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Study of the microstructural and mechanical properties of FRP reinforcement

TDK thesis

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Table of Contents

Table of Contents	1
Abstract.....	2
1 Introduction	3
2 Literature review	4
3 Methodology	6
3.1 Water absorption test.....	6
3.2 Fiber mass content.....	7
3.3 Durability	8
3.4 Shear strength test.....	8
3.5 SEM analysis.....	9
4 Materials	11
5 Results and discussion.....	12
5.1 Water absorption.....	12
5.2 Fiber mass content.....	13
5.3 Shear strength test.....	14
5.4 SEM analysis	15
6 Conclusion.....	22
Acknowledgment	23
7 References	24
8 List of figures	25
9 List of tables	26
Appendix A: Detailed results of water absorption test.....	27
Appendix B: Detailed results for shear test	33

Abstract

Fiber reinforced polymer (FRP) composite materials are gaining acceptance as possible alternatives to traditional steel reinforcement for concrete structures. The use of glass FRP (GFRP) and basalt FRP (BFRP) bars is increasing in reinforced concrete (RC) elements particularly in applications where electrolytical corrosion is expected. Furthermore, FRP bars possess additional advantages such as low specific density, electromagnetic transparency, and high tensile strength. Yet, some of the properties and behavior of FRP bars are still under investigation to facilitate a more widespread acceptance by the construction industry. This study focuses on the microstructure of FRP bars and the correlation of the microstructural properties with the mechanical ones. Moreover, the alteration of the microstructural properties over time is studied by exposing some of the investigated bars to accelerated conditioning in an alkaline solution according to the description of the ISO 10406-1 standard. Parameters of the study include test type (e.g., water absorption, fiber mass content, SEM, shear etc.), bar diameter (6, 8, 10, 12 mm) and specimen conditioning (as it is, aged for 30 and 90 days). The data acquired from experimental test are analyzed and conclusions are drawn.

Keywords: FRP, GFRP, BFRP, microstructure, SEM, shear, composite, durability, conditioning.

1 Introduction

Fiber Reinforced Polymer (FRP) materials are composite materials used in a variety of industries, that consist of fibers embedded in a resin matrix. The fibers provide stiffness and strength, and matrix bonds and protects the fibers from environmental attack, while transferring the stresses. FRP reinforcing is made from several types of fibers such as glass (GFRP), aramid (AFRP), carbon (CFRP) or basalt (BFRP) (Hota V.S. GangaRao, 2007).

FRP is a relatively newly discovered group of lightweight, strong, non-corrosive materials, used for a wide range of structural engineering applications.

FRP rebars are used in most applications to reduce the danger of corrosion in concrete structures operating in harsh marine environments or being exposed to deicing salts. The durability of the internal reinforcement is strictly correlated with the service life of these types of constructions. The use of FRP rebars in concrete structures exposed to harsh environments generates a significant potential for extending the service life of these structures and lowering their overall life cycle cost, even though their initial cost and environmental impact (CO₂ emission during the manufacturing process) may be slightly higher than that of conventional steel (Nanni, 2014).

This report contains an experimental inquiry aiming at evaluating and contrasting the mechanical and microstructural characteristics of various FRP bar types. Also, the tests results on the long-term durability of these bars conditioned in an alkaline solution simulating a moist concrete environment are provided.

2 Literature review

FRPs are a subgroup of the class of materials referred to more generally as composites. Composites are defined as materials created by the combination of two or more materials, on a macroscopic scale, to form a new and useful material with enhanced properties that are superior to those of the individual constituents alone (ISIS, 2003).

Fiber reinforced polymer (FRP) have become an important step in the evolution of new materials from more traditional ones. Advanced composites are starting to replace traditional materials (commodities) utilized for load-bearing structural components for infrastructure applications. These materials are employed increasingly frequently in the defense and aerospace industries. These distinctive materials are currently utilized globally for both the construction of brand-new structures and the rehabilitation of existing ones. Due to the numerous advantageous qualities of composites that set them apart from more traditional materials like steel, concrete, and wood, they are now frequently used in infrastructural systems (Hota V.S. GangaRao, 2007).

Comparable glass formulations, such window glass or bottle glass, are substantially weaker in bulk than glass fibers. Glass fibers keep their strength well when they are shielded from moisture, airborne contaminants, and contact contamination (Singh, 2014).

FRP composites are ideal for a variety of applications in various industries thanks to their novel qualities, including high tensile strength and modulus, lightness, corrosion resistance, electromagnetic transparency, and the ability to "engineer" their mechanical properties by altering constituent composition and fiber type and orientation (Nanni, 2014). Different procedures are used to wet and cure fibers with resins depending on the production process. To achieve the right curing characteristics, viscosity, durability, appearance, and finish during manufacture, resins are blended with additives and modifiers. Some crucial factors that have an impact on both short- and long-term properties are:

- Fiber properties and configurations
- Resin parameters
- Modifiers and additives

- Resin and fiber content
- Manufacturing process (Hota V.S. GangaRao, 2007)

For structural designers thinking about the use of engineering materials, the mechanical properties are obviously of utmost relevance. Environmental and durability factors, however, are equally crucial when examining potential materials and systems for use in infrastructure applications. Failure to consider the effects of variables including temperature, moisture, ultraviolet radiation, various chemicals, and fire can result in unsatisfactory performance because exposure to a variety of adverse environments can dramatically alter the mechanical performance of FRP materials (ISIS, 2003).

The most popular type of reinforcing fiber for FRPS is glass, which is produced by extruding molten glass through an orifice. Their benefits include inexpensive price, great tensile strength, and superior insulating qualities. E-glass and S-glass are the two types of glass fibers that are most frequently employed. E-glass is the most affordable reinforcing fiber currently on the market and is utilized for a variety of applications where strength, electrical resistance, acid resistance, and cheap cost are crucial. (B.Benmokrane, 1995)

The mechanical behavior of FRP reinforcement in flexure has not been adequately defined. The long-term properties of FRP reinforcement in concrete should also be taken into consideration since it is primarily designed for usage in hostile situations. (Pilakoutas, 2002)

FRPs are relatively insusceptible to harsh environmental conditions, it might be said. However, some circumstances have greater negative effects than others on mechanical and microstructural features.

Despite the fact that FRP composites are corrosion resistant enough to be employed in coastal areas, prior research have indicated that their durability when used with concrete (i.e., in an alkali environment) could be a serious problem. (Bazli, 2020), Under various immersion conditions (such as alkaline, neutral, chloride salt, acidic environments, etc.), severe temperature environments, and sustained loads, the mechanical characteristics of FRP bars deteriorate. (Z. Dong, 2019) Due to the low elastic modulus of the FRP bars, FRP reinforced concrete (FRP-RC) beams typically showed quick stiffness deterioration and significant crack propagation once cracking (H.L. Dong, 2019) (Z. Saleh, 2019).

3 Methodology

To study the microstructural and mechanical properties of FRP bars the following tests were performed:

- Water absorption
- Fiber mass content
- Durability
- Shear strength
- SEM analysis

3.1 Water absorption test

Water absorption test was carried according to ASTM D570 standard. Test specimen (25 mm length), beforehand dried in the oven for 24 h at 50 °C, was weighted to the nearest 0.0001 g in a normal state and immersed in the water by an analytical scale. According to the standard, the samples have to be weighed before the immersion in 2 conditions: dry/normal state and while floating in the water (Figure 1)



Figure 1 The process of weighting the sample in normal state and while floating in the water

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Conditioned specimens were placed in the containers of distilled water maintained at a temperature of 23 °C and 50 °C for 24 h.

To collect the data after 24 h and 14 weeks (long term immersion) all the specimens were removed from the water, wiped with dry cloth, and weighted to the nearest 0.0001 g immediately.

3.2 Fiber mass content

ASTM D2584 standard was used for fiber mass content test done in this paper. Specimens, 25 mm long, were conditioned for at room temperature and 50 % humidity for 40 h and after weighted to nearest 0.0001 g.

Pre-conditioned samples, inside of pre-heated crucibles, were placed in a furnace for 565 °C. After all the carbonaceous material was burned down, the specimens were cooled down and weighted again to the nearest 0.0001 g.

The reference state and the state after the carbonaceous material disappeared, can be seen compared in Figure 2.



Figure 2 Fiber mass test result compared to reference state

3.3 Durability

During the durability test the specimens were placed in the alkaline solution (8,0 g of NaOH and 22,4 g of KOH in 1 l of deionized water) for 30 and 90 days for aging. In order to prevent the penetration of the solution through the ends of the bars, both ends of each specimen were coated with epoxy resin.

According to the ISO 10406-1 standard the temperature of the solution was maintained 60 °C, and specimens were stored in vertically standing closed container, to prevent the alkaline solution from evaporating and absorbing carbon dioxide (Figure 3). After the immersion the samples were washed in water.

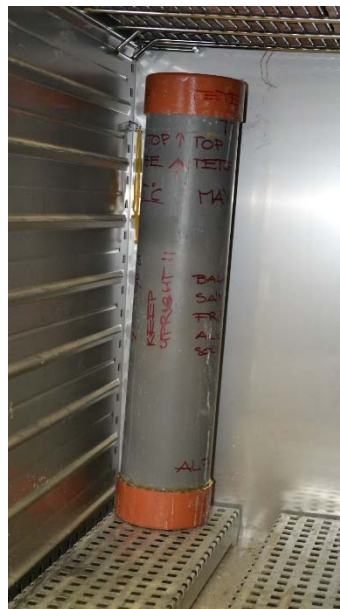


Figure 3 Storage of the specimen during the durability test

3.4 Shear strength test

Shear test was done according to Transverse Shear Strength – ASTM D7617 standard.

This test was done on bars with three different conditions: reference (no aging), aged for 30 days and 90 days (immersed in alkaline solution for 30 and 90 days), respectively. The specimens were cut using high precision blade saw to 300 mm length.

All specimens were conditioned at room temperature at 50% relative humidity for 24 h prior to the test and their nominal area was measured.

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A fixture was used to apply a transverse compressive load to the bar (7 kN/min), resulting in an evenly distributed load delivered to the bar in a double shear configuration. The set-up is shown on Figure 4.

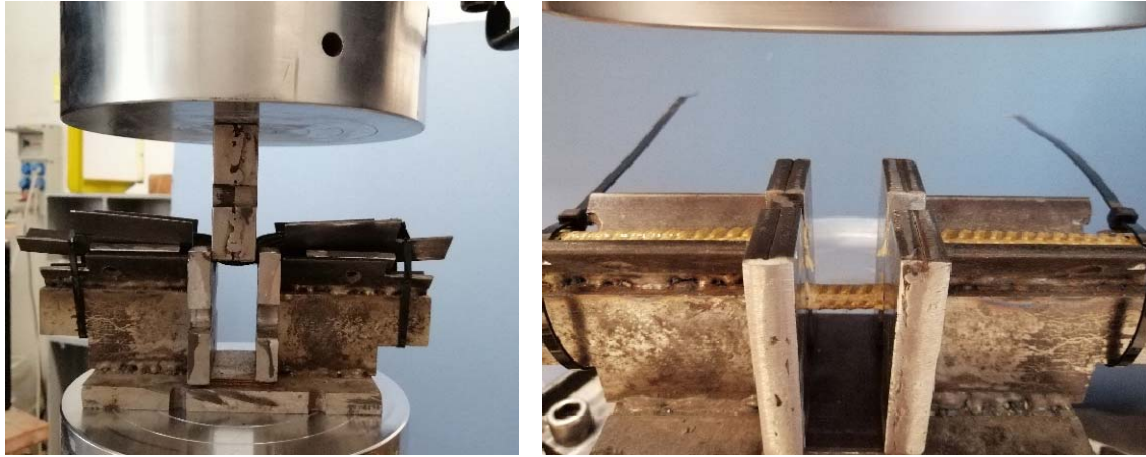


Figure 4 Setup for transverse-shear test

3.5 SEM analysis

For Scanning Electron Microscopy (SEM) observations Phenom XL SEM (Figure 5) was used. Analysis was carried on 3 conditions of bars: reference, aged for 30 days and 90 days (immersed in alkaline solution for 30 and 90 days), respectively.



Figure 5 SEM analysis set-up

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The specimens were cut across, embedded in resin, and properly polished along the surface (Figure 6).



Figure 6 Prepared samples (reference and 30 days aged states, respectively) for SEM analysis

SEM analyses were conducted at medium (100-200x) magnification level, high vacuum setting and at 15 kV accelerating voltage.

4 Materials

Different types of FRP bars were used in this research, with the following symbols: T, K, B, A, Y, K, P, S and Y (Figure 7 from left to right)



Figure 7 Types of bars used in the research

Table 1 contains a list of the physical characteristics and distinctive features of the examined bar types.

Table 1 List of physical characteristics of the specimens

<i>ID</i>	<i>Diameter [mm]</i>	<i>Surface enhancement</i>	<i>Fiber</i>	<i>Resin</i>
S	8, 12	Indented	ECR GLASS	vinyl ester
Y	6, 8	Helically Wrapped + Sand coating	ECR GLASS	vinyl ester
K	6, 8, 10, 12	Helically Wrapped	ECR GLASS	epoxy
T	12	Helically Wrapped	ECR GLASS	vinyl ester
B	8	Sand Coating	Basalt	polyamine
P	8	Sand Coating	Glass	polyamine
A	12	Helically Wrapped + Sand coating	ECR GLASS	vinyl ester

5 Results and discussion

5.1 Water absorption

The test was carried in 2 conditions: immersing the samples in the water temperature for 23 °C and 50 °C.

To calculate the increased weight of the specimens the following formula was used:

$$\text{Increase in weight [\%]} = \left(\frac{\text{wet weight} - \text{conditioned weight}}{\text{conditioned weight}} \right) \times 100$$

Where: - wet weight is the weight of the specimen after the 24 h immersion [g],

- conditioned weight is the weight of the specimen before the immersion [g].

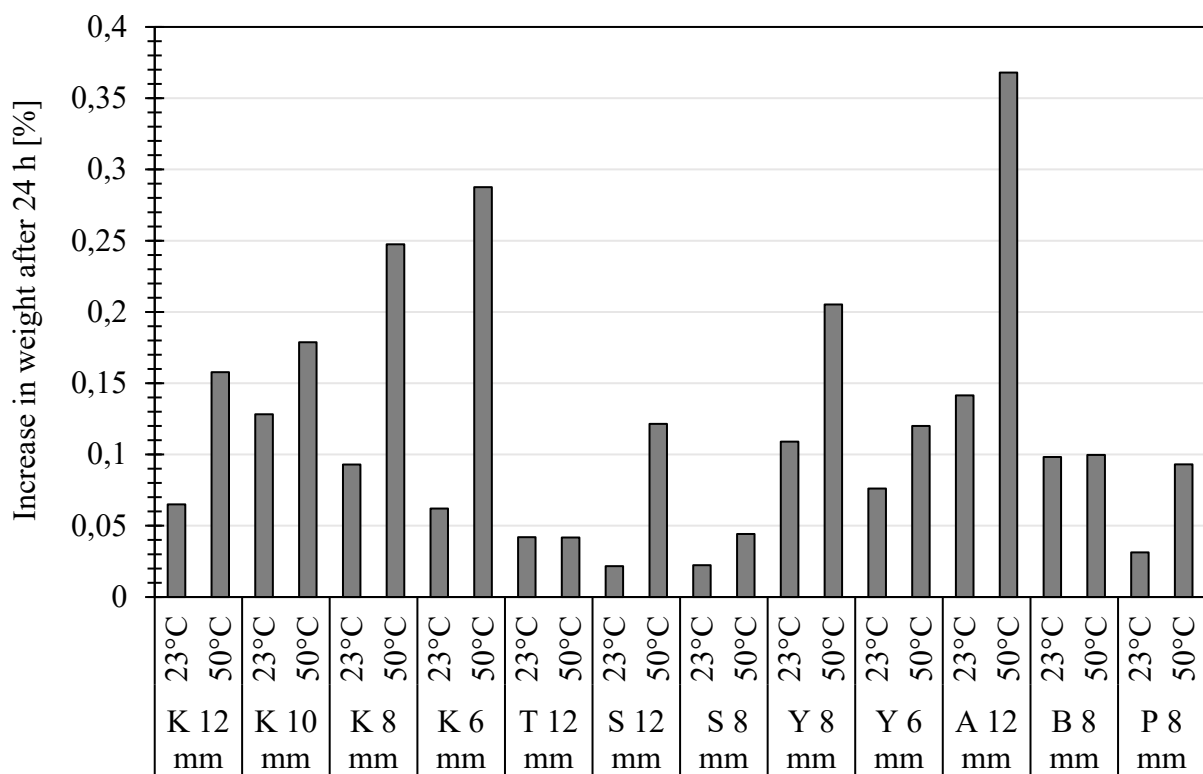


Figure 8 Increase in weight after 24h water immersion.

As it can be seen from results presented in the Figure 8, the specimens stored in water temperature at 50 °C achieved higher increase in weight after 24 h immersion.

One of the highest differences in increase in weight, comparing both cases was observed for P (8 mm), K (12, 8, 6 mm) S (12 mm), Y (8 mm) and A (12 mm) samples. Considering the diameters of the samples, can be noticed that same samples, but with different diameter values, have different results. For example, the K (10 mm) and S (8 mm) have small differences between 2 cases, what cannot be said about K (12, 8, 6 mm) and S (12 mm).

By comparison of the results, can be observed that B (8 mm) and T (12 mm) samples had had the lowest difference in the increase in weight.

5.2 Fiber mass content

To calculate the resin and fiber mass content (Figure 9) the following formulas were used, respectively:

$$RC [\%] = \left(\frac{W_1 - W_2}{W_1} \right) \times 100$$

$$FC [\%] = 100 - \left(\left(\frac{W_1 - W_2}{W_1} \right) \times 100 \right)$$

Where: - W_1 is the weight of the rebar specimen,

- W_2 is the weight or residue, fibers only.

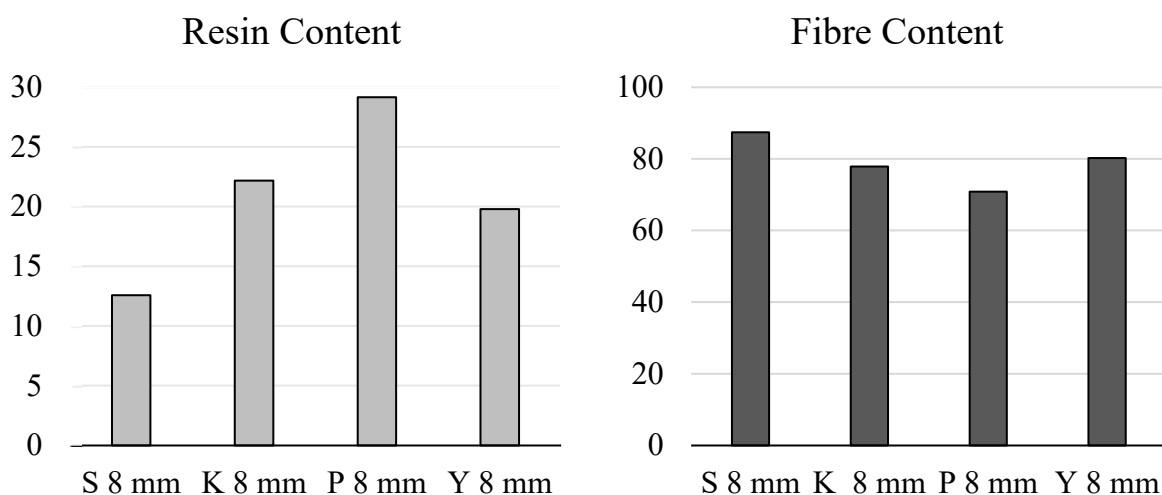


Figure 9 Resin and fiber content of the specimens

5.3 Shear strength test

The shear test was done on 3 conditions of bars: reference, aged for 30 days and 90 days (immersed in alkaline solution for 30 and 90 days, respectively), to see the shear strength capacity change due to aging of the specimens (Figure 10).

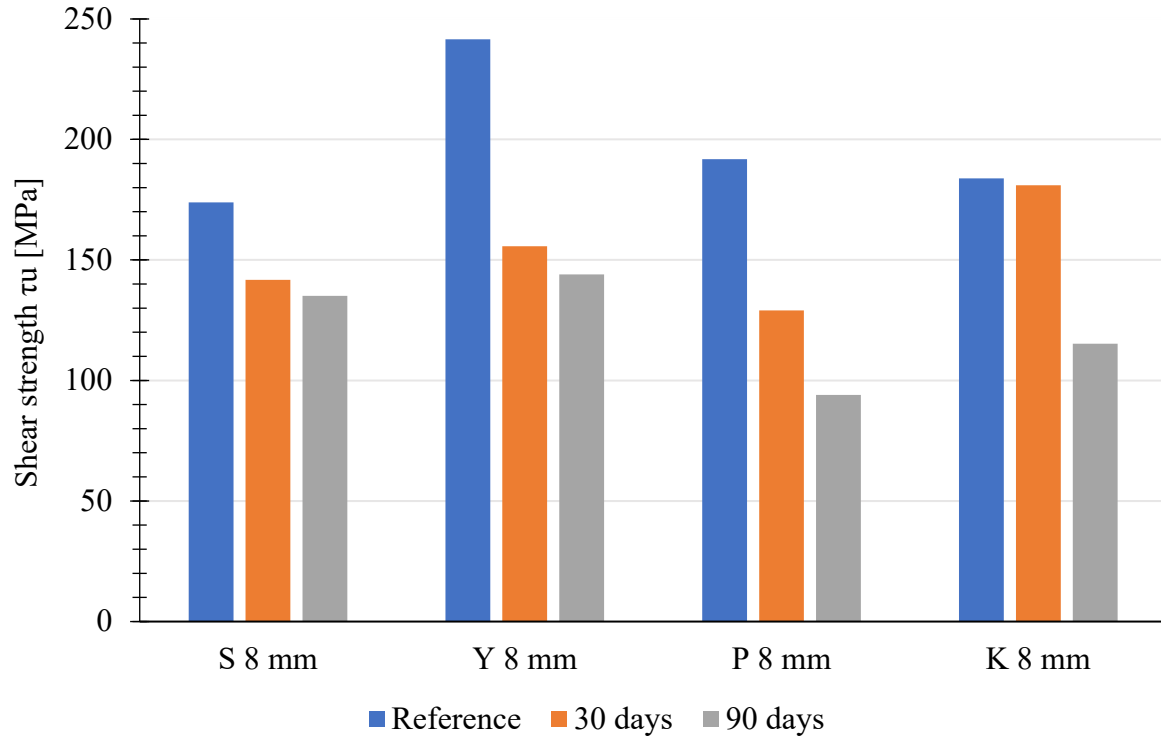


Figure 10 Shear strength

The shear strength was calculated according to formula:

$$\tau_U = \frac{P_{max}}{(2 \times A_{nom})}$$

Where: - τ_U is nominal transverse shear strength,

- P_{max} is the maximum failure force,

- A_{nom} is the nominal cross-section area.

Table 2 Decrease in shear strength in relation to the reference state [%].

	<i>S 8 mm</i>	<i>Y 8 mm</i>	<i>P 8 mm</i>	<i>K 8 mm</i>
<i>after 30 days</i>	18,459	35,524	32,704	1,5450
<i>after 90 days</i>	22,299	40,381	50,992	37,309

As it can be seen from the results presented above (Table 2), due to aging there is a significant drop in shear strength for Y, P and K specimens. However, the K sample didn't show any change after 30 days, what cannot be said about the results for 90 days aged specimen.

5.4 SEM analysis

The SEM analysis was done on 3 conditions of bars, presented below: reference, aged for 30 days and 90 days (immersed in alkaline solution for 30 and 90 days, respectively),

In Figure 11 to Figure 13 can be seen the pictures taken of different parts of the cross-section: image showing the outer part, while the and right inner one of the bar S (8 mm). Referenced and aged specimens are presented as well.

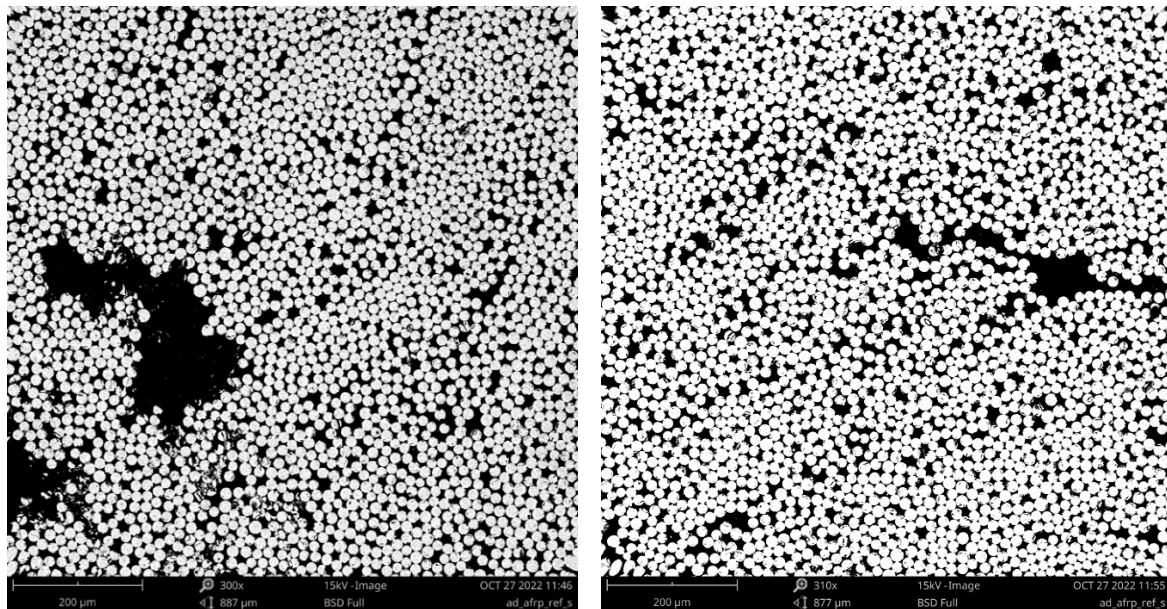


Figure 11 SEM analysis: sample S – reference state, outer (left) and inner (right) part of the cross section

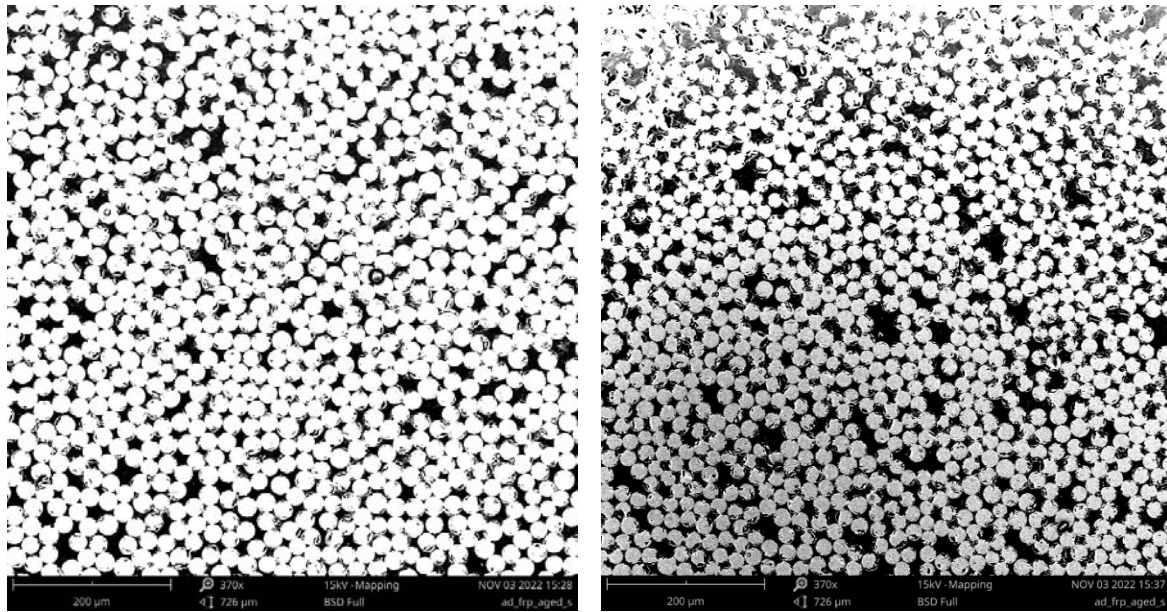


Figure 12 SEM analysis: sample S - aged for 30 days, outer (left) and inner (right) part of the cross section

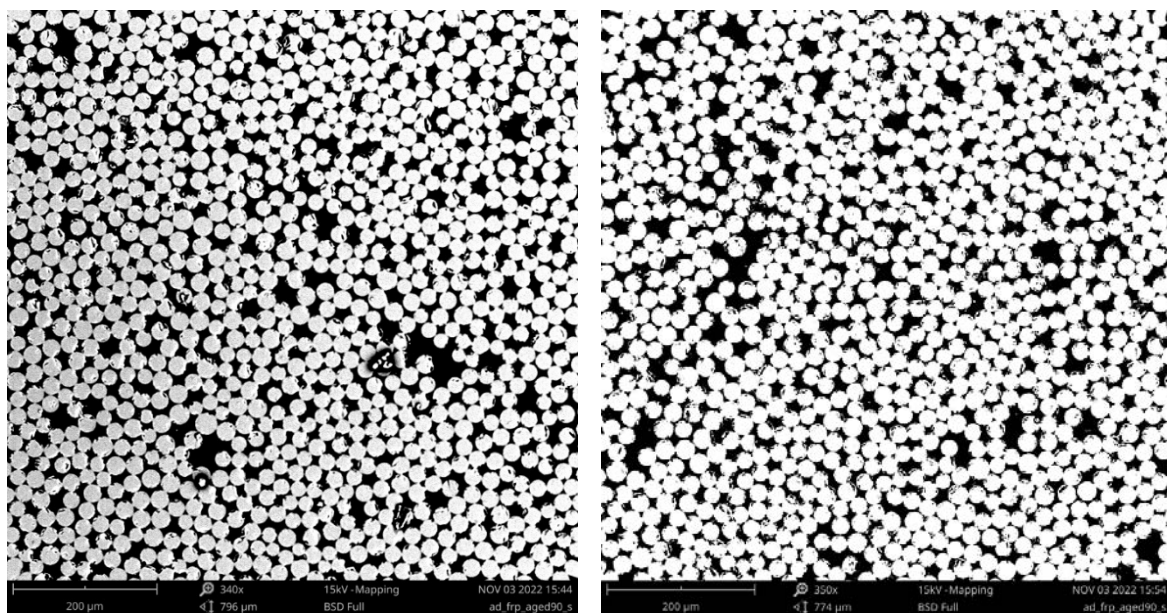


Figure 13 SEM analysis: sample S- aged for 90 days, outer (left) and inner (right) part of the cross section

In the Figure 14 to Figure 16 below, can be seen the pictures taken for the cross-section of the bar P (8 mm).

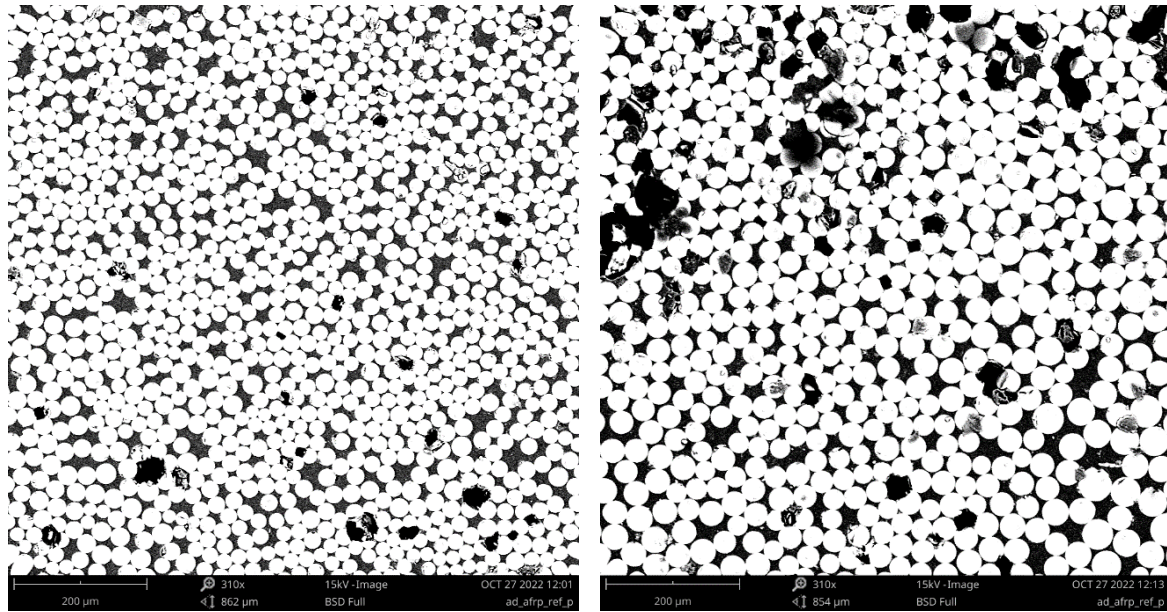


Figure 14 SEM analysis: Sample P- reference state, outer (left) and inner (right) part of the cross section

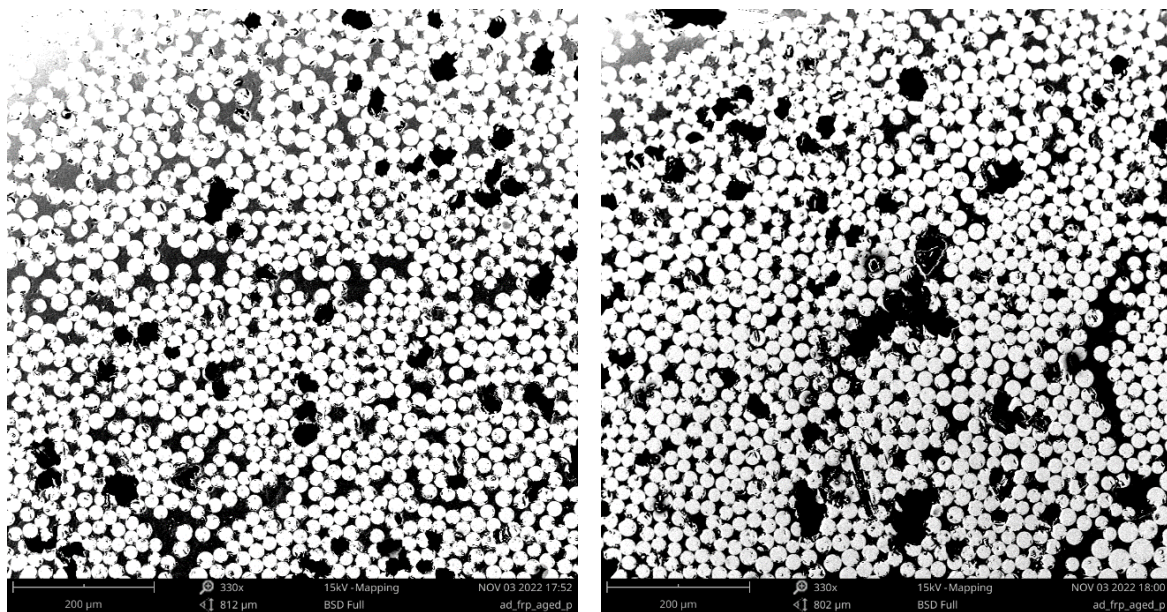


Figure 15 SEM analysis: Sample P- aged for 30 days, outer (left) and inner (right) part of the cross section

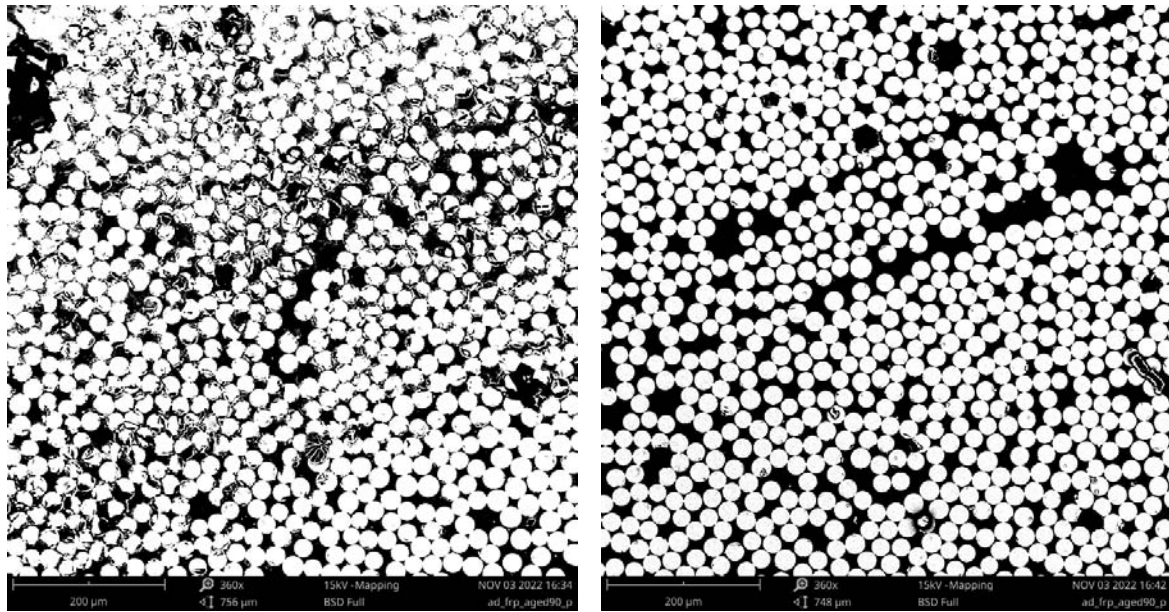


Figure 16 SEM analysis: Sample P- aged for 90 days, outer (left) and inner (right) part of the cross section

In the Figure 16 (left) it is seen that the alkaline solution in which the specimen P (8 mm) was aged for 90 days, penetrated the surface and left a whitish residue that can be observed in the upper left part of the picture, between the fibers, In the Figure 17 to Figure 19 below, can be seen the pictures taken for area closer to edge of the cross-section of the bar K (8 mm) and area in the middle, respectively.

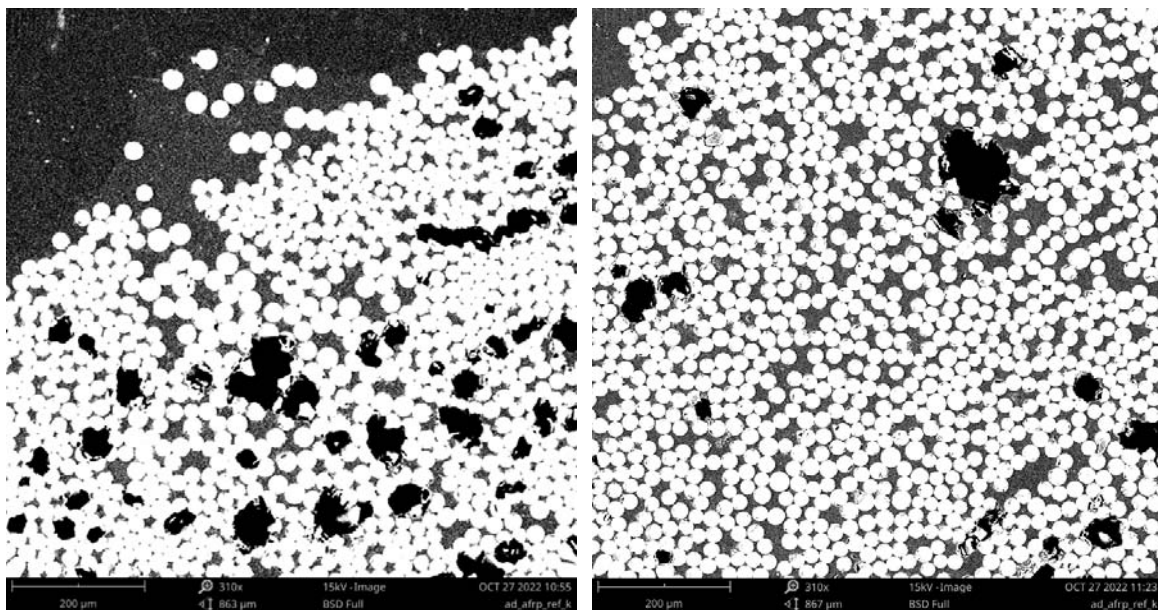


Figure 17 SEM analysis: Sample K-reference state, outer (left) and inner (right) part of the cross section

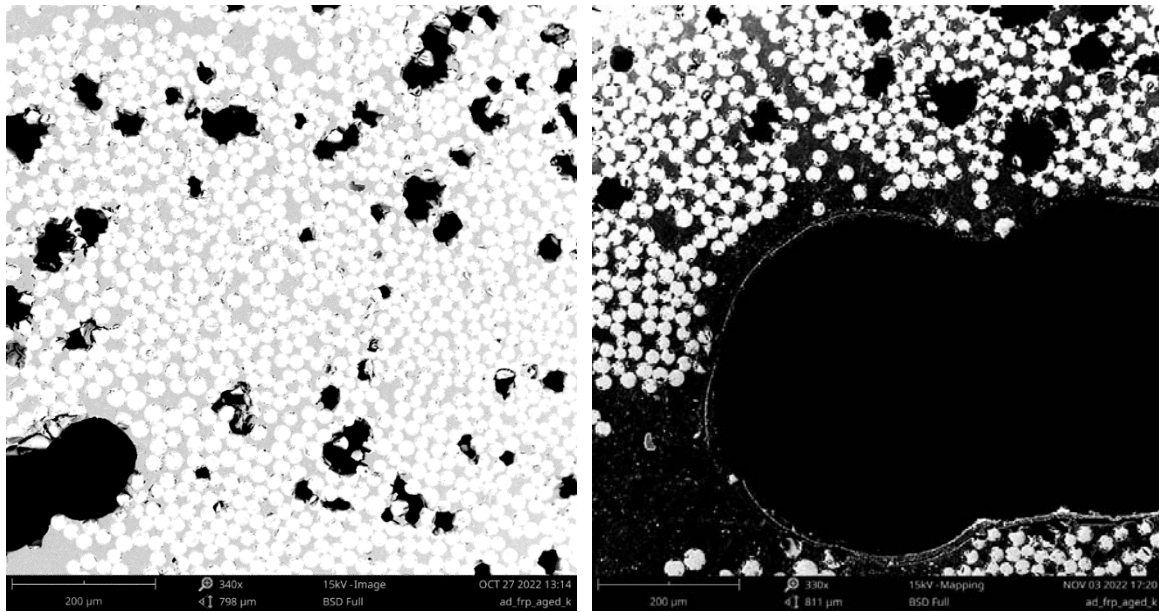


Figure 18 SEM analysis: sample K-aged for 30 days, outer (left) and inner (right) part of the cross section

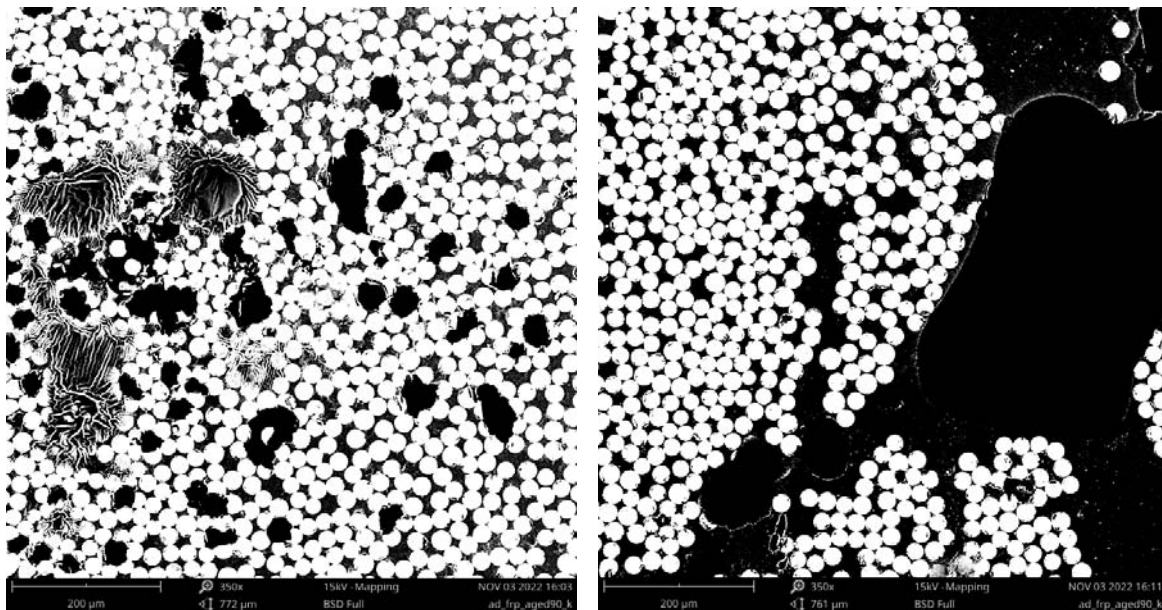


Figure 19 SEM analysis: Sample K-aged for 90 days, outer (left) and inner (right) part of the cross section

Unfortunately, in case of sample K (8 mm) the alkaline solution was found to be inside the specimen (Figure 19, left). Also a large void between the fiber at the center of the cross-section was observed in Figure 18 (right) and Figure 19 (right).

In the Figure 20 to Figure 22 below, can be seen the pictures taken for area closer to edge of the cross-section of the bar Y (8 mm) and area in the middle, respectively.

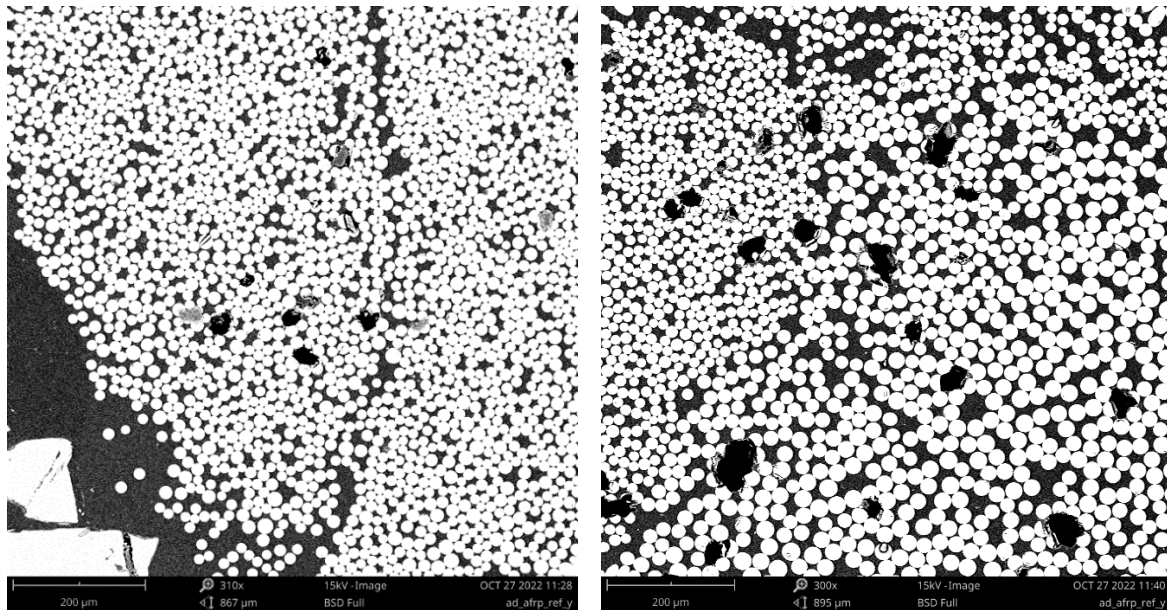


Figure 20 SEM analysis: Sample Y-reference state, outer (left) and inner (right) part of the cross section

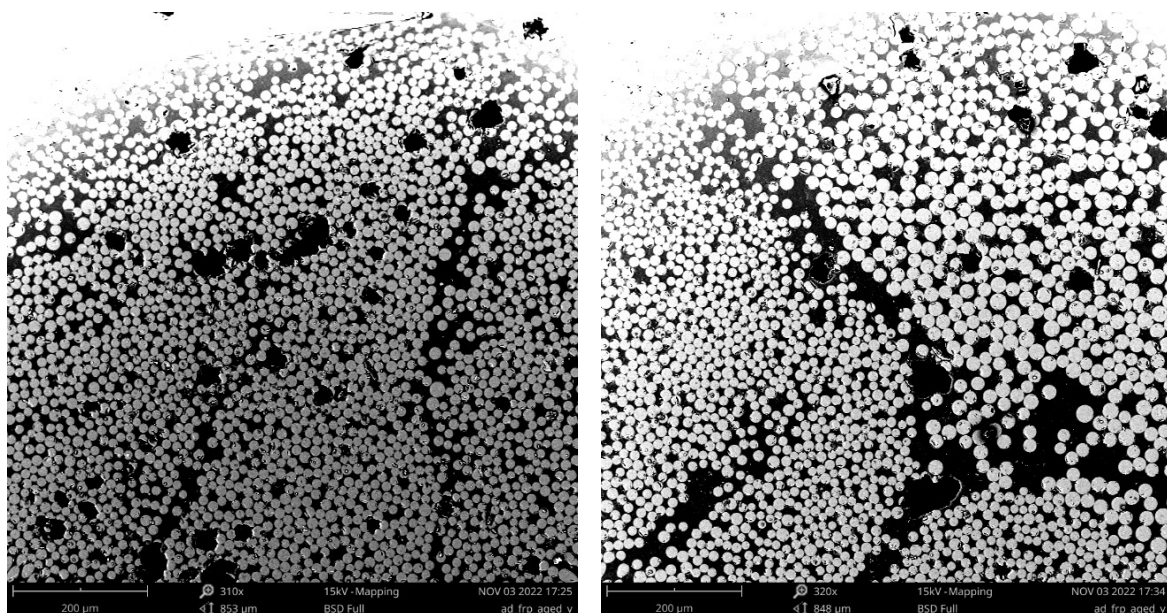


Figure 21 SEM analysis: Sample Y-aged for 30 days, outer (left) and inner (right) part of the cross section

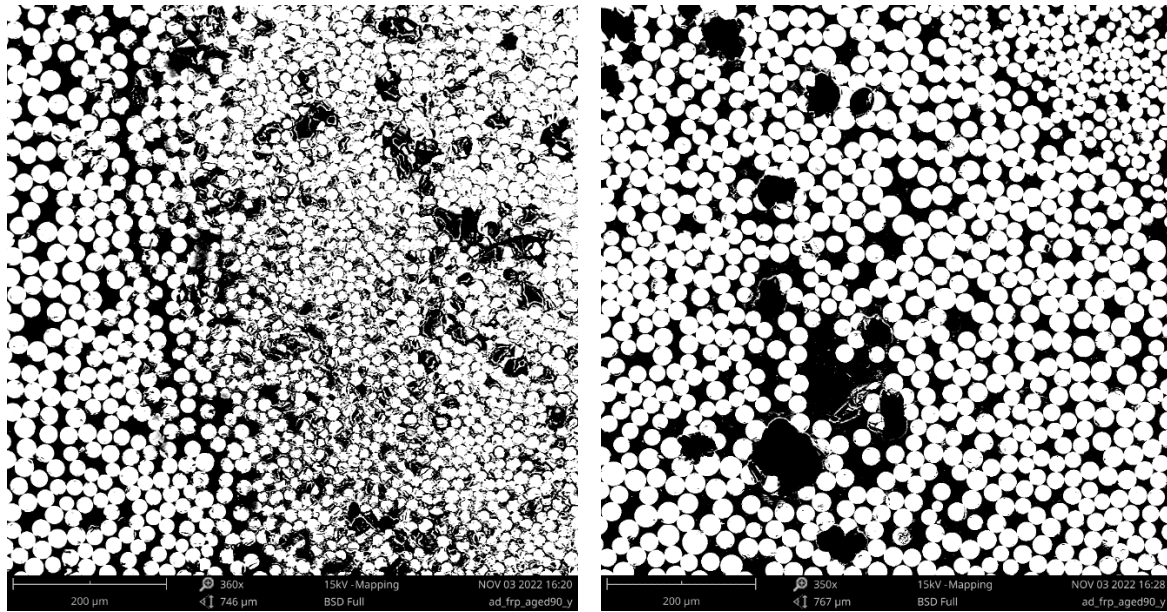


Figure 22 SEM analysis: Sample Y-aged for 90 days, outer (left) and inner (right) part of the cross section

The same situation as with previous samples was observed for specimen Y (8 mm): the alkaline solution penetrated the surface of the bars, letting obvious white residue in-between the fibers (Figure 22).

Observing the results after SEM analysis, was noticed the alkaline solution inflow through the bars surfaces in 3 out of 4 bars tested, sample S was an exception. But the inflow happened only after 90 days aging process, no solution penetration was marked for 30 days aged bars.

6 Conclusion

In this paper several tests were performed to compare the mechanical and microstructural properties of FRP bars.

Based of the above presented results the following conclusions are drawn:

1. It can be noticed from the results the temperature influence on microstructural properties of the bars. Specimens immersed in water maintained at 50 °C had twice higher increase in weight than samples placed in 23 °C temperature water.
2. P bars had the most significant drop in shear strength capacity after aging process, and the highest increase in weight after water absorption test. Looking at pictures taken during SEM analysis, it can be seen that on the surface along the bars there was penetration of alkaline solution. Which can be related to coating properties of the bars and porosity. Thus, it appears that the microstructural properties can help to predict the decrease in mechanical properties in long-term applications.
3. The same penetration of alkaline solution after 90 days was noticed for K bars from SEM analysis. Resulting in a decrease of shear strength capacity by approximately 30-40 % on average for 90 days aged specimens.

The SEM analysis showed high amount of void number for K, which could result in alkaline solution inflow inside the specimen.

4. Unfortunately, the same behavior was observed for Y samples. As it can be seen from results, the behavior of the bar did not change comparing 30 days and 90 days specimens. The same penetration of solution was noticed along the bar surface, which was looking like a whitish residue.
5. In spite of the fact that S specimen had lower initial shear strength compared to other samples, its behavior did not change due to aging solution. No inflow of the solution was noticed during the SEM analysis and in case of S (8 mm) there was the lowest increased of weight after water absorption test, small difference between immersing in 23 °C and 50 °C temperature water. This can be related to the fact that S (8 mm) bar had the highest fiber content. Proper microstructural properties (low number of voids in the cross-section, low water absorption) resulted in little mechanical (shear stress) degradation.

Dragush Anzhelika:

Study of the microstructural and mechanical properties of FRP reinforcement

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8 List of figures

Figure 1 The process of weighting the sample in normal state and while floating in the water	6
Figure 2 Fiber mass test result compared to reference state	7
Figure 3 Storage of the specimen during the durability test	8
Figure 4 Setup for transverse-shear test	9
Figure 5 SEM analysis set-up.....	9
Figure 6 Prepared samples (reference and 30 days aged states, respectively) for SEM analysis	10
Figure 7 Types of bars used in the research	11
Figure 8 Increase in weight after 24h water immersion.....	12
Figure 9 Resin and fiber content of the specimens	13
Figure 10 Shear strength	14
Figure 11 SEM analysis: sample S – reference state, outer (left) and inner (right) part of the cross section	15
Figure 12 SEM analysis: sample S - aged for 30 days, outer (left) and inner (right) part of the cross section	16
Figure 13 SEM analysis: sample S- aged for 90 days, outer (left) and inner (right) part of the cross section	16
Figure 14 SEM analysis: Sample P- reference state, outer (left) and inner (right) part of the cross section	17
Figure 15 SEM analysis: Sample P- aged for 30 days, outer (left) and inner (right) part of the cross section	17
Figure 16 SEM analysis: Sample P- aged for 90 days, outer (left) and inner (right) part of the cross section	18
Figure 17 SEM analysis: Sample K-reference state, outer (left) and inner (right) part of the cross section	18
Figure 18 SEM analysis: sample K-aged for 30 days, outer (left) and inner (right) part of the cross section	19
Figure 19 SEM analysis: Sample K-aged for 90 days, outer (left) and inner (right) part of the cross section	19

Figure 20 SEM analysis: Sample Y-reference state, outer (left) and inner (right) part of the cross section	20
Figure 21 SEM analysis: Sample Y-aged for 30 days, outer (left) and inner (right) part of the cross section	20
Figure 22 SEM analysis: Sample Y-aged for 90 days, outer (left) and inner (right) part of the cross section	21

9 List of tables

Table 1 List of physical characteristics of the specimens	11
Table 2 Decrease in shear strength in relation to the reference state [%].	15
Table 3 Detailed results from water absorption test (23 °C).....	27
Table 4 Detailed results from water absorption test (50 °C).....	30
Table 5 Detailed results from shear test: reference state.....	33
Table 6 Detailed results from shear test: aged for 30 days	34
Table 7 Detailed results from shear test: aged for 90 days.	35

Appendix A: Detailed results of water absorption test

Table 3 Detailed results from water absorption test (23 °C)

ID	Diameter [mm]	Dry weight [g]	Weight after immersion [g]	Increased weight [%]
K	12	6,3988	6,4023	0,0547
		6,4456	6,4498	0,0652
		6,4062	6,4099	0,0578
		6,4137	6,4187	0,0779
		6,4750	6,4795	0,0695
	10	2,9918	3,0008	0,3082
		3,0181	3,0199	0,0596
		2,9733	2,9763	0,1009
		3,0101	3,0133	0,1063
		3,0032	3,0054	0,0133
	8	2,7037	2,7052	0,0555
		2,6940	2,6955	0,0557
		2,6918	2,6924	0,0223
		2,6875	2,6939	0,2381
		2,6799	2,6824	0,0933
	6	1,5209	1,5221	0,0789
		1,5447	1,5454	0,0453
		1,5679	1,5686	0,0446
		1,5691	1,5702	0,0701
		1,5366	1,5377	0,0716

<i>ID</i>	<i>Diameter</i> <i>[mm]</i>	<i>Dry weight</i> <i>[g]</i>	<i>Weight after</i> <i>immersion [g]</i>	<i>Increased weight</i> <i>[%]</i>
<i>S</i>	12	7,5166	7,5177	0,0146
		7,4666	7,4685	0,0254
		7,4877	7,4889	0,0160
		7,4908	7,4926	0,0240
		7,5458	7,5479	0,0278
	8	3,4185	3,4198	0,0380
		3,4140	3,4149	0,0264
		3,4009	3,4013	0,0118
		3,3947	3,3950	0,0088
		3,3756	3,3765	0,0267
<i>T</i>	12	7,4702	7,4719	0,0228
		7,5323	7,5356	0,0438
		7,5192	7,5230	0,0505
		7,5392	7,5434	0,0557
		7,5966	7,5994	0,0369
<i>A</i>	12	4,3466	4,3538	0,1656
		4,3353	4,342	0,1546
		4,3519	4,3563	0,1011
		4,3547	4,3616	0,1584
		4,3139	4,3194	0,1275
<i>Y</i>	8	3,0632	3,0663	0,1012
		3,0629	3,0666	0,1208
		2,9516	2,9543	0,0915
		2,9903	2,9929	0,0869
		3,0393	3,0437	0,1448
	6	1,8139	1,8157	0,0992
		1,8519	1,8541	0,1188
		1,8634	1,8656	0,1181
		1,8710	1,8712	0,0107
		1,7807	1,7813	0,0337

Dragush Anzhelika:

Study of the microstructural and mechanical properties of FRP reinforcement

<i>ID</i>	<i>Diameter</i> <i>[mm]</i>	<i>Dry weight</i> <i>[g]</i>	<i>Weight after</i> <i>immersion [g]</i>	<i>Increased weight</i> <i>[%]</i>
<i>B</i>	8	2,8519	2,8533	0,0491
		2,8634	2,8667	0,1152
		2,8303	2,8340	0,1307
		2,8384	2,8417	0,1163
		2,8850	2,8873	0,0797
<i>P</i>	8	2,9330	2,9340	0,0341
		2,9746	2,9752	0,0202
		2,9302	2,9314	0,0409
		2,9224	2,9235	0,0376
		2,8943	2,9850	3,1338

Table 4 Detailed results from water absorption test (50 °C).

ID	Diameter [mm]	Dry weight [g]	Weight after immersion [g]	Increased weight [%]
K	12	6,4280	6,4368	0,1369
		6,3971	6,4075	0,1626
		6,4354	6,4457	0,1601
		6,4024	6,4116	0,1437
		6,4089	6,4217	0,1997
	10	2,9789	2,9825	0,1208
		3,0089	3,0139	0,1662
		2,9787	2,9870	0,2786
		3,0310	3,0362	0,1716
		3,0007	3,0054	0,1566
	8	2,6931	2,7019	0,3268
		2,7194	2,7281	0,3199
		2,7079	2,7136	0,2105
		2,6829	2,6887	0,2162
		2,6854	2,6898	0,1638
	6	1,5660	1,5706	0,2937
		1,5522	1,5563	0,2641
		1,5355	1,5388	0,2149
		1,5603	1,5662	0,3781
		1,5688	1,5733	0,2884
S	12	7,4875	7,5008	0,1776
		7,4495	7,453	0,0470
		7,4953	7,4978	0,0334
		7,4750	7,4983	0,3117
		7,4653	7,4681	0,0375

<i>ID</i>	Diameter [mm]	Dry weight [g]	Weight after immersion [g]	Increased weight [%]
<i>S</i>	8	3,3623	3,3637	0,0416
		3,4170	3,4184	0,0409
		3,3988	3,4000	0,0353
		3,3922	3,3939	0,0501
		3,3880	3,3898	0,0531
<i>T</i>	12	7,5973	7,6010	0,0487
		7,5825	7,5858	0,0435
		7,5034	7,5047	0,0173
		7,4517	7,4548	0,0416
		7,6378	7,6422	0,0576
<i>A</i>	12	4,3865	4,4040	0,3989
		4,3481	4,3661	0,4140
		4,3414	4,3567	0,3524
		4,3309	4,3453	0,3325
		4,3546	4,3695	0,3422
<i>Y</i>	8	2,9847	2,9905	0,1943
		2,9220	2,9273	0,1814
		2,9884	2,9956	0,2409
		2,9830	2,9882	0,1743
		2,9759	2,9829	0,2352
	6	1,7864	1,7886	0,1232
		1,8650	1,8678	0,1501
		1,8164	1,8187	0,1266
		1,8728	1,8751	0,1228
		1,8092	1,8106	0,0774
<i>B</i>	8	2,8650	2,8665	0,0524
		2,8561	2,8597	0,1260
		2,8688	2,8719	0,1080
		2,8821	2,8837	0,0555
		2,8752	2,8797	0,1565

Dragush Anzhelika:

Study of the microstructural and mechanical properties of FRP reinforcement

<i>ID</i>	Diameter [mm]	Dry weight [g]	Weight after immersion [g]	Increased weight [%]
<i>P</i>	8	2,9241	2,9254	0,0445
		2,9622	2,9647	0,0844
		2,9279	2,9312	0,1127
		2,8812	2,9847	0,1249
		2,9345	2,9374	0,0988

Appendix B: Detailed results for shear test

Table 5 Detailed results from shear test: reference state.

<i>ID</i>				
<i>S</i>	Max. force	Diameter	Area	Shear strength
	kN	mm	mm ²	MPa
	1	25,65	9,055	64,397
	2	17,75	9,050	64,326
<i>Y</i>	3	23,73	9,050	64,326
	Max. force	Diameter	Area	Shear strength
	kN	mm	mm ²	MPa
	1	25,84	8,000	50,265
<i>P</i>	2	22,75	8,000	50,265
	3	24,24	8,000	50,265
	Max. force	Diameter	Area	Shear strength
	kN	mm	mm ²	MPa
<i>K</i>	1	22,90	8,075	51,212
	2	15,51	7,985	50,077
	3	19,08	7,855	48,460
	Max. force	Diameter	Area	Shear strength
	kN	mm	mm ²	MPa
	1	12,27	7,945	49,577
	2	18,99	7,910	49,141
	3	24,11	8,090	51,403

Table 6 Detailed results from shear test: aged for 30 days

ID				
S				
	Max. force	Diameter	Area	Shear strength
	kN	mm	mm ²	MPa
1	19,91	9,000	63,617	156,482
2	16,76	9,050	64,326	130,274
3	18,64	9,255	67,273	138,539
Y				
	Max. force	Diameter	Area	Shear strength
	kN	mm	mm ²	MPa
1	20,92	8,680	59,174	176,767
2	18,49	8,650	58,765	157,320
3	15,49	8,610	58,223	133,022
P				
	Max. force	Diameter	Area	Shear strength
	kN	mm	mm ²	MPa
1	14,38	9,085	64,824	110,915
2	15,49	9,030	64,042	120,936
3	17,98	8,585	57,886	155,306
K				
	Max. force	Diameter	Area	Shear strength
	kN	mm	mm ²	MPa
1	15,08	7,965	49,827	151,325
2	18,44	8,130	51,912	177,607
3	20,56	7,820	48,029	214,037

Table 7 Detailed results from shear test: aged for 90 days.

ID				
S				
	Max. force	Diameter	Area	Shear strength
	kN	mm	mm ²	MPa
	1	15,73	9,020	63,900
Y	2	20,23	9,090	64,896
	3	16,18	9,030	64,042
P	Max. force	Diameter	Area	Shear strength
	kN	mm	mm ²	MPa
	1	16,08	8,670	59,038
	2	15,75	7,690	46,445
K	3	11,09	7,480	43,943
P	Max. force	Diameter	Area	Shear strength
	kN	mm	mm ²	MPa
	1	10,28	8,155	52,231
	2	9,82	8,055	50,959
K	3	9,48	8,320	54,367
K	Max. force	Diameter	Area	Shear strength
	kN	mm	mm ²	MPa
	1	12,11	7,925	49,327
	2	10,88	7,905	49,079
K	3	10,58	7,750	47,173