



UPPSALA
UNIVERSITET

INDEPENDENT PROJECT IN CHEMICAL ENGINEERING MAT-VET-K 22006

Analysis of Resin Impregnated Non-woven

In collaboration with Hitachi Energy

Ahmed Al-Saedi, Anders Hedenfeldt, Andrea García,
Anna-Karin Kron, Cornelia Bergström, Lova Källkvist

Contact person at Hitachi Energy: Francisco Penayo
Examiner: German Salazar Alvarez
2022-06-10

Abstract

High voltage bushings are the most critical components of power transformers. A common material used in bushings is resin impregnated paper (RIP). Hitachi Energy is investigating whether this can be replaced with a new material, resin impregnated non-woven (RIN). One of the main reasons is that non-woven is less prone to absorb moisture compared to paper. Thus, for design purposes the mechanical, thermal and absorption properties of RIN have been studied and compared to RIP. The mechanical properties were tested by tensile and bending tests at room temperature and 80 °C, showing that RIN has a lower elastic modulus and tensile strength than RIP at both temperatures. However, it was demonstrated that RIN does not retain its elongation at break and elasticity properties at elevated temperatures. The bending test showed no significant differences in flexural properties for RIN between room and high temperature. The thermal properties were studied with the transient plane source method (TPS) showing that both RIN and RIP had a higher specific heat capacity than pure epoxy. The thermal conductivity of the materials will be measured and included later. Lastly, the water absorption test was performed in order to provide information about the suitability of the materials used in bushings. For this different methods were used; water immersion and water vapor testing. The immersion test showed that non-woven is more water resistant than paper and that the composites only absorb a small amount of water. No useful information was achieved from the water vapor test due to limited testing time. The results demonstrate the promising potential of RIN in bushings.

Table of contents

1. Introduction	5
1.1 Background	5
1.2 Purpose	5
2. Method	5
2.1 Mechanical properties	5
2.1.1 Background	5
2.1.2 Sample preparation	6
2.1.3 Mechanical tests	6
2.2 Transient Plane Source	7
2.2.1 Background	7
2.2.2 Sample preparation	7
2.2.3 Specific heat	7
2.2.4 Thermal conductivity	8
2.3 Water absorption	8
2.3.1 Background	8
2.3.2 Sample preparation	9
2.3.3 Water immersion absorption test	9
2.3.4 Water vapor absorption test	9
3. Results and Evaluation	9
3.1 Mechanical properties	9
3.1.1 Tensile test	9
3.1.2 Bending test	11
3.2 Transient plane source	12
3.2.1 Specific heat	12
3.2.2 Thermal conductivity	13
3.3 Water absorption	14
3.3.1 Water immersion absorption test	14
3.3.2 Water vapor absorption test	17
3.4 Permeability	18
3.5 Overall evaluation and further analysis	18
4. Conclusion	19
5. Acknowledgements	20
References	21

2022-06-10

Appendix A	24
Appendix B	25
Appendix C	29
Appendix D	31
Appendix E	34

1. Introduction

1.1 Background

Hitachi Energy is a world leading company within the energy industry. The company manufactures high voltage bushings which are hollow electric insulators. They allow an electrical conductor to pass through a conducting barrier without making electrical contact with it. The space between the conductor and the insulator is filled with some dielectric such as oil or gas [1]. Hitachi Energy produces dry bushings for AC and DC transformers and reactors, AC and DC wall applications, and AC switchgear and breakers. A common material used in bushings is resin impregnated paper (RIP). As with most things, there are some disadvantages to using RIP. Therefore, the company is investigating a new material called resin impregnated non-woven (RIN). RIN uses a synthetic fabric as spacers between the capacitive layers and epoxy resins, a class of thermoset [2], are used as the main insulation material. The outdoor insulation for RIN is made from silicone rubber material [3]. In contrast, RIP consists of a core wound from crepe paper impregnated with a curable resin. The outdoor insulation for RIP is made of a composite insulator with silicone sheds or porcelain [4]. The main reason for RIN being investigated as a substitute to RIP is due to the fact that the synthetic fabric is believed to absorb less water than paper before and after impregnation. This is desirable for the company both in manufacturing and the use of the final component.

1.2 Purpose

The main purpose of this project is to provide information about mechanical, thermal and water absorption properties for RIN and compare the result with a reference material, RIP. Information about RIN is therefore of great value for the company in order to expand their knowledge and further investigate the possibility of replacing RIP in some constructions.

2. Method

2.1 Mechanical properties

2.1.1 Background

When dimensioning machine parts, it is important to analyze the amount of load the construction material can withstand before plastic deformation or even fracture. A simple way to obtain this material property is through tensile testing. Depending on the type of material and its use it is appropriate to use a specific standard. In this case, the standard ISO 527-2/1A suitable for thermoset materials is used since the material tested consists mostly of epoxy resins [5, 6].

Composites are anisotropic and generally brittle, thus the properties and strength of the material differ depending on the direction of the applied load or force. Therefore alignment is critical for composite testing applications. In the direction parallel to the fiber orientation the

2022-06-10

tensile strength of a composite material is usually very high, while a lower tensile strength is obtained when testing in any other direction [7].

For the application of high voltage bushings, the flexural strength test is of interest due to the bushing being submitted under the load of its own weight as well as environmental factors. In order to test this property a bending test can be performed to obtain flexural strength and other important properties. Bending tests are conducted by placing the material across a span and bending it until failure through applied force.

Depending on the use of the material, different portions of the material can be tested through either 3-point or 4-point bending. 3-point involves one point of deflection while 4-point applies force to two points separated from the center of the material. By 4-point, a larger portion of the material is tested since the separation of the two point sources spreads the region of bending out from the center compared to only one point of deflection [8]. In order to test a larger portion of the material a 4-point bending is desired as the method to be performed. The suitable standard for fiber-reinforced thermosetting plastic composites is ISO 14125 [9].

2.1.2 Sample preparation

The samples for the tensile test of RIN and RIP were prepared at Hitachi Energy following the standard ISO 527-2/1A. The samples were cut parallel to the fiber orientation. The sample size was 150×20 mm² with a gauge length of 80 mm.

The samples for the bending test of RIN and RIP were prepared at Hitachi Energy following the standard ISO 14125. The samples were cut parallel to the fiber orientation. The sample size was 60×15 mm² with a thickness of 2 mm.

2.1.3 Mechanical tests

Before the execution of the tensile strength test, a test studying the adhesion between the sample and fixture for the instrument was performed to make sure the heated samples did not react with the fixture. For this some samples were heated in an oven and others on a hot plate to temperatures above room temperature. These were then placed on plates of stainless steel while pressure was applied.

The tensile strength test was performed using a 100 kN Instron 8516 testing machine. An extensometer was used to increase the accuracy by eliminating machine compliance and only measuring the displacement of the sample. The extensometer was mounted directly to the specimen until a 1% elongation increase of the gauge length was reached for all the specimens except three out of five RIN samples at high temperature where it was set to 0,8% due to a faster observed fracture. The tensile test was conducted under a test speed of 1 mm·min⁻¹. The test specimens were tested at room temperature and at around 80 °C. For the high temperature specimens an external oven was set to 120 °C during 5 hours and to 140 °C during 30 minutes to see whether the samples could reach higher temperatures. The temperature of the samples at high temperature was measured before and after the tensile test using an infrared thermometer. A total number of 4-5 specimens were tested at each temperature for both RIN and RIP.

The bending test was performed using a 5 kN Shimadzu AGS-X universal testing machine. The sample length, width and thickness were measured using a caliper. When preparing for the experiment it showed that the samples were 4 mm in thickness instead of the requested 2 mm. This, along with the fact that a 15 mm inner span was unavailable for the machine setup, caused the need to switch to three-point bending in order to keep following the ISO 14125 standard. Four samples of RIN were tested at room temperature and five were heated in an external oven to 120 °C overnight. All the samples were mounted on the bottom two-point mount with a span of 40 mm. The above loading point was then mounted into position in the middle of the outer span, with the sample symmetrically placed on the mounting. The test started from a preload of 1 N. The speed of testing was determined to 1 mm·min⁻¹ and each test specimen was deflected until fracture. During the test, the force applied to the specimen and the displacement of the top sample surface was measured [9].

2.2 Transient Plane Source

2.2.1 Background

According to the standard ISO 22007-2 [10] the Transient Plane Source (TPS) method can be used to determine the thermal conductivity, thermal diffusivity, thermal effusivity and specific heat capacity of many types of materials ranging from metals to ceramics and electric insulation material [11]. This makes it a suitable method for this project in determining the thermal transmitting properties of RIP and RIN. The measurement can be done for anisotropic materials. However, to determine the thermal conductivity along both axes the specific heat of the material is needed. This property can be determined using a sensor extension of the TPS instrument, designed to measure the output heat (W) and change in temperature (°C) precisely allowing easy calculation of the specific heat capacity. Both types of sample, RIN and RIP, consist mainly of an epoxy matrix. The specific heat for epoxy is expected to be in the order of 1100 J·kg⁻¹·K⁻¹ and has a thermal conductivity of 0,2 W·m⁻¹·K⁻¹ [12] but it can be treated in order to raise this value [13]. The samples are expected to be in the same order of magnitude in regards to specific heat and thermal conductivity.

2.2.2 Sample preparation

For the specific heat capacity measurement the samples were cut to 10×10×4 mm³. For the thermal conductivity measurement the dimensions were set to 30×30×30 mm³ cubes. However, the received samples for the thermal conductivity measurement had differing geometry and dimensions.

2.2.3 Specific heat

The dimensions of the samples were measured using a vernier caliper. The samples were weighed on a scale afterwards. In order to establish suitable measurement parameters, power and time, a set of trial runs were performed with the gold cell empty as well as using RIP sample 1. The sample stage was raised until the sensor could rest flat on the isolating cup. After the top of the gold cell was placed on the sensor, the isolating cup was then placed on top. A screw covered by a bushing held the cup in place, ensuring little to no gap for airflow between the two isolating cups. A black cover was put over the setup. The setup was allowed to rest for two hours before each measurement in order to avoid drift of temperature. Three

2022-06-10

measurements were taken for each reference and sample run. Overnight, a set of reference measurements were taken at different measurement times and powers, 640 s, 320 s, 160 s and 80 s. The setting 65 mW and 160 s was chosen as the appropriate measurement time due to it giving a total temperature increase of 8,4 K. Trials were performed with the sample in order to get a transient that follows the reference and reaches a similar total temperature increase. Pliers were used when interacting with the sample as to not influence its temperature. The settings chosen were 85 mW and 160 s. The resulting specific heat capacity and specific heat was then calculated using 50 data points from the measurements. The data points were selected in order to yield the highest specific heat capacity due to the method being an underappreciation of the value. This is in accordance with recommendations from Hot Disk for measuring specific heat with the TPS 2200 instrument.

2.2.4 Thermal conductivity

The dimensions of the samples were measured using a vernier caliper. A set of trial runs were done for each set of samples in order to determine what measurement time and power was to be used. Pliers were used when interacting with the samples to not influence their temperature. A power of 120 mW and a measurement time of 80 s was used for batch 1 of RIP. For batch 2, 40 mW and 40 s was used. Batch 1 and 2 of RIN used the settings 100 mW and 80 s. An anisotropic measurement was done with a 5501 F2 sensor for all batches except for RIP batch 2 where the smaller sensor 5465 F2 was used. This was due to its smaller dimensions making it unsuitable to use the larger sensor. Before each measurement a wait time of 60 minutes was issued. This is to avoid temperature drift. Data points were chosen to remove the initial contact resistance on the transient curve, which resulted in points 40-200 in most cases. The instrument then calculated both the axial and radial thermal conductivity.

2.3 Water absorption

2.3.1 Background

The amount of water absorbed by a material depends on its properties and is affected by external effects, such as humidity and rain. Variations in climate may lead to greater water absorption which has been shown to increase the current leakage. A component with a lower ability to absorb water is therefore favorable to decrease leakage of current, prolonging the lifetime of the component. Changing to a material less prone to absorb water will also lead to lower overall expenses because a higher efficiency is maintained. Therefore water absorption is an important parameter to consider when constructing high voltage insulators containing epoxy [14].

The ISO 62 standard will work as an outline. According to the standard, an allowed sample size is $w \leq 100d$, where w is the length of one side and d is the thickness [15]. Equation 1 will be used to calculate the increase in weight percent [16]:

$$\text{Percent water absorption} = \left(\frac{\text{Wet weight} - \text{Dry weight}}{\text{Dry weight}} \right) \times 100 \quad (1)$$

According to a similar standard, ASTM D570, a usual measuring time is 24 hours [16]. This has also been proven to be common throughout literature. For samples that absorb water slowly, the immersion time needed for saturation may be longer [16].

2.3.2 Sample preparation

The samples of RIN and RIP were prepared at Hitachi Energy following the guidelines for allowed sample sizes as described in paragraph 2.3.1. The samples had dimensions of approximately $50 \times 50 \text{ mm}^2$ with thickness 2 mm. Four samples of RIN and four samples of RIP were prepared. The composite samples were cleaned with ethanol and acetone in an ultrasonic bath before the experiment was initiated. Four samples each of non-woven and paper were cut with scissors to $50 \times 50 \text{ mm}^2$.

An additional three samples of paper and three samples of non-woven were cut out using scissors. These had dimensions of $10 \times 10 \text{ mm}^2$ and were used in the water vapor experiment.

2.3.3 Water immersion absorption test

The samples were weighed and then placed on millimeter paper. Pictures were taken of each sample by using a system camera, to be able to measure the dimensions. All samples were then dried in an oven at 80°C for 15 hours to make sure that no water was absorbed in the samples. The dried samples were weighed and photographed again, and then immersed into beakers containing approximately 250-300 ml deionized water. The samples were divided into batches; two samples of each type (paper, non-woven, RIP, RIN) were left at room temperature and two of each type were placed in an oven at 40°C . The samples were patted dry and weighed repeatedly. The test was terminated after approximately 46 hours. Pictures were taken of the samples after finishing the experiment and transferred to a computer software called ImageJ [17], together with the pictures from before the test and after the drying. The dimensions of the samples were measured.

2.3.4 Water vapor absorption test

A saturated saline solution was prepared by mixing 177 g of sodium chloride (NaCl) with 500 ml water. This yields a concentration of $6 \text{ mol} \cdot \text{L}^{-1}$ and results in a relative humidity of 75% [18]. The solution was poured into a desiccator. The paper and non-woven samples were weighed and placed onto a watch-glass. The watch-glass was then placed in the desiccator which was sealed and left at room temperature. The samples were weighed repeatedly and the test was terminated after 46 hours.

3. Results and Evaluation

3.1 Mechanical properties

3.1.1 Tensile test

The experimental results obtained from stress strain curves for RIN and RIP at room temperature and high temperature are presented in figure 1. The obtained values can be seen in Appendix A table A2 and A3. The specific temperatures for the heated samples are presented in Appendix A table A1.

2022-06-10

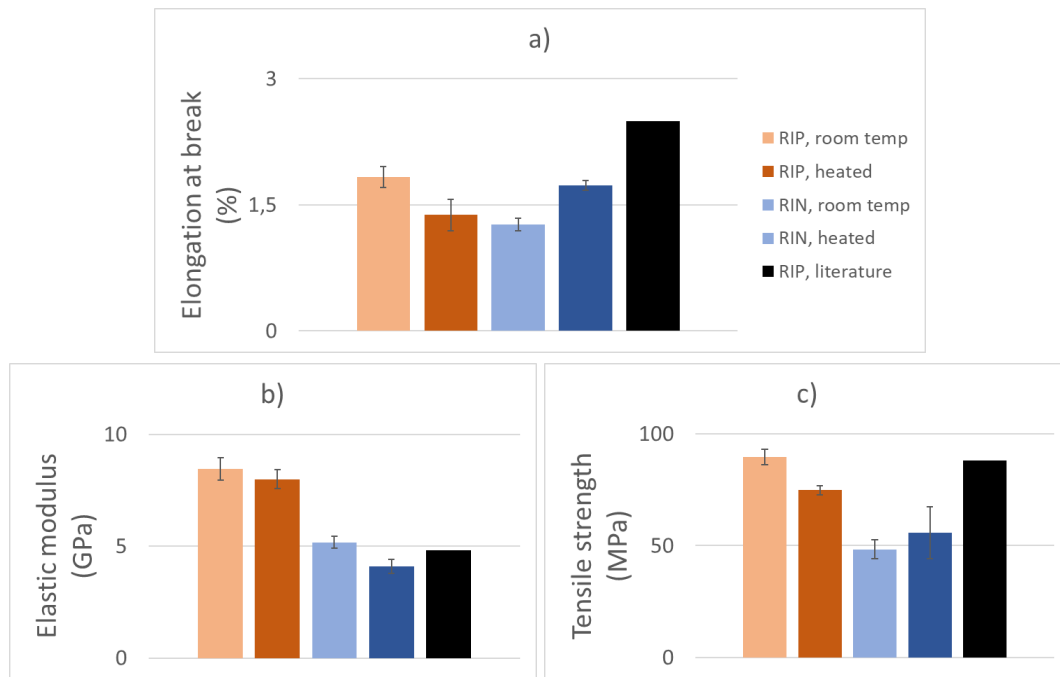


Figure 1. Mean and standard deviation values obtained from stress strain curves for RIP and RIN samples at room temperature and heated: a) elongation at break (%), b) tensile strength (MPa) and c) elastic modulus (GPa). The literature value is shown in black [19].

From figure 1 it is possible to compare the modulus of elasticity, tensile strength and elongation at break for RIN and RIP. As can be seen in figure 1a) the elongation at break for both RIP and RIN is lower than the literature value. This is expected for RIN since it consists of non-woven instead of paper, resulting in different mechanical properties. As for RIP, it could be due to differences in sample preparation. It can also be seen that the elongation at break decreased for RIP, indicating a more brittle behavior at higher temperatures. Whereas RIN shows a higher ductility at higher temperatures.

In figure 1b) it can be seen that the elastic modulus for RIN is similar to the literature value. This indicates similar elasticity between the analyzed RIN samples and the literature RIP samples. However, the experimental value of RIP is significantly higher than the literature. As mentioned before this could be due to sample preparation. Also, between the RIP samples at room and high temperature there is no significant difference according to the standard deviation. However, there is a significant difference between the RIN samples. This indicates that the non-woven material used is more elastic at higher temperatures.

The experimental and literature tensile strength values between the experimental RIP value at room temperature and the literature value of RIP show no significant difference as seen in figure 1c). Further, as the temperature increases the tensile strength decreases for RIP whereas there is no significant difference in the tensile strength for RIN between room and high temperature.

Moreover, it was possible to observe that it took a very long time for the samples to reach higher temperatures. The initial plan was to perform the test at 120 °C. However, after the samples had been in the oven at 120 °C for 5 hours they had reached temperatures around 80

2022-06-10

°C. On the other hand, it was observed that the samples lost heat very quickly when outside the oven as seen in Appendix A table A1. To prevent this, a tensile test instrument with a mounted furnace can be used to maintain the samples at a constant temperature during the test. It is also recommended to test more samples to obtain more accurate data and reduce possible deviation of results caused by sample defects.

3.1.2 Bending test

The experimental results obtained from stress strain curves for RIN at room and high temperature are shown in figure 2. The individual test results for each sample are presented in Appendix B table B3.

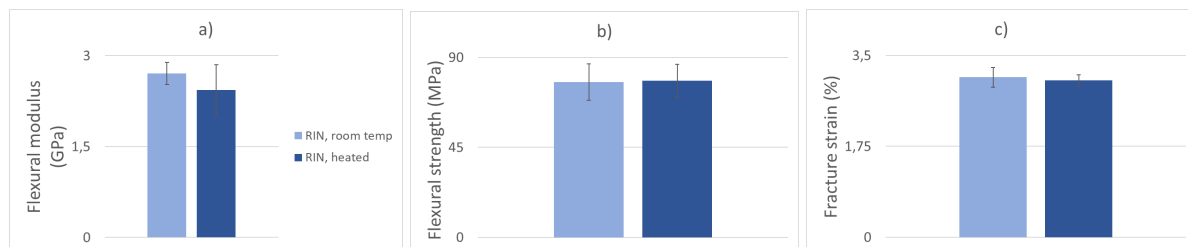


Figure 2. Mean and standard deviation values obtained from stress strain curves for RIN at room temperature and heated: a) flexural modulus, b) flexural strength and c) fracture strain.

The initial plan was to perform the test at 120 °C. However, even though the samples were heated at this temperature overnight they had only reached around 80-90 °C. The temperature values of each sample are presented in table B2 in Appendix B.

The results of the flexural modulus and flexural strength seem to be reasonable with regard to the compared literature values. The literature value indicates that the flexural modulus of epoxy resin should be in the interval of 2,4-205 GPa. The flexural strength of epoxy should be in the interval of 75,8-1890 MPa [20]. Comparing the flexural modulus values in figure 2a), it is shown that there is no significant difference between the results of a sample tested at room temperature and after heating. Thus, the RIN samples seem to retain their mechanical properties at higher temperatures.

Another interesting observation that was made during the test is how the material behaves after reaching the point of elongation at break. Instead of breaking off and crumbling from the lower or upper part, a snapping breakage was observed. It is therefore difficult to determine where the fracture begins on the samples. For this a high speed and resolution camera could be used to record and locate the fracture to determine the dominant cause of the break.

The observed standard deviations could be explained by the fact that the samples lost heat very quickly. The samples had temperatures of around 80-90 °C and at fracture the temperature was around room temperature. This could be improved by performing the test with a furnace mounted to the instrument. Also, defects in the samples as seen in Appendix B figure B1 could lead to an early sample failure. Moreover, the sample dimensions seen in Appendix B table B1 had a slight deviation compared to the required dimensions from the ISO standard used, leading to deviation from the literature. Finally, in order to obtain more accurate data further testing on a larger amount of samples is required.

2022-06-10

A second test was performed for both RIP and RIN at room and high temperature following the same procedures as for the initial test. The experimental results obtained from stress strain curves are presented in figure 3. The individual test results for each sample are presented in Appendix B table B4 and B5. The measured temperatures for each sample are presented in Appendix B table B6 and B7.

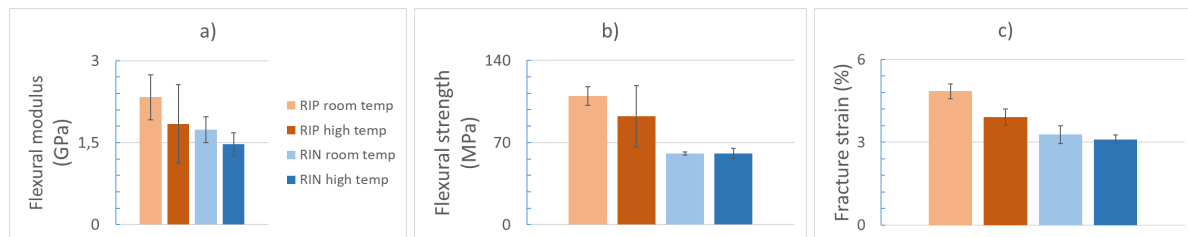


Figure 3. Mean and standard deviation values obtained from stress strain curves for RIN and RIP at room and high temperature: a) flexural modulus, b) flexural strength and c) fracture strain.

Figure 3a) shows that due to the obtained standard deviation there is no significant difference of flexural modulus between RIP and RIN at room and high temperature. The large standard deviation could be decreased by increasing the amount of samples. Since only 5-6 samples were analyzed, it is possible that samples with defects affect the results significantly. Figure 3b) presents the flexural strength. A significant difference can be observed between RIP and RIN. However, neither the flexural strength of RIP nor RIN changes as the temperature increases. Lastly, figure 3c) shows the fracture strain where a significant difference can be observed between RIP and RIN. Further the fracture strain of RIP decreases as the temperature increases. However, there is no significant difference between the fracture strain of RIN at room temperature and high temperature.

3.2 Transient plane source

3.2.1 Specific heat

REDACTED

Figure 4. REDACTED

3.2.2 Thermal conductivity

REDACTED

Figure 5: REDACTED

3.3 Water absorption

3.3.1 Water immersion absorption test

The results from the water absorption test are presented in figure 6. The values presented are averages between the two samples in each batch and were calculated using equation 1. The 24 hour immersion time is comparable with literature while the 46 hour immersion gives an idea about the maximum amount of water that can be absorbed (saturation). Even longer immersion time would be needed to obtain the true value of the saturation weight.

2022-06-10

Unfortunately, the intended time for the experiment ran out and no further testing could be done.

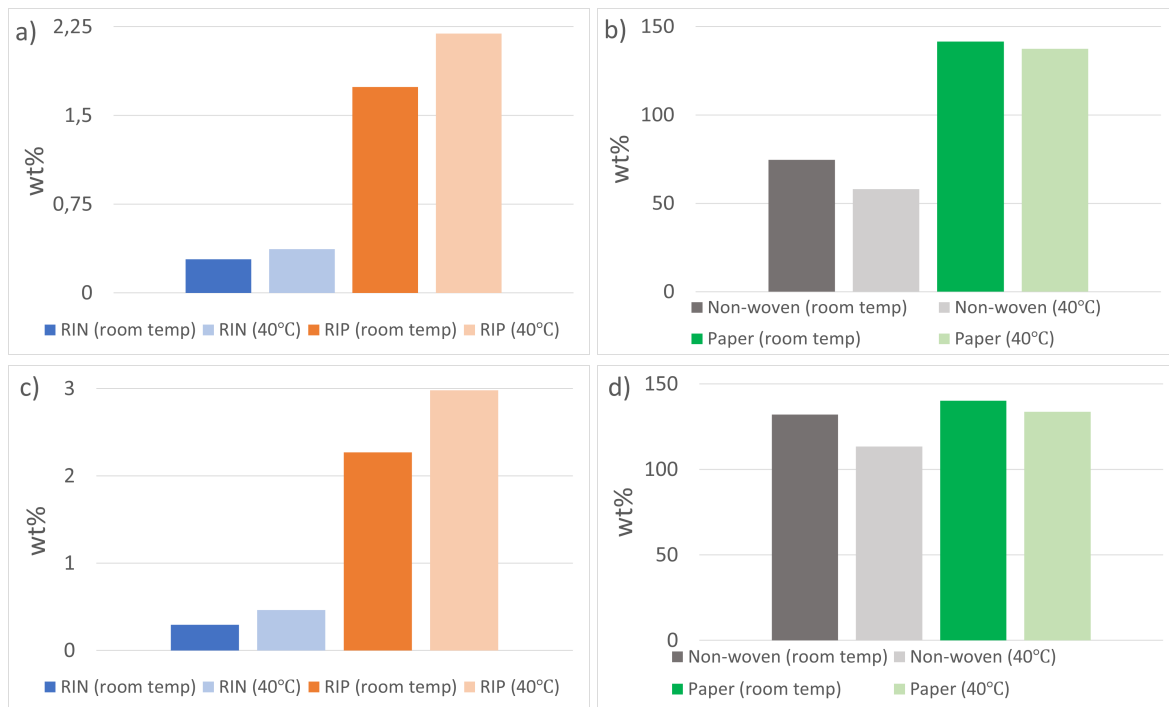


Figure 6. Presents the average values for the water absorption in wt% for a) and b) 24 hours and for c) and d) 46 hour immersion.

As expected, paper absorbs a large amount of water after a short time which can be seen in Appendix D, figure D1. The paper was almost completely saturated after the first measurement, i.e. one hour. The 24 hour immersion time resulted in a water absorption of 141 wt% for room temperature and 137 wt% for 40 °C. Non-woven shows a different saturation process where a major increase occurs at approximately 25 hours. Before this point the non-woven is a lot more water resistant than paper. The non-woven absorbed 74,6 wt% water at room temperature and 58,0 wt% water at 40 °C. Figure D2 in Appendix D illustrates the change in weight between measurements over time for paper and non-woven at room temperature and 40 °C. This graph confirms the fact that paper absorbs water fast and then stabilizes whereas the non-woven has a more complex absorbance pattern. Water absorption at room temperature for paper and non-woven tends to be a bit higher than in 40 °C but since only two samples of each type were studied, nothing can be concluded.

The results clearly show that RIN and RIP absorb much less water than non-woven and paper (Figure D1 in Appendix). Figure 7 shows the change in wt% over time for RIN and RIP. RIP absorbs more water than RIN in both room temperature and 40 °C. RIP absorbs 1,74 wt% water in room temperature and 2,19 wt% water in 40 °C whereas RIN absorbs 0,284 wt% water in room temperature and 0,370 wt% water in 40 °C. For both RIN and RIP, the experiment at 40 °C tends to lead to a higher water absorption than at room temperature.

2022-06-10

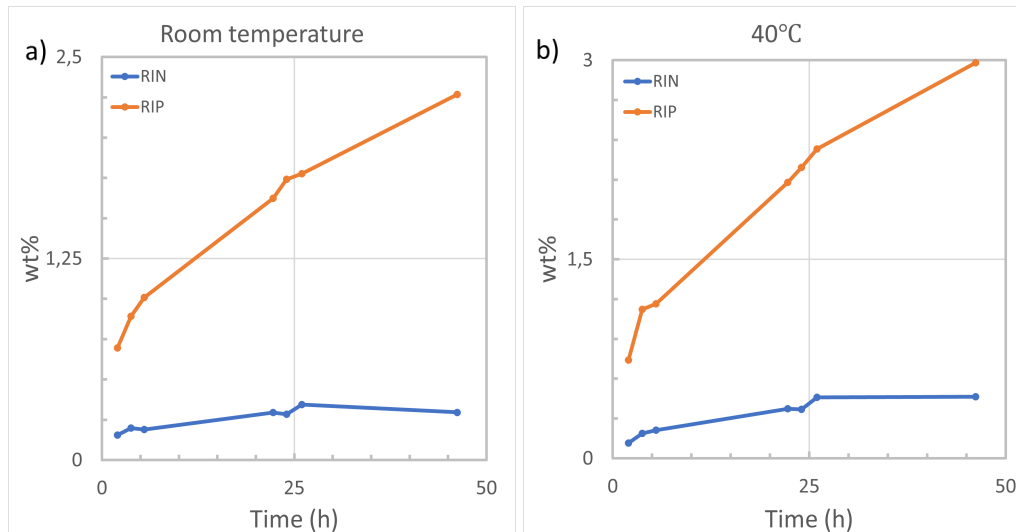


Figure 7. Weight % over time for RIN and RIP at a) room temperature and b) 40 °C.

Only two samples were tested for each material and temperature, therefore further testing with more samples is strongly recommended to obtain more accurate data. It should also be mentioned that there are several sources of error to consider, for example that the samples were dried before weighing. To account for the increasing weight of the samples during immersion time, the same samples were taken out of the water at different times and then re-immersed into water. This causes the samples to dry during the time in air which disturbs the immersion time. An improvement to this error would be to start with many samples and only pick up a sample once at a given time. This would result in a continuous immersion and no set back in time.

Another source of error is that the received composite samples had uneven edges and different surfaces, where some had exposed aluminum and some did not (Figure D3 i Appendix D). This might have affected the amount of water that could be absorbed by each piece.

The greatest difference in weight from the first to the last measurement occurred for non-woven. The large increase in weight between 24 and 26 hours (Figure D1 in Appendix D) suggests that the method involving uptaking and re-immersion of the samples may have affected the water absorption. It is quite unlikely that an immersion for two hours increased the weight more than the immersion for around 17 hours (between 5,25 and 22 hours). When the samples were patted dry before weighing they were compressed which might have disturbed the water resistance of the material. By observing the samples after different immersion times, it can be noted that there are some dark spots in the material that are growing with time (Figure D4 in Appendix D). The spots are parts of the material that absorbs lots of water. The growth of the spots seems to vary between the samples which explains the irregular absorption pattern. The leading hypothesis is that the spots increase with the compression since it forces water to move through channels in the material. To further investigate this hypothesis the samples could be analyzed with SEM.

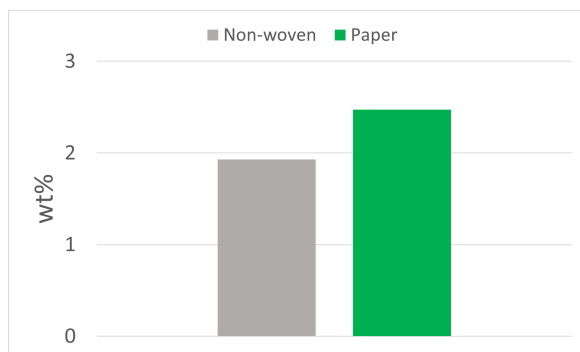
2022-06-10

Pure epoxy resins should absorb approximately 0,1-1,4 wt% of water [21]. This corresponds relatively well to the results achieved in the experiment. The values for RIN are within this interval but RIP deviates slightly from the literature. RIP contains paper which consists of cellulose fibers. These are hydrophilic and can form hydrogen bonds with water, i.e. water is absorbed [22]. This entails that composites reinforced with cellulose tend to absorb more water than other composites [22]. The tested non-woven consisted of a random network of polyester fibers. According to literature, polyester has a really low ability to absorb water (0,06-0,09%) which deviates from the results from the experiment. This may originate from a difference in structure, where the values from the literature might describe the water absorption of one polyester fiber and the result from this project focuses on the water absorption of a random network of fibers. Water accumulates in pores and voids between the fibers resulting in an overall weight gain.

Apart from the weight, the dimensions of the samples were measured before and after the experiment. Measuring with a caliper was very hard and time consuming, and therefore a camera was used to take pictures of the samples on a millimeter paper. The pictures were analyzed in an image analysis software and dimensions of each sample were obtained (Table D2 in Appendix D). The results from this procedure show that the dimensions of the paper had changed, since the creping was lost during the immersion. A slight increase in the dimensions of non-woven was also observed. The accuracy in the measurement is low and therefore this can not be established. The dimensions for RIN and RIP do not seem to have changed since some samples increased and some decreased after the experiment. This is probably due to inaccurate measuring since the samples had a curved shape.

3.3.2 Water vapor absorption test

The results from the water vapor absorption test are presented in figure 8. One of the samples of non-woven showed a very unstable weight change resulting in a decrease in weight at the last measurement (Table D3 in Appendix D). This is most likely an error due to the scale and the value is therefore excluded in the figure below. Figure 8 shows that both paper and non-woven increased in weight in the experiment, indicating that water had been absorbed. Paper also tends to absorb more water than non-woven. However, this can not be established since the experiment only lasted for 46 hours in an atmosphere with 75% relative humidity. The absorbency of the materials was relatively low in this environment, resulting in a weight increase of approximately 0,3 mg. Therefore, slight errors may occur when weighing, resulting in unreliable data. Another source of error might be that only three samples of each type were studied.



2022-06-10

Figure 8. Water vapor uptake after 46 hours, presented as an average weight% for non-woven and paper.

To reach a reliable result, a further analysis of the tendency of non-woven and paper to absorb water from vapor is required. The experiment should be carried out for a longer period, for example 30 days, to ensure that water is absorbed. Instead of creating a steady relative humidity with a saturated saline solution, the process can be accelerated by performing the experiment in a humidity chamber containing supersaturated steam.

3.4 Permeability

The initial plan was to test the permeability of paper, non-woven, RIP and RIN at room temperature and 40 °C. The permeability of the composites is relevant to the overall evaluation of the material. Unfortunately this test could not be executed due to difficulties in sample preparation. Thin samples are needed to perform the test within a reasonable time frame. The thickness of the samples that could be provided by Hitachi Energy was 1 mm, which would correspond to about a month of testing time. A solution to this problem would be to grind the samples to decrease the thickness and therefore reduce the time. The problem that occurs is that the grinding would most likely result in uneven plates, possibly resulting in holes. These conditions are not favorable and the results would be inaccurate. Performing a permeability test with water vapor on the paper and the non-woven was not considered relevant since the water absorption was already tested. The water absorption test provides similar information as the permeability test would have, regarding the efficiency of the components.

For the company, the most important information about the permeability is not the water vapor transmission, but the permeance of epoxy through the material. The permeability parameter is of great value when simulating the impregnation rate when optimizing the manufacturing process. Due to the fact that epoxy contains hazardous substances, experiments involving epoxy can be dangerous and extensive measures are needed. Experiments with epoxy are also a lot more expensive than experiments with water. This is the reason why no testing will be executed. The possibility of calculating the permeability from similar data, without having to do an experiment, has been investigated. The idea is to calculate the permeability of epoxy through non-woven from either of the following data sets; epoxy through paper or water through non-woven.

Unfortunately, the studied components in the data sets have different properties. Water is a small and highly polar molecule while epoxy is large and not as polar. The interaction between water and non-woven will therefore be different from the interaction between epoxy and non-woven. Similarly, the paper has a different structure than the non-woven. Factors such as fiber volume fraction, porosity, surface-active groups and capillary forces need to be closely considered when attempting an approximation [24, 25].

3.5 Overall evaluation and further analysis

The main advantage for non-woven compared to paper is its ability to resist water. This was established during the water absorption test (paragraph 3.3). It is important that the raw material, as well as the finished composite, absorbs as little water as possible since the water absorbent property is associated with the cost and durability of the components. Hitachi

2022-06-10

Energy currently uses RIP which has shown to absorb more water than RIN. Therefore, it may be preferable to use RIN instead of RIP in terms of water absorption.

Regarding the mechanical properties both tensile and bending test results also indicate that RIP has more preferable mechanical properties for intended use compared to RIN. For instance, it is important that the material can withstand a high amount of load or stress until it stretches and breaks. This implies that stiffness is of great importance, where elastic and flexural modulus are high. RIP exhibits a higher tensile strength, flexural strength and elastic modulus compared to RIN at both temperatures. However, due to the high standard deviation, no significant difference can be observed between the flexural modulus of RIP and RIN.

A reason for RIP exhibiting more advantageous mechanical properties than RIN could be due to the different orientations of fibers between paper and non-woven. The paper is made from cellulose fibers that have a defined order compared to the non-woven material that lacks a strict fiber orientation. The paper would hold together the epoxy and therefore a slower material fracture is to be expected compared to RIN that behaves more like pure epoxy. To further analyze the components, the adhesion between the epoxy and fibers can be studied using SEM.

The porosity of the materials can also be analyzed. The pores in the material need to be minimized for the component to function at its highest capacity. The porosity affects all the properties studied in this report, and is therefore important to evaluate. In terms of mechanical properties, pores can make the material unpredictable and unreliable. Water can also be gathered in pores and make the material absorb more water, which is undesirable. The porosity can be analyzed with, for instance, X-ray tomography or gas adsorption.

4. Conclusion

In conclusion, the materials in high voltage bushings, RIN and RIP, were evaluated and compared by testing mechanical, thermal and water absorption properties.

The mechanical properties were tested by tensile and bending tests. The results from the tensile test indicate that RIN has a lower elastic modulus and tensile strength than RIP at both room and high temperature. Moreover, RIN does not retain its elongation at break and elastic properties at elevated temperatures, however, it does retain its tensile strength. The bending test shows that both materials retain their flexural modulus at elevated temperatures. Also, it shows no significant difference between RIP and RIN. However, a significant difference was observed in the flexural strength and fracture strain, where RIP exhibits higher values at both room and elevated temperatures compared to RIN.

The water immersion absorption test indicated that paper absorbs water quickly and is saturated almost immediately. Non-woven is more resistant to water than paper but eventually saturates. The composites do not absorb much water but the results suggest that RIP absorbs more water than RIN. The water vapor absorption test was incomplete and further testing is required.

Overall, RIN seems to be favorable to RIP when considering the water absorption, but shows no major benefits when it comes to mechanical and thermal properties. Depending on the

application of the bushing, the deficit in mechanical properties may be deemed acceptable in favor of improved water resistance.

5. Acknowledgements

We would like to extend our deepest gratitude to Hitachi Energy for providing us with this project. Especially to Francisco Penayo who provided us with the information needed and was our main contact. Also to both Francisco and Elson Montibon for inviting us to the headquarters in Ludvika and taking such good care of us.

We would also like to express our thanks to the project supervisor Germán Salazar Alvarez. Furthermore, we would like to recognize the invaluable assistance of Athira Anil, who in spite of being very busy, took time to guide and help us plan and perform our experiments. Also, we are very grateful for the help provided by Ana Grzeszczak and Cecilia Persson in equipment for performing tensile and bending tests at high temperatures.

Finally, we thank Malin Wohler and Robin Elo for their willingness to help us.

References

1. Ganguly A, Gorayan RS. Performance of High Voltage Bushings Under Polluted Conditions. In: Kamalakannan C, Suresh LP, Dash SS, Panigrahi BK, editors. Power Electronics and Renewable Energy Systems. New Delhi: Springer India; 2015. p. 255-64. (Lecture Notes in Electrical Engineering). doi: 10.1007/978-81-322-2119-7_26.

2022-06-10

2. Gibson G. Chapter 27 - Epoxy Resins. In: Gilbert M, editor. *Brydson's Plastics Material (Eighth Edition)* [Internet]. Butterworth-Heinemann; 2017 [cited 2022 Apr 19]. p. 773-97. doi: 10.1016/B978-0-323-35824-8.00027-X.
3. Resin impregnated synthetic (RIS) | Hitachi Energy [Internet]. [cited 2022 Apr 13]. Available from: <https://www.hitachienergy.com>
4. Resin Impregnated paper (RIP) | Hitachi Energy [Internet]. [cited 2022 Apr 13]. Available from: <https://www.hitachienergy.com>
5. TestResources. ISO 527 - Tensile Test of Plastics Composites [Internet]. TestResources [cited 2022 Apr 5]. Available from: <https://www.testresources.net>
6. Ekholm F. Instruktioner till laborationen Dragprovning [laboratory manual on the internet]. Uppsala: Uppsala Universitet; 2022 [cited 2022 Apr 5].
7. Saba N, Jawaid M, Sultan MTH. 1 - An overview of mechanical and physical testing of composite materials. In: Jawaid M, Thariq M, Saba N, editors. *Mechanical and Physical Testing of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites* [Internet]. Woodhead Publishing; 2019 [cited 2022 Apr 20]. p. 1-12. (Woodhead Publishing Series in Composites Science and Engineering). doi: 10.1016/B978-0-08-102292-4.00001-1.
8. Khan Y. Characterizing the Properties of Tissue Constructs for Regenerative Engineering. In: Narayan R, editor. *Encyclopedia of Biomedical Engineering* [Internet]. Oxford: Elsevier; 2019 [cited 2022 Apr 19]. p. 537-45. doi: 10.1016/B978-0-12-801238-3.99897-0.
9. British Standard Institution. ISO 14125 Fibre-reinforced plastic composites- Determination of flexural properties. London: BSI; 1998.
10. International Organization for Standardization. ISO 22007-2 Plastics — Determination of thermal conductivity and thermal diffusivity - Part 2: Transient plane heat source (hot disc) method. Switzerland: ISO; 2008.
11. Zhang H, Li Y-M, Tao W-Q. Theoretical accuracy of anisotropic thermal conductivity determined by transient plane source method. *Int J Heat Mass Transf.* 2017;108:1634-44. doi: 10.1016/j.ijheatmasstransfer.2017.01.025.
12. Guo Y, Ruan K, Shi X, Yang X, Gu J. Factors affecting thermal conductivities of the polymers and polymer composites: A review. *Compos. Sci. Technol.* 2020;193:108-34. doi: 10.1016/j.compscitech.2020.108134.
13. Li S, Yu X, Bao H, Yang N. High Thermal Conductivity of Bulk Epoxy Resin by Bottom-Up Parallel-Linking and Strain: A Molecular Dynamics Study. *J. Chem. C.* 2018;122(24):13140-7. doi: 10.1021/acs.jpcc.8b02001.

2022-06-10

14. Mbougou E, Mavon C, Friedt J-M, Bergeon C, Fromm M. Impact of Water Content on the Electrical Behavior of Epoxy Insulators. *IEEE Trans Dielectr Electr Insul.* 2008;15(2):311-8. doi: 10.1109/TDEI.2008.4483447.
15. CEN. ISO 62 Plastics - Determination of water absorption. Brussels: European committee for standardization; 2008.
16. ASTM International. D570 Standard Test Method for Water Absorption of Plastics. Pennsylvania: ASTM International; 2019.
17. Schneider, C. A., Rasband, W. S., & Eliceiri, K. W. (2012). NIH Image to ImageJ: 25 years of image analysis. *Nature Methods*, 9(7), 671–675. doi: 10.1038/nmeth.2089
18. Saturated Salt Solutions and control of Air Humidity [Internet]. [cited 2022 May 24]. Available from: <https://www.engineeringtoolbox.com>
19. ABB Technology Products AB Components. Resin impregnated paper bushings [brochure]. Ludvika: ABB Technology Products AB Components; 1997 [cited 2022 May 2]. Available from: <https://library.e.abb.com>
20. Matweb. Overview of materials for Epoxy Cure Resin [Internet]. Blacksburg: MatWeb; [cited 2022 May 2]. Available from: <https://www.matweb.com>
21. Faruk O, Tjong J, Sain M, editors. Lightweight and Sustainable Materials for Automotive Applications. Boca Raton: CRC Press; 2017- 513 p. doi: 10.1201/9781315152967.
22. Almari H, Low I.M. Mechanical properties and water absorption behaviour of recycled cellulose fibre reinforced epoxy composites. *Polym Test.* 2012;31(5):620-8. doi: 10.1016/j.polymertesting.2012.04.002.
23. Ebnesajjad S. 5 - Operational Classification of Fluoropolymers. In: Ebnesajjad S, editor. *Fluoroplastics (Second Edition)* [Internet]. Oxford: William Andrew Publishing; 2015 [cited 2022 May 4]. p. 39-47. doi: 10.1016/C2012-0-05998-4.
24. Hammond V.H, Loos A.C. The Effects of Fluid Type and Viscosity on the Steady-State and Advancing Front Permeability Behavior of Textile Preforms. *J Reinf Plast Compos.* 1997;16(1): 50-72. doi: 10.1177/073168449701600105.
25. Monticeli F.M, Almeida Jr J.H.S, Neves R.M, Ornaghi Jr H.L, Trochu F. The influence of fabric architecture on impregnation behavior and void formation: Artificial neural network and statistical-based analysis. *Polym Compos.* 2022: 2812-23. doi: 10.1002/pc.26578

2022-06-10

2022-06-10

Appendix A

Table A1. Temperature (°C) values for each specimen of RIP and RIN before and after the tensile test.

Sample	RIN		RIP	
	Before	After	Before	After
1	85	30	60	30
2	82	25	70	25
3	85	30	75	42
4	80	38	75	45
5	85	50	80	44

Table A2. Obtained values from stress strain curves for room temperature and heated RIN samples.

Sample	Tensile strength (MPa)	Elongation at break (10^{-3})	Modulus of elasticity (GPa)
1 room temp	53,15	13,40	5,010
2 room temp	45,43	11,93	5,481
3 room temp	46,35	12,76	5,010
1 heated	64,61	22,27	4,140
2 heated	38,11	8,463	4,001
3 heated	65,78	22,34	4,266
4 heated	60,06	18,07	4,178
5 heated	50,49	15,33	3,926

Table A3. Obtained values from stress strain curves for room temperature and heated RIP samples.

Sample	Tensile strength (MPa)	Elongation at break (10^{-3})	Modulus of elasticity (GPa)
1 room temp	90,90	18,63	7,762
2 room temp	89,19	17,90	8,829
3 room temp	93,36	19,88	8,449
4 room temp	85,37	16,84	8,770
1 heated	76,12	13,12	8,562
2 heated	71,70	11,41	7,521
3 heated	77,05	16,14	8,154
4 heated	74,58	13,17	8,082
5 heated	74,54	15,24	7,673

2022-06-10

Appendix B

Table B1. Dimensions measured of RIN samples using a vernier caliper for test 1.

Length (mm)	Width (mm)	Thickness (mm)
60,48	14,01	4,08
60,71	14,27	3,94
60,76	14,50	3,90
59,27	13,68	3,87
59,39	14,09	4,24
-	14,79	4,17
60,51	14,27	3,8
59,25	14,20	3,98
60,01	14,45	4,01

Table B2. Measured temperature (°C) for RIN before and after the bending test for test 1.

RIN sample	Before (°C)	After (°C)
1	80	28
2	90	25
3	93	28
4	70	30
5	68	29

Table B3. Obtained values from stress strain curves for room temperature and heated RIN samples for test 1.

RIN sample	Flexural strength (MPa)	Flexural modulus (GPa)	Fracture strain (%)
1 room temp	75,04	2,21	3,01
2 room temp	87,24	2,79	3,15
3 room temp	68,44	1,94	3,04
4 room temp	82,33	2,77	2,88
1 heated	83,9	2,72	3,25
2 heated	83,7	2,93	3,11
3 heated	78,7	2,71	3,16
4 heated	64,3	2,48	2,81

2022-06-10

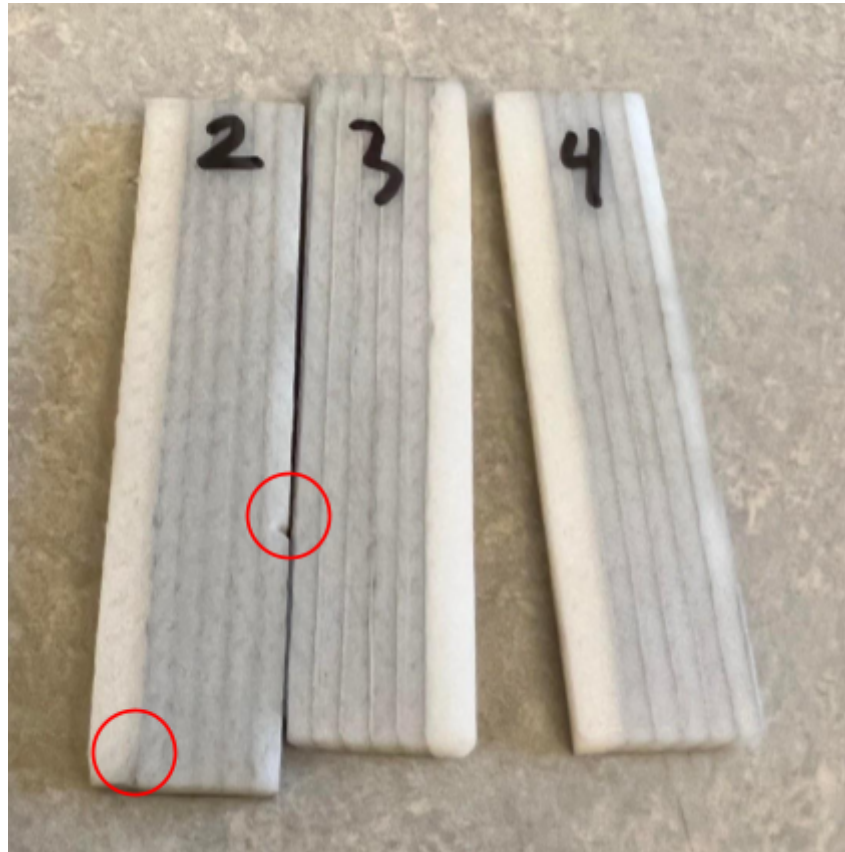


Figure B1. RIN samples showing visible defects marked in red.

2022-06-10

Table B4. Obtained values from stress strain curves for room temperature and heated RIN samples for test 2.

RIN sample	Flexural strength (MPa)	Flexural modulus (GPa)	Fracture strain (%)
1 room temp	62,8	1,65	3,82
2 room temp	61,0	1,53	3,18
3 room temp	59,7	1,60	3,17
4 room temp	60,4	1,78	3,25
5 room temp	60,1	2,12	2,96
1 heated	58,2	1,54	3,21
2 heated	59,1	1,12	3,27
3 heated	67,8	1,69	3,18
4 heated	56,5	1,53	2,94
5 heated	61,3	1,47	2,94

Table B5. Obtained values from stress strain curves for room temperature and heated RIP samples for test 2.

RIP sample	Flexural strength (MPa)	Flexural modulus (GPa)	Fracture strain (%)
1 room temp	102	2,51	4,61
2 room temp	117	1,94	5,04
3 room temp	105	1,83	5,20
4 room temp	120	2,73	4,61
5 room temp	105	2,64	4,76
1 heated	107	1,76	4,03
2 heated	95	1,79	3,42
3 heated	115	2,01	4,31
4 heated	112	3,13	3,95
5 heated	47	1,10	3,88
6 heated	79	1,28	3,91

Table B6. Measured temperature (°C) for RIN before and after the bending test for test 2

RIN sample	Before (°C)	After (°C)
1	66	27
2	54	33
3	50	30
4	64	44

2022-06-10

5	76	24
---	----	----

Table B7. Measured temperature (°C) for RIP before and after the bending test for test 2

RIP sample	Before (°C)	After (°C)
1	60	23
2	56	24
3	42	23
4	64	26
5	60	33
6	76	33

2022-06-10

Appendix C

REDACTED

2022-06-10

Appendix D

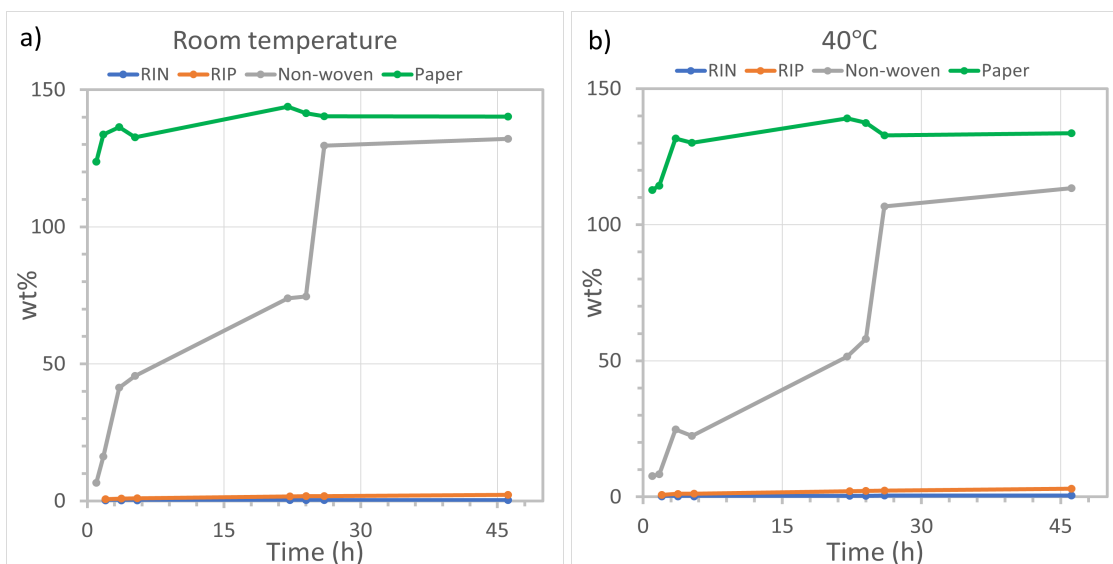


Figure D1. Comparison between RIN, RIP, non-woven and paper at a) room temperature and b) 40°C.

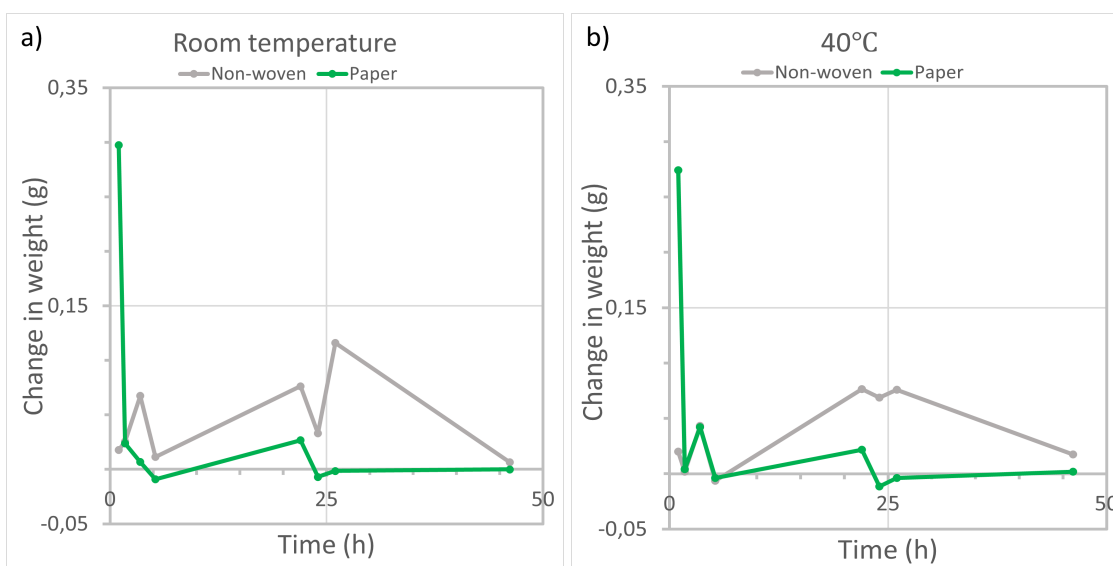


Figure D2. Change in weight between measurements for non-woven and paper at a) room temperature and b) 40°C.

2022-06-10

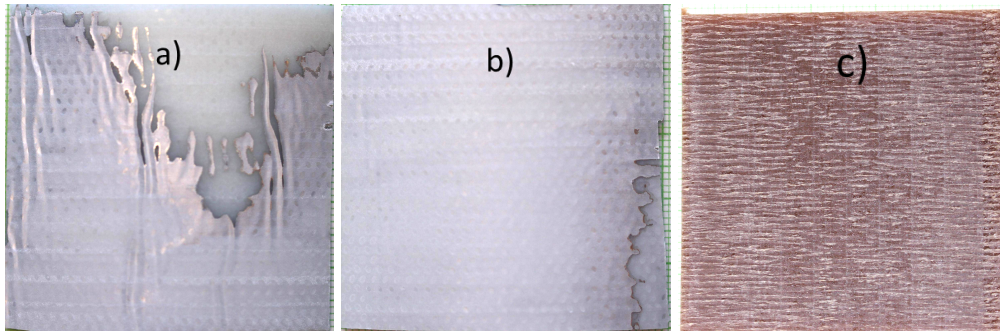


Figure D3. Displays the differences between the RIN samples a) and b), as well as a defect on the edge of a RIP sample c).

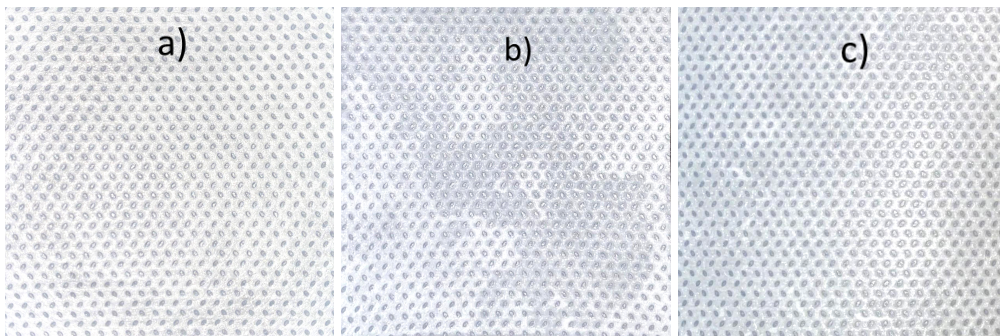


Figure D4. Comparison of spots in non-woven a) before immersion, b) after 5,25 hour immersion and c) after 46 hour immersion. Note that the pictures are taken at different times and with different lighting which can make the differences between the samples muted.

Table D1. Identification of the samples at each temperature. A batch consists of two samples tested at the same temperature.

	RIN	RIP	Non-woven	Paper
Room temperature	1a	2a	3a	4a
	1b	2b	3b	4b
40 °C	1c	2c	3c	4c
	1d	2d	3d	4d

Table D2. Average dimensions before and after 24 hour immersion. The sample names are explained in table D1.

Sample	Before immersion (cm)	After 24 h immersion (cm)
1a/1b	7,17	7,13
1c/1d	7,04	7,07
2a/2b	7,10	7,10
2c/2d	7,08	7,08

2022-06-10

3a/3b	7,02	7,06
3c/3d	7,10	7,18
4a/4b	7,20	8,39
4c/4d	7,24	8,52

Table D3. Presents all the wt% of the samples individually at every measurement for the water vapor absorption test.

	Time	Weight%		
Non-woven		1	2	3
	16	1	2,20	0,952
	20	1	1,10	0
	24	0	0	0
	40	0	2,20	1,90
	46	1	-2,20	2,86
Paper		4	5	6
	16	1,79	3,08	-1,85
	20	1,79	3,08	-1,85
	24	0,893	1,54	1,85
	40	3,57	3,85	2,78
	46	3,37	3,85	0