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Experimental study on flexural creep of self-compacting concrete reinforced with vegetable and synthetic fibers

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Amouri Chahinez[1,3]
https://orcid.org/0000-0003-3295-9024
Belkadi Ahmed Abderraouf[2,4]
https://orcid.org/0000-0002-4271-7988
Achour Yacine[2,5]
https://orcid.org/0000-0003-4249-5884
Kessal Oussama[2,6]
https://orcid.org/0000-0002-3669-6164

[1]University Mentouri of Constantine, Laboratory of Materials and Durability of Constructions (LMDC), Algeria.

[2]Mohamed Elbachir Elibrahimi University of Bordj Bou, Department of Civil Engineering, Arreridj, Algeria.

E-mails : [3]amouri.chahinez@umc.edu.dz, [4]ahmedabderraouf.belkadi@univ-bba.dz, [5]y.achour@univ-bba.dz, [6]oussama.kessal@univ-bba.dz

Abstract

This article evaluates the impact of different fiber types on the flexural creep of self-compacting concretes (SCC). The study focuses on the effects of vegetable fibers (Hemp, [H] and Dis [D]) and synthetic fibers (Polypropylene [P]) on SCC. To assess the SCC, various tests such as spreading, J Ring, compressive strength, and flexural strength are conducted. The authors developed a test configuration and methodology to subject beams measuring 120 cm in length to sustained flexural stresses for 200 days. Two curing modes of the beams are also studied: total creep (beams exposed to air) and endogenous creep (beams protected from air). Moreover, the plant fibers were previously subjected to two treatments separately; the first involves immersing them in a 5% alkaline solution of NaOH (HN and DN) and the second in a solution of the polymer styrene-butadiene rubber (SBR) (HS and DS). The findings show that the treatment of vegetable fibers by SBR reveals high mechanical properties as well as a good capacity for endogenous and total creep. SCC-DS shows an increase in flexural strength of 9% and 13% with a decrease in total creep of 4% and 16% compared to SCC without fiber and SCC-DN, respectively. These results are promising for further reflection on a large scale to explore the issue of strengthening SCC with treated vegetable fibers.

Keywords: self-compacting concrete, vegetable fibers, hemp, dis, polypropylene, styrene-butadiene rubber, flexural creep.

1. Introduction

The deformation of concrete structural members under continuous load (creep) is known to be several times greater than the instantaneous deformation during loading (Babafemi & Boshoff, 2015). This allows us to consider the deformation due to creep as an important factor in the realization of constructions in the medium to long term (García-Taengua *et al*., 2014). The bending creep type has two major advantages. It is easier to perform and can be directly correlated to the bending test for better characterization. Self-compacting concrete (SCC) is generally considered as a special type of ordinary concrete containing high amounts of fines and a lower water-to-binder ratio compared to other concretes (Bensalem *et al*., 2014). This leads to greater delayed deformations of SCC compared to ordinary concrete (Benkechkache & Houari, 2009). Therefore, self-compacting concrete has particular responses concerning creep.

The effectiveness of using fibers as reinforcement in self-compacting concrete has already been demonstrated in reducing creep deformation and improving some mechanical properties (Basser *et al*., 2022; Li *et al*., 2021b; Marangon *et al*., 2012). However, most of the tests have been conducted on SCC reinforced with steel fibers and/or polypropylene, despite their high cost and considerable CO_2 emissions during production from non-renewable resources (Denzin Tonoli *et al*., 2010). As a result, current research is exploring the possibility of replacing these fibers with natural ones (Wei & Meyer, 2015). Plant fibers, which are biodegradable and renewable (Di Bella *et al*., 2014), offer a sustainable option and can be obtained from local resources in certain countries, such as Algeria.

Thus, vegetable fibers can make it possible to achieve interesting mechanical properties, while significantly reducing the cost price of the cementitious composite (Denzin Tonoli *et al*., 2010; de Andrade Silva *et al*., 2010; Ahmed, 2013). In research (Mohamed *et al*., 2010), the authors found that natural fibers reduce the static segregation of SCCs. (Ahmed , 2013) showed that adding 2 kg/m^2 of flax fibers reduces SCC workability and increases compressive and tensile strength with a percentage of 8.3 and 17, respectively. (Awwad *et al*., 2012) found an increase in flexural strength of 30% for concrete with 0.5% hemp fibers and a decrease in compressive strength of 20% at 28 days. Walid Laifa (Laifa *et al*., 2014) explained that the improvement in tensile strength by bending of SCCs with Dis fiber is probably due to the roughness of this fiber.

Most of these studies were conducted for the effect of natural fibers on the properties of cementitious materials in the short term (de Azevedo *et al*., 2021; Banjo Ayobami Akinyemi & Dai, 2020; Reis, 2012). However, in order to use these fibers in structural applications, it is necessary to study their long-term behavior. Sales (2006) studied the effect of bamboo pulp fibers on the compression creep of cementitious composites. It was concluded that the presence of 8% and 14% of bamboo fibers causes an increase in basic creep capacity of 6 and 11 times greater than for the matrix without fiber, respectively. Iranildo Barbosa da Silva *et al*. (da Silva Junior *et al*., 2021) studied the tensile and flexural creep behavior of cementitious materials containing sisal fibers. The authors used these fibers with natural humidity and saturated with water. They found that the composites made from the natural moisture fibers showed larger cracks due to the low pull-out strength of these fibers. On the other hand, composites with saturated fibers showed greater deformation and efficiency in maintaining cracks. They concluded that it is necessary to give importance to the ITZ between the plant fiber and the matrix.

Currently, there is significant interest among researchers in the treatment of plant fibers to enhance the physical and mechanical properties of cementitious composites through improved matrix/fiber adhesion. This has been explored in several recent studies, including those by Li *et al*., Dridi *et al*., and Chiker *et al*. (Li *et al*., 2021b; Dridi *et al*., 2022; Chiker *et al*., 2021; Kundu *et al*., 2018). Belkadi *et al*. (Belkadi *et al*., 2018) sought to replace a significant portion of cement with 30% of metakaolin to reduce the degree of alkalinity in the composite and improve the durability of plant fibers. Other researchers have investigated the effects of NaOH treatment on plant fibers such as Dis and Sisal, which has been found to increase matrix/fiber adhesion and reduce impurities on the fiber surface (Dridi *et al*., 2022; Li *et al*., 2021b). In a recent study, (Candamano *et al*., 2021) demonstrated that the use of commercial acrylic latex in the cementitious matrix improved the adhesion between chemically pretreated hemp fibers and the matrix, resulting in decreased water porosity in the composite. Ferreira *et al*. (Ferreira *et al*., 2020) found that immersing hemp fibers in a styrene butadiene polymer significantly enhanced the adhesion of the matrix/fiber and improved the tensile strength of these fibers. Furthermore, recent works by Candamano *et al*. (2021), Fidelis *et al*. (2016), and Li *et al*. (2021), and Banjo A Akinyemi & Adesina, (2021). have demonstrated good compatibility and bonding between plant fibers and polymers.

The aim of this research is to assess the potential of utilizing Hemp fiber and Dis, treated with NaOH and styrene-butadiene, as reinforcing elements in self-compacting concrete (SCC). The study investigates the impact of the nature of fibers (Dis, hemp, and polypropylene) on the fresh behavior of SCCs, evaluated using the test of spreading and J Ring, as well as their hardened behavior, measured by compressive and flexural strength. Additionally, the delayed behavior of the different SCC mixtures, including total and endogenous flexural creep, was examined. The findings of this study may assist in the acceptance of the incorporation of pre-treated plant fibers by industry and standards compliance bodies.

2. Materials and methods

2.1 Materials

Portland CEMI 42.5 cement and LF limestone filler were utilized as the binder in this study. Table 1 provides information on the chemical composition and physical properties of the cement and LF. class 0/3 sand was sourced from limestone rock with a density of 2680 kg/m^3, while class 3/8 and 8/15 gravels, with a density of 2600 kg/m^3, were selected. Additionally, a super-plasticizer of Glenium 26 type, based on polycarboxylic ether, was employed. The study included two types of fibers: plant-based (Hemp and Dis) and synthetic (Polypropylene).

Table 1 - Chemical composition and physical properties of cement and limestone filler (LF).

Component (%)	CaO	SiO_2	Na_2O	Al_2O_3	K_2O	P_2O_5	Fe_2O_3	SO_3	Specific gravity (kg/m^3)	Blaine (cm^2/g)
LF	55.88	0.01	0.01	0.01	0.01	0.01	0.01	0.002	2700	4100
Cement	61.60	20.4	/	5.53	/	/	3.54	2.29	3100	3600

Hemp fiber is widely cultivated in China, Canada, and Europe due to its high tensile strength of between 600 and 1100 MPa, making it suitable for use in various applications, including the paper industry and as a reinforcement material in cementitious composites (Hamzaoui *et al*., 2014). Dis fiber (Ampélodesmos Mauritanicus) which is derived from Ampélodesmos Mauritanicus, is a wild grass species that is found in the Mediterranean basin. It is abundant in countries, such as the Maghreb, Greece, Spain, and southern France. Its fibrous nature makes it an ideal candidate for use as a conventional fiber in cementitious materials (Laifa *et al*., 2014). The Hemp and Dis fibers used in this study were cut to a length of about 2 cm. To remove impurities and improve the adhesion between the vegetable fibers and the matrix, the fibers were treated with a solution containing 5% of sodium hydroxide (NaOH) at a temperature of 20° C for two hours. These fibers are then dried in front of a heater at a temperature of 40° C. Subsequently, the fibers were dried at 40°C to remove any residual moisture. This chemical treatment removes lignin and waxy substances from the surface of the fiber cell wall. NaOH is a commonly used chemical solution for bleaching and/or cleaning the surface of vegetable fibers

(Reis, 2012). Additionally, the vegetable fibers were treated by immersing them in a solution of styrene-butadiene rubber (SBR) for 20 minutes, followed by drying at 25°C (Figure 1). According to literature, this treatment significantly reduces the water absorption of vegetable fibers, thereby improving the fiber/matrix adhesion (Ferreira *et al.*, 2020). Table 2 presents the mechanical and physical characteristics of untreated vegetable fibers and polypropylene.

Table 2 - The physical, chemical, and mechanical characteristics of plant fibers and polypropylene.

Fiber nature	Hemp (Sedan *et al.*, 2007)	Dis (Laifa *et al.*, 2014)	Polypropylene (Laifa *et al.*, 2014)
Absolute density (kg/m^3)	1580	1320	900
Lignins (%)	6	35	/
Cellulose (%)	56.1	43	/
Hemicellulose (%)	10.9	8	/
Tensile strength (MPa)	600-1100	376	450
Diameter (μm)	110	900-2480	24.2
Water absorption (%)	158	90	/

Figure 1 - Photographs showing the different fibers used.

2.2 Mixture proportions

The Bétonlab-Pro software (de Larrard & Sedran, 1996) was utilized to determine the design of SCC mixes, taking into account all data relating to the materials used. A total of six formulations were prepared, which included SCC without fiber (SCC-C), SCC with hemp fiber treated with NaOH (SCC-HN) and with SBR (SCC-HS); SCC with Dis fiber treated with NaOH (SCC-DN) and with SBR (SCC- DS); and SCC with polypropylene fiber (SCC-P). A fixed quantity of binder, consisting of cement and limestone filler, was chosen at 520 kg/m^3. Consequently, the same amount of aggregates was used for all the SCCs with fibers, with slight adjustments made to the water content and superplasticizer. The fiber content was uniformly set at 2 kg/m^3. Table 3 displays the proportions of the self-compacting concrete mixtures developed in this study.

Table 3 - The proportions of self-compacting concrete with and without fibers.

Quantities (kg/m^3)	Cement	Limestone Filler	Sand	Gravel (3/8)	Gravel (8/15)	Water	SP	fibers
SCC-C	400	120	804.8	161.3	648.8	203	9.5	/
SCC-PP						208	10.1	2
SCC-HEN						208	10.1	2
SCC-HES						208	10.1	2
SCC-DSN						203	10.1	2
SCC-DSN						203	10.1	2

2.3 Sample preparation and testing procedure

All six mixes of self-consolidating concrete (SCC) were prepared in accordance with EN-206-1 (NF-206-1 2004) using a 60-liter capacity concrete mixer. Fresh property tests, including the Spread and J ring tests, were conducted after preparing the SCC. The SCC mixtures were then poured into steel molds and left for 24 hours. After this time, specimens measuring 10x20 cm^2 and 7x7x28 cm^3 were removed from the molds for compressive and flexural strength tests, respectively. These specimens were then hardened in water at 20 ± 2°C until the age of the test (7 and 28 days).

The beams for bending creep were cast in prismatic molds measuring 10x10x120 cm^3. After demolding, half of the beams were completely sealed with three layers of adhesive aluminum foil to determine the endogenous creep, while the remaining specimens were left unprotected to determine the total creep. Both types of beams were stored in a room with a temperature of 20 ± 1°C and humidity of 55 ± 5%.

To measure the deflection at the mid-span of the joist, the beams were placed on a suitable frame and subjected to "four-point" bending using a manual loading system. A comparator with a precision of 1/1000th (0.001 mm) was used to measure the displacement on the side of the face in tension. The loading was imposed after 7 days of curing in ambient air, with a constant 120 kg load applied to the four mixtures, equivalent to 35% of the breaking load of the control concrete without fiber at 7 days. The deflection was manually measured at regular intervals over a charging time of more than 200 days. Figure 2 illustrates the different beams subjected to a continuous flexural load.

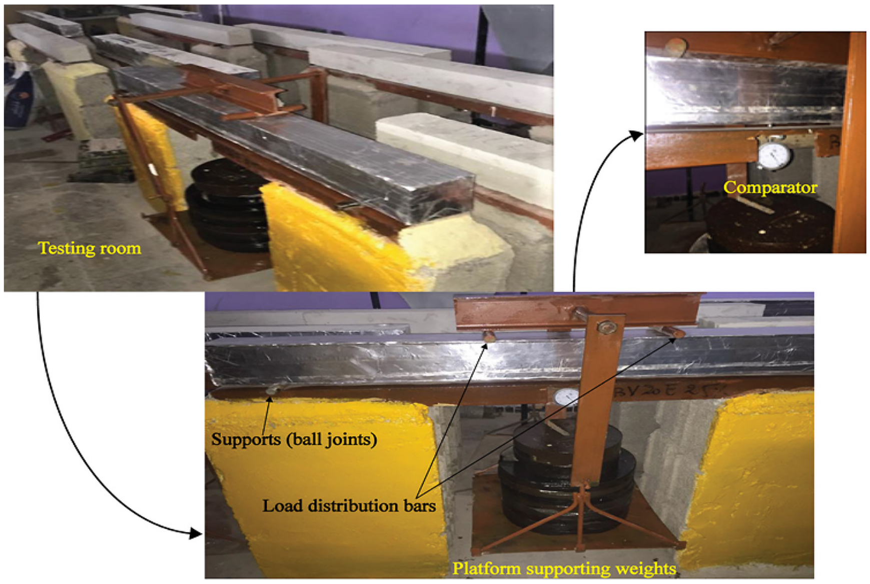

Figure 2 - Flexural creep device (Benkechkache & Houari, 2009).

3. Results and discussion

3.1 Fresh properties

The spread test evaluates the ability of SCC to deform under weight against a wall surface, while the J-Ring test measures the flow capacity of SCC in a confined medium. Figure 3 illustrates the variation in the spread and J-Ring diameters of SCCs. The results show that the spread of the different SCCs ranges from 60 cm to 73 cm, indicating satisfactory spreading in all mixtures in accordance with the criteria required by the EN-206 standard. However, the presence of fibers had a slightly negative effect on workability. The treatment of plant fibers with SBR improved the fluidity of SCC compared to fibers treated with NaOH, possibly due to the decreased water absorption and the good distribution of SBR-treated fibers, avoiding the effect of clogging. According to (Ferreira *et al*., 2020), coating natural fibers with SBR considerably decreases their water absorption. Regarding the J-Ring diameter, the presence of P and Hemp fibers had a negative effect on the ability of SCCs to pass through a confined medium, with values ranging from 50 to 61 cm. However, mixtures showed good homogeneity and cohesion.

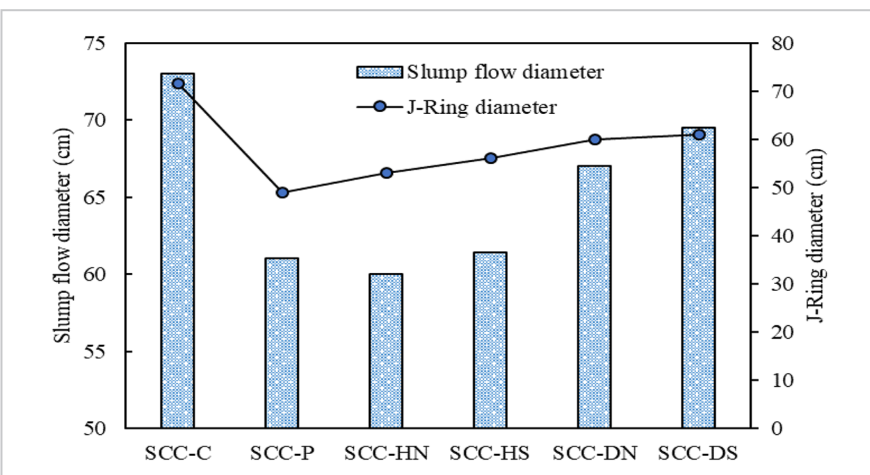

Figure 3 - Effect of fibers on the diameters of the spread and the J-Ring of the different SCCs.

3.2 Mechanical properties
3.2.1 Compressive strength

Figure 4 shows the compressive strength of the SCC-C, SCC-P, SSC-HN, SCC-HS, SCC-DN, and SCC-DS mixtures at different ages. The introduction of P fibers causes a decrease in compressive strength of 12% and 6% compared to the strength of the SCC-C at 7 and 28 days, respectively. Banthia & Sheng (1996) reported that the weak interfacial bonding between polypropylene fibers and cement paste is due to their smooth surface. Furthermore, polypropylene is chemically inert and hydrophobic, which eliminates the possibility of chemical bonding.

The compressive strength of the SCC-HS mixture is 6% higher than that of SCC-HN. Moreover, SCC-DS exhibits an overall increase in strength compared to the other SCCs. These results demonstrate the effectiveness of treating plant fibers with SBR. This treatment enhances the compatibility between vegetable fibers, and SBR latex and improves the adhesion of the transition zone between the fibers and the matrix (Ferreira *et al*., 2020; Fidelis *et al*., 2016; Li *et al*., 2021a). In addition, this treatment offers protection for plant fibers against the alkaline environment of cement. Coating plant fibers with SBR considerably reduces their water absorption which promotes complete hydration of cement (Banjo A Akinyemi & Adesina, 2021).

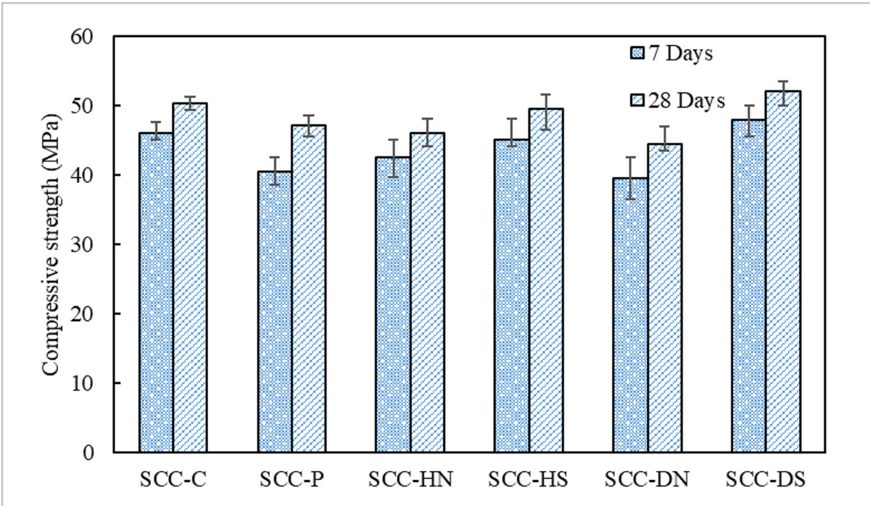

Figure 4 - Effect of vegetable fibers on the compressive strength of SCCs.

3.2.2.Flexural strength

Figure 5 shows the flexural strength of the SCC-C, SCC-P, SSC-HN, SCC-HS, SCC-DN, and SCC-DS mixtures obtained at different ages. The results reveal that the SCC-P mixture exhibits a decrease in bending strength by about 2% compared to the SCC-C at various ages. On the other hand, SCC-HS shows an increase in strength of 11% and 8% compared to SCC-C and SCC-HN, respectively at 7 days. Furthermore, SCC-DS demonstrates a 9%, 13%, and 4% higher flexural strength than SCC-C, SCC-DN, and SCC-HS, respectively, at 28 days. According to Walid Laifa *et al.*, (2014), the enhancement in tensile strength by bending of SCCs with Dis fiber is likely due to the roughness of this fiber. These findings indicate that the treatment of vegetable fibers with SBR leads to an improvement in the mechanical performance of self-compacting concrete.

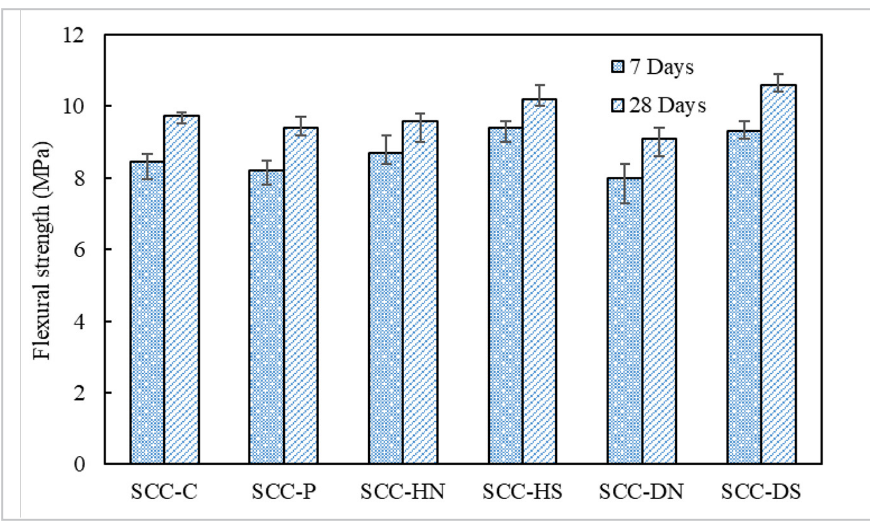

Figure 5 - Effect of vegetable fibers on the flexural strength of SCCs.

3.2.3 Relationship between compressive and flexural strength

The relationships between the compressive and flexural strength of the different mixtures are shown in Figure 6. It emerges from these results that the compressive strength of SCCs is proportional to the bending strength with a correlation coefficient R^2= 0.82.

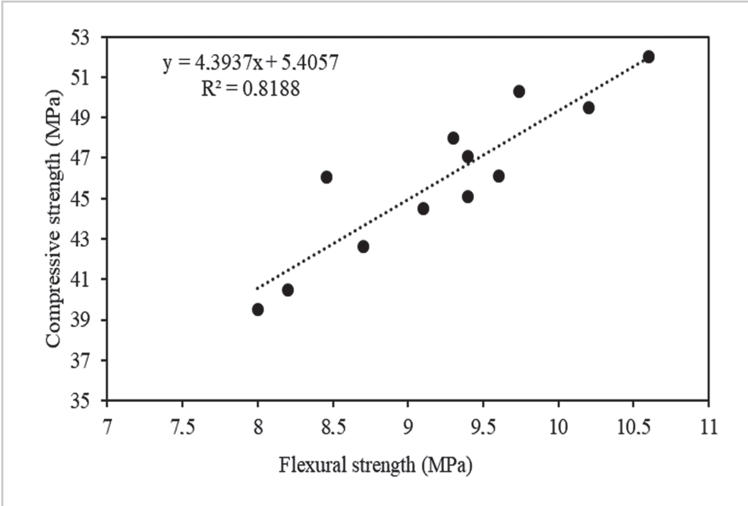

Figure 6 - Correlation between flexural and compressive strength.

3.3 Delayed behavior under constant load

3.3.1 Endogenous creep

Figure 7 depicts the evolution of endogenous creep during bending of the mixtures up to 200 days after loading, based on the type of fibers used. During the first days of loading, the increase in the deflection is observed whatever the type of fiber. Initially, the deflection increases for all fiber types, consistent with the short-term endogenous creep theory. This theory relies on the micro-diffusion of water under pressure (Ranaivomanana *et al.*, 2013) and the capillary tensions generated by cement hydration (Benboudjema, 2002), where the stresses applied during loading enhance the effect of capillary tensions (Bazant *et al.*, 1997). Water plays a fundamental role in the endogenous creep mechanism of concrete.

Notably, has the lowest creep order among the SCCs studied. The introduction of fibers in the SCCs increased creep at 200 days by 12%, 21%, and 25% for SCC-P, SCC-HN, and SCC-DN, respectively, compared to SCC-C. The increased creep for SCC-P may be attributed to the smooth and hydrophobic nature of the polypropylene fiber, causing a decrease in adhesion and creating microcracks. The increase in creep for SCC-HN and SCC-DN is due to the dissolution of extractable on the surface of these fibers, which disturbs cement hydration and delays setting (Sedan *et al.*, 2007; Diquélou *et al.*, 2015; Tonoli *et al.*, 2010). The transition zone between the fibers and cement paste can also affect creep by creating microcracks in the concrete. As per (da Silva Junior *et al.*, 2021) water absorption by plant fibers reduces the kinetics of cement hydration, leading to decreased mechanical performance. Treating Hemp and Dis fibers with SBR latex resin significantly reduced endogenous creep by 14.2% and 21.3%, respectively, compared to SCC-HN and SCC-DN at 200 days (Figure 7). However, a slight increase in creep was observed compared to SCC-C. This improvement in the behavior of plant fibers treated with SBR is due to improved adhesion between the fiber and the matrix. Coating the fibers with SBR also considerably reduces water absorption, leading to complete hydration of cement and increasing mechanical performance of the cementitious composite (Li *et al.*, 2021a).

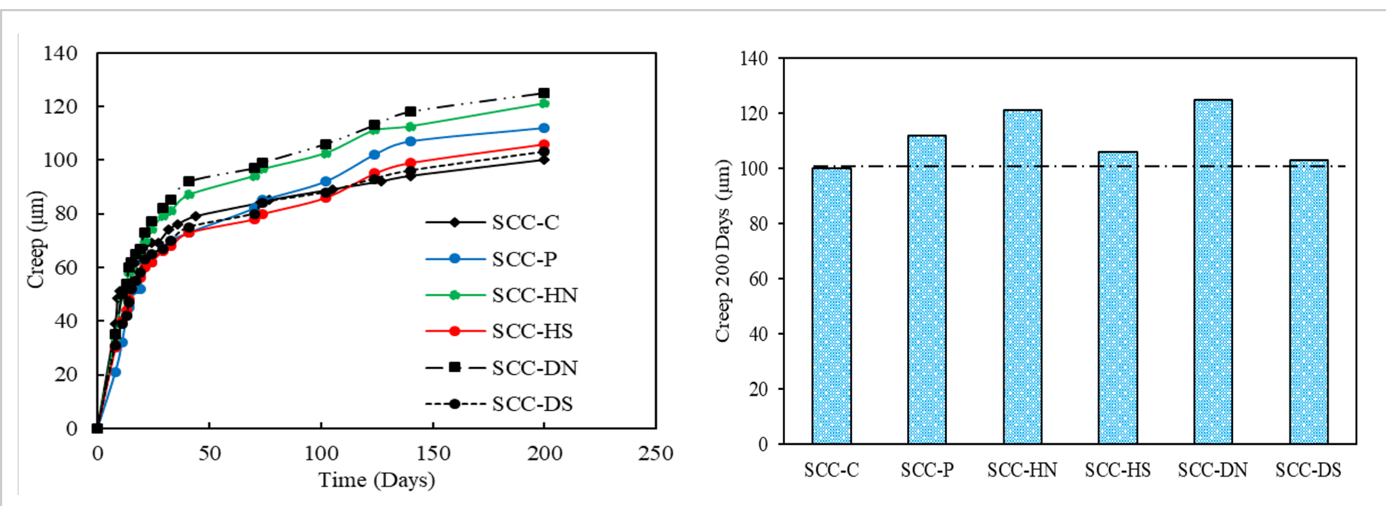

Figure 7 - Endogenous creep of different mixtures.

3.3.2 Total creep

Figure 8 illustrates the progression of total deferred deformations in SCC-C and SCC-F under bending stress. The figure clearly indicates that substituting polypropylene fibers with vegetable fibers results in reduction in total creep. (Zhao *et al*., 2016) examined the impact of polypropylene fibers and alcohol on specific creep and concluded that adding these fibers to concrete increases creep deformation due to two different mechanisms. Fibers with higher elasticity moduli exhibit better creep resistance capacities by pinning microcracks in the concrete. This study shows that SBR-treated Dis fiber is stiffer than the other fibers and demonstrates good resistance to creep deformation compared to SCC-C. Moreover, coating Hemp and Dis fibers with SBR latex leads to a decrease in total creep of 10% and 16%, respectively, at 200 days compared to SCC-HN and SCC-DN (Fig. 8). This is because good fiber/matrix adhesion promotes an increase in mechanical performance. According to (Zhao *et al.,* 2016), the addition of fibers to concrete can introduce internal defects in two ways. First, non-homogeneous distribution of fibers may result in weaknesses in various concrete performances. Second, the fiber-matrix interface may create microcracks inside the concrete.

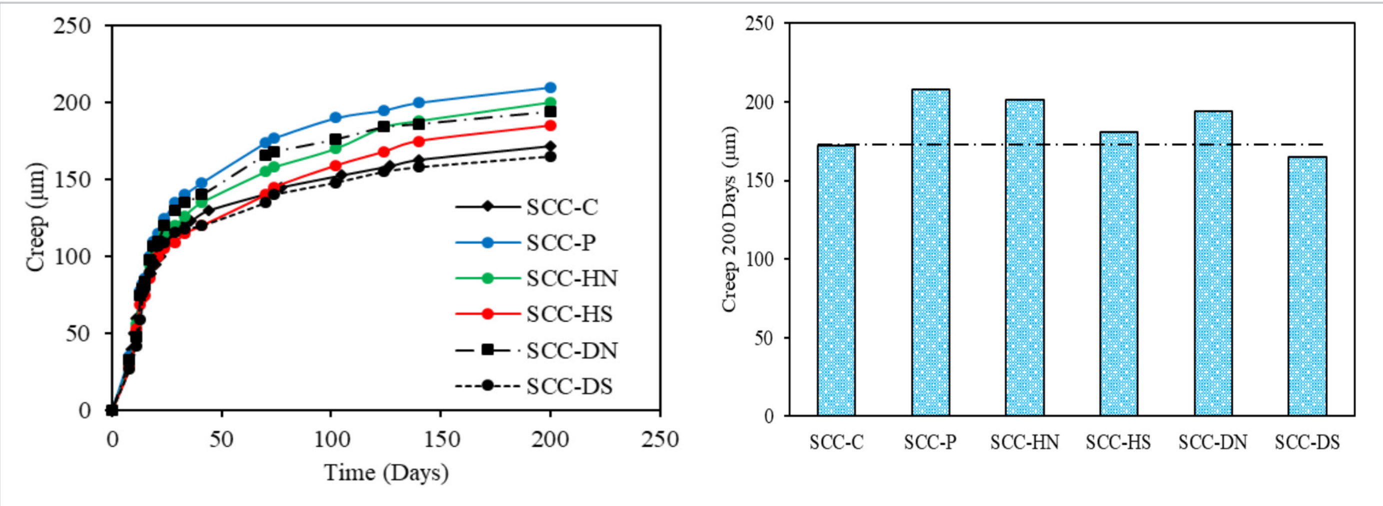

Figure 8 - Total creep of the different mixtures.

4. Conclusions

The study investigated the effect of different types of fibers, subjected to two treatments, on the fresh and hardened behavior of self-compacting concretes (SCCs). The bending creep behavior of the SCCs was evaluated. Hemp and Dis fibers were used as reinforcement in the SCCs after being immersed in NaOH and SBR solutions. The following conclusions can be drawn:

- The addition of fibers in the SCCs led to a decrease in their filling capacity in both an unconfined (spreading) and confined (J-RING) medium. However, the treatment of plant fibers with SBR latex improved the fresh state characteristics of SCCs by approximately 8%. This can be attributed to the reduced water absorption of the treated fibers and the reduction of friction between the fibers, aggregates, and walls.
- SCC-DS exhibited higher flexural strength than SCC-C, SCC-DN, and SCC-HS, by 9%, 13%, and 4%, respectively, at 28 days. Therefore, the treatment of plant fibers with SBR can enhance the mechanical performance of self-compacting concretes.
- The presence of fibers in the SCCs resulted in internal defects, reducing its ability to resist creep. These defects include non-uniform fiber distribution and the defective interface between the fibers and the cementitious matrix. However, the use of Hemp and Dis fibers treated with SBR latex in the SCCs decreased the total creep by 10% and 16% compared to SCC-HN and SCC-DN, respectively.

In conclusion, the coating of vegetable fibers with styrene-butadiene rubber is highly effective in improving the short- and long-term mechanical performance of self-compacting concretes.

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