Long-term monitoring of a hybrid SFRC slab on grade using recycled tyre steel fibres

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Abstract. This paper presents one of the demonstration projects undertaken during the FP7 EU-funded Anagennisi project (innovative reuse of all tyre components in concrete-2014-2017) on a full-scale (30 m²×40 m, thickness: 0.2 m) Steel Fibre Reinforced Concrete (SFRC) slab-on-grade using a blend of manufactured steel fibres (MSF) and Recycled Tyre Steel Fibres (RTSF). The aim of the project was to assess the use of RTSF in everyday construction practice. The Anagennisi partners, Dulex Ltd in collaboration with Gradmont-Gradacac Ltd and University of Zagreb, designed, cast and monitored the long-term shrinkage deformations of the indoor slab-on-grade slab at Gradmont’s precast concrete factory in Gradacac, Bosnia and Herzegovina. A hybrid RTSF mix (20 kg/m³ of MSF+10 kg/m³ of RTSF) was used to comply with the design criteria which included a maximum load capacity of 20 kN/m². The slab was monitored for one year using surveying equipment and visual inspection of cracks. During the monitoring period, the slab exhibited reasonable deformations (a maximum displacement of 3.3 mm for both, horizontal and vertical displacements) whilst after five years in use, the owners did not report any issues and were satisfied with the construction methodology and materials used. This work confirms that RTSF is a viable and sustainable solution for slab-on-grade applications.

Keywords: slab-on-grade; long-term monitoring; hybrid fibre reinforced concrete

1. Introduction

Steel Fibre Reinforced Concrete (SFRC) is widely used in the construction industry for industrial flooring (slabs-on-grade and suspended slabs) as well as tunnel applications, due to the ability of the steel fibres to control crack propagation (Erdoğdu et al. 2018, Mansouri et al. 2020, Rajeshwari and Sivakumar 2020, Satish Kumar et al. 2017, Sharma and Bansal 2019, Sorelli et al. 2006). While manufactured steel fibres (MSF) are the most widely used type of fibres to reinforce concrete, with approximate worldwide consumption of around 500,000 t/y, the number of potential sources of fibres from different waste streams is growing continuously (Mohajerani et al. 2019). However, enough must be available to ensure the successful implementation of recycled fibres in the construction industry. One of the main advantages of Recycled Tyre Steel Fibres (RTSF) is their availability, with approximately 750,000 ton of steel being available annually worldwide, most of which is remelted for steel production. Recent research conducted on the use of RTSF as reinforcement in concrete (Baricevic et al. 2017, Hu et al. 2018, Martinelli et al. 2015, Mastali et al. 2018, El-Sayed 2019, Liew and Akbar 2020), showed that the flexural properties of concrete can be improved if RTSF are blended with Manufactured Steel Fibres (MSF) to produce Hybrid Steel Fibre Reinforced Concrete (HSFRC). The use of both types of fibres, not only makes concrete more environmentally friendly (use of less MSF) but also improves the overall flexural behaviour of concrete, since RTSF control early cracking more efficiently than MSF which are activated post peak. RTSF, due to their geometrical characteristics (much shorter and thinner than MSF), can arrest microcracks in a more efficient manner and delay their coalescence to form macrocracks. For MSF replacement up to 50% (by mass) and at total fibre dosage of 30 kg/m³, research has shown that HSFR can exhibit similar residual flexural values to SFRC reinforced only with MSF (Baricevic et al. 2017). At higher total fibre dosages, such as 45 kg/m³, the flexural behaviour of SFRC, expressed in terms of residual strength at 0.5 mm and 1.5 mm (fR1; and fR2, respectively) is improved by 10-15% for up to 77% MSF replacement by RTSF (Hu et al. 2018).

Despite their excellent mechanical characteristics and the significant experimental research conducted so far, the market for RTSF is still relatively small. Whilst a significant amount of work has been undertaken on the effect of mechanical properties of RTSF reinforced concrete (Farhan et al. 2018, Mastali and Dalvand 2016, Aiello et al. 2009, Centonze et al. 2012, Caggiano et al. 2017, Grzymski et al. 2019, Leone et al. 2018, Ahmadi et al. 2017, Frazão et
al. 2019, Zamanzadeh et al. 2015, Simalti and Singh 2020, Samarakoorn et al. 2019, Skarżyński and Suchorzewski 2018), as well as on free and restrained shrinkage under laboratory conditions (Al-Kamani et al. 2018), there is still limited work on the applicability of RTSF on a life-size project. Hence, there is a need for in-situ performance assessment of life-size slabs to provide industry with the proof that RTSF SFRC slabs-on-grade work well. Furthermore, in many cases, there may be a need to modify existing fibre integration machines to ensure even fibre distribution on site.

Based on the results of a study on an indoor full-scale slab-on-grade which was monitored for a 12-month period, therefore, this paper provides evidence that a hybrid fibre solution can be effectively integrated in large scale projects and demonstrates that HSFRC can be a viable alternative for slabs-on-grade.

The slab examined in this paper was part of a series of demonstration projects performed during the FP7 EU-funded collaborative project “Anagennisi” which dealt with the innovative reuse of all end-of-life tyre components in concrete applications (Project Anagennisi 2014-2017). One of the key objectives of the “Anagennisi” project was to assess the mechanical and durability properties of concrete, reinforced with end-of-life tyre by-products and identify structural concrete applications and open a market for environmentally friendly in-situ applications.

2. Site location and geometrical characteristics

The indoor slab-on-grade was constructed at Gradmont-Gradacac Ltd precast concrete plant in Bosnia-Herzegovina, whilst casting was undertaken by Dulex Ltd (SFRC contractor and specialist) - both companies were part of the Anagennisi project consortium. The authors designed and developed the quality control procedures for this demonstration project. The slab was 30 m wide, 40 m long and 20 cm thick, designed to withstand loads developed during the manufacturing process of prestressed concrete elements, up to 20 kN/m². Fig. 1 shows the geographical location of the construction site and its plan view at the concrete plant.

3. Research programme and concrete specification

The aim of this demonstration project was to assess the use of RTSF in practical in-situ concrete applications. Although the authors have published a considerable amount of work assessing various mechanical characteristics of RTSF reinforced concrete (Baricovic et al. 2017, Hu et al. 2018, Project Anagennisi 2014-2017), the results were based only on laboratory testing. Laboratory testing and casting are conducted under controlled conditions and cannot reflect the complexities and uncertainties of in-situ conditions. The work presented in this paper was carried out in three phases to examine the effect of using local materials and fibres integration technologies on the final concrete properties:

- **Phase A:** 3-point flexural tests - laboratory-cast prisms: concrete was cast using laboratory-sized specimens (600 x 150 x 150 mm) and tested at 28 days to determine the effect of locally sourced materials on concrete’s flexural properties.
- **Phase B:** slab-on-grade construction and long-term monitoring: hybrid fibre reinforced slab-on-grade covering an area of 1.200 m² was constructed,
- **Phase C:** 3-point flexural tests - in-situ-cast prisms: conformity control - laboratory specimens [same moulds as in phase A] were cast during the construction of the slab by sampling concrete from three different concrete mixer trucks.

For all phases, concrete was produced using a pan mixer available at Gradmont’s precast concrete plant. Concrete batching plant used in this study has maximum capacity of 0.75 m³ per batch, here 0.5 m³ per batch was prepared.

3.1 Materials and mix design

Concrete constituents, concrete delivery and production control procedures were followed as described in EN 206:2013. Portland cement type CEM II/A-M (S-V) 42.5 N and river aggregates of sizes of 0/4 mm, 4/8 mm and 8/16 mm were used (note: size 0/4 mm was crushed river aggregates).

Fig. 2 shows the aggregate grading used for the slab-on-grade. To achieve concrete workability class S4, a
Table 1 Geometrical and mechanical properties of MSF and RTSF (Francic Smrkic et al. 2017)

<table>
<thead>
<tr>
<th>Type</th>
<th>Geometrical shape</th>
<th>Length, L (mm)</th>
<th>Diameter, D (mm)</th>
<th>Aspect ratio, L/D (−)</th>
<th>Tensile strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSF</td>
<td>Straight with hooked ends</td>
<td>30</td>
<td>0.6</td>
<td>50</td>
<td>1100</td>
</tr>
<tr>
<td>RTSF</td>
<td>Irregular</td>
<td>20 ± 2</td>
<td>0.15 ± 0.04</td>
<td>133</td>
<td>2850</td>
</tr>
</tbody>
</table>

*mix code name: 20M10RTSF - MSF: 20 kg, RTSF: 10 kg

Table 2 Mix design and fibre dosages for slab on grade

<table>
<thead>
<tr>
<th>Components</th>
<th>20M10R* (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>370</td>
</tr>
<tr>
<td>Water</td>
<td>170</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>2.22</td>
</tr>
<tr>
<td>w/c</td>
<td>0.46</td>
</tr>
<tr>
<td>Fibres</td>
<td></td>
</tr>
<tr>
<td>MSF</td>
<td>20</td>
</tr>
<tr>
<td>RTSF</td>
<td>10</td>
</tr>
<tr>
<td>Aggregate</td>
<td></td>
</tr>
<tr>
<td>0/4 mm</td>
<td>1062</td>
</tr>
<tr>
<td>4/8 mm</td>
<td>177</td>
</tr>
<tr>
<td>8/16 mm</td>
<td>531</td>
</tr>
</tbody>
</table>

superplasticiser was used.

Manufactured steel fibres (MSF) (straight with hooked ends) were purchased from a local supplier, whilst classified RTSF were provided by an Anagennisi project partner-Twincon Ltd. RTSF are extracted from end-of-life tyres, have irregular shape and vary in length and diameter. To make them suitable for concrete reinforcement, the recycled fibres are further processed to remove the majority of long fibres (>40 mm) that can cause balling and very short fibres (<10 mm) that are too short to anchor and develop significant stresses.

Table 1 shows the geometrical and mechanical properties of both MSF and RTSF, while the fibre length distribution is shown in Figure 3a. The values of RTSF represent averages (based on a 10k fibre sample) obtained using a specially developed QA device, which uses photogrammetry techniques. Fig. 3b shows typical samples of both fibre types.

Based on previous relevant research work and mix optimisations (Baricevic et al. 2017), the HSFRC mix design shown in Table 2 was used for the slab.

3.2 Casting, curing and test methods

It is known that casting conditions can affect concrete properties even if the same concrete mix design is used. For this reason, small scale specimens were cast in the laboratory (phase A - section 3) and in-situ (from the same materials used to cast the slab: phase C - section 3). Both groups of specimens were tested in flexure to evaluate the
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conformity of the locally available materials and identify variations in their post cracking flexural behaviour. Post cracking flexural behaviour was assessed by measuring the central deflection. The load was recorded at deflection of 0.47, 1.32, 2.17 and 3.02 mm which correspond to the crack mouth opening displacement (CMODs) of 0.5, 1.5, 2.5 and 3.5 mm (TR34 2013). Fresh state properties and compressive strength were also evaluated in both phases.

The mixing procedure was kept the same for all three phases (A, B and C): Before mixing, all materials were weighed and the aggregate humidity was obtained. Firstly, aggregates and half of the water were blended to allow the aggregates to saturate. The cement was then added and mixing commenced with continuous addition of the residual water and superplasticiser. The steel fibres were dispersed in fresh concrete using: 1) a specially manufactured perforated rotating drum (Fig. 4) for phase A and 2) rotating drum + a modified fibre blower for phases B and C. For phase A, the fibres were dispersed directly to the concrete mixer using only the rotating drum to disperse the fibres and avoid agglomeration. For phases B and C, the concrete was first mixed with a pan mixer, then transferred to the concrete mixer trucks where both MSF and RTSF fibres were blown into each truck and mixed for another 5 minutes. To ensure a uniform dispersal, the perforated drum was installed right before the blower nozzle. Trials were made to ensure that the fibre dispersion was successful (Fig. 5).

Table 3 shows the testing standards used for assessing the fresh and hardened concrete properties. Specimens used for phases A and C were cast in moulds according to the standards (cubes, prisms and cylinders), and then were covered with plastic sheets to minimise evaporation. All specimens were kept at constant environmental conditions (20±2°C), demoulded after 24 hours and cured in water tanks (20°C) for 28 days until tested.

### 3.3 Experimental results—Laboratory small-sized specimens: Phases A and C

For both phases A and C, the experimental results showed that 20M10RTSF mix satisfied all requirements for fresh and hardened concrete (Table 3; Fig. 6). To obtain the fresh properties of the concrete mix during phase C, samples were taken from 3 different batches in accordance with EN 12350-1:2009.

The $f_t$ values of Phase C were less than 50% of the corresponding $f_t$ values obtained from phase A (section 3.3). This discrepancy is probably caused by the methodology used for the dispersion of fibres in the...
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During in-situ casting the concrete was first transferred to a concrete mixer truck and then a blower was used to integrate the fibres. Improvements were necessary on the blower to ensure the proper integration of RTSF, due to their different geometrical characteristics (much shorter and thinner than MSF). Nonetheless, as this was the first time the modified blower was used, discrepancy may have still occurred due to uneven RTSF dosing during the integration process.

4. Design of the slab-on-grade

The slab-on-grade was designed to withstand stresses developed during the manufacturing process of heavy concrete elements and steel moulds. Hence, for live actions, a UDL of 20 kN/m² was used.

For the slab design, the characteristic flexural strength of plain concrete and the residual flexural strength of HSFRC were determined from the phase A results (section 3.3). The compressive strength results obtained from 150 mm cubical specimens enabled that concrete can be classified as C30/37. Following, the mean compressive strength on cylinder (Φ/h=150/300 mm) was determined based on TR 34 (TR34 2013). Table 4 lists the main properties of both plain and fibre reinforced concrete. The important parameters for the design such as the modulus of subgrade reaction, (TR34 2013), were taken in-situ prior to casting (see section 5.1).

The ultimate moment capacity (per m width) for a fibre-only slab was calculated based on the simplified assumptions of TR34 (compressive strain in concrete 0.0035) (TR34 2013). The maximum negative moment is
induced between a pair of loads, which in this case are moulds for casting heavy concrete elements. Table 5 summarises the design moment capacities.

### 5. Construction phase

Before any concrete casting took place, the subgrade was thoroughly compacted by a vibrating single-drum road roller machine targeting a modulus of deformation of at least 80 MN/m² (Fig. 7(a), (b)). The modulus of compressibility was found to be on average 83.6 MN/m², determined by using a circular plate on nine locations according to JUS/BAS U.B1.046.

To reduce the risk for cracking, the slab was designed to be restraint-free with no connection to any elements of the structure. The compacted substrate was covered with PE foil (thickness 0.15 mm) in two layers with overlaps, ensuring a low friction coefficient between the slab and the subgrade. After setting the PE foil on the subgrade, isolation joints were made using 10 mm thick plastic strips between the floor and adjoining building elements.

The concrete was prepared in Gradmont’s factory concrete plant and 240 m³ of concrete were transported to the site by concrete mixer trucks. To assure the uniform dispersion of RTSF in concrete, a modified fibre blower was used as shown on Fig. 7(c). For a successful casting and finishing of an industrial floor, it is essential for the concrete to be well mixed and to have similar workability between batches (Fig. 7(d)). Therefore, continuous checks of consistency and air content were performed during casting and specimens were cast for conformity control (see Table 3, phase C). Delivery of concrete was continuous without delays of more than 15 minutes. A laser-guided levelling machine was used to eliminate thickness variations (Fig. 7(e)). The areas around the slab edges were compacted by using portable concrete pokers.

Shortly after casting, quartz was uniformly spread at 3 kg/m² over the top surface of the slab. The topping was left to soak up moisture before final finishing with a power float (Fig. 7(f)).

Installation and compaction were undertaken indoors, offering protection from the environment and thus reduced shrinkage, whilst achieving the required surface hardness and durability. The curing process started immediately after finishing casting and lasted for 7 days. The top surface of the slab was covered with PVC sheets to reduce water loss and crack formation due to plastic shrinkage as well as to minimise the temperature difference between the concrete and environment. After 24 hours, a joint (4 mm wide, 70 mm deep (equivalent to about one-third of the slab thickness depth)) was cut in the middle of the slab. After 2 weeks from curing, the slab was ready for use (Fig. 7(g), (h)).

### 6. Long-term deformation monitoring

To monitor the long-term deformations of the slab, displacement measurements were taken on ten different days. The first three measurements were taken during the first three measurements were taken during the first two months (Table 6). The areas around the slab edges were compacted by using portable concrete pokers.

#### 6.1 Geodetic network

To measure accurately the horizontal and vertical displacements of the slab, a geodetic network needed to be set up comprising a control and a reference network. The control network consisted of twenty-two geodetic bolts.
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(Fig. 8(a), (b)) fixed onto the slab. The bolts were drilled into the concrete slab and bonded using a two-component adhesive.

The reference network was set up outside the slab, in locations (i.e., other slabs/columns) that were not affected by the slab deformations. Five reference points (P1-P5-Fig. 9) were fixed using similar geodetic bolts as the control network. To determine the horizontal displacements, four additional reference points (P6-P9-Fig. 9) were fixed by using reflective tapes (60x60 mm) on the concrete columns (Fig. 8(c), (d)).

Following this approach, the absolute slab displacements were determined using deformation analysis algorithms based on the Hannover model (Niemeier 1985).
By global analysis of displacements using the Hannover model, it is possible to determine whether there have been any significant displacements of points in the geodetic network between two sets of measurements (Niemeier 1985, Pelzer 1971, Niemeier 1976).

6.2 Geodetic equipment

Vertical displacements were obtained by the automatic level Topcon AT B2 equipped with an optical micrometre OM5 following the recommendations of ISO 17123:2:2001. The achievable accuracy according to ISO 17123-2 a-priori testing procedure was determined ≤0.5 mm/km. A total station Leica TPS1201 was used to measure the horizontal displacements according to ISO 17123-3:2001 and ISO 17123-4:2012. Achievable accuracy according to ISO 17123-3:2001 and ISO 17123-4:2012 a-priori testing procedure was ± (1 mm + 1 ppm) for distance measurements and 1” for angle measurements.

6.3 Analysis of the deformation monitoring

Results of the displacement monitoring are presented in Fig. 10, where the first measurement (Fig. 10(a)) was taken as reference measurement. Fig. 10(b), (c), (d), (e) show a graphical representation of the determined vertical and horizontal displacements after the 4th, 7th, 9th and 10th measurements.

Vertical displacements (positive and negative values) with a maximum value of 0.4 mm were recorded from the 4th to 7th measurement. At the same time, the maximum measured horizontal displacement was considered negligible, i.e., 1.4 mm, as it was within the estimated standard deviation of horizontal displacements.

Before the 8th measurement (i.e., 105 days after casting), two cracks were observed on the slab surface, both of which, initiated at the corner of the manholes. An investigation revealed two main causes for this: a) insufficient attention was put on the detailing of the manholes during construction, b) early loading of the slab which caused pinning of the slab to the subgrade. Although, these cracks are considered as non-structural, the owner insisted on additional saw cutting of the slab.

Significant vertical displacements were observed in points 4, 5, 6, 19 and 20 in the 8th, 9th and 10th measurement, followed by a change in displacement direction (in measurement 7-negative, whilst in measurement 9-positive) (Fig. 10(c), (d), (e)). During the 9th measurement, the horizontal displacements along the X axis ranged from -0.6 mm to 0.7 mm, as for the 9th measurement. The same was observed for the horizontal displacements of the 10th measurement which ranged from -3.3 mm to 2.8 mm on the X axis, and from -0.2 mm to 2.2 mm on the Y axis.

5. Conclusions

Recent laboratory studies have shown that HSFRC with RTSF and MSF can offer similar properties to SFRC produced with MSF. To encourage the market uptake of these innovative and environmentally friendly fibres, life-size projects are crucial to demonstrate their long-term performance and applicability in the construction industry. This paper examines the applicability of HSFRC, reinforced with MSF and RTSF, with the construction of a life-size slab-on-grade.

The slab was design to withstand loads up to 20 kN/m² using experimental data provided by the Anagennisi project. The HSFRC was prepared with a total fibre dosage of 30 kg/m³, where 10 kg/m³ of MSF was replaced with RTSF.

One of the most important factors when steel fibres are used (both MSF or RTSF) is to avoid balling and ensure even fibre dispersion in concrete. Fibre dispersion may be affected by the drum rotating speed, the blowing pressure and even the method by the fibres are added into the drum. For the project discussed in this paper, modifications to the fibre blower were made to ensure the uniform dispersion of RTSF in the mix.

Initial laboratory testing was performed to check the conformity of local materials (phase A) and results were compared with data obtained from specimens cast on site during the construction of the slab (phase C). Construction quality control demonstrated that the HSFRC mix cast in-situ met the required design criteria, although significant reductions (more than 50%) in residual flexural strengths (f₀) were observed when compared to the f₀ values obtained from specimens cast during initial tests using the exact
Fig. 10 Graphical representation of determined vertical and horizontal displacements after: (a) 1\textsuperscript{st}-reference, (b) 4\textsuperscript{th}, (c) 7\textsuperscript{th}, (d) 9\textsuperscript{th}, (e) 10\textsuperscript{th} measurement
same concrete mix design in the laboratory. This discrepancy was attributed to the non-uniform dispersion of the fibres in the concrete mixer, due to insufficient integration. This demonstrates the importance of on-site conformity checks and the need for further investigation on in-situ casting of HSFRC with RTSF. Using the experience gained from this trial and laboratory experience, it is recommended to keep hybrid fibre content up to 30 kg/m³ in life-size projects.

The performance of the RTSF in the slab-on-grade application was examined through long-term geodetic measurements. Long-term monitoring detected a maximum displacement of 3.3 mm in both, horizontal and vertical directions. Since the detected displacements were within the range of the expected standard deviation, it can be concluded that the slab-on-grade performed satisfactorily.

The slab was cast without any major technical issues and it has been used without any problems for the last five years. The users did not report any issues related to the method of construction or the recycled materials used. Based on the above, it can be concluded that a high-quality product can be made with reduced the monetary (-15%) and environmental cost (-97% of CO₂ emissions for RTSF fibres) per cubic meter of concrete.

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