# GLASS FIBER REINFORCED CONCRETE FOR SLABS ON GROUND – MATERIAL CHARACTERIZATION AND APPLICATION

LÖBER Philipp[1], HEIDEN Björn[2], HOLSCHEMACHER Klaus[3], BARRAGAN Bryan[4]

## Abstract

*The use of fibers as an alternative to steel welded wire mesh and rebars is today an extended practice for the reinforcement of concrete floors, but even when the use of fibers as only reinforcement for slabs on ground can lead to a highly improved productivity, simpler execution, increased durability, etc., the share of fiber reinforced concrete (FRC) solutions is still very limited with respect to its potential.*

*This paper presents a characterization of concrete reinforced with innovative glass macro-fibers (length= 36 mm, equivalent diameter= 0.54), in terms of workability and flexural tension response. It also discusses the appropriateness of the behavior for highly indeterminate structures such as slabs on ground and presents case studies showing the convenience of the material for such type of applications.*

*It is observed that the relatively high post-cracking performance provided by glass macro-fibers at low crack openings is especially convenient for highly indeterminate structures such as floor slabs, where the ultimate capacity involves very low crack openings (usually below 0.5 mm). New design codes (i.e. the fib Model Code 2010) allow taking into account these specific material and structural behaviors, leading to competitive FRC floor designs.*

**Keywords: Structural Concrete, Glass Fiber Reinforced Concrete, Slabs on Ground, FRC, Model Code 2010**

## 1. Introduction

Currently 70% of all FRC applications in Germany are industrial floors [1], whereas FRC floors only represent an approximately 30-40% of the overall floor market [2] (with a

[1] LÖEBER Philipp, Institute of Concrete Construction, HTWK, University of Applied Sciences, Leipzig, Germany, Karl-Liebknecht Straße 143, philipp.loeber@htwk-leipzig.de

[2] HEIDEN Björn, Institute of Concrete Construction, HTWK, University of Applied Sciences, Leipzig, Germany, Karl-Liebknecht Straße 143, bjoern.heiden@htwk-leipzig.de

[3] HOLSCHEMACHER Klaus, Professor and Head of the Institute of Concrete Construction, HTWK, University of Applied Sciences, Leipzig, Germany, Karl-Liebknecht Straße 132, klaus.holschemacher@htwk-leipzig.de

[4] BARRAGAN Bryan, Global Technical Leader and Program Manager, Owens Corning, Chambéry, France, 767 Quai des Allobroges, 73000 Chambéry, France, bryan.barragan@owenscorning.com

major presence of steel fibers competing with different types of polymer fibers). Hence, besides the clear possibilities to grow the use of FRC in other applications, there is still a big potential for the case of slabs-on-ground.

One of the reasons of this situation has been the inexistence of general international design guidelines and/or the semi-empirical and over-conservative characteristics of existing design approaches that lead to uncompetitive FRC solutions. This inconvenient state of affairs for FRC has been remediated up to a large extent by the new fib Model Code 2010, MC 2010 [3–5]. Regarding, specifically, FRC design, the fib MC 2010 introduces an open and performance-driven approach, through a rational use of the actual material response.

All over the world, alkali-resistant (AR) glass is and has been during more than four decades the preferred reinforcement for high performance cementitious composite used in very thin precast elements (panels, small diameter pipes, cladding, roofing, etc.). This glass fiber reinforced concrete, known as GRC, is rather a fine mortar that incorporates relatively high or very high dosages (3 – 5 Vol.-%) of short and integral AR glass fibers (12 – 50 mm) [6, 7]. Mainly because of the specific matrix compositions and processing techniques of GRC (sprayed or cast), the use of these composites has not been extended to larger structural elements.

AR glass macro-fibers (integral fibers with equivalent diameter 0.5 – 0.6 mm) are the most recent development in glass fibers for concrete reinforcement. Following several years of successful application, the mechanical contribution of these fibers have proved sufficient to be considered as primary reinforcement in load-bearing ground-supported slabs.

AR glass fibers have a total affinity with the cementitious matrix, high strength and modulus of elasticity, density similar to the aggregates (i.e. no segregation), flexibility, and high dispersal. In terms of mechanical performance, the significant post-cracking performance provided by glass macro-fibers at low crack openings is especially convenient for highly indeterminate structures such as floors, where the ultimate capacity involves very low crack openings. Interestingly, the MC 2010 design approach allows taking into account these specific material and structural behavior, leading to competitive FRC floor designs.

## 2. Material characterization

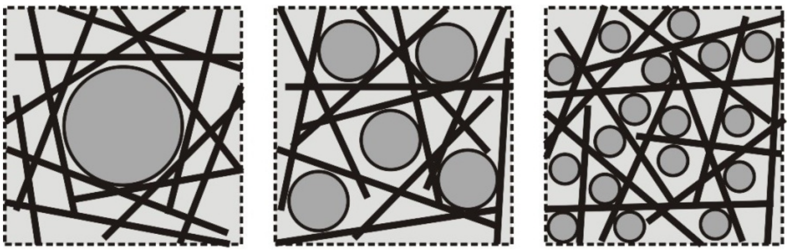
Structural glass fiber reinforced concrete uses short, integral, alkali-resistant glass-macro-fibers with a length of 36 mm and an equivalent diameter of 0.54 mm. Material properties are shown in Tab.1.

Tab.1: Material properties of the used glass fibers Anti-Crak HP 67/36

| | | | |
|---|---|---|---|
| Length | [mm] | 36 |  |
| Equivalent diameter | [mm] | 0,54 | |
| Density | [g/cm³] | 2,68 | |
| Tensile strength (filament) | [N/mm²] | 1700 | |
| Modulus of Elasticity | [N/mm²] | 72000 | |
| Ultimate strain | [%] | 2,0 | |
| Electrical conductivity | [-] | Very low | |
| Chemical resistance | [-] | Very high | |
| Zirconium oxide | [% by weight] | > 16% | |

Glass macro-fibers do not corrode and are flexible, which reduces the risk of harming in case of near-surface fibers and supports the concrete very well during setting, reducing the risk of shrinkage induced cracking at early age. With their length of 36 mm these fibers are also able to bridge visible cracks up to a certain extend resulting from external loads.

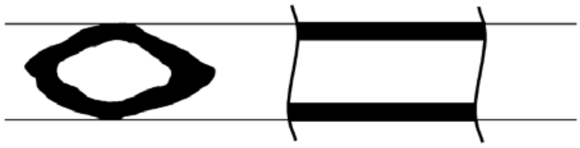
The used base concrete matrix can be considered typical for slab-on-ground applications. Concretes for structural use need to have at least a maximum aggregate size of 8 mm according to EN 206 [8]. For slab-on-ground applications, to ensure proper load transfer, reduction of shrinkage and less water demand, it is recommended to use a higher maximum grain size of 16 mm. Fibers are mixed as one more concrete component and are homogeneously dispersed in the concrete mass during the mixing process.-Although bigger grain sizes reduce the uniformity of fiber distribution (see Fig. 1) this effect can be neglected with larger dimensions of the member, as it is usual in structural applications, where fibers are considered uniformly distributed throughout the member, with a random and 3D orientation.



(a) 20 mm Grain (b) 10 mm Grain (c) 5 mm Grain

Fig. 1: Fiber distribution and orientation depending on different grain sizes [9]

Given the total affinity between the AR-glass fibers and the cementitious matrix (adherence), no deformation/ embossment is necessary to increase the bond of the fiber to the matrix. This bond is characterized by the so called 'fill in-zone' [10]. This zone represents the outer filaments of the fiber, which are penetrated by the cement/binder paste, whereas the inner filaments are considered as binder-free.



(a) fiber cross section (b) longitudinal section

Fig. 2: Fill in-zone [10]

Cement particles are in most cases too big and are filtered by the filaments, which have a distance of a few μm between each other. On the other hand much smaller hydration products of the cement and water can penetrate filaments up to a certain extend building punctual bridges or connections with limited lengths [10]. Hence, the fiber design is straight with a rather elliptical cross section improving the specific surface. This entails a fast dispersion of the fibers during the mixing process, finally meaning that very short mixing times are required for an entirely homogeneous distribution of the fibers in the concrete mix. It is suggested to add the glass fibers after properly mixing all other component materials, i.e. once the mixing of the base concrete is complete. Generally, it is recommended to mix the fibers less than 1 minute in central batching plants and 2-3 minutes fast speed mixing in concrete trucks once all other component materials have been mixed and additives have been added. Even if rarely observed, this short mixing time also avoids the damage of fibers that could possibly take place under a critical combination of mixing sequence and mixing time, angular characteristics of the coarse aggregate and low workability class.

## 3. Mix designs and fresh properties

The aim of investigations at the University of Applied Sciences Leipzig was to develop structural glass fiber reinforced concretes for use in foundations of houses and industrial floors. The structural concrete was developed in accordance with EN 206 [8] following exposition classes XC2, XF1 for case 1 (houses) and exposition classes XC4, XD3, XF4, XM2 for case 2 (industrial floors). Mixture 1 represents lower demand with a target strength class of C25/30 and a maximum water-binder ratio of 0,6 whereas mixture 2 is a C30/37 with a maximum $w/c_{equ}$ of 0,45. Tab.2 shows different versions of these compositions variating amount of mortar in order to improve workability when adding fibers.

Tab.2: Variation of mix compositions 1 and 2

| **Mixture** | **1** | **1a** | **1b** | **1d** | **2** | **2a** | **2b** | **2c** | **2d** |
|---|---|---|---|---|---|---|---|---|---|
| Cement, [kg/m³] | 320 | 350 | 350 | 360 | 340 | 350 | | | |
| $w/c_{equ}$ [-] | 0,58 | 0,55 | 0,55 | 0,6 | 0,45 | | | | |
| Fly ash, [kg/m³] | 80 | 80 | 80 | 90 | 60 | 90 | | | |
| Aggregates | [% by volume] | | | | [% by volume] | | | | |
| Sand 0/2 | 36 | | 40 | | 36 | | 40 | | |
| Gravel 2/8 | 32 | | 20 | | 32 | | 20 | | |
| Gravel 8/16 | 36 | | 40 | | 36 | | 40 | | |
| Superplasticizer (PCE), [% by weight of cement] | 0,2 | 0,2 | 0,2 | 0,2 | 0,8 | | | | 0,9 |
| Air-entrainer, [% by weight of cement] | 0 | 0 | 0 | 0 | 0,2 | 0,2 | 0,3 | 0,35 | 0,32 |

The following chart gives an overview about the influence of water/cement-ratio and amount of mortar on the flow spread and thus the workability class (F1 “stiff” to F6 “very fluid”, see Flow table test, [11]). As usual, the effect of fiber reinforcement on workability will in any case depend on the characteristics of all concrete component materials, mix proportions, and workability class. The flow spreads have been taken 5 minutes after mixing and 30 minutes later. It is visible that the addition of 7 kg/m³ has nearly no impact on the workability. With increasing amount of paste (cement, fly ash and thus more water), the workability can be increased significantly. When comparing mixture 1 without and 1a with 7kg/m³ fibers, it can be seen that the workability is better, even with a lower water/cement ratio and fibers. Because of their high specific surface, the fibers bind cement paste, which together with the effect of their slenderness; can give place to a less workable mix with a “stony” aspect (a typical effect of all types of fibers). This situation can be prevented or reduced by increasing the amount of mortar. For this reason, variations b and d contain 4% more sand, while the amount of 2-8 mm was reduced. This change of increased sand volume resulted in lesser workability, due to higher water demand, but much better homogeneity while reducing the chance of bleeding. When pumping the concrete to the site, a homogeneous mix is mandatory. At least a minimum workability class F3 (42 mm, “soft”) is preferred, whereas a higher amount of paste can reduce the wall skin friction between pipe and concrete [12]. The positive effect of higher contents of mortar and water/binder ratio can be seen very significantly when comparing mix 1 and 1d, both with 20 kg/m³ fibers.

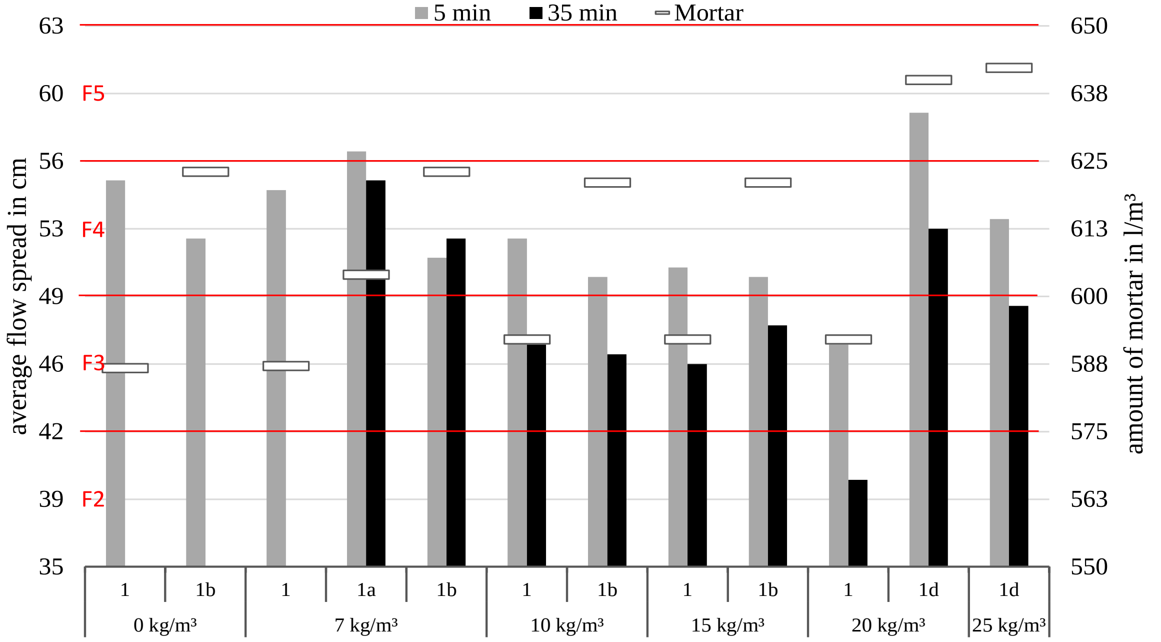



Fig. 3: Flow spreads of mixtures 1 with a strength class of C25/30

Fig. 4 shows the same chart for mixture 2 (industrial floor). In this case, the effective water/binder ratio was constant at 0.45 resulting from restrictions of the exposition classes. The findings from mixture one are also applicable on air entrained concrete. Significant is the direct dependency between amount or mortar and flow spreads after 35 min. The workability also becomes better with higher air content as the air volume is part of the amount of mortar.

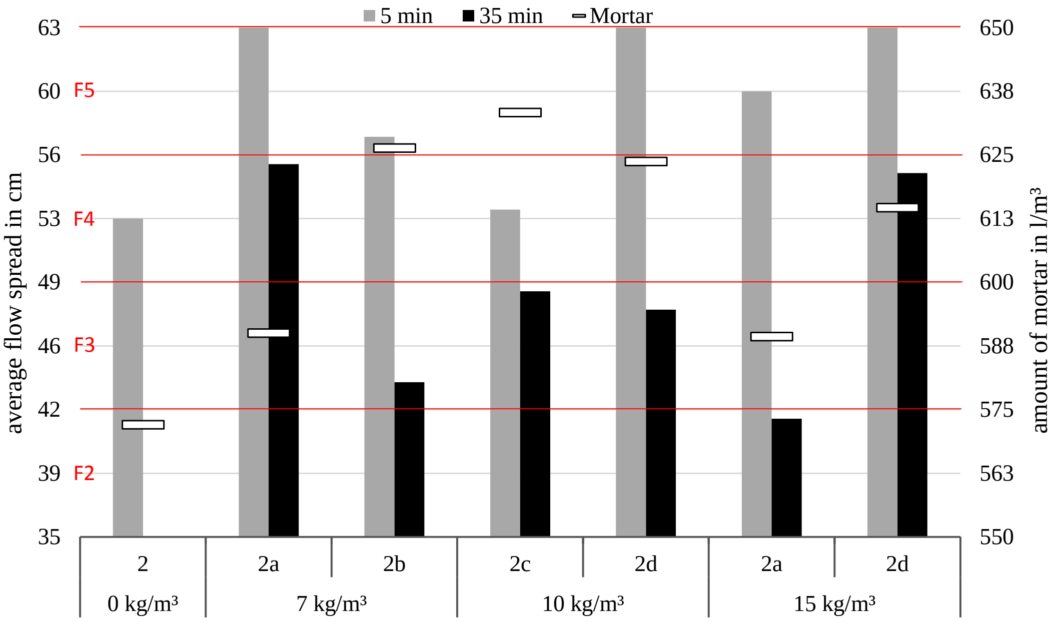



Fig. 4: Flow spreads of mixtures 2 with a strength class of C30/37

## 4. Design of FRC floors

As summarized in [13], design methods for FRC ground-supported slabs were traditionally based on simplified linear elastic models. After the introduction into the market of finite element codes, the latter became a powerful tool for performing elastic analyses. However, since fibers activate after cracking of the concrete matrix, where structural behavior is markedly non-linear, correct methods of analysis of FRC pavements should be based on non-linear fracture mechanics [14] that properly consider the post-cracking behavior of concrete [15] and take into account the significant amount of energy provided by FRC [4, 5]. In fact, limit analysis methods based on the yield line theory [16], [17] allow determining the ultimate load but do not provide information at Serviceability Limit States that, as mentioned above, are particularly important for concrete pavements.

The fib Model Code 2010 introduces an open and performance-driven approach, through a rational use of the actual material response. This is in practice achieved through:

Considering FRC as a composite material formed by a cementitious matrix and discrete fibers. Unlike most of previous design guidelines, fibers can be made of different materials (glass, steel, polymers, etc.), with the exception of fibers with a modulus of elasticity significantly affected by time, temperature, and/or moisture conditions.

- a minimum mechanical performance has to be guaranteed for the FRC when it is used to replace reinforcement bars ($f_{R1k}/f_{Lk} \geq 0.4$; $f_{R3k}/f_{R1k} \geq 0.5$)
- design involves the use of FRC constitutive laws that consider the post-cracking residual strength provided by the fiber reinforcement
- fibers can be used to improve the behavior in the serviceability limit state, since they can reduce the crack spacing and crack width, consequently improving durability

Note that early-age crack control or fire resistance are not considered as structural use.

The key parameter for structural design with FRC is the post-cracking tensile strength, but considering the difficulties in performing the uniaxial tension test, the MC 2010 proposes the flexure test according the Standard EN 14651 [18] to determine the fundamental mechanical performance of FRC. This three-point bending test is performed on a prismatic beam of 150 x 150 x 550 mm including a notch at mid-span, and a span between supports of 500 mm. The displacement-controlled testing system introduces a specific deflection or CMOD (Crack Mouth Opening Displacement) rate, and records load and displacement up to deflection or CMOD limits of 3.5 or 4 mm, respectively. The FRC performance is evaluated by means of residual (post-cracking) flexural strength values at 0.5, 1.5, 2.5, and 3.5 mm of CMOD, named $f_{R1}$, $f_{R2}$, $f_{R3}$ and $f_{R4}$, respectively, while the MC 2010 only uses $f_{R1}$ and $f_{R3}$ for design. Fig. 5 and Fig. 6 show the basic configuration of the test and the complete response of a softening-type FRC, together with the stress formula (the Standard assumes a linear stress distribution along the net height of the specimen).

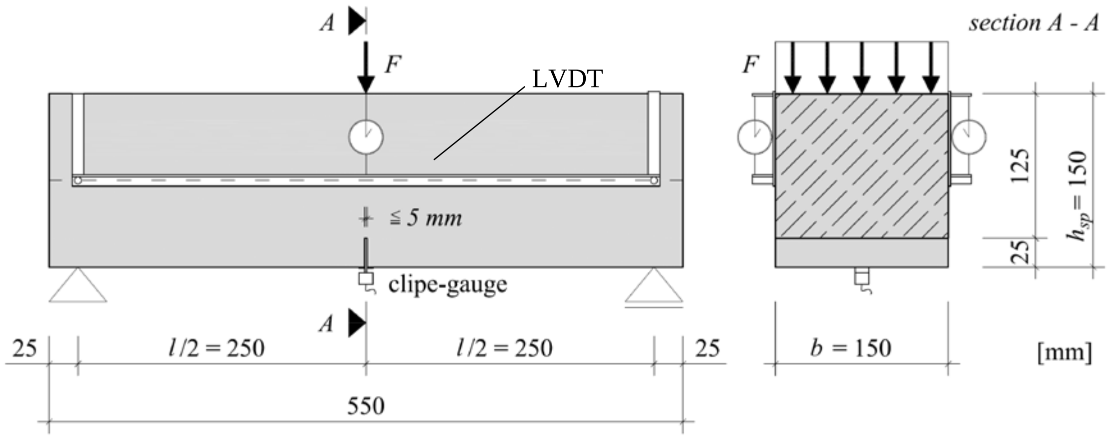
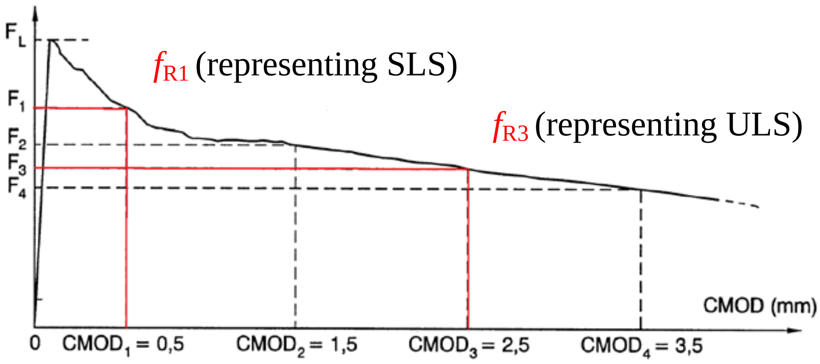



Fig. 5: Test setup for Three-Point-Bending tests according to EN 14651 [18]




The residual tensile strengths, provided linear stress distribution are calculated as follows:

$$f_{R,j} = \frac{3F_j l}{2bh_{sp}^2} \tag{1}$$

Fig. 6: Typical Load-Displacement-Curve for softening FRC

The following data shows the general performance of a C25/30 concrete reinforced with 5, 10, and 15 kg/m3 of Anti-CRAK® HP 67/36 alkali-resistant glass macro-fibers in terms of mean values of mechanical properties (compressive strength and residual strength values from 12 specimens in each case). Because of their high bond to the surrounding matrix, glass fibers start working before the peak load, at micro cracking stage, which leads to a slight increase of the peak strength. Especially the $f_{R1}$-value, which represents SLS, can be increased significantly when adding more fibers (see Fig. 8).

Interestingly for the design of concrete floors, the height of the Standard flexure specimen is very much in line with the usual thicknesses of concrete pavements, which regardless of the support conditions, makes the test specimen rather representative of the real application.

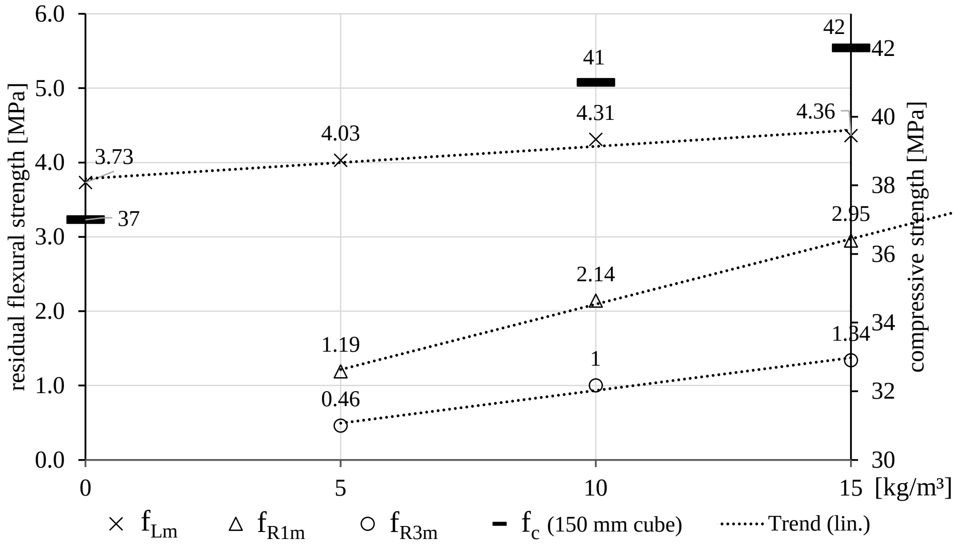



Fig. 7: Flexural properties of FRC beams reinforced with glass-macro-fibers

It is noteworthy that the MC 2010 addresses a generic design for all kind of structural elements, but not the case of specifically the extremely indeterminate ground-supported floor slabs. Hence, the formulation can be rather conservative for this application, since such high structural redundancy leads to very small crack openings (i.e. < 0.5mm) at ultimate capacity. In this case, the requirements for minimum $f_{R3}$ values (residual strength at 2.5 mm of crack opening) lose sense in this particular application, and design could be driven by $f_{R1}$ (residual strength at 0.5 mm of crack opening).

Overall, these considerations are permitting FRC floor solutions to be more competitive, yet keeping a right level of safety. A fib Model Code 2010 - based design considering the above approach has been extensively used in the last years for the design of glass FRC ground-supported floor slabs.

## 5. Case studies

This section presents examples of different types of ground-supported slabs reinforced only with glass fibers.

The reinforcement of self-compacting concrete is shown in Fig. 8 (top), representing a high-end automobile dealership, in France. This 3,700 $m^2$ slab included a C20/25 self-leveling screed reinforced with 5 kg/$m^3$ of AR-glass macro-fiber Anti-CRAK HP 67/36. The thickness of the slab is 50 mm and joints were cut only at critical locations such as around pillars, making it a practically jointless slab. For a maximum control also of plastic shrinkage cracking, this concrete mix also incorporated 0.6 kg/$m^3$ of glass micro-fiber Anti-CRAK HD 12. The bottom part shows the completion of a roundabout in road K 1060/1013, in Germany. This road application (1,300 $m^2$) included a C30/37 concrete reinforced with 10 kg/$m^3$ of AR-glass macro-fiber Anti-CRAK HP 67/36. The thickness of the slab is 260 mm and joints are cut in radial direction every 5-6 m.


Fig. 8: Self-leveling screed project for a high-end automobile dealership, France (above) and Roundabout road K 1060/1013 in Renningen, Germany (below)

## 6. Conclusions

This paper presents an evaluation of the fresh and hardened properties of concrete reinforced with glass macro-fibers and its use in highly indeterminate applications such as slabs-on-ground.

Within the typical dosages for flooring applications (5-10 kg/m$^3$), glass macro-fibers may introduce only marginal effects on the material workability, leading to easily process able mixes for this application.

The flexure performance of glass macro-fiber FRC is characterized by a relatively high residual strength at small crack openings, which is crucial for the load-bearing capacity of ground-supported slabs, and strongly benefits the performance of the floor in service (arresting cracks at very small crack openings).

Two case studies are presented showing the performance of glass macro-fiber reinforced concrete at industrial scale, where the benefits anticipated at material-scale have been proven.

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