Nano World Journal

https://doi.org/10.17756/nwj.2023-s2-027

Research Article

Open Access

Tensile Load-bearing Behavior of Concrete Components Reinforced with Impregnated Flax Fiber Textiles

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Received: July 24, 2023
Accepted: September 25, 2023
Published: September 27, 2023

Citation: Zecherle K, Ricker M, Feiri T, Binde J, Haxter C. 2023. Tensile Load-bearing Behavior of Concrete Components Reinforced with Impregnated Flax Fiber Textiles. *NanoWorld J* 9(S2): S149-S156.

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Published by United Scientific Group

Abstract

In recent years, the use of natural flax fibers as a reinforcement in composite building materials have witnessed a growing interest amongst research communities due to their green, economical, and good mechanical properties. These benefits are only slightly limited when using biodegradable or bio-based resins for the impregnation. Yet, robust load-bearing models to design concrete components reinforced with textiles made of natural fibers – including flax fibers – are still underdeveloped or even lacking. In this paper, the load-bearing behavior under uniaxial tension load of concrete components reinforced with textiles made of impregnated flax fibers is investigated. To this, the results of uniaxial tensile tests on concrete components with three-layered reinforcements impregnated (I) and non-impregnated (NI)) are presented and discussed. The tests consisted in systematically varying textile parameters, such as the fineness of the weft threads, the spacing between warp and weft threads, or the number of reinforcement layers. Overall, the results indicate that reinforcement made of flax fibers works satisfactory for concrete components bearing uniaxial tension. Furthermore, an increase in failure load was achieved compared to concrete components without reinforcement. The stress-strain-diagrams show that the curves can be divided into three typical areas: Uncracked cross-section (*State I*), phase of initial crack formation (*State IIa*) and phase of completed crack formation (*State IIb*). Also, a very finely distributed crack pattern with multiple cracks was observed. The impregnated textiles reached higher failure stresses with less strains in comparison to the textiles without impregnation.

Keywords

Flax fiber textiles, Impregnated, Non-impregnated, Load-bearing behavior

Introduction

Within the last years, the growing ecological, social and economic awareness and the intent to reduce CO_2-emissions have highlighted the importance of sustainability and new environmental regulations and have stimulated the search for green materials compatible with the environment [1-5]. Hence, more than ever, alternative, and more eco- and sustainability-friendly solutions are urged across the construction sector to promote a more sustainable consumption pattern of building materials.

Over the last years, extensive research work has been conducted on the behavior of non-metallic reinforcements (i.e., textile reinforcement) subjected to various types of loading and incorporating different types of fibers applied in various sizes and materials, such as steel, glass, and carbon [6-8]. The results suggest that non-metallic reinforcements are promising alternatives to conventional materials (e.g.,

reinforcing steel) due to their good physical and mechanical properties, mostly in terms of load-bearing capacity and flexural performance. Additionally, the required nominal dimension of the concrete cover can be minimized, and reinforcement cross-sections can be reduced without affecting the load-bearing capacity due to their excellent corrosion-resistant properties and a comparable, and sometimes even higher, tensile strength than reinforcing steel. From the environmental perspective, reduced dimensions can save cement consumption - and ultimately, lead to CO_2-savings. These characteristics have been raising the interest of scientific communities on the potential of textile reinforcements. In Germany, for example, well-known research projects conducted by the TU Dresden and the RWTH Aachen University (SFB 528 and SFB 532) have been investigating the load-bearing behavior of concrete elements reinforced with AR-glass or carbon fibers [9-14]. In addition, within the research project C^3 (Carbon Concrete Composite) a guideline for the design of textile-reinforced structural elements is expected [15] with the goal to replace the lengthy experimental investigations that are normally required for the verification of load-bearing capacity with design provisions. However, textiles made of natural fibers - including flax fibers - have not been included in these research efforts.

The results of previous investigations show that textile reinforcements made of natural fibers have promising mechanical properties, making them suitable for structural applications despite their natural scatter when employed in different composites [16-19]. The potential of flax fibers has been investigated due to their reduced carbon emissions, their low embodied energy expenditure, harmless environmental impact after degradation [20, 21] and their inoffensive presence in terms of occupational health and safety [22, 23]. Natural flax fibers are also rich in cellulose and are soft and flexible due to the high length/diameter ratio. These characteristics have prompted the development of interesting structural applications. For example, the Fraunhofer Institute for Wood Research (Wilhelm-Klauditz-Institut WKI in Germany) presented a first prototype of a natural fiber-reinforced concrete walkway (i.e., a concrete slab reinforced with flax fiber textiles) at the BAU 2019, a reputable trade fair for architecture, construction materials and systems in Germany. With the development of such prototype, the bond between the concrete and the natural fiber was demonstrated and the relevance of natural flax fibers as a resource-saving and cost-effective reinforcing solution was highlighted [21]. In this solution, suitable impregnation of the reinforcement was used to avoid its degradation in the alkaline concrete and increase the durability of a structural member. Nevertheless, despite these developments, well-defined load-bearing models, or even guidelines, for the design of concrete components reinforced with textiles made of natural flax fibers seem to be still lacking to structural engineering practitioners.

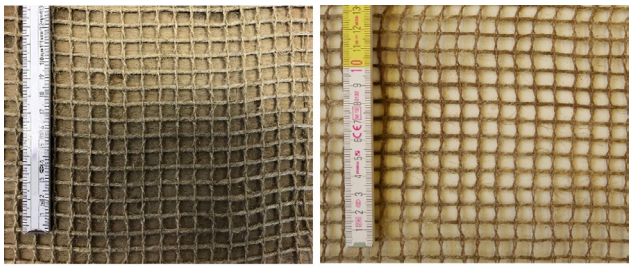
This paper was developed in the context of a research initiative – *"Investigation on sustainable reinforcements made of natural fibers for textile concrete components (laboratory phase)"* – founded by the German Federal Environmental Foundation (DBU) (in German: *Deutsche Bundesstiftung Umwelt*) with the goal to investigate the bond and tensile load-bearing behavior as well as the uniaxial flexural load-bearing behavior of concrete components with a textile reinforcement made of flax fibers. Since there is evidence that textile reinforcements made of natural fibers should be impregnated [24], an additional goal of the project is to use bio-based impregnations that have less negative impact on the environment instead of the commonly used polymer-based impregnations, such as epoxy resins. This paper presents the results of the experimental tension tests on the composite and investigates the tensile load-bearing behavior. In the sections to follow, the stress-strain behavior under uniaxial tension as well as the influence of the impregnation on the load-bearing capacity are analyzed.

Experimentation

Materials

For the sake of this project, a tailor-made concrete mixture labelled as C5 was developed [25] to meet the requirements of satisfactory workability (e.g., high flowability and penetration of the fabric) and to guarantee suitable mechanical properties (e.g., relatively low tensile strength and normal or high compressive strength). It should be noted here that standard concrete mixtures produced according to DIN EN 206 [26] could not be used at the early stages of the investigation due to the dimension of the grain (2 mm in this case) resulting from the opening width of the textiles. Table 1 shows the characteristics of the mixture in terms of composition and its essential strengths. Therefore, on each concreting day, six prisms (l x w x h_b = 160 x 40 x 40 mm produced according to DIN EN 196-1 [27]) were poured out of the same concrete mixture used for the tensile test specimens. To determine the mean flexural and the mean compressive strength of the mixture, they were stored under the same conditions as the test specimens and tested on the same days. The uniaxial tensile strength f_{ctm} was calculated using the provisions of *fib*-Model Code for Concrete Structures 2010 [28] from the mean value of the flexural tensile strength $f_{ctm,fl}$ which was determined according to DIN EN 196-1 [27].

The textiles consisting of flax fiber yarns (Figure 1) were developed by the Fraunhofer Institute for Wood Research (Wilhelm-Klauditz-Institut WKI in Germany) and were produced as leno fabric with a double-rapier weaving machine with Jacquard attachment. In a leno fabric, two threads are combined in the warp direction (i.e., in the machine direction):



(a) **(b)**

Figure 1: Flax fiber textiles used for the tensile tests (weft threads horizontal aligned): **(a)** non-impregnated and **(b)** impregnated.

Table 1: Characteristics of the concrete mixture C5.

Composition	kg/m³	Strengths (experimental, mean values)	MPa
CEM II 32.5 N/LH	424.7	Flexural strength (following [27])	6.86
Sand 0/2	1039.1	Uniaxial tensile strength (following [28])	3.03
Limestone powder	707.8	Mortar compressive strength (following [27])	47.24
Silica powder	54.4		
Superplasticizer	3.6		
Water	288.9		

(i) the ground thread that runs at right angles to the weft thread, and (ii) the leno thread that turns 180° around the standing thread after each weft thread, enclosing it afterwards. Due to the twist, leno fabrics are more resistant to displacement than other conventional 2D fabrics (e.g., plain weave fabrics) when executing the required wide yarn spacings. During the weaving process, the undulation of the weft threads was minimised to reduce damage of the yarns [29].

The textiles used in the test campaign consisted of a weft thread with various values of fineness. In this investigation, the fineness of 1200 tex and 1500 tex are discussed. The standing and leno threads in the warp direction have a fineness of 500 tex each. The fabrics have opening widths of 8 mm and 10 mm in weft direction and 10 mm in warp direction. For comparison, textiles with and without impregnation were also tested. For the impregnation, a bio-based epoxy-resin consisting of 56 % of its molecular structure of renewable origin was utilized. The textiles geometry as well as the results of the tensile tests with single yarns (according to [30]) are characterised in Table 2. The clamping of the impregnated single yarns was adapted to avoid premature failure according to the provisions in [31].

Test specimens and test setup

The tensile tests were conducted on bone-shaped test specimens that were previously used within the scope of comparable tests on concrete components with textile reinforcement made of synthetic fibers [13, 32, 33]. In contrast to the geometry described in bibliographic references, the web thickness in the free strain length was increased from 10 mm to 15 mm since the non-impregnated reinforcement made of natural fibers has a larger cross-section than textiles made of synthetic fibers. The geometry adopted in the test specimens is shown in Figure 2.

Prior to concreting, the textiles were glued on perforated steel plates (t = 2 mm) on their end areas to ensure that the reinforcement could be centrally placed, while being orthogonal to the expected crack direction. Since the non-impregnated textiles were less dimensionally stable than impregnated textiles, the textiles were slightly tensed in the formwork to guarantee that the non-impregnated textiles were easily activated during the tensile test.

For reference, test specimens without reinforcement were regularly produced. The specimens were removed from the formwork one day after concreting and stored under water until the 14th day to avoid early cracking. Afterwards, they were stored under constant conditions (i.e., 20 °C, 60% relative humidity) until the 28th day. To consider the unavoidable scatter, each test was repeated three to four times; therefore, a corresponding number of specimens were also produced. The characteristics of the experimental programme are described in Table 3.

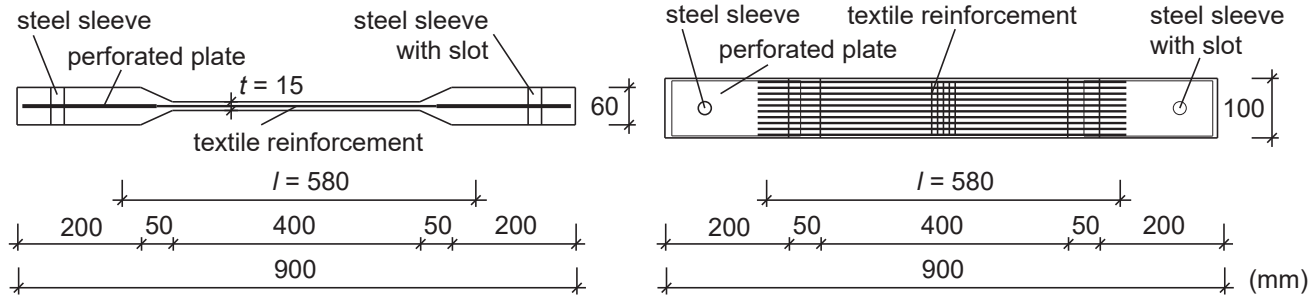


Figure 2: Geometry of the test specimen for the tensile tests (warp threads are only illustrative).

Table 2: Characteristics of the flax fiber textiles used as leno fabrics.

Textile construction	Properties	Strengths (experimental, mean values)	MPa
Spacing of weft threads (mm)	8, 10	Tensile strength of 1200tex-yarn (NI/I)	312.8/382.9
Spacing of warp threads (mm)	10	Tensile strength of 1500tex-yarn (NI/I)	362.6/421.7
Fineness of weft threads (tex)	1200, 1500		
Fineness of warp threads (tex)	2 x 500		
Impregnation	Non, SICOMIN GreenPoxy 56		
Reinforcement cross-section (mm²/m)	107.1		

Table 3: Experimental program.

Test ID	NI-8/10-1200-3-x	NI-10/10-1500-3-x	I-8/10-1200-3-x	I-10/10-1500-3-x
Impregnation	Non	Non	GP56	GP56
Spacing weft threads (mm)	8	10	8	10
Spacing warp threads (mm)	10	10	10	10
Fineness of weft thread (tex)	1200	1500	1200	1500
Number of layers	3	3	3	3
Reinforcement cross-section (mm^2)	32.14	32.14	32.14	32.14
Reinforcement ratio (%)	2.14	2.14	2.14	2.14
Number of tests	4	4	3	4

Cardan joints were used to ensure a nearly axial load application during the test procedure. Further, the force as well as the displacement were continuously recorded using a load cell and two inductive displacement transducers (i.e., LVDT), which were placed laterally at the test specimens (Figure 3). Following the provisions in [35], the measurement length was set to 580 mm, which equates the spacing between the brackets where the LVDTs were installed. To determine the strain, the measurement length of 400 mm was equivalent to the free strain length. However, due to some prior failure of the test specimen and additional cracks next to the free strain length, the measurement length was maintained at 580 mm, both to install the LVDTs and to calculate the strains. Such procedure guaranteed that all the occurring strains were considered despite having a change in the cross-section of the component.

The tests were conducted in a path-controlled manner. Up to 1000 N, the force was applied by 1 mm/min [36] and beyond that, the speed increased to 5 mm/min until failure. The speed was set according to bibliographic provisions [36, 38]. To complement such provisions, preliminary tests showed that the specimens with non-impregnated textiles might reach much higher strains compared to the specimens with textile reinforcement made of synthetic fibers shown in literature [13, 32, 33]. Thus, an increased speed until failure was set to achieve a comparable strain rate to the tests with synthetic fibers.

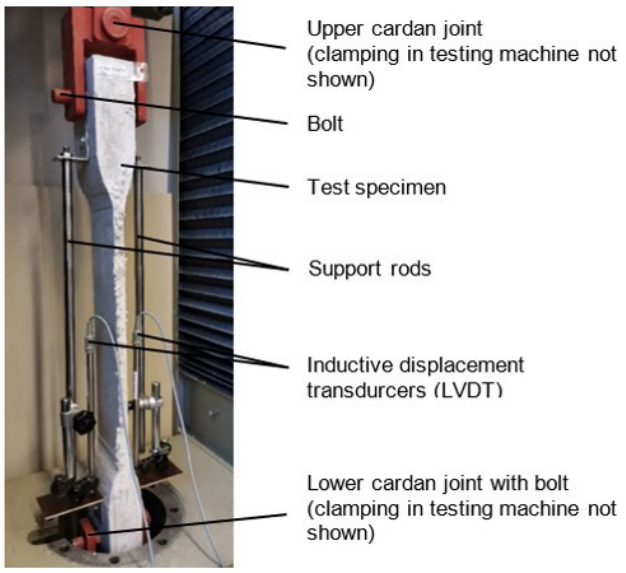


Figure 3: Test setup for the tensile tests with concrete components reinforced with textiles made of natural fibers.

Results and Discussion

Failure modes

During the tensile test campaign, two main failure mechanisms were observed. First, a reinforcement rupture occurred in the free measurement length of the test specimen (i.e., in the thin web). This failure was expected and, thus, it was used as a reference for the analysis. Second, a textile rupture occurred within the transition of the cross-section between web and thicker part of the test specimen or in the thicker part itself. This premature failure occurred due to the plain areas (i.e., due to the steel plates) and the plain surface of the epoxy resin on them. Since this failure mode was not observed during the first tests with non-impregnated textiles, it can only be partially used to draw conclusions concerning the tensile load-bearing behavior.

It can be argued that the failure modes observed were brittle compared to steel reinforced concrete, even though the failure was pre-announced by finely distributed crack patterns with equally opening crack widths (Figure 4). The post-failure behavior was caused by the finite-length natural fibers of the textile yarns being pulled apart or tearing. In this context, it can be added that a successive failure of the individual yarns occurred.

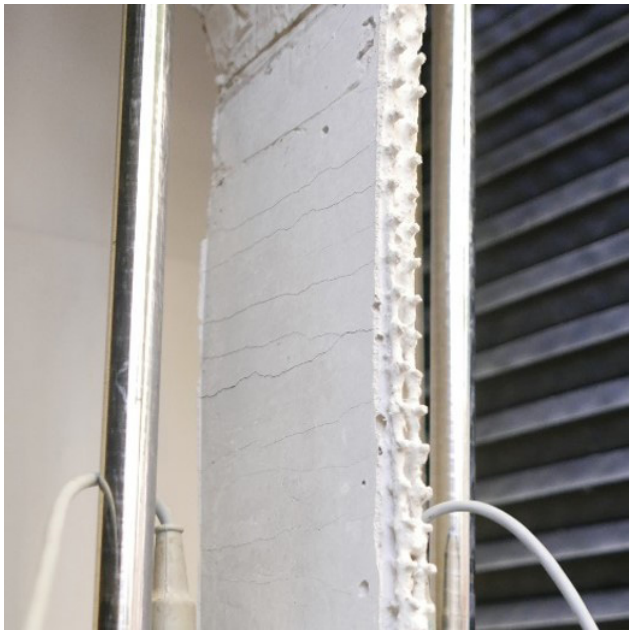


Figure 4: Finely distributed crack pattern with equal crack width of a test specimen during testing.

Stress-strain behavior

The following stress-strain diagrams in Figure 5 were derived from the relationship of force to deformation of the LVDTs according to [39]. Thus, the stress of the textiles in the concrete was calculated by dividing the corrected machine force by the effective cross-section of the textile reinforcement (i.e., the cross-sections were determined while considering the gravimetric densities before and after impregnation). Due to the external LVDTs, the actual textile strain could not be directly measured. Therefore, the mean strain of the composite is shown in the axis of abscissas in Figure 5a and 5b. This strain was determined as the ratio of the mean displacement to the original measuring length, which was set to 580 mm.

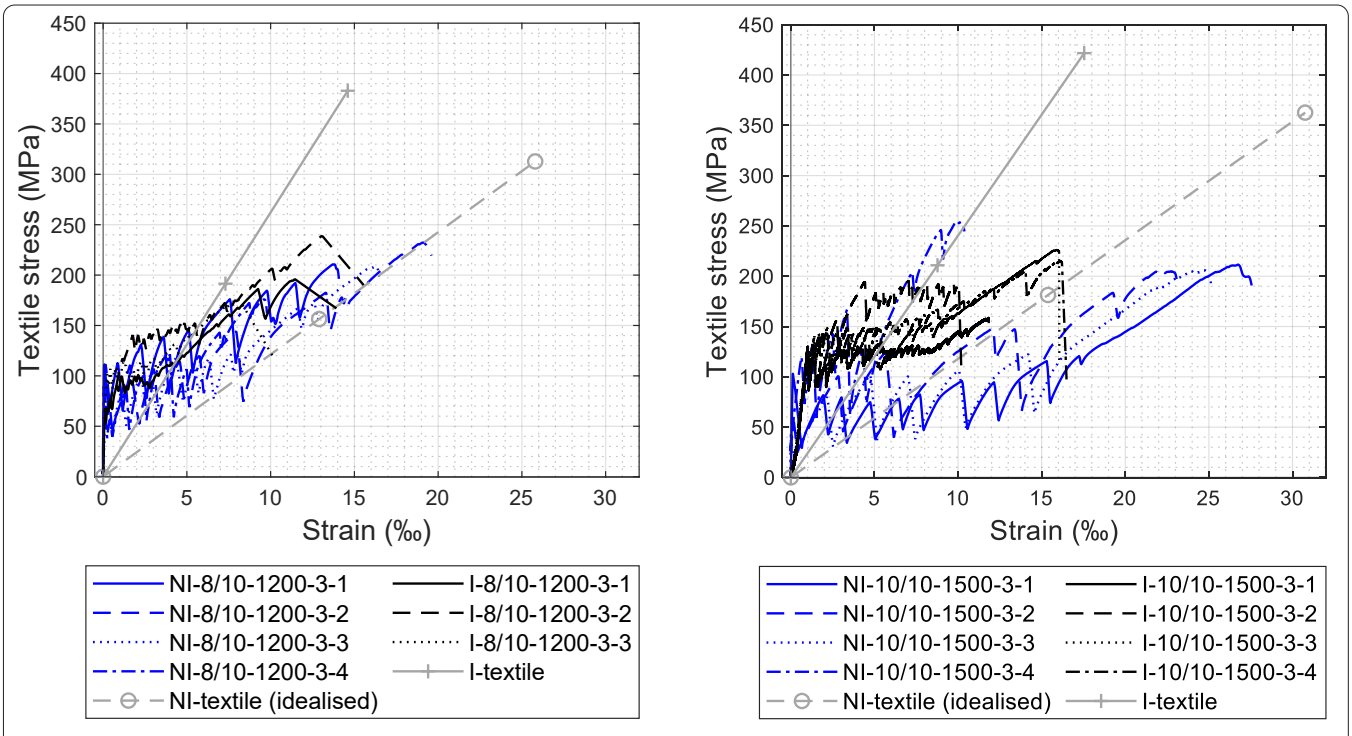
The test results presented in Figure 5 and Table 4 refer to concrete specimens with both types of textile reinforcement: impregnated (I) and non-impregnated (NI). The reinforcements were installed in three layers and the set-up of the textile reinforcement followed the above-described experimental campaign (Table 3). The reinforcement cross-section was set to 32.14 mm^2 for all the test specimens. For comparison, the curves of the tensile tests of the yarns are also shown in Figure 5. Note that these curves are idealized in the sense that the starting effects of the testing machine are neglected.

In Figure 5a and 5b it is visible that the test specimens show the typical behavior of a reinforced tensile component exhibiting different stages of crack formation: *State I* (uncracked cross-section), *State IIa* (cracking), and *State IIb* (completed crack pattern). These areas are common for reinforced concrete specimens bearing tensile stress.

In *State I*, the concrete cross-section is uncracked, and the tensile load is almost exclusively carried by the concrete. The strain in the concrete equals that in the textile reinforcement. The formation of the first crack triggers the phase of initial cracking (*State IIa*). The abrupt load drops in the load-displacement curves observed in *State IIa* indicate the formation of cracks. In the cracks, the load is absorbed and transferred to the textile. However, there are remaining areas in the component between the cracks where the strains of the concrete and the reinforcement are equal. In these areas, the tensile stresses in the concrete continue to increase with loading, and further cracks may develop in the concrete. Once the final cracking condition has been reached, a further increase in load to *State IIb* can be observed. However, the loads introduced into the concrete through bond forces no longer exceed the tensile strength in any location, which explains the absence of further cracking. The continued growth in strain with loading then leads to a significant crack width increase without the formation of additional cracks. Finally, the sudden rupture of the textile causes the specimen to fail. In both figures (Figure 5a and 5b), this can be derived from the load drop after the maximum load has been reached. The post-failure behavior results from the fact that the finitely long natural fibers of the textile yarns are pulled apart or torn off completely. This is caused by successive failure of the individual yarns.

The test results described in Table 5 indicate that with impregnated textiles, smaller crack spacings were attained compared to those without impregnation. This suggests the improved bonding behavior of the impregnated textiles.

The tests also showed an increase in load compared to concrete specimens without reinforcement. The ultimate



Figures 5: Stress-strain diagrams of test specimens with non-impregnated (NI) and impregnated (I) textiles: **(a)** 8 mm spacing between weft threads and 1200tex fineness of weft threads and **(b)** 10 mm spacing between weft threads and 1500tex fineness of weft threads.

Table 4: Results of the experimental program.

Test ID	I/NI	Failure load	Failure strain	Mean crack spacing	Mean failure load	Mean failure strain	Mean crack spacing for the test series
		(MPa)	(%)	(mm)	(MPa)	(%)	(mm)
NI-8/10-1200-3-1	NI	210.57	13.74	66.7	206.77	14.68	54.6
NI-8/10-1200-3-2		232.31	19.09	57.1			
NI-8/10-1200-3-3		208.46	16.32	44.4			
NI-8/10-1200-3-4		175.73	9.58	50			
NI-10/10-1500-3-1	NI	211.53	26.74	36.4	218.83	21.05	65.1
NI-10/10-1500-3-2		204.21	22.86	100			
NI-10/10-1500-3-3		205.79	24.75	66.7			
NI-10/10-1500-3-4		253.80	9.85	57.1			
I-8/10-1200-3-1	I	195.81	11.48	11.8	203.51	10.87	13.7
I-8/10-1200-3-2		238.54	13.12	11.8			
I-8/10-1200-3-3		176.19	8.02	17.4			
I-10/10-1500-3-1	I	158.33	11.84	12.9	197.89	13.4	12.2
I-10/10-1500-3-2		191.45	10.02	-			
I-10/10-1500-3-3		226.89	15.92	11.4			
I-10/10-1500-3-4		214.90	16.17	-			

stresses of the reinforced specimens are multiple times higher than the level of the first cracking, which is similar to the failure loads of components without reinforcement. These failure loads ranged between 1.5 and 3 kN. These results are a preliminary indication that textile reinforcements made of flax fibers present a comparable load-bearing behavior under tensile load in relation to components reinforced with synthetic fibers (e.g., AR-glass or carbon) [13, 32, 33].

Furthermore, in terms failure loads registered on the specimens with impregnated and non-impregnated reinforcements, it can be argued that the failure loads within the test series are somewhat similar. In fact, Table 4 shows that the ultimate stresses of the test series with non-impregnated textiles are within the same range of those with impregnated textiles. It should be noted here that according to the literature [35, 36], the failure loads of impregnated textiles, typically reach higher failure loads than the non-impregnated textiles. Thus, further tests are still required.

All the test specimens addressed in this investigation have the same reinforcement cross-section, indicating that various spacings between the weft threads and various values of fineness of the weft threads only play a minor role compared to the impregnation influence.

From Table 4 it can be also seen that the overall stiffness of the concrete specimens reinforced with impregnated textiles is higher than the stiffness of the test specimens reinforced only with non-impregnated textiles. This can be seen as the measured strains of the test specimens with impregnated textiles are in total smaller than the strains of the corresponding test specimens with non-impregnated textiles. This behavior can be explained by the waviness of the non-impregnated textiles [40] and, thus, less dimensionally stable textiles, which leads to a delayed activation. It shall be highlighted here that this delayed activation could not be totally compensated by the above-described tensioning mechanism. Another reason has to do with the use of impregnation itself: On the one hand, the use of impregnation leads to more dimensionally stable textiles. On the other hand, it improves the inner bonding behavior of the textile. Hence, not only the outer fibers being in direct contact with the concrete contribute to the load-bearing capacity, but also the inner fibers can be better activated due to the impregnation. Furthermore, the impregnation helps to minimise the influence of small defects in the yarns, which are inevitably caused, for example, during the weaving or reaping process.

Conclusions

This paper investigates the uniaxial tensile load-bearing behavior of concrete elements reinforced with and without impregnated textiles made of flax fibers. Furthermore, the study addresses the basic suitability of flax fiber textiles with a bio-based impregnation as a textile reinforcement since there is evidence that impregnation leads to advantages not only in terms of load-bearing capacity, but also concerning the durability of the components (i.e., impregnation helps to prevent or, at least, reduce the rotting process of the natural fiber reinforcement in the alkaline environment of concrete [24]). To conduct this investigation, a set of uniaxial tensile tests were performed according to the experimental program described in Section 2 of this paper. The following conclusions were attained:

- The test results show that in terms of load-bearing behavior, the specimens with textile reinforcement sustained higher failure loads compared to the specimens without reinforcement. This means that the load-bearing behavior can be comparable to conventional (i.e., AR-glass or carbon) textile-reinforced concrete components.
- The test specimens showed a finely distributed crack pattern which suggests satisfactory bonding behavior between textiles and concrete. The tests confirm that an effective bond behavior can already be achieved when using non-impregnated textiles. Note that for a practical

application, an impregnation is necessary to prevent the flax fiber fabrics from rotting in the alkaline environment of concrete.

- The results also show that the impregnated textiles reached higher failure loads, showed less elongation, and a smaller crack spacing.
- Regarding the crack formation pattern, the tests presented three states which are common in reinforced concrete elements: uncracked cross-section (*State I*), phase of initial crack formation (*State IIa*) and phase of completed crack formation (*State IIb*). In State IIb, a stiffness deficit was observed, which was attributed to a reduction of the bond stresses as a result of the transverse contraction of the yarns subjected to tensile stress.
- In the tests, the failure mechanism was mostly brittle. During the tests, the final crack appears suddenly, although the ultimate failure was pre-announced due to the finely distributed crack pattern and considerable strains leading to larger crack widths. The post-failure behavior is described as a successive failure of the individual yarns rupturing gradually.

For future examinations of the elements reinforced with flax fiber textiles, the geometry of the test specimens should be further optimised to prevent premature failure. Additionally, further tests with different reinforcement cross-sections shall be carried out. The bending load-bearing behavior and the shear force load-bearing behavior shall be further studied. Investigations on the durability of the impregnated natural fiber textiles in the concrete matrix are also required for a suitable practical application of this type of reinforcement.

Acknowledgements

The financial support from the Deutsche Bundesstiftung Umwelt (DBU, German Federal Foundation for Environment, reference number 35830/01-25) is gratefully acknowledged.

Conflict of Interest

None.

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