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# The effect of fibers on the loss of water by evaporation and shrinkage of concrete

# *Efeito das fibras na perda da água por evaporação e na retração do concreto*

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## Abstract

Shrinkage is one of the least desirable attributes in concrete. Large areas of exposed concrete surfaces , such as in shotcrete tunnel linings, where it is practically impossible to make a moist cure, are highly susceptible to plastic shrinkage at early ages. The autogenous and drying shrinkage can lead to states of greater than threshold strength, causing fracture, mechanical damage and lack of durability of concrete structures. The addition of fibers can greatly reduce plastic shrinkage, but has limited effect in mitigating autogenous and drying shrinkage. To evaluate the performance of polypropylene and steel fibers to understand their effect on shrinkage of concrete, a study was carried out to relate the loss of water from the paste and the shrinkage during the first 28 days of age, and compare it with a control mix without fiber. The loss of water was obtained by the weight loss of the specimens at different ages, since the only component that could contribute for the loss of weight was the water lost by the paste of the concrete. And the paste itself is the only source of shrinkage. Uniaxial compressive tests from very early ages enabled the determination of time when plastic shrinkage ended. It was observed that the control concrete mix lost three times more water and developed plastic and drying shrinkage 60 % higher than the fiber reinforced concrete mixes. It was possible to demonstrate that the reduced loss of water caused by the incorporation of fibers is related to the mitigation of plastic shrinkage. It was observed that the fibers are effective to restrain the movement of water through the cement paste in the plastic state, however such effect is limited after concrete starts the hardening state.

***Keywords***: fiber reinforced concrete, plastic shrinkage, drying shrinkage, water loss, early age properties.

## Resumo

A retração é um dos atributos menos desejáveis em concreto. Grandes áreas de superfícies expostas de concreto, tais como nos túneis em concreto projetado, onde é praticamente impossível proceder a uma cura úmida, são altamente suscetíveis à retração plástica nas primeiras idades. Retrações autógena e por secagem podem conduzir a estados de tensões maiores que a limite, provocando fratura, comprometimento mecânico e da durabilidade das peças de concreto. A adição de fibras pode reduzir consideravelmente a retração plástica, mas apresenta efeito limitado na mitigação das retrações autógena e por secagem. Na busca pela avaliação do desempenho das fibras e entendimento dos seus efeitos na retração do concreto relacionou-se a perda de água da pasta com a retração no período dos primeiros 28 dias. Concretos reforçados com fibras de polipropileno e de aço tiverem seus desempenhos em retração e perda de água comparados com um traço de controle sem fibra. A perda de água foi obtida pela perda de peso dos espécimes em diferentes idades, pois o único componente que contribui para a perda de peso é a perda de água pela pasta. E a pasta é a única fonte de retração. Testes de compressão uniaxial em idades muito precoces auxiliaram na determinação da idade quando a retração plástica terminou. Foi observado que o traço de controle perdeu três vezes mais água e desenvolveu retração plástica e por secagem 60 % mais altas do que os traços com fibras no mesmo período. Foi possível demonstrar que a redução da perda de água causada pela incorporação das fibras está relacionada com a mitigação da retração plástica. Observou-se que as fibras são eficazes em conter o movimento de água através da pasta de cimento no estado plástico, mas o mesmo não se dá após o início do endurecimento do concreto.

***Palavras-chave:*** concreto reforçado com fibra, retração plástica, retração por secagem, perda de água, propriedades nas primeiras idades.

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## 1. Introduction

Plastic shrinkage is the volume contraction due to the loss of water in the plastic paste. Drying shrinkage is the volume change associated with the loss of water from the hardened paste structure. Autogenous shrinkage is the change due to the consumption of water during the hydration process. Shrinkage has harmful effects on concrete structure life span if the right measures are not taken place on time [1]. For this purpose, it is reported in the history of concrete that Romans, more than 2000 years ago, incorporated horse hair to reduce shrinkage in concrete; as well as the industry of concrete technology has developed shrinkage-reducing admixtures to reduce the harmful effects of shrinkage. It is also largely accepted that plastic shrinkage can be prevented through wet curing, however large areas of exposed concrete surfaces, such as lining of tunnels in shotcrete, where is practically impossible to make a moist cure, are highly susceptible to plastic shrinkage [2]. Tunnels are also subjected to great movement of warm or cool air, which propitiates evaporation, increasing water loss and consequent plastic shrinkage on the concrete surface [3]. If the loss of water is severe, internal strains may develop due to capillary pressures in the concrete mass causing concrete to shrink [4]. In structures restrained by a substrate, such as tunnel linings and concrete sidewalks, shrinkage generates internal tensile stresses in the concrete mass that can lead to crack if the internal tensile stress exceeds the low tensile strength of the concrete at early ages [1,2]. It is reported in the literature that plastic shrinkage cracking in concrete develops within about the first 3 hours after placement of the material and have a "map" like pattern [5]. Plastic shrinkage cracks can cross an entire slab and form planes of weakness reducing the integrity of the structure before concrete has achieved its final strength. The addition of fibers, such as steel and polypropylene, can bridge the forces across the cracks and can reduce plastic shrinkage cracking up to 70-80 % [5].

Currently polypropylene fibers are the favorite in tunnels because they prevent concrete spalling during events of fire [6,7]. In the plastic state, such fiber inhibits exudation and segregation due to their large surface area, by the accumulation of water on its surface, suppressing plastic shrinkage cracking at early ages. They are low cost, easily dispersible and inert in high pH. It has been reported that polypropylene fibers are more effective for this purpose than steel fibers [2,5,6,7].

If the loss of water in the paste is closely related to shrinkage, it will be possible to cross both parameters to better understanding the phenomenon of shrinkage on its different phases, plastic and hardened. This procedure can lead to a better choice for the compounds of a concrete mixes.

However, it is important to determine when plastic shrinkage ended and concrete started the hardening process. Some authors call this time as the *"time zero"* [8]. Up to now, there is no agreement among the technical community, on the exact time to be considered "*time zero*"; some adopted the initial setting time; others the final setting time; and others even another different time [8].

This paper aims to determine the influence of fibers, not only on plastic shrinkage, but also on drying shrinkage, by crossing the loss of water with measured shrinkage on unloaded specimens, during the first 28 days, for 3 concrete mixes: Plain Concrete (PC) as control, Polypropylene Fiber Reinforced Concrete (PFRC) and Steel Fiber Reinforced Concrete (SFRC).

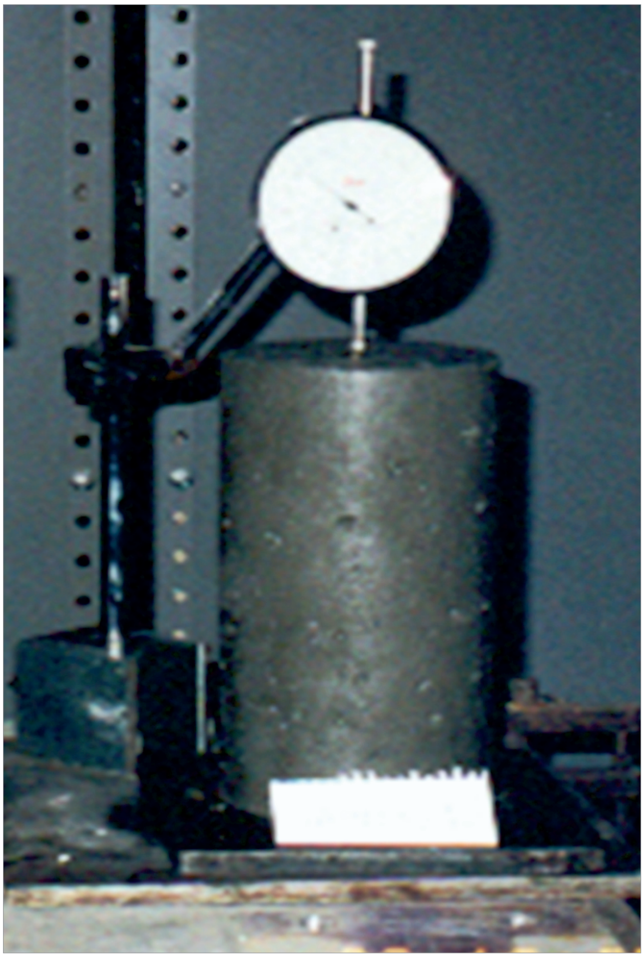
## 2. Materials and experimental program

The basic plain concrete (PC) used as a control mix for the steel (SFRC) and polypropylene (PFRC) fiber reinforced mixes, consisted of: Australian type SL (shrinkage limited) Portland Cement (420 kg); silica fume (40 kg); fly ash (60 kg); coarse aggregate (450 kg) (10 mm crushed river gravel); coarse sand (770 kg); fine sand (370 kg); water (210 kg) and Rheobuild 100 superplasticizer (1 liter); the water/ binder ratio was 0.40 (Table 1). Fibers were added to the above reference mix to produce the two fiber reinforced concrete mixes (PFRC and SFRC). Novotex FE 0730 steel fiber for SFRC, with tensile strength of 1200 MPa; modulus of elasticity

Table 1 – Mix proportion for PC, SFRC and PFRC

| Mix | Control | Steel fiber | Polypropylene fiber |
|---|---|---|---|
| | (PC) | (SFRC) | (PFRC) |
| Portland Cement (kg/m$^3$) | 420 | 420 | 420 |
| Silica fume (kg/m$^3$) | 40 | 40 | 40 |
| Fly ash (kg/m$^3$) | 60 | 60 | 60 |
| Coarse aggregate (kg/m$^3$) | 450 | 450 | 450 |
| Coarse sand (kg/m$^3$) | 770 | 770 | 770 |
| Fine sand (kg/m$^3$) | 370 | 370 | 370 |
| Water (kg/m$^3$ and W/B ratio) | 210 and 0.4 | 210 and 0.4 | 210 and 0.4 |
| Superplasticizer (liter) | 1 | 1.6 | 0.75 |
| Steel fiber (kg/m$^3$ and vol.%) | – | 60 and 2.5 | – |
| Polypropylene fiber (kg/m$^3$ and vol.%) | – | – | 9 and 1 |
| Moist content (%) | 10.2 | 9.9 | 10.2 |

Figure 1 – Shrinkage specimen



of 210 GPa; 30 mm long by 1.5 mm in diameter; flat ends, were added at a proportion of 2.5% by weight of concrete (i.e. at a dosage of 60 $kg/m^3$). The specific weight of the steel fiber was 7.9 ($kg/dm^3$) and the dosage rate by volume was therefore 0.76% (based on a concrete density of 2400 $kg/m^3$). Polypropylene S-152 HPP fibers were used for PFRC mix. These crimped fibers were 50 mm long, 2.5 mm diameter, specific weight of 0.91 ($kg/dm^3$), with a tensile strength of 400 MPa and a modulus of elasticity of 4.80 GPa. And a dosage rate of 0.38% by weight of concrete (i.e. 9 $kg/m^3$) or 1% by volume. The SL (shrinkage limit) type of Portland Cement was specified by AS 3972 94 , which allows a maximum drying shrinkage strain of 750 µstrain at 28 days of age, with shrinkage tests starting from 7 days of age [10]. The superplasticizer was a sodium naphthalene formaldehyde sulphonate based admixture (Rheobuild 1000, BASF), with solids content of 38-42%.

The moisture content was measured by using standard small tin containers filled with the fresh concrete and weighed immediately on a high precision scale, while the cylinders were casted. The tins were placed in a multi-use electrical oven with a temperature of 105 ºC for more than 12 hours. After that, when the samples have cooled they were weighed again. For example, for PFRC the self-weight of the container was 25.8 g, the wet concrete weighed 167.9 g; the dry concrete weighed 152.3 g. Therefore the mass of water evaporated was 15.6 g, which provided a moisture content of 10.2 % for PFRC.

The loss of water was obtained by the weight loss of the specimens at different ages, since the only component that could contribute for the loss of weight was the water lost by the paste of the concrete. And the paste itself is the only source of shrinkage.

Shrinkage and compressive strength were measured on cylinders of 100 mm diameter x 200 mm (see Figure 1). Plastic cylinder moulds with a longitudinal cut and tighten by belts allowed to strip the specimens with no disturbance, enabling testing the green concrete at very early ages, say less than 4 hours after casting. Moisture content was taken from all mixes; PC and PFRC had 10.2 % moist content, while SFRC had 9.99%. All specimens were stored and tested in the same ambient conditions (T= 23 ºC and RH= 73%), and stripped from moulds at 4 hours after casting.

Shrinkage tests started at 4 hours after casting without any wet cure, using the standard apparatus with dial gauges with divisions of 0.002 mm as shown at (Figure 1). During the first 12 hours, readings of shrinkage and RH were taken at each hour. Compressive strength (Table 2) and weight loss were taken at every 2 hours in the first 8 hours. After this age, shrinkage and RH were measured every day; while weight loss and compressive strength were measured at 24, 72, 96, 168 and 672 hours. No specific autogenous shrinkage test was performed on sealed specimens, therefore the measured shrinkage here presented contains the plastic, the autogenous and the drying components depending on the age analyzed.

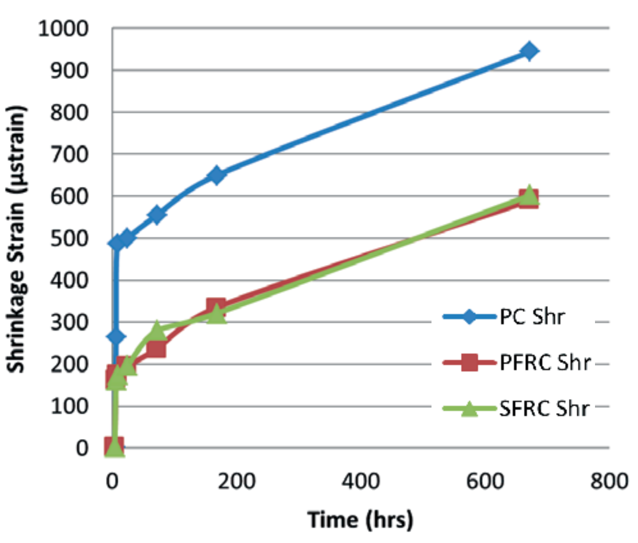
## 3. Results and discussions

The compressive strength results for PC, PFRC and SFRC from 2 hours to 28 days after casting, as a reference of the mixes are presented at Table 2. It can be observed that the Fiber Reinforced Concretes developed higher compressive strengths during the first

Table 2 – Compressive strength (MPa)

| Mix | 2 hrs | 4hrs | 6 hrs | 8 hrs | 24 hrs | 72 hrs | 168 hrs | 672 hrs |
|---|---|---|---|---|---|---|---|---|
| PC | 0.03 | 0.09 | 0.3 | 0.7 | 16 | 27.3 | 32 | 38.4 |
| PFRC | 0.08 | 0.39 | 1.15 | 2.0 | 15.3 | 23.6 | 30 | 37.5 |
| SFRC | 0.08 | 0.3 | 0.7 | 1.64 | 14.3 | 23 | 29 | 35 |

Figure 2 – Shrinkage strain versus time during 28 days test



8 hours of age when compared with the control mix PC. Fibers may act like a sort of accelerator, interfering on setting time of concrete, as Soroushian et al apud Tanesi and Figueiredo [6] already mentioned. Soroushian et al found that fibers can accelerate the initial and final set from 9% to 27% respectively with and addition of 0.1 % of fibers, but not enough data to prove such find yet. Based on Mindess [9], the final setting time starts when concrete achieves a compressive strength of 0,7 MPa in a cylindrical specimen under compression test. Therefore, based on Table 2, it can be implied that PFRC has set say at 5 hours after casting, SFRC from 6 hours after casting, while PC sets from 8 hours of age on. After 8 hours of age, all mixes developed similar compressive strengths, where PC indeed developed compressive strengths slightly higher than PFRC and SFRC as shown on Table . These facts will be also observed on the studies of shrinkage and loss of water presented subsequently.

The Shrinkage curves depicted at (Figure 2) are the average measure of 2 specimens. It shows that PC developed a total shrinkage strain at 28 days of age of about 944 µstrain, while PFRC and SFRC had similar behaviour with 590 µstrain and 602 µstrain, respectively. Therefore, PC had 60 % more total shrinkage than PFRC and SFRC, demonstrating that the fibers are the sole compound that might contribute for the reduced shrinkage in these mixes. As can be also observed, PFRC and SFRC developed steep shrinkage curves in the first 6 hours of age reaching about 160 µstrain, while PC developed a significant steep shrinkage curve during the first 8 hours of age reaching 485 µstrain (Figure 2). After 8 hours of age all mixes developed similar shrinkage rates as shown in (Figure 3). Therefore, based on Table 2 and Figure 3, it can be assumed that PFRC and SFRC are on their plastic state prior 6 hours of age, while PC is on its plastic state until 8 hours of age. After that, all mixes behaved similarly with regard shrinkage and compressive strength, showing that the fibers are effective on mitigating plastic shrinkage, but does not interfere during the hardening state.

When Shrinkage and Loss of Water are analysed altogether along the period of 28 days, as shown in (Figure 4), PC also had an inferior performance if compared with its fiber counterparts, losing 8%

Figure 3 – Shrinkage strain versus time with de dominium of plastic and hardening states

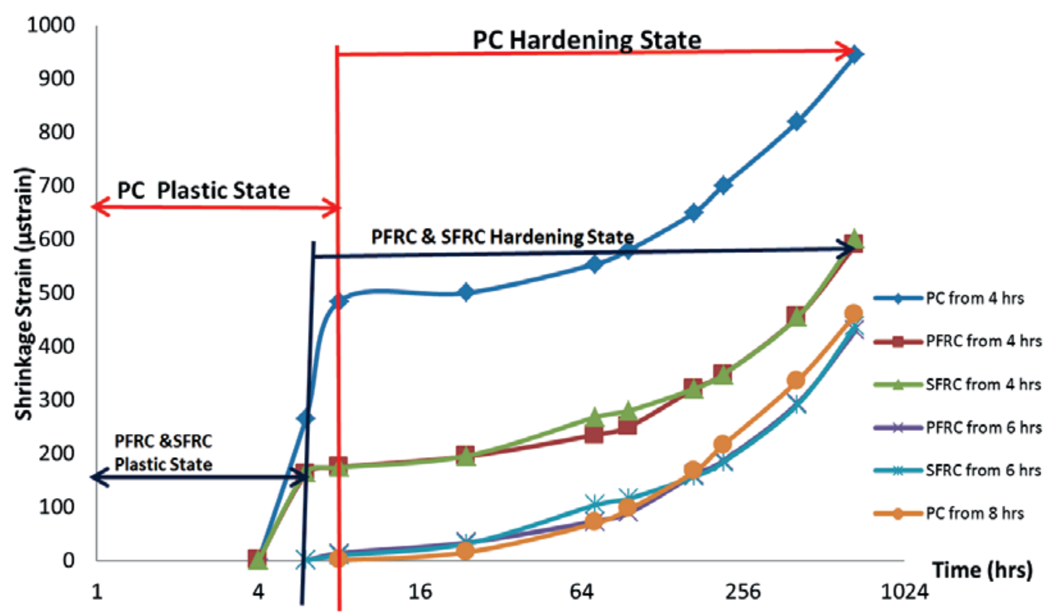
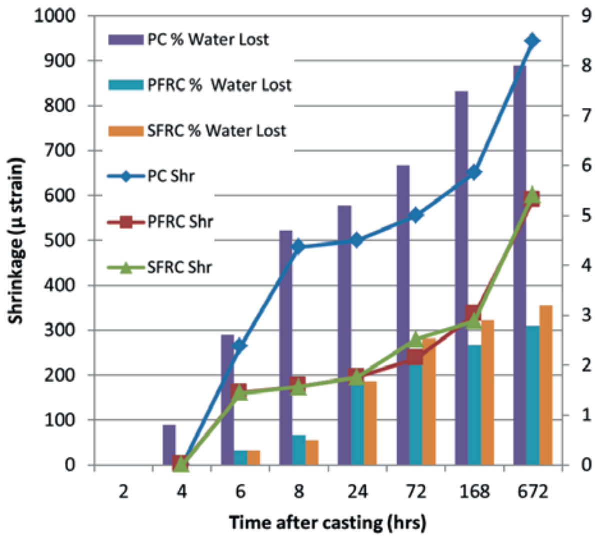


**Figure 4 – Results of tests on shrinkage strain and loss of water of PC, SFRC and PFRC**



of its initial moisture content, while PFRC and SFRC lost 2.8% and 3.2 % respectively, during the same period of time. It can also be observed at Figure 4 that the PFRC and SFRC lost 0.6% and 0.5 % respectively of its initial moisture content during the first 8 hours after casting, which is a minor quantity if compared with the 4.7 % lost by PC in the same period. This period of time can be associated with the phase of the most vigorous plastic shrinkage at PC, as described on the previous paragraph. Most of the water lost by PFRC and SFRC happened during the hardened phase (2.2% and 2.3 % respectively), while PC lost a great quantity of water (4.7%) during its plastic phase and 3.3 % on its hardening. Therefore, after 8 hours of age, in the hardening state, all mixes lose water in a similar manner (Figure 4), developed similar shrinkage strain rates (Figure 3), and similar compressive strengths (Table 2).

Therefore, the fibers provided an effective mechanism to inhibit exudation and segregation during the plastic phase, by accumulating water on its surface by adsorption, resulting on both, lower shrinkage and loss of water than PC, of around 1/3 of what PC presented. Polypropylene fibers performed better than steel fibers because even PFRC having slightly higher moist content than SFRC, it still retained more water than SFRC and developed smaller shrinkage than SFRC. This can be regarded to its long length and large surface area. Such facts justify the use of fibers, and can clearly demonstrated that while plastic shrinkage prevailed, the fibers were highly effective to adsorb water impeding the movements of water in the paste, diminishing evaporation during the plastic state.

Also based on Cusson [8] the called *"time zero"* to identify at which time shrinkage can cause stresses, it could be assumed that it corresponds to the initial time of the "*hardening state"* at Figure 3. For PFRC and SFRC this time can be 6 hours and to PC corresponds to 8 hours; and the shrinkage which happened before this time can be disregarded for shrinkage stress calculation, in a restrained element.

## 4. Conclusions

Both, Polypropylene and Steel fibers, presented effective performances on reducing plastic shrinkage in comparison with the plain control mix. It was clearly demonstrated that shrinkage is closely related to the loss of water, as PC lost 3 times more water during the first 28 days of age than PFRC and SFRC. Also PC achieved the highest shrinkage strain of 944 μstrain, while PFRC and SFRC achieved 36% less shrinkage during this same period of time.

When the hardening state started, all mixes attained similar shrinkage strains and lose water in similar rates, demonstrating that fibers were effective on impeding the loss of water during the plastic state, but were not as effective after this phase.

PFRC had a slightly superior performance when compared with SFRC with regard to reduction of shrinkage, loss of water and compressive strength during the plastic phase. It could be observed that indeed fibers seem to accelerate setting, which is a topic to be explored in future.

It is also possible to identify the plastic and hardening phases of concrete on the shrinkage strain curves tested from early ages. The plastic phase coincides with the steep part of such curves; and the hardening phase is the region of the curve where it becomes steady with lower increases rates of strains. This is only possible to obtain when shrinkage tests start at very early ages.

Finally, it can be seen from the above that the method of separating the volume fraction of paste from a mix; weighing the samples from very early ages and crossing its values with the shrinkage measured at the same period of time, showed to be effective to a better understanding of the phenomenon of shrinkage to identify its plastic and hardening phases.

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