Autogenous and drying shrinkage of fibre reinforced high performance concrete
Drago Saje, Branko Bandelj, Jakob Šušteršič, Jože Lopatič

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**Abstract**

This paper reports the results of laboratory investigations into the time history of the shrinkage of fibre reinforced high-performance concrete with 0.25%, 0.50% and 0.75% by volume of longer IRI 50/30 or shorter IRI 50/16 steel fibres or polypropylene fibres. To allow suitable comparisons, measurements of the shrinkage of a comparable plain concrete were also performed. The results of the measurements of the autogenous shrinkage of the tested composites and of the comparable plain concrete at early and later ages of the specimens are presented. The results of the performed laboratory tests show that the use of steel fibres is more effective for the reduction of early autogenous shrinkage than that of dry polypropylene fibres. For the reduction of later autogenous shrinkage, the polypropylene fibres are almost as effective as the steel fibres. The least drying and total shrinkage of the composites at later ages occur in the case when polypropylene fibres are used.

**1. Introduction**

High-performance concretes of strength class C55/67 or higher are frequently used in construction practice, not only due to their high strength, but also due to their higher resistance to other external actions. Since, in concrete, high strength is mainly achieved by reducing the water-to-binder ratio, the amount of free water in the concrete falls below the value which is necessary for the chemical process of hydration. In this case, in the chemical process of the hardening of the cement gel, part of the water from the fine pores is used up, which results in negative pore pressures and tensile forces, which act on the pore walls. The consequence of this is the reduction of the volume of the relatively deformable, as yet unhardened cement paste or concrete. This physical phenomenon is called autogenous shrinkage of concrete. In the case of high-performance concretes, autogenous shrinkage represents an important part of the total concrete shrinkage (Barr et al. 2003; Saje et al. 2003), in comparison with concretes of normal strength. The evaporation of water through the surface of the concrete causes drying shrinkage of the concrete.

When designing concrete composites, it is necessary to select the material, length, diameter, and volume content of fibres by means of which the mechanical and rheological properties, as well as the ductility and resistance of the composite to the occurrence and widening of cracks, can be best improved. The results of experimental investigations and numerical simulations performed by various researchers (Chuan et al. 1990; Swamy et al. 1979; Paillere et al. 1989; Banthia et al. 2006; Bentur et al. 2007; Zhang et al. 2001; Mangat et al. 1988; Li Zhen et al. 2006), as well as those performed by the authors themselves (Bandelj et al. 2011), have shown that by adding short strengthening fibres to concrete, it is possible to improve mechanical, rheological and some other important properties in comparison with comparable plain concrete. Chuan et al. (1990) noted that, apart from the type and volume content of the fibres, the ratio between the length and nominal diameter of the fibres also has an influence on the reduction of the shrinkage of the composite. Paillere et al. (1990) found that the autogenous shrinkage of a composite with 0.8% by volume of fibres is, in general, less than that of a comparable HPC. From Kamen’s (2006) research, it emerged that the autogenous shrinkage of an ultra high performance composite with 6.0% by volume of steel fibres was 35% less than that of a comparable concrete without fibres. Balaguru et al. (1988) found that, over a period of 500 days from mixing, the shrinkage of a composite with a compressive strength of 55 MPa was 10% less than that of a comparable concrete without fibres, whereas Chuan et al. (1990) have claimed that the shrinkage of a composite containing longer steel fibres is less than that of a similar composite containing short ones. Swamy et al. (1979) assert that the shrinkage of a composite containing 1% by volume of steel fibres is 20% less than that of a comparable plain concrete. According to Barr et al. (2003), the optimum fibre content for the reduction of composite shrinkage is 1%. When the fibre content was increased above 1%, they did not observe any significant additional reduction in the shrinkage of the composite.
Banthia et al. (2006) found that, in composites, polypropylene fibre reinforcement is very effective in limiting cracking due to plastic shrinkage, thinner and longer fibres being more effective than thicker and shorter ones. Kovler et al. (1992) reported that the presence of polypropylene fibres results in a considerable decrease in plastic shrinkage, but that up to 0.2% by volume of such fibres is much less effective in reducing the total shrinkage of the composite. According to their findings, crack width can be reduced by as much as 50% by appropriately increasing the volume content of polypropylene fibres. Swamy et al. (1979) found that the drying shrinkage of polypropylene fibre reinforced concrete was about 20% less than that of a comparable concrete without fibres. Zollo (1984) and Zollo et al. (1986) have argued that, in the case of an appropriate quantity of added polypropylene fibres, the drying shrinkage of concrete can be reduced by as much as 75%. The results of previous authors’ investigations (Saje et al. 2011) show that the addition of previously moistened polypropylene fibres to concrete with adequately reduced mixing water is more effective for the reduction of early autogenous shrinkage of composites than the addition of dry polypropylene fibres to concrete with a normal amount of mixing water.

Contrary to the findings of previously cited authors, Kovler et al. (1997) maintain that steel fibres do not cause any reduction in composite shrinkage as compared with concrete without fibres. Myers et al. (2008) are of the opinion that polypropylene fibres in fibre reinforced concrete have a very small influence on the reduction of composite shrinkage. Aly et al. (2008) maintain that the shrinkage of fibre reinforced concrete with 0.50% by volume of polypropylene fibres, after the latter has been cured for 1 day and then exposed to a temperature of 23°C and a relative humidity of 50%, is 15% greater, and, when the concrete has been cured for 7 days, 22% greater than the shrinkage of a comparable concrete without fibres. However, these authors state that their results are in disagreement with those of several other authors. They justify their results with the increased porosity, and consequently the accelerated decrease in moisture in the fibre reinforced concrete as compared to concrete without fibres.

Within the framework of the authors’ own research work, the influence of various volumes of polypropylene fibres, and of steel fibres of different lengths, on the autogenous as well as on the total and drying shrinkage of high-performance composites was studied. Laboratory investigations of high-performance composites were performed at 0.25%, 0.50% and 0.75% by volume content of steel and polypropylene fibres, respectively.

2. Experimental investigation programme

The effect of steel and polypropylene fibres on the shrinkage of high-performance fibre reinforced concrete was investigated at a water-to-binder ratio of the fresh composite mixtures of 0.36. Measurements of the shrinkage of these composites were performed on prism-shaped test specimens. For the estimation of the concrete or composite strength class, cube-shaped test specimens were used. For each of the investigated volume contents (0%, 0.25%, 0.50% and 0.75%), and for each of the two different lengths of steel fibres (l = 16 mm and l = 30 mm), as well as for the polypropylene fibres, 6 test prisms measuring 10×10×40 cm, as well as three 15x15x15 cm cube-shaped specimens, were prepared. The autogenous shrinkage of the composites and of the comparable plain concrete was measured on three sealed prisms from each mix. The total shrinkage of the fibre reinforced high-performance composites and the comparable plain concrete was measured on the remaining three unsealed prisms. All the test specimens were, during the experimental investigations, stored in a climatic chamber at a constant relative humidity of 70% ± 3% and at a temperature of 22°C ± 3°C.

3. Preparation of the test specimens

The fibre reinforced and comparable plain concrete test specimens were prepared from washed and crushed limestone aggregate with a maximum nominal grain size of 16 mm, and added fine silica sand. The cement used was CEM II / A-S 42.5 R. To ensure sufficient workability (EN 206 2000) at the selected, relatively low water-to-binder ratio, a naphthalene type superplasticizer was used, which was, according to its chemical

![Fig. 1 Polypropylene fibres used in the composites.](image-url)
composition, a sulphonated naphthalene-formaldehyde condensate. The test specimens were reinforced by polypropylene fibres as shown in Fig. 1, whose properties are presented in Table 1, or by hooked steel fibres as shown in Figs. 2a and 2b, whose properties are presented in Table 2. In our country, the polypropylene and steel fibres used in our investigations have been frequently applied in construction practice over many years.

Polypropylene fibres have a fibrillated form. They are produced as polypropylene film sheets by an extrusion process, and then slit longitudinally into tapes of more or less equal width, which are cut to the desired lengths. Zonsveld (1975) found that fibrillated polypropylene fibres achieved a very good mechanical bond with cement paste. Balaguru and Shah (1992) categorized steel fibres as being, in general, straight, deformed, rippled, with special ends (e.g. enlarged or hooked ends), or with irregular cross sections. The early development of different types of steel fibres, between 1912 and 1933, can be seen in data from patents, which were documented by Naaman (1985). After this many new types of steel fibres have been produced. The bond of end-hooked steel fibres has been well described by Foster (2009); it is concentrated at the hook and within the snubbing zones.

The test specimens were made from nine different mixtures of fibre-reinforced high-performance concrete, and one mixture of a comparable plain concrete. Mixture M1 contained no fibres, whereas mixtures M2, M3 and M4 or mixtures M5, M6 and M7 contained 0.25%, 0.50% and 0.75% volumes of the shorter IRI 50/16 or longer IRI 50/30 steel fibres, respectively. Mixtures M8, M9 and M10 contained equivalent amounts of polypropylene fibres. The total content of the binder in each of the mixtures was 400 kg per m³ of the composite or plain concrete, 90% of which was cement (360 kg/m³) and 10% silica fume (40 kg/m³). The composition and properties of the fresh and hardened comparable concrete without fibres, and of the fibre reinforced concrete mixtures, are given in Table 3.

### Table 1 Properties of the used polypropylene fibres (P).  
<table>
<thead>
<tr>
<th>Density (g/cm³)</th>
<th>Length (mm)</th>
<th>Cross-section (μm)</th>
<th>Tensile strength (MPa)</th>
<th>Modulus of elasticity (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.91</td>
<td>12</td>
<td>35 × (250-600)</td>
<td>340-500</td>
<td>8500-12500</td>
</tr>
</tbody>
</table>

### Table 2 Properties of the hooked steel fibres.  

<table>
<thead>
<tr>
<th>Steel fibres</th>
<th>Fibre length (mm)</th>
<th>Oval cross sections – obtained by measurement</th>
<th>Equivalent diameter de (mm)</th>
<th>Wire tensile strength (MPa)</th>
<th>Fibre class (ASTM A 820)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRI 50/16 (V1)</td>
<td>16</td>
<td>0.491 × 0.502</td>
<td>0.496</td>
<td>797</td>
<td>Type 1</td>
</tr>
<tr>
<td>IRI 50/30 (V2)</td>
<td>30</td>
<td>0.491 × 0.502</td>
<td>0.496</td>
<td>797</td>
<td>Type 1</td>
</tr>
</tbody>
</table>

4. Performance of the laboratory investigations

The shrinkage of the test specimens was, during the first 24 hours, monitored continuously by means of electronic measurements, whereas later measurements were performed first at one-day intervals, then at intervals of several days, and then at weekly intervals. The autogenous shrinkage of the fibre-reinforced concrete was measured on the test specimens, which were sealed in impermeable polyethylene foil in order to prevent drying out. The test specimens for the measurements of the total shrinkage of the fibre reinforced concrete remained in their moulds, and were covered by polyethylene foil for the first 24 hours. In this way, they were exposed to practically the same conditions as the sealed specimens.

Fig. 2a View of the steel fibres IRI 50/16 (V1) - on the left, and of the steel fibres IRI 50/30 (V2) - on the right.

Fig. 2b Oval and equivalent cross-sections of the steel fibres IRI 50/30.
on which the measurements of autogenous shrinkage of the respective concretes were performed. The test specimens were de-moulded after 24 hours, and then exposed to an environment with a constant temperature of 22°C ± 3°C and a constant relative humidity of 70% ± 3%, in a test chamber. Because drying of the test specimens was prevented by means of the moulds and the additional polyethylene foil, it was considered that the total specimen shrinkage over the first 24 hours would be equal to the autogenous shrinkage. Drying shrinkage was defined as the difference between the total shrinkage of the composite, measured on the unsealed specimens, and the autogenous shrinkage, measured on the sealed test specimens. Computer-controlled measurements of the autogenous shrinkage of the sealed test specimens were performed in accordance with the provisions of the corresponding Japanese standard (JIS A 1129-1 2001; Tazawa 1999), by means of an electronic displacement transducer (Fig. 3b). A polytetrafluoroethylene sheet was inserted between the test specimen and the base in order to reduce the friction between the two surfaces (Fig. 3a).

The moulds for the preparation of the test specimens for the measurement of autogenous shrinkage, in the first 24 hours, were adapted so that holes could be bored through their front steel plates for the insertion of shrinkage measurement pins. The pins were inserted in such a manner that the length of the measuring base was 380 mm. The temperature in the middle of the specimen was measured by means of a thermocouple. Capturing and processing of the measured results was automated. The measuring pins, intended for the measurement of autogenous shrinkage during the later shrinkage period using a mobile displacement transducer, were installed on the sealed test specimens 24 hours after the casting of the test specimens.

The total shrinkage of the fibre reinforced concrete of the test specimens, which were de-moulded 24 hours after casting and fitted with measuring pins, was measured by using a 0.001 mm precision displacement transducer (Fig. 4). To determine the shrinkage of the test specimens, the mean value of two shrinkage measurements, made on opposite sides of the prisms, was taken into account.

---

### Table 3 Mix proportions and properties of the fresh and hardened composites.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>M7</th>
<th>M8</th>
<th>M9</th>
<th>M10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine aggregate 0-4 mm (kg/m³)</td>
<td>1133</td>
<td>1135</td>
<td>1130</td>
<td>1126</td>
<td>1135</td>
<td>1130</td>
<td>1126</td>
<td>1135</td>
<td>1130</td>
<td>1126</td>
</tr>
<tr>
<td>Coarse aggregate 4-16 mm (kg/m³)</td>
<td>755</td>
<td>756</td>
<td>753</td>
<td>750</td>
<td>756</td>
<td>753</td>
<td>750</td>
<td>756</td>
<td>753</td>
<td>750</td>
</tr>
<tr>
<td>Steel fibres</td>
<td>- (V1)</td>
<td>- (V1)</td>
<td>- (V1)</td>
<td>- (V2)</td>
<td>- (V2)</td>
<td>- (V2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Polypropylene fibres</td>
<td>-</td>
<td>-</td>
<td>0.25</td>
<td>0.5</td>
<td>0.75</td>
<td>0.25</td>
<td>0.5</td>
<td>0.75</td>
<td>0.5</td>
<td>0.75</td>
</tr>
<tr>
<td>Volume of fibres (% by composite volume)</td>
<td>0.36</td>
<td>0.36</td>
<td>0.36</td>
<td>0.36</td>
<td>0.36</td>
<td>0.36</td>
<td>0.36</td>
<td>0.36</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>Water-to-binder ratio</td>
<td>144</td>
<td>144</td>
<td>144</td>
<td>144</td>
<td>144</td>
<td>144</td>
<td>144</td>
<td>144</td>
<td>144</td>
<td>144</td>
</tr>
<tr>
<td>Mixing water (kg/m³)</td>
<td>2436</td>
<td>2455</td>
<td>2405</td>
<td>2452</td>
<td>2393</td>
<td>2385</td>
<td>2420</td>
<td>2409</td>
<td>2459</td>
<td>2383</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>68.9</td>
<td>89.3</td>
<td>63.7</td>
<td>86.6</td>
<td>85.5</td>
<td>77</td>
<td>85.5</td>
<td>74.3</td>
<td>76.5</td>
<td>78.2</td>
</tr>
</tbody>
</table>

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**Fig. 3a** Schematic representation of the measurement of test specimen shrinkage.  
**Fig. 3b** Measurement of the autogenous shrinkage of a test specimen.
5. Experimental results

5.1 Deformation measurements of the composites and of the plain concrete

The measured variations of the length of the test specimens over time consisted of variations due to the shrinkage of the concrete, and variations due to changes in the temperature of the specimen. The temperatures in the middle of the test specimens, and the corresponding changes in specimen length, were measured simultaneously. The variations over time of specimen shrinkage were determined from the differences between the development over time of the measured deformations, and the temperature expansion of the test specimens due to variations in temperature. Because the specimen temperature varied only during the period of rapid setting of the cement, i.e. during the first 24 hours, but was later approximately equal to the ambient temperature, the influence of temperature variations on the actual variations of specimen length have to be considered within the first 24 hours only. The variations over time of the test specimen length due to temperature variations in the period of rapid setting of the cement, i.e. in the first 24 hours, were determined analytically from the coefficient of thermal expansion of the concrete, and the measured variations over time of the temperature. Thus a value of $\alpha_{T,T} = 1.48 \times 10^{-5}$, determined by separate measurements (Saje 2001), was taken into account for the coefficient of thermal expansion of the fresh concrete, and a value of $\alpha_f = 1.0 \times 10^{-5}$ was assumed for the coefficient of thermal expansion of the hardened concrete. The concrete was considered fresh until its temperature began to rise significantly. After 24 hours, when the specimen temperature had become approximately constant, the concrete was treated as hardened with respect to its coefficient of thermal expansion. During this time the specimen temperature was constant and did not affect the variation over time of the specimen length, so the shrinkage of the composite was equal to the measured change in specimen length. In order to determine intermediate values of the coefficient of thermal expansion in the period of rapid hardening of the concrete up until 24 hours after its casting, linear interpolation between the values for fresh concrete and the values for hardened concrete were used. This applies to the determination of both the autogenous shrinkage and the total shrinkage. Figure 5 shows the mean values of the temperature and the total deformations measured on the three test specimens of mixture (M1), during the first 24 hours after casting. The lower curve in Figure 5 also shows the time dependence of the autogenous shrinkage of concrete, determined from the mean values of the differences between the total deformations measured on three specimens, and their calculated deformations due to the increase in temperature. In the same way, the time history of the total shrinkage of the fibre reinforced and of the comparable plain high-performance concrete, during the first 24 hours after casting of the specimens, was determined. From the 24th hour onwards, as the specimen temperature became constant, it was considered that the measured deformations of the specimens were equal to the shrinkage of the fibre reinforced or plain high-performance concrete.

$$e_{ca} = \varepsilon_c + \varepsilon_{\Delta T}$$

$$e_{ca} = \Delta L / L + \alpha_f \Delta T$$

$\Delta L$...change in the length of the specimen

$L$...length of the specimens

$\Delta T$...change in the temperature of the specimen
5.2. Autogenous shrinkage of the composites and plain concrete

The results of the measurements of autogenous shrinkage of the composite and of the comparable plain concrete are presented in Figs. 6 to 11. In order to provide a clearer overview of the measurement results, the autogenous shrinkage over the first 24 hours is shown in Figs. 6 to 8 to a larger scale, separately from the autogenous shrinkage obtained throughout the entire period of measurements (shown in Figs. 9 to 11). All specimens could not be prepared at the same time. This is the reason why the initial temperature at the beginning of the measurement is not the same for all specimens. The greatest difference amounted to 4°C. The experimental findings of the authors' own studies, as well as those of other authors, have shown that the initial temperature of the test specimens has an effect mainly on the time at which autogenous shrinkage of the specimens begins, and much less on the size of the autogenous shrinkage. Taking into account the results of Lura et al. (2001, 2002), the effect of the scatter of the initial temperatures of the test specimens, which in our case amounted to 4°C at the most, could have contributed, during the first 24 hours to 3.3 % at the most and at 48 hours after the preparation of the test specimens to about 0.5% of the autogenous shrinkage.

Figure 6 shows the temperature variation in the middle of the specimens and the autogenous shrinkage of the comparable plain concrete and composites with 0.25% by volume of IRI 50/16 or IRI 50/30 steel fibres or polypropylene fibres, over the first 24 hours after casting. From the presented measurement results, it can be seen that the early autogenous shrinkage of the high-performance composite (M8), which contained polypropylene fibres, was, 14 hours after mixing of the test specimens, approximately 16% less, and after 24
hours only still 5% less, than the early autogenous shrinkage of the comparable concrete (M1) without fibres. The autogenous shrinkage of the composite (M2), with shorter steel fibres IRI 50/16, was, over most of the time interval concerned, less than the autogenous shrinkage of the composite (M8) with polypropylene fibres, but greater than that of the composite (M5) with longer steel fibres IRI 50/30. Over the period of 24 hours since the casting of the test specimens, the autogenous shrinkage of the composite (M2) with shorter steel fibres was 18% less than that of the comparable plain concrete (M1), whereas that of the composite (M5) with longer steel fibres IRI 50/30 was the least over most of the time interval concerned, and 24 hours after casting, was 28% less than that of the comparable plain concrete.

**Figure 7** shows the temperature variation in the middle of the specimens and the autogenous shrinkage of the high-performance plain concrete and composites with 0.50% by volume of polypropylene fibres or shorter (IRI 50/16) or longer (IRI 50/30) steel fibres, over the first 24 hours after casting of the test specimens. From the presented results it can be seen that the autogenous shrinkage of the composite (M2), with 0.50% by volume of polypropylene fibres, was over the first 10 hours, approximately equal to the autogenous shrinkage of the comparable plain concrete (M1), whereas later it was less than that of the latter. During the first 24 hours after the casting of the test specimens, the autogenous shrinkage of the composite (M9) with polypropylene fibres was approximately 15% that of the composite (M3) with shorter steel fibres (IRI50/16), approximately 28% that of the composite (M6) with longer steel fibres (IRI50/30), and approximately 38% less than that of the comparable plain concrete (M1).

**Figure 8** shows the temperature variation in the middle of the specimens, and the autogenous shrinkage of the high-performance plain concrete and composites with 0.75% by volume of shorter (IRI 50/16) or longer (IRI 50/30) steel fibres or polypropylene fibres, over the first 24 hours after casting. From the measurement results it can be seen that the autogenous shrinkage of all the tested composites was, over the first 24 hours after casting of the test specimens, less than that of the comparable plain concrete. It should be noted that the shrinkage of the composite (M10) with polypropylene fibres was the greatest, and amounted, 24 hours after casting, to 26% less than that of the comparable plain concrete. The autogenous shrinkage of composite (M4), which contained the steel fibres IRI 50/16, was, over most of the period concerned, the least, and was, 24 hours after casting, 41% less than that of the comparable plain concrete. The autogenous shrinkage of the composite (M7), which contained the steel fibres IRI 50/30, was, over most of the period concerned, approximately in the middle, between the autogenous shrinkage of the composite with polypropylene fibres and that of the composite containing IRI 50/16 steel fibres, and 24 hours after casting it was approximately 32% less than that of the comparable plain concrete.

The time histories of the total autogenous shrinkage of the sealed test specimens of the high-performance composites with 0.25%, 0.50% and 0.75% by volume of polypropylene fibres or of shorter (IRI 50/16) or longer (IRI 50/30) steel fibres, are shown in **Figs. 9 to 11**. **Figure 9** shows the results of measurements of the total autogenous shrinkage of the high-performance plain concrete and of the composites containing 0.25% by volume of polypropylene or shorter (IRI 50/16) or longer (IRI 50/30) steel fibres. In the first part of the measuring period, up until the 70th day after casting, the differences between the time histories of the autogenous shrinkage of the composite (M8) containing polypropylene fibres, of the composite (M2) containing shorter steel fibres, and of the plain concrete (M1), are very small, whereas over the remaining part of the

![Fig. 8 Autogenous shrinkage of the high-performance composites containing 0.75% by volume of polypropylene or IRI 50/16 or IRI 50/30 steel fibres and of the comparable plain concrete, over the first 24 hours after casting of specimens.](image-url)
measuring period, they amount to between 2% and 5%. The autogenous shrinkage of the composite (M5) containing the longer steel fibres was, over the whole measuring period, the least of all the composites considered. At the end of the measuring period it was 10% less than that of the comparable plain concrete.

The differences between the autogenous shrinkages of the composites (M9), (M3) and (M6), containing 0.50% by volume of polypropylene or shorter (IRI 50/16) or longer (IRI 50/30) steel fibres (Fig. 10) were very small over the first 100 days after casting. During this period, the autogenous shrinkage of the composites considered was approximately 4% less than that of the comparable plain concrete. Over the remaining part of the investigated time period, up until the end of the measurements, the autogenous shrinkage of the composites containing the longer or shorter steel fibres was about 6% to 7% less than that of the comparable plain concrete, but the autogenous shrinkage of the composite containing polypropylene fibres was approximately the same as that of the latter.

The autogenous shrinkage of the composites (M10), (M4) and (M7), containing 0.75% by volume of polypropylene or shorter (IRI 50/16) or longer (IRI 50/30) steel fibres, is shown in Fig. 11. The autogenous shrinkage of the composite with polypropylene fibres was, 70 days after casting of the test specimens, 16% less, and during the remaining period of time up to the end of the measurements 10% less than that of the comparable plain concrete. The autogenous shrinkage of the composite (M7) with longer steel fibres IRI 50/30 was, among all the observed composites, the greatest.
over practically the whole duration of the measurements. The autogenous shrinkage of the composite (M4) with the shorter IRI 50/16 steel fibres was, over the greater part of the measurement period, less than that of the composite with the longer IRI 50/30 steel fibres, but larger than that of the composite with polypropylene fibres.

5.3. Total shrinkage and drying shrinkage of the composites and of the comparable plain concrete

The time histories of the total shrinkage of high-performance composites containing 0.25%, 0.50% and 0.75% of polypropylene fibres or of shorter (IRI 50/16) or longer (IRI 50/30) steel fibres, as well as of the total shrinkage of the comparable plain concrete, all of which were exposed to drying, are shown in Figs. 12, 13 and 14. The time histories of the drying shrinkage of these composites and of the comparable plain concrete are shown in Figs. 15, 16 and 17.

The time histories of the total shrinkage of the composites containing 0.25% by volume of polypropylene fibres or of shorter (IRI 50/16) or longer (IRI 50/30) steel fibres and of the comparable plain concrete are shown in Fig. 12. During the first part of the measuring period, up until the 210th day after casting, the extreme values of the total shrinkage of the composites changed between the three observed composites, over individual shorter time intervals, but in general they were about 15% to 17% less than that of the comparable plain con-
crete. From the 210th day after casting onwards, up until the end of the measurement period, the total shrinkage of all three observed composites varied little between one another, and at the end of the measurement period this shrinkage was 17% less than the total shrinkage of the comparable plain concrete.

The time histories of the total shrinkage of the high-performance composites (M9), (M3) and (M6), containing 0.50% by volume of polypropylene fibres or of shorter (IRI 50/16) or longer (IRI 50/30) steel fibres, and of the comparable plain concrete (M1), are shown in Fig. 13. The total shrinkage of the composite (M9) containing polypropylene fibres was, over the whole measurement period, the least among all three observed composites. On the 14th day after casting, it was 28% less, and, at the end of the measurement period, 23% less than the total shrinkage of the comparable plain concrete. The total shrinkage of the composite with the shorter IRI 50/16 steel fibres was approximately equal to that of the composite with the longer IRI 50/30 steel fibres, and on the 14th day after casting, was approximately 20%, and at the end of measurement period approximately 17% less than the total shrinkage of the comparable plain concrete.

The time histories of the total shrinkage of the high-performance composites (M10), (M4) in (M7), containing 0.75% by volume of polypropylene fibres or of shorter (IRI 50/16) or longer (IRI 50/30) steel fibres, and of the comparable plain concrete (M1), are shown in Fig. 14. The total shrinkage of the composite containing polypropylene fibres was, over the whole measurement period, the least among all three observed composites. On the 14th day after casting of the test specimens, it was 36% less, and at the end of the measurement period 30% less than the total shrinkage of the comparable plain concrete. At the end of the measurement period,
the total shrinkage of the composite with the shorter IRI 50/16 steel fibres was approximately 25%, and that of the composite with the longer IRI 50/30 steel fibres 19% less than the total shrinkage of the comparable plain concrete.

The time histories of the drying shrinkage of the composites containing 0.25% by volume of polypropylene fibres or of shorter (IRI 50/16) or longer (IRI 50/30) steel fibres, and of the comparable plain concrete, are shown in Fig. 15. The drying shrinkage of the composite containing polypropylene fibres (M8), which on the 98th day after casting was approximately 70%, and at the end of the measurement period, 80% less than the drying shrinkage of the comparable plain concrete, was, over the entire measurement period, the least of the measured drying shrinkages of all three investigated composites. The drying shrinkage of the composite (M5) containing the longer (IRI 50/30) steel fibres, which on the 98th day after casting was approximately 35%, and at the end of the measurement period was approximately 46% less than the drying shrinkage of the comparable plain concrete, was, over the whole measurement period, the largest among all three investigated composites. The drying shrinkage of the composite (M2) with the shorter IRI 50/16 steel fibres was, over the whole measurement period, greater than the drying shrinkage of the composite (M8) with polypropylene fibres, and less than that of the composite (M5) with the longer IRI 50/30 steel fibres.

From the results of the experimental investigation of the drying shrinkage of the composites with 0.50% by volume of polypropylene or of shorter (IRI 50/16) or longer (IRI 50/30) steel fibres, it can be seen (Fig. 16) that the drying shrinkage of the composite (M9) containing polypropylene fibres, which on the 98th day after casting of the test specimens was approximately 83%,
and at the end of the measurement period 88% less than that of the comparable plain concrete, was, over the entire observed measurement period, the least of the measured drying shrinkages of all three investigated composites. The drying shrinkage of the composite (M6) containing the longer IRI 50/30 steel fibres, which was, on the 98th day after casting of the test specimens, approximately 43%, and at the end of measurement period approximately 53% less than the drying shrinkage of the comparable plain concrete, was, over the whole measurement period, the largest among all three of the investigated composites. The drying shrinkage of composite (M3), with the shorter IRI 50/16 steel fibres, which was, on the 98th day after the casting of the test specimens, approximately 54%, and at the end of measurement period approximately 59% less than the drying shrinkage of the comparable plain concrete, was, over the whole measurement period, greater than the drying shrinkage of the composite with polypropylene fibres (M9), and less than that of the composite (M6) containing the longer IRI 50/30 steel fibres.

The time histories of the drying shrinkage of the composites (M10), (M4) and (M7), containing 0.75% by volume of polypropylene fibres or of shorter (IRI 50/16) or longer (IRI 50/30) steel fibres, are shown in Fig. 17. The drying shrinkage of the composite (M10) containing polypropylene fibres was the least among the three tested composites. At the end of the measurement period, it was approximately 84% less than that of the comparable plain concrete (M1). The drying shrinkage of composite (M4), with shorter IRI 50/16 steel fibres, was, at the end of the measurement period, approximately 74% less than that of the comparable plain concrete. The drying shrinkage of composite (M7), with the longer IRI 50/30 steel fibres, which, over the entire measurement period, was the largest among the investigated composites, was, at the end of the measurement period, approximately 52% less than that of the comparable plain concrete.

6. Comparison and discussion of the experimental results

The results of our experimental investigation have shown that the early autogenous shrinkage of polypropylene fibre reinforced composites with 0.25%, 0.50% and 0.75% by volume of fibres (Figs. 6 to 8) are, except over the first 8 hours, larger than that of both types of steel fibre reinforced composites. In the case of 0.25% and 0.5% by volume of fibres, the least early autogenous shrinkage was measured in the case of the composite containing the longer IRI 50/30 steel fibres, whereas in the case of 0.75% by volume of fibres, the least such shrinkage was measured in the case of the composite containing the shorter IRI 50/16 steel fibres.

In the case of the young composites, the stiffness and bearing capacity of the steel fibres, and to a lesser extent the polypropylene fibres, are relatively high in comparison with those of the, as yet not hardened, cement paste. For this reason, they affect the general properties of the young composite to a greater extent than in later periods of hardening. The fibre forces are transferred from the fibres into the concrete through the bond along the stress transfer lengths and through the snubbing zones at the cracks, by all types of fibres, and additionally through the end-hooks by steel fibres (Foster 2009). In the case of low fibre contents (0.25% and 0.50%), IRI 50/30 steel fibres are more effective than IRI 50/16 steel fibres or polypropylene fibres in the reduction of the early autogenous composite shrinkage. However, at a fibre content of 0.75% by volume, the IRI 50/16 steel fibres are more effective in the reduction of the early autogenous shrinkage of the composites. One of the reasons for this could be the balling of fibres, which is more frequent in the case of the longer IRI 50/30 steel fibres.
fibres than in the case of the shorter IRI 50/16 steel fibres.

The effect of the type and quantity of contained fibres on the total autogenous shrinkage of the composite at later times of the shrinkage period is relatively small (Figs. 9, 10, 11). Depending on the type and quantity of the fibres, the total autogenous shrinkage of the composites varies from that of the comparable plain concrete by between 0.1% and 9.0%. The fact that, at 0.25% and 0.50% by volumes of fibres, the total autogenous shrinkage of the composites with the longer steel fibres IRI 50/30 was the least, whereas that of the composites with polypropylene fibres was the greatest, is the consequence of the relatively high stiffness of the steel fibres in comparison with that of the polypropylene fibres and of the hardened cement paste, as mentioned a few paragraphs earlier. At a fibre content of 0.75% the total autogenous shrinkage of the composites containing IRI 50/30 steel fibres was the greatest of all the considered composites. This could be due to the increased likelihood of fibre balling.

Taking into account all the considered types and volume percentages of fibres (Figs. 12, 13 and 14), the total shrinkage of the composites was less than that of the comparable plain concrete. The total shrinkage values varied only a little between one another during the whole measurement period. During the greater part of the shrinkage period, the total shrinkage of all the considered composites was between about 15%, at 14 days after the start of the measurements, and 29%, at the end of the measurement period, less than that of the comparable plain concrete.

The drying shrinkage of the composites containing polypropylene fibres (Figs. 15, 16 and 17) was, throughout the whole measurement period, the least and was, at the end of the measurement period, depending on the fibre content, about 79% to 85% less than that of the comparable plain concrete. The drying shrinkage of the composite containing IRI 50/30 steel fibres was over the whole measurement period, the largest among all the investigated composites, and amounted at the end of the measurement period, depending on the fibre content volume, to between 52% and 60% less than that of the comparable plain concrete.

The experimental results showed that the total shrinkage (Figs. 12 to 14), measured on the non-sealed specimens of the composites, and the total autogenous shrinkage (Figs. 9 to 11), measured on the sealed specimens, increased throughout the whole measurement period. The drying shrinkage of the composites (Figs. 15 to 17) represents the difference between the total shrinkage and the autogenous shrinkage of the composites. For this reason, the apparent reduction over time of the drying shrinkage of the composites in the second part of the shrinkage period does not indicate swelling of the composites but is rather a consequence of the fact that, over this period of time, the total shrinkage of the composites decelerates more quickly than the corresponding total autogenous shrinkage. Additionally, the autogenous shrinkage included in the total shrinkage of the composites measured on the non-sealed specimens is not exactly the same as the autogenous shrinkage measured on the sealed specimens.

The drying shrinkage of the composites and of the comparable plain concrete depends to a great extent on the permeability to water of the composite or plain concrete. When steel fibres were added to the concrete there was an increase in water permeability, regardless of the quantity of added fibres or their length. These fibres act as bridges between the pores, so that the flow rate, as well as the water permeability, increases. The value of the water permeability coefficient of plain concrete, which was investigated by Miloud (2005), was 4.02×10⁻¹⁹ m², whereas that of the corresponding concrete composites which had been reinforced with 0.5% by volume of steel fibres was 6.71×10⁻¹⁹ m² for a fibre length of 10 mm, 23.36×10⁻¹⁹ m² for a fibre length of 20 mm, and 65.49×10⁻¹⁹ m² for a fibre length of 30 mm. For this reason, in the case of all fibre volume contents, the drying shrinkage of the composites with IRI 50/30 steel fibres was greater than that of those containing IRI 50/16 steel fibres, but less than that of the comparable plain concrete. The drying shrinkage of the composites containing polypropylene fibres was the least among all the investigated composites.

In the composites, the polypropylene fibres occur partly as individual fibres, and partly in bunches which are distributed within the composite. Taking into account the fact that the wetting angle of the propylene fibres is less than 90° (Felekoglu et al. 2009), it can be assumed that these fibres are not absolutely hydrophobic. Apart from this, 3-dimensional pores are formed between individual fibres in the bunches of fibres. Due to the capillary osmotic pressure, these 3-dimensional pores or channels between the fibres pick up part of the free water from the cement paste (Smolej et al. 1976). This is one of the reasons that the drying shrinkage of high-performance composites containing polypropylene fibres is less than that of composites containing steel fibres.

Reinforcing fibres increase the water permeability of composite (Miloud 2005) and consequently its drying shrinkage, but the stiffness of the contained fibres hinder the drying shrinkage of the composite. For this reason, in the later shrinkage period of quite hardened composite, the contribution of the fibres to its stiffness and consequently to reduction of its drying shrinkage is relatively low. On the other hand, the contained fibres, especially steel fibres, markedly increased the permeability of the composite and consequently its drying shrinkage. While the second effect of fibres (permeability) prevails the first one (stiffness), the drying shrinkage of composites containing polypropylene fibres was, in the later part of the considered shrinkage period, less than that of the composites containing steel fibres. Because the longer IRI 50/30 steel fibres increase the wa-
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References


