deeper investigation was done by a group of international universities brought together by RILEM (RILEM TC162-TDF, 2003) [5]. This cooperation resulted in a test and a design method worked out and fully backed-up by theory and experiments. Also overseas, in 2008, ACI 318 incorporated steel fibres as a structural element to take up shear forces in concrete elements. Different countries (e.g. Germany, Sweden and Italy) also published in the meantime national design guidelines and/or codes, often as an add-on to EN1992-1-1.

A new milestone in 2014 was reached when the final version of the Model Code 2010 was published. Steel fibres were fully incorporated in this state-of-the-art concrete design guideline. This document was also the trigger for the launch of TC 250/SC2/WG1/TG2 (CEN); this task group works on the integration of steel fibres into the future EN1992-1-1.

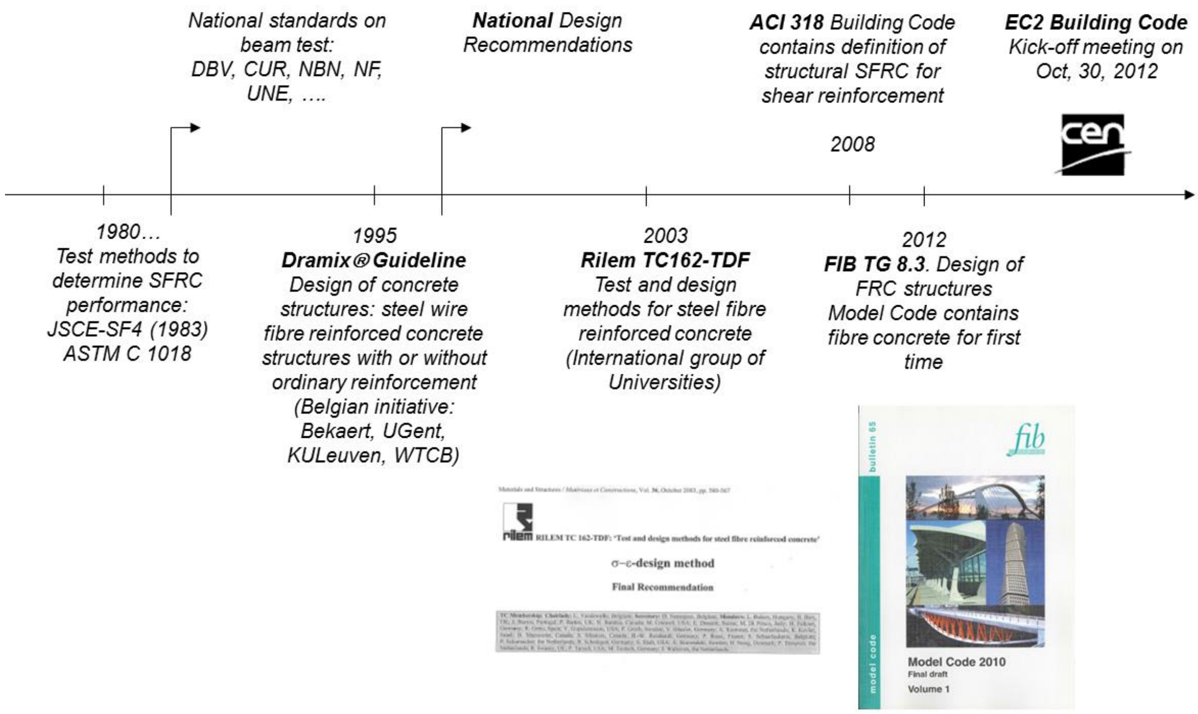

Figure 3. Evolution of SFRC test and design standards from 1980 to present.

4. Design approach and software development

In the available standards, the constitutive laws of SFRC are available as basis for the design. The results of the initial type testing are used for deriving the section capacity according to the sigma-epsilon diagram. Based on this, all section capacities are worked out. Until then, software tools to make use of the section capacity under bending/shear/punching and for a crack width calculation in a design were still in backlog. Meanwhile some relevant development has been undergone to provide design tools.

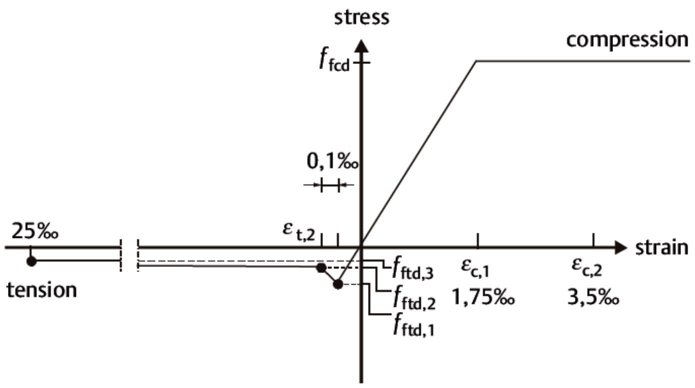

Figure 4. Stress-strain diagram of steel fibre reinforced concrete (design values for strength).

4.1 Bending resistance

The bending moment capacity of steel fibre-reinforced section can be calculated for a cross-section with or without axial force based on the following assumptions

- Flat cross-sections remain flat.
- The strain distribution is aligned with the strain distribution of reinforced concrete.

In order to calculate the cross-section bending moment capacity, the static equilibrium needs to be determined. Figure 4 schematically represents the relation between stresses and strains.

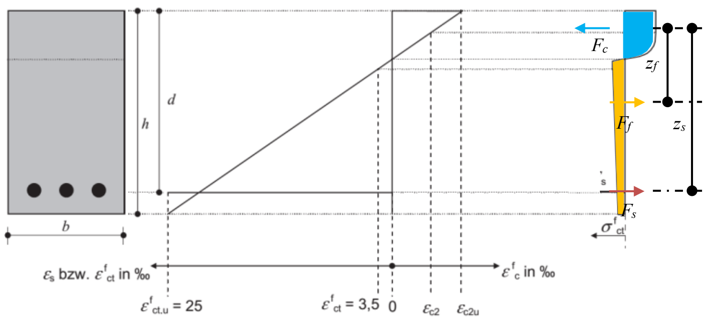

Figure 5*:* Static equilibrium of the cross section under bending.

With the calculation tool: Dramix® Pro Moment Capacity, the bending moment capacity of SFRC only or combined reinforcement can be calculated.

4.2 Shear and punching resistance

The effect of the steel fibres in shear and punching resistance is taken into account by an additional component in the equations. Steel fibres act like a shear reinforcement over the entire cross section of the structure. The shear capacity of the element increases as a function of the performance of the steel fibre concrete used. This can lead to a significant reduction or elimination of conventional shear reinforcement. [3] takes the increased shear resistance due to steel fibre concrete into account by introducing an additional element $V_{Rd,cf}$ into the equations for conventional shear design.

$$V^f_{Rd,c} = V_{Rd,c} + V_{Rd,cf} \text{ (without conventional shear reinforcement)} \quad (1)$$

$$V^f_{Rd,s} = V_{Rd,s} + V_{Rd,cf} \leq V_{Rd,max} \text{ (with conventional shear reinforcement)} \quad (2)$$

Dramix® Pro Shear Capacity is able to calculate the capacity of the section for shear or punching shear.

4.3 Crack width calculation

The design corresponds to the method for reinforced concrete in EC2. Following the DAfStb-Richtlinie, the rules of EC2 are amended by the post crack tensile strength provided by the steel fibre concrete. This is done by introducing the factor α_f as the ratio of the post crack tensile strength over the first crack tensile strength. The basic principle is that due to increasing post crack strength the released force at crack formation decreases. As consequence, the reinforcing steel needs to transfer only a reduced force back into the concrete. The strain in the reinforcing steel, as well as the required transfer length, is reduced.

$$w_k = s_{r,max} \cdot \left(\varepsilon_{sm}^f - \varepsilon_{cm}\right) \tag{3}$$

$$s_{r,max} = \left(1 - \alpha_f\right) \cdot \frac{d_s}{3.6 \cdot \rho_{p,eff}} \leq \left(1 - \alpha_f\right) \cdot \frac{\sigma_s \cdot d_s}{3.6 \cdot f_{ct,eff}} \tag{4}$$

$$\varepsilon_{sm}^f - \varepsilon_{cm} = \frac{(1-\alpha_f)\cdot\left(\sigma_s - 0.4 \cdot \frac{f_{ct,eff}}{\rho_{p,eff}}\right)}{E_s} \geq 0.6 \cdot \left(1 - \alpha_f\right) \cdot \frac{\sigma_s}{E_s} \tag{5}$$

The use of steel fibres can significantly decrease the required amount of reinforcing steel. By defining the normalized ratio of α_f based on the 28-day strengths and by subsequently multiplying it with$f_{ct,eff}$, the fibre effect is aligned to the concrete age at the time considered for the design. The tool Dramix® Pro Combi Slab calculates the mean value of the crack width under the chosen condition.

4.4 Software development

Software tools based on Excel programs for applications like slab on ground, slab on piles, raft foundations are available and meanwhile further developed.

A new milestone in terms of software integration for SFRC is achieved in cooperation between SCIA and Bekaert. SFRC is integrated in a Finite Element Method tool that enables the design for SFRC or combined reinforcement in both methods, linear-elastic and non-linear. This development gives the engineer the opportunity to design quickly with steel fibre concrete or with a combination of steel fibre concrete and traditional reinforcement. The methodology of non-linear design is regulated in EC2 and applies also to SFRC as it is suitable to the material behavior of SFRC.

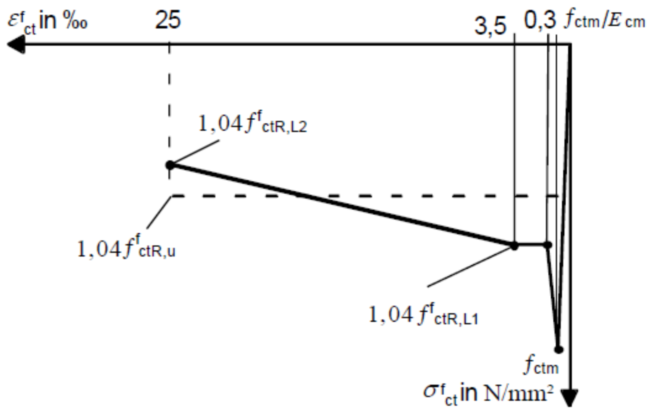

Figure 6. Stress-strain diagram for non-linear design methodology proposed in [3].

Non-linear design method is a very complex and detailed design methodology that engages the entire concrete member behaviour considering the stiffness change in each deformation state and for each crack opening in every face of the concrete member. That enables a simulation of real material behaviour at different crack phases. Those design methods need intensive verifying in order to ensure the rightness of results for such a design methodology. The following picture shows the comparison between a large scale test (real case), an elevated slab that was accordingly loaded and stresses and cracks were monitored and evaluated and between a result of a design using the non-linear methodology of that software solution. The result difference with approx. only 2.38% proofs the extremely high conformity between full scale test and design outcome and thus the optimisation and the projection of the actual material behaviour.

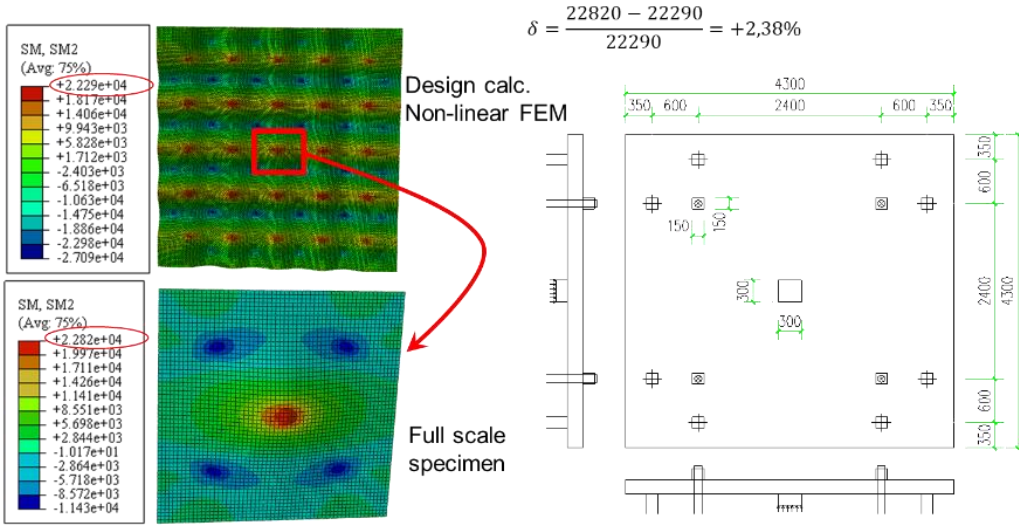

Figure 7. Comparison between full scale test and SCIA non-linear design methodology for SFRC.

5. Quality control system for SFRC

5.1 Introduction

Two main approaches for quality control (QC) of steel fibre concrete can be distinguished:

- Direct verification of the residual strength by testing
- Indirect verification of the residual strength by process control

5.2 Verification of residual strength based on beam testing

One way to check the residual strength of the delivered steel fibre concrete is beam testing. The defined number of specimens is cast on site at a defined sampling frequency. The residual strength is determined in the laboratory later on, typically at the age of 28 days. The test results can then be compared to the specified limits and tolerances.

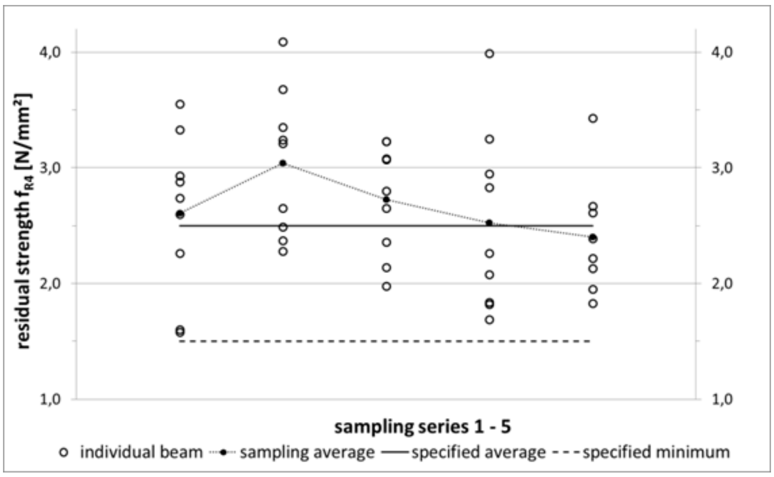

Figure 8. Results from in situ sampling.

In this example for each sampling series 9 beams were randomly taken over the volume of the truck mixer. The residual flexural strength was determined in accordance with EN 14651.

When comparing individual f_{R4} values (circle) to a specified minimum values (dashed line), all samples pass the specific requirement of (in this case) 1.5 N/mm. Alternatively the average values of each series (full dot) could be compared to a specified average value (full line). In that case, series 5 would not pass the requirement of (in this case) 2.5 N/mm. Corrective actions would be required.

5.3 Verification of residual strength based on process control

Another way to ensure that the residual strength of the delivered steel fibre concrete is conforming to the specified residual strength is a combination of initial type testing (ITT) and process control.

This concept is already applied in [3] which is a national amendment to EN 1992-1-1 on code level for the design and execution of steel fibre reinforced concrete structures. The process control concept accepts that for the same concrete mix design the residual strength will not change, given that the same constituents are used and are properly mixed, the compressive strength of the concrete stays within the limits and the right amount of the right fibre type is evenly distributed throughout the mix. From that moment onwards, the concrete composition and its constituents are not changed anymore and full focus is on controlling the process from constituents to delivery. The correct fibre type can be easily identified by the delivery papers and quality labels. The correct dosage can be ensured by using automatic dosing systems or counted number of required packaging units. Finally it has to be verified that the fibres are homogeneously distributed throughout the concrete. Wash-out tests can be used to verify the fibre distribution. [3] suggests taking 3 samples over the concrete volume of about 10 litres each. Individual samples should not contain less than 80% of the specified dosage. The average should not be less than 85% of the specified values. In Table 1 wash-out results taken from 6 different truck loads are presented. All results comply with the limit on the average value (-15%). However, the third sample of truck 1 misses out on the individual limit (-20%). In this case, corrective actions could be initiated as soon as the results for truck 1 were available.

Table 1. Results from in situ wash-out tests.

Truck	$m_{f,1}$	$m_{f,2}$	$m_{f,3}$	$m_{f,average}$
truck 1	13%	4%	-26%	-3%
truck 2	3%	-17%	26%	4%
truck 3	9%	-11%	0%	-1%
truck 4	-12%	-4%	1%	-5%
truck 5	9%	-2%	10%	6%
truck 6	16%	-10%	6%	4%

5.4 Assessment of the quality control principles

Both quality control approaches are suitable methods to ensure the quality of SFRC. Practical experience is available as well as national standards [3]. The advantage of the material property based approach described in section 5.1 is the direct verification of the residual strength which is delivered on site. One major disadvantage is the time which has to pass until the beam test results are available. The process control approach described in section 5.3 allows for much shorter reaction time. If required, results from wash-out test can be available within a couple of hours. Although there is no confirmation of the residual strength, the mix design in combination with the compressive strength testing closes that gap. However, this approach requires detailed procedures and relies on well-controlled constituents.

5.5 Methods to determine homogeneity in fresh concrete
Whatever quality control approach is applied, a homogeneous fibre distribution is crucial. Wash-out test methods are available to verify this in fresh concrete and are an established and feasible method to determine the fibre amount and fibre distribution. Results can be available within a couple of hours. They are already implemented in standards like EN 206-1 / EN 14721 and [3]. As this methodology is regulated and applied since long, further introduction into the principles are not within the scope of this paper.

Figure 9. Wash-out test using pipe magnet.

Despite the fact that wash-out tests are rather simple to execute, a certain effort is required and only a small volume can be assessed. Still quite some time passes before a possible need of corrective actions is identified. It is obvious that wash-out can only provide a snapshot of the real situation.

6. New quality control system for SFRC: “Real time” quality control: eyeD®

The construction industry is advancing. Production processes are optimized and smart solutions are now being used to monitor both production and execution. In that context, beam tests or wash-out tests can hardly be integrated in a process driven, smart environment. The resolution of these test methods is small and immediate results cannot be obtained. An automated real time quality control system would be the ideal solution, both in terms of process integration as well as quality assurance.

6.1 EyeD® measuring device
NV Bekaert SA has developed the eyeD® measuring device – which

- allows for the quality control of steel fibre concrete in real time
- can be configured to determine fibre type, amount and distribution
- can be linked into the production and quality control processes
- operates mostly automatically
- allows remote access of results

Figure 10. eyeD® system connected to the chute of a truck mixer.

The eyeD® is connected to the truck mixer (Figure 10) by an adjustable interface and should fit all major truck mixer types. The concrete flow is continuously determined through regular ultrasound height sensors and especially developed speed sensors. The variation of the fibre's electromagnetic response is measured and plotted as a deviation from the mean value. Results can be accessed as soon as the unloading process has finished. This can be done with any WiFi-capable device right on site. Furthermore, the eyeD® is equipped with a GSM module which transfers the data to a central server. It is accessible from any internet connected device as long as there is a GSM connection on the jobsite. The eyeD® provides instantaneous quality data in real time. Corrective actions can be taken immediately.

6.2 Measurement results

More than 100 truckloads have been examined with the eyeD®. Figure 6 shows a typical example of a homogeneous mix, expressed in relative values for both fibre dosage and concrete volume.

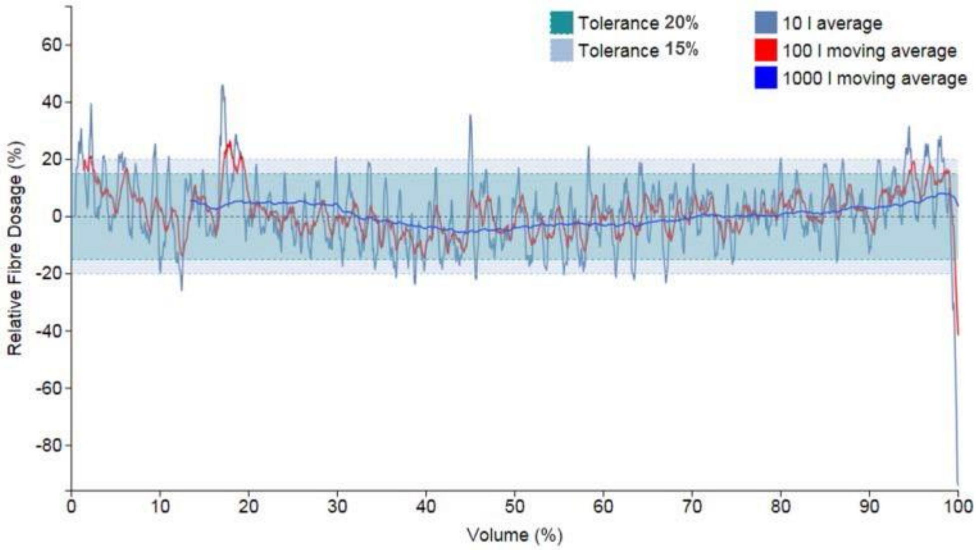

Figure 11. eyeD® measurement result: homogeneous fibre distribution.

The measured data can be processed to match different sample sizes. Moving averages of e.g. 100 litres and 1000 litres allow for an improved interpretation of the fibre distribution. In Figure 12 an insufficient fibre distribution is shown. The fibres were dosed right into the truck mixer using a conveyor belt. However, the required additional mixing time after fibre addition was not met. Additional concrete remixing before pouring did not take place. The result on fibre distribution could be figured out immediately with the eyeD® device.

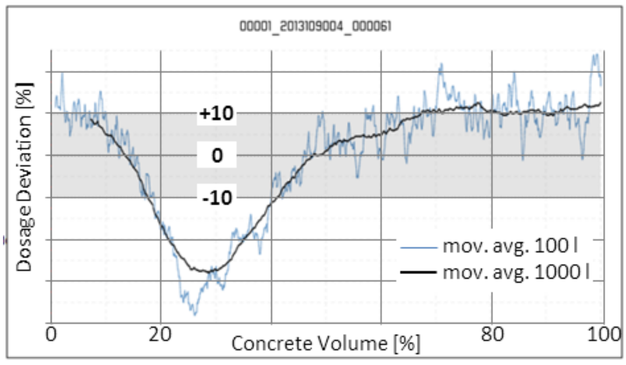

Figure 12. eyeD® measurement result: inhomogeneous fibre distribution due to insufficient mixing time.

6.3 Interpretation of results

The eyeD® system allows for full and detailed monitoring of the steel fibre distribution for the whole truck load. Therefore it is possible to judge the homogeneity of the complete concrete volume. Peaks can be identified as peaks and trends can be identified as trends. Even if individual data points plotted with a 10 litre resolution should not meet the tolerance limit defined for 10 litre wash-out samples (e.g. –20%), the whole truck load can be judged and the result can be put in perspective. Based on the measurements done with the eyeD® system so far, it appears that a moving average of 100 litres and a moving average of 1000 litres allow for a more appropriate judgement on the homogeneity.

6.4 Summary

The eyeD® system allows for a full assessment of type, amount and distribution of steel fibres in steel fibre reinforced concrete. The measuring device is attached to the chute of a truck mixer so that the full truck load can be assessed. Results are delivered in almost real time, as soon as unloading is completed. Access via local WiFi or remotely via the internet is possible so that immediate actions can be triggered in case the measurements should not comply with the specifications.

7. Conclusion

Steel fibre concrete is a material that has developed from use in minor applications to the use for structural applications, steel fibre only or combined reinforcement. Guidelines and recommendations have evolved into national standards and codes. Next version of EC 2 intends to subject SFRC for structural concrete too. Design methods, design tools are further established and also the quality control is going to developed more and more in a smart way.

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