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Research Paper

Effect of Temperature and Moisture on the Impact Behaviour of Adhesive Joints for the Automotive Industry

Daniel Rosendo[1], Guilherme Viana[2], Ricardo Carbas[3], Eduardo Marques[4], Lucas FM da Silva[5]

[1] Departamento de Engenharia Mecânica, Faculdade de Engenharia da Universidade do Porto (FEUP), 4200-465 Porto, Portugal, Email: up201306631@fe.up.pt

[2] Departamento de Engenharia Mecânica, Faculdade de Engenharia da Universidade do Porto (FEUP), 4200-465 Porto, Portugal, Email: em08173@fe.up.pt

[3] Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial (INEGI), 4200-465 Porto, Portugal, Email: carbas@fe.up.pt

[4] Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial (INEGI), 4200-465 Porto, Portugal, Email: emarques@fe.up.pt

[5] Departamento de Engenharia Mecânica, Faculdade de Engenharia da Universidade do Porto (FEUP), 4200-465 Porto, Portugal, Email: lucas@fe.up.pt

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Corresponding author: Lucas FM da Silva (lucas@fe.up.pt)

Abstract. This study focuses on evaluating the impact of aluminum adhesive joints as a function of temperature and moisture, in an effort to understand how these conditions affect their mechanical properties and behavior. After preparing the required specimens (using two different adhesives and adherend thicknesses), several tests have been made in order to determine these properties and compare their values to the predictions made using analytical methods. These tests were repeated with several distinct combinations of temperatures and moisture levels so that the effect of these properties can be properly interpreted. It was observed that higher temperatures strongly increase the ductility of the adhesive but mixed with moisture this can degrade them. Moisture can increase the energy absorbed through increased plastic deformation of the adhesive and improve behaviour at low temperatures.

Keywords: Adhesive joint, Structural adhesive, Impact, Single-lap joint, Temperature, Moisture.

1. Introduction

Nowadays, the automotive industry has been assessing different methods for reducing the weight of their structures to reduce bot the environmental impact and fuel efficiency. By using adhesive bonding, different materials can be joined while providing smooth joined surfaces and improving corrosion and fatigue resistance and, most importantly, granting a uniform stress distribution without holes or discontinuities. Adhesive bonding is also the only method that can join composite materials efficiently. When designing a joint using structural adhesives for the automotive industry, one of the most important factors to consider is its resistance to impact loads. High toughness of the adhesive is important in these situations and as such epoxy adhesives are commonly used. Even though pure epoxy resins are brittle, technological advances have allowed them to be produced with improved toughness without forfeiting too much of the joint strength [1 - 7].

Especially in the automotive industry, it is crucial to understand how the mechanical properties of an adhesive and therefore a joint's strength can vary as their service temperature goes up or down. It is of extreme importance not to go past an adhesive's glass transition temperature (Tg) to avoid a drastic loss of strength, and even at temperatures close to this value its properties may already be reduced to a level that will effectively harm an adhesive joint's performance. It is also necessary to consider the thermal expansion coefficients of both the adhesive and the adherends, since dissimilar values will create additional stresses which can compromise the joint's strength when it is submitted to different temperatures [8, 9]. Thus, when designing an adhesive joint, its maximum service temperature should be carefully determined beforehand. In the case of the automotive industry, where operation temperatures range from -40°C to 80°C [10], both the highest and lowest temperature may negatively affect the strength of the adhesive joints. The adhesive's strength is lowered as the temperature gets too high (once again, especially close to its Tg), while at lower temperatures thermal stresses start becoming relevant. However, it is important to consider that the stiffness of bonded joints, when tested at low temperature using an epoxy adhesive, are more affected by the adherends' response than by the adhesive's modulus [11, 12].

The variable environmental conditions that adhesively bonded structures face during their lifetime is a major concern. It is extremely important to know how different conditions affect the behaviour of the joints considering that, under high strain-rate, the different temperatures and moisture absorption levels of the adhesive can affect its behaviour. Experimental testing of joints under impact load while exposed to these different conditions is, for these reasons, very important in order to design the most efficient possible structures using adhesive bonding. Low temperatures are known to decrease the ductility of adhesives. It is also known that under high strain rate conditions some polymers tend to become quite brittle. Brittle polymers are usually not as

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strain rate dependent as more ductile polymers. Therefore, when joints bonded with epoxy adhesives are loaded at low temperatures, different strain rates are not expected to give significantly different results at failure. On the other hand, at high temperatures, ductility increases on the adhesive due to its proximity to the Tg and leads to much higher strain rate dependence. While above Tg, the toughness of structural adhesives is usually very low, below Tg it is normally high and independent of temperature [13 - 15]. It is therefore very important to keep the adhesive always below Tg, otherwise the adhesive joint may not be capable of resist any impact [16, 17].

However, the strength of a bonded joint is not just a function of temperature and strain rate. Many studies have been done on the effect of different geometries and materials on joint performance. The failure load has been demonstrated to be strongly dependent on parameters such as the overlap's length or the thickness of the adhesive layer. The combination of different adherends and adhesives with distinct ductility has also been proved to be critical in the joint performance, especially when discussing single lap joints (SLJs), loaded in tension. The joint design chosen for this study tried to mirror as closely as possible a real application in the automotive industry. In these applications, the energy that is absorbed by the adhesive joint depends mostly on the substrate and thus high strength adherends do not allow for ideal energy absorption during impact. In order to absorb high impact energy, mild steel or other soft and ductile materials should be used because they allow for very large plastic deformation before failure [18 - 21]. Focusing on SLJ drop weight impact tests, using ductile epoxy adhesives with high elongation, the failure mode is generally the same as with low-speed, quasi-static loads. Nevertheless, due to their sensitivity to high strain rates, they do not deform as much, reducing the absorbed energy but increasing the maximum load before failure [22, 23]. The energy absorbed in the adhesive is in fact very small and its true role is to hold the two adherends together while they deform plastically in tension. A joint with high yield strength adherends will therefore have good strength even when coupled with a low ductility adhesive but this is not the case for ductile adherends which will inevitably fail at low loads and promote reduced energy transfer to the substrates [24, 25].

The objective of this study is to analyze the behaviour of adhesive bonded joints under several conditions that emulate environmental changes and conditions representative of service in the automotive industry, focusing mainly on impact loads. Two different new adhesives were studied, which have suitable properties for this type of application though, after further analysis, may behave differently under different temperatures or moisture level. To understand how the bending of the substrates affects the joints' behaviour and strength, different adherend thicknesses were also used. Finally, to compare how the strain-rate affects the failure of the adhesive joint, tensile quasi-static tests were performed (Fig. 1).

2. Experimental Procedure

2.1 Testing Variables

The objective of this work is to study how the different conditions affect the single lap joints. In order to do so, the conditions presented on Table 1 were considered and the tests were made using their possible combinations.

2.2 Materials

2.2.1. Adhesive

Two adhesives suitable for use in the automotive industry were selected:

- The epoxy adhesive XNR 6852-1, supplied by NAGASE CHEMTEX® (Osaka, Japan). This adhesive is a one-part system that cures at 150°C for 3 hours;
- The epoxy adhesive SikaPower 4720 was, supplied by SIKA® (Portugal, Vila Nova de Gaia). This adhesive is a two-part system that cures at room temperature for 24 hours.

The properties of both adhesives were studied as a function of test rate (1 and 100 mm/min) in a previous work [26]. Even though this test rate will not be used for this study, the relation between these values allow the properties at impact velocity to be extrapolated to predict the joints' behaviour. Table 2 show some elastic properties as a function of rate test.

The Tg of both adhesives before and after ageing has been determined in a previous study [27]. Results showed the Tg of XNR 6852-1 not to be very moisture sensitive. SikaPower 4720, on the other hand, is very moisture dependent, and its Tg when aged is lower than room temperature. Ageing was also found to decrease its strength and elastic modulus.

2.2.2. Adherends

The adherends were manufactured from a high strength aluminium alloy (6082-T6). This is a medium strength structural alloy that is commonly used for machining. This alloy presents a very high strength as well as considerable ductility. Prior to bonding, the adherends received a phosphoric acid anodization, according to the ASTM D3933 standard, improving their adhesion under hostile environments.

2.3 Water Absorption Tests

2.3.1. Experimental Procedure

To perform the tests in humid conditions, the amount of time that the specimens were submerged for was constant. Depending on the coefficient of diffusion of the adhesive, the saturation level of the joint will vary and can be determined.

While the coefficient of diffusion of the SikaPower 4720 is already known from previous studies [27], the value for the XNR 6852E-2 is unknown and must be determined beforehand.

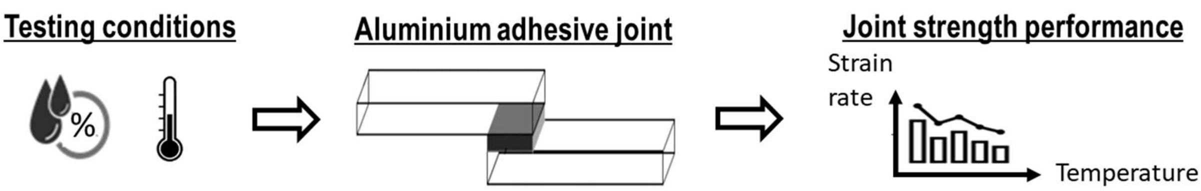

Fig. 1. Schematic representation of the objective of this study.

Table 1. Variables considered for testing the joints

Adherend thickness	2 mm and 5 mm
Adhesives used	Nagase XNR 6852E-2 and SikaPower 4720
Temperature	-20 °C, 80 °C and room temp. (~23 °C)
Humidity	Dry and moist
Tests	Quasi-static and impact

Table 2. Basic properties of the SikaPower 4720 and the XNR 6852E-2 as a function of test rate [26]

Adhesive	Young's modulus (MPa)		Tensile strength (MPa)	
	1 mm/min	100 mm/min	1 mm/min	100 mm/min
SikaPower 4720	2170	2431	32	38
XNR 6852E-2	1830	1803	41	46

For this purpose, three specimens (with the dimensions of 60 by 60 mm and a thickness of 1 mm) were tested. The specimens were placed in a silica gel filled container for at least a week to ensure that they were completely dry at the beginning of the test.

After gently abrading their surfaces with sandpaper and making sure they are totally clean, their initial weight and thickness were measured using a precision scale capable of measuring 4 decimal places and a calliper, respectively. They were then submerged in a jar of distilled water where they remained until saturated at a temperature of 32.5°C, the same temperature at which the joints will be submerged while ageing. This means this is the temperature for which the coefficient of diffusion will be determined.

Initially, their weight and thickness were measured in 2 hours intervals and, as they absorbed more and their mass growth rate reduced, the interval between measurements decreased.

2.3.2. *Experimental Results and Diffusivity*

The obtained curve is presented in Fig. 2. These values were obtained during a 30 days period, after which the specimens had reached their saturated values.

In the initial stage, the water intake is clearly higher for the specimen tested at 50°C. This means that, the coefficient of diffusion is higher for the higher temperature as expected, even though the maximum intake is the same. The 50°C specimen also reached saturation slightly faster than the 32.5°C one.

To determine the coefficient of diffusion, a dual Fick behaviour was assumed, based on the results - the adhesive presents a linear intake rate of water in the initial stages which later becomes a constant curve until saturation. This means that two coefficients of diffusion would need to be calculated to properly predict the amount of water in the adhesive after a certain amount of time. The obtained values for the diffusion coefficients and corresponding saturation are presented on Table 3.

The values for the SikaPower 4720 (single Fick) were determined in previous studies [28] and are presented in Table 4.

2.3.3. *Water Content Prediction*

The next step is to determine the water content of the joints that are going to be tested after ageing, in order to know exactly what is being tested. This was done using the Abaqus® finite element analysis software and the procedure will be described for each adhesive. To hasten the simulation process, only a fourth of the adhesive layer was modelled (Fig. 3) and the water uptake from two sides was considered. Since it is horizontally and vertically symmetrical, the values can correctly be predicted for the whole adhesive area using this simplified analysis.

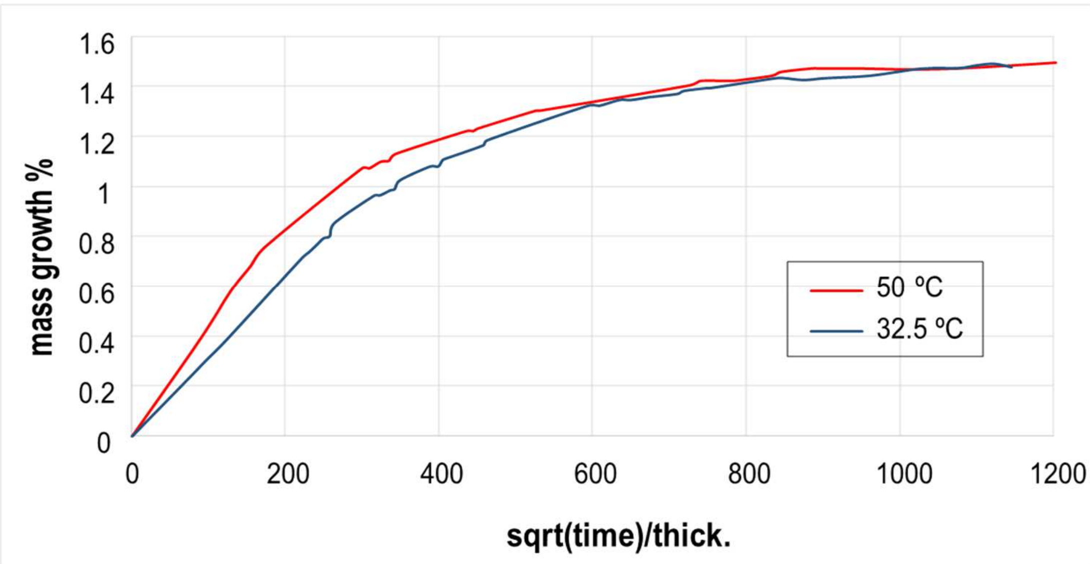

Fig. 2. Average mass uptake of the bulk specimens of Nagase XNR 6852E-2 over time.

Table 3. Coefficients of diffusion and corresponding saturation levels for the XNR 6852E-2 adhesive.

	Coefficient of diffusion (m2/s)		Maximum saturation (%)	
	Average	St. deviation	Average	St. Deviation
First Fick	1.60 x 10^{-12}	1.34 x 10^{-13}	0.96	0.01
Second Fick	1.27 x 10^{-13}	2.55 x 10^{-14}	0.55	0.02

Table 4. Coefficient of diffusion and corresponding saturation level for the SikaPower 4720 adhesive [28].

	Coefficient of diffusion (m2/s)	Maximum saturation (%)
Sika Power 4720	8.94 x 10^{-14}	32.5

To perform the simulations, a key assumption was made. The mathematics behind heat transfer and mass diffusion are the same so a material's temperature is equivalent to its water content percentage, meaning its thermal diffusivity is equivalent to its coefficient of mass diffusion. Thus A 4-node linear heat transfer quadrilateral element type could therefore be used, available in the Abaqus® library as DC2D4. The mesh of the two-dimensional model included 12500 elements.

Nagase XNR 6852E-2

Because of the dual Fick behaviour of this adhesive two simulations were conducted, one for each behaviour, which were afterwards combined to obtain the correct amount of water absorbed. Important information can be extracted from these simulations. For instance, it is possible to obtain the water gained in any exact point of the adhesive as time passes or the average value throughout the whole layer. Figure 4 shows the different rates at which the water penetrates the adhesive, for 3 different points.

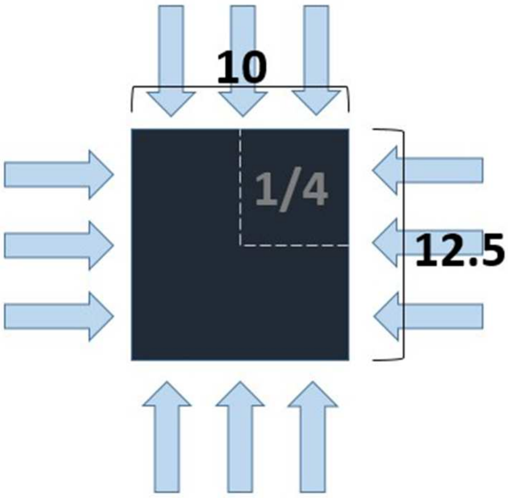

Fig. 3. Modelled area of the adhesive layer and directions from which water is absorbed (dimensions in mm).

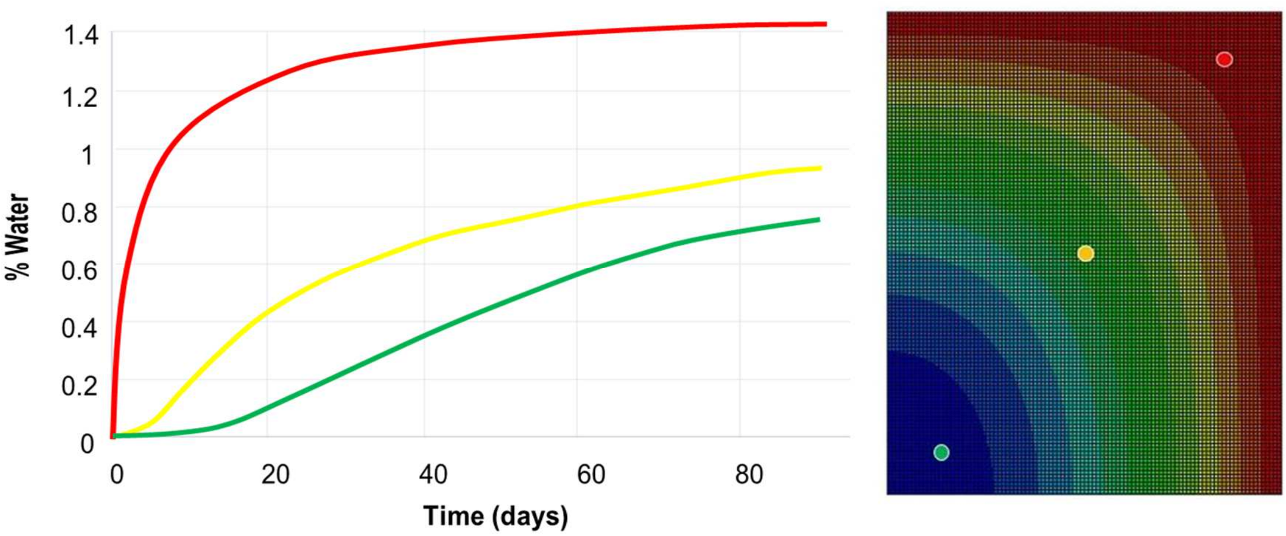

Fig. 4. Water absorption in 3 different points of the XNR 6852E-2 adhesive layer.

On the right side, three points are marked – The red point is closest to the edge of the adhesive layer and the green point is closer to the centre. The yellow point represents a middle ground. The graph to the left shows the evolution of water absorbed as time passes for each one of these points, represented by their respective colour. As expected, the closer the point is to the centre of the layer, the longer it takes for the percentage of water to begin increasing. The red point is the fastest to reach saturation level while the green one takes the longest.

To determine the water percentage in the adhesive of the joints that are to be tested after ageing, considering the geometry represented in Figure 3 with a 2 mm thick adhesive layer, a similar graph (Fig. 5) can be drawn with the average values for all the points of the adhesive.

The marked point corresponds to the amount of time the ageing joints remained submerged before being tested and the corresponding average water content of the adhesive. It can be concluded that after 40 days of ageing the joints bonded with the XNR 6852E-2 adhesive will have 0.84 % of water content.

SikaPower 4720

For this adhesive the procedure is identical to the one described for the XNR 6852E-2 adhesive, though it is slightly simpler, as the adhesive presents a single Fick behaviour. Once again, it is possible to obtain the water percentage throughout the adhesive layer as time passes for any point (Fig. 6).

This adhesive has a lower coefficient of diffusion but a higher maximum saturation, making it take longer to reach maximum water content and for the points further from the edges of the layer to begin absorbing water. For this reason, the yellow point has a very low amount of water gain over the first three months and the green point has virtually none, while the red point, closer to the border, has a very high amount of water content after this period of time. Figure 7 shows the average values of water content throughout the whole adhesive layer.

It can be concluded that after ageing for 40 days, the joints made with the SikaPower 4720 adhesive will have 7.13 % of water content.

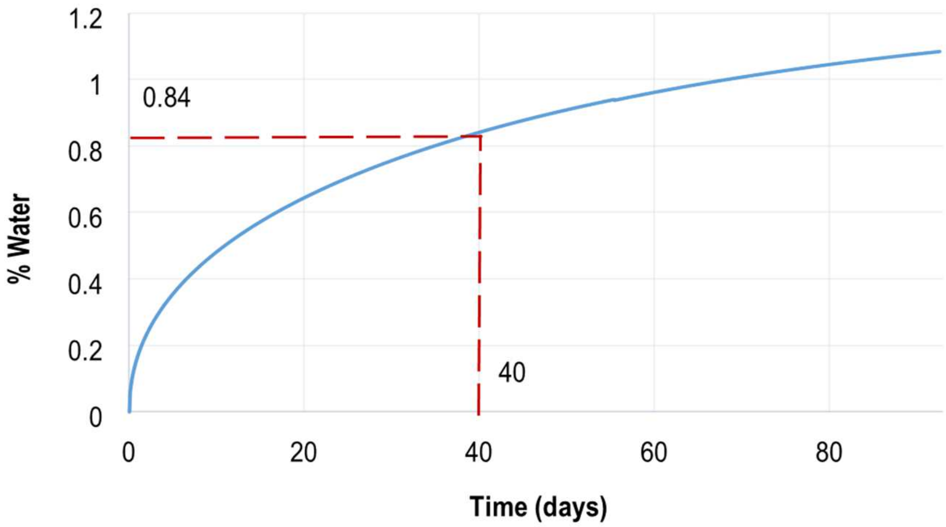

Fig. 5. Average water content on the XNR 6852E-2 adhesive layer.

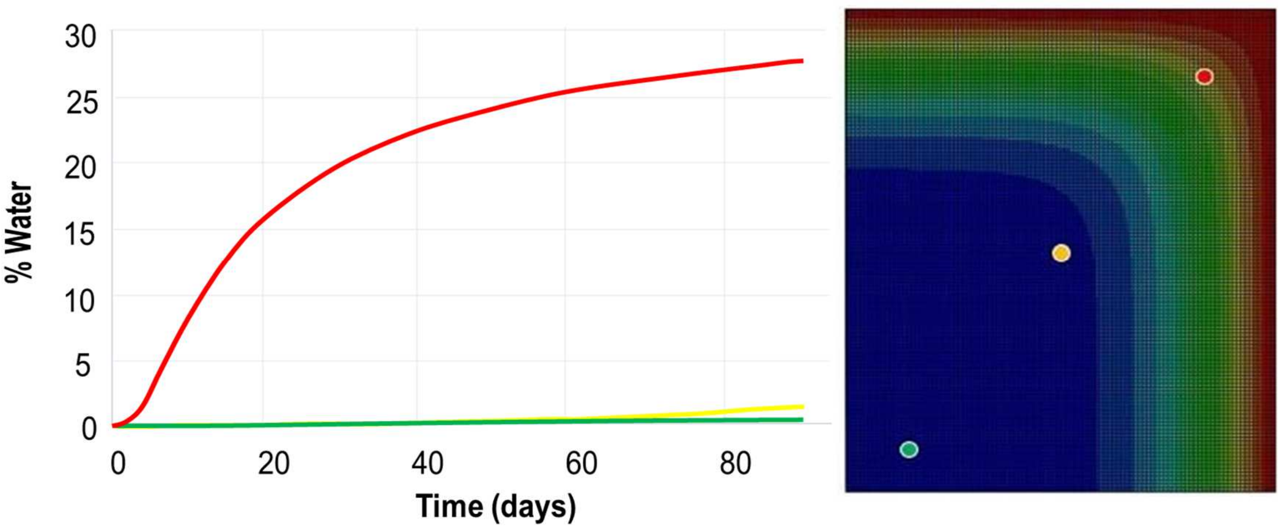

Fig. 6. Water absorption in 3 different points of the SikaPower 4720 adhesive layer.

2.4 Joint Geometry

To perform the required tests, a set of SLJs was manufactured to experiment with all the possible combinations of adhesive, adherend thickness, temperature, humidity and testing rate (quasi-static and impact tests). The geometry of the SLJs is shown in Fig. 8.

The SLJ consists of two aluminum adherends, anodized with phosphoric acid, bonded together. By using a mould, the SLJs were bonded with the correct alignment and a controlled adhesive layer thickness of 0.2 mm.

2.5. Test Procedure

2.5.1 Quasi Static Tests

For the quasi-static tests, an INSTRON® model 3367 (Norwood, Massachusetts, USA) universal testing machine was used, capable of applying loads up to 30 kN and measuring the displacement during the test. The tests were performed at a rate of 1 mm/min. A heating chamber was used for the tests at low and high temperature.

2.5.2 Impact Tests

The drop-weight impact tests were conducted in a Rosand® Instrumented Falling weight impact tester, type 5 H.V. (Stourbridge, West Midlands, U.K.). This machine drops a mass from a predefined height until it impacts a device that holds the specimen. For the joints tested in this study, it was determined that 20 J of impact energy would be sufficient to ensure that all specimens fail, so a mass of 26 kg was applied to the impactor. The height was also adjusted so that the impact speed was 1.24 m/s. In order to perform impact tests at low temperatures, liquid nitrogen was injected around the overlap area of the specimens until the temperature stabilized at -20ºC. The high temperature impact tests were made possible using an in-house designed induction coil to warm the specimens up to 80ºC. The high heat conductivity of the steel adherends allows the temperature to be uniform along the entire overlap area. The temperature was monitored using a thermocouple and a thermographic camera.

3. Results

The experimental results were predicted using analytical models and the failure mechanisms were evaluated for different conditions.

3.1. Maximum Load of the Impact and Quasi-Static Tests

3.1.1. Maximum Loads under different Testing Rates

The first results analysed are the maximum load values obtained for each joint configuration. The results are presented in a way so that the effect of temperature, moisture, adherend thickness and rate speed is easily observable for both adhesives. Figures 9 and 10 show the results for the SLJs with the XNR 6852E-2 adhesive.

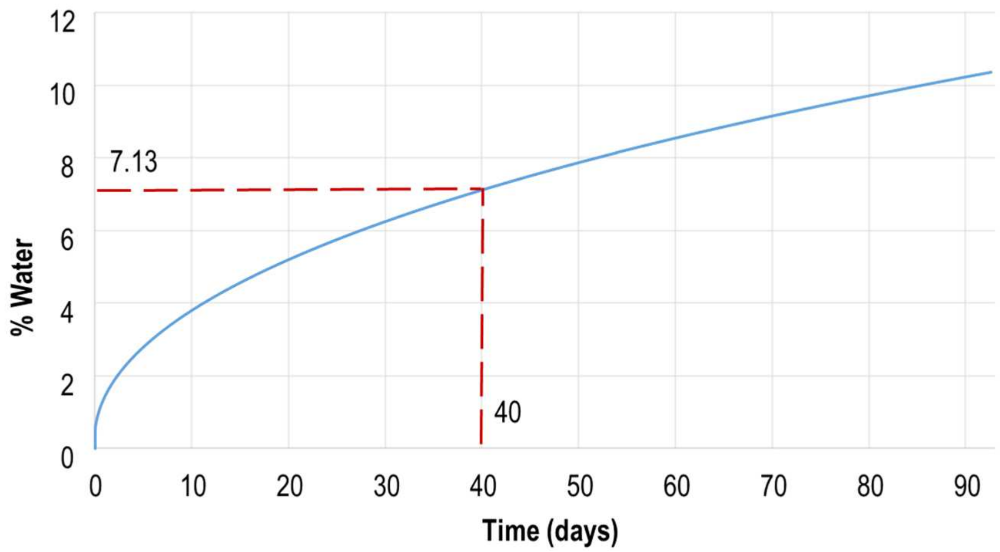

Fig. 7. Average water content on the SikaPower 4720 adhesive layer.

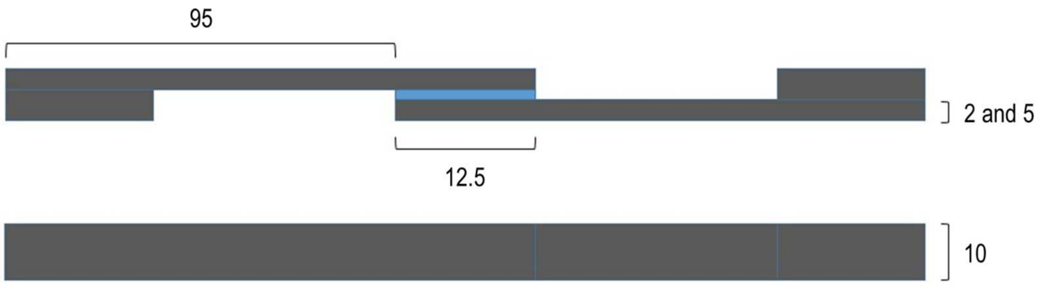

Fig. 8. Dimensions of the single lap joints used for testing (dimensions in mm).

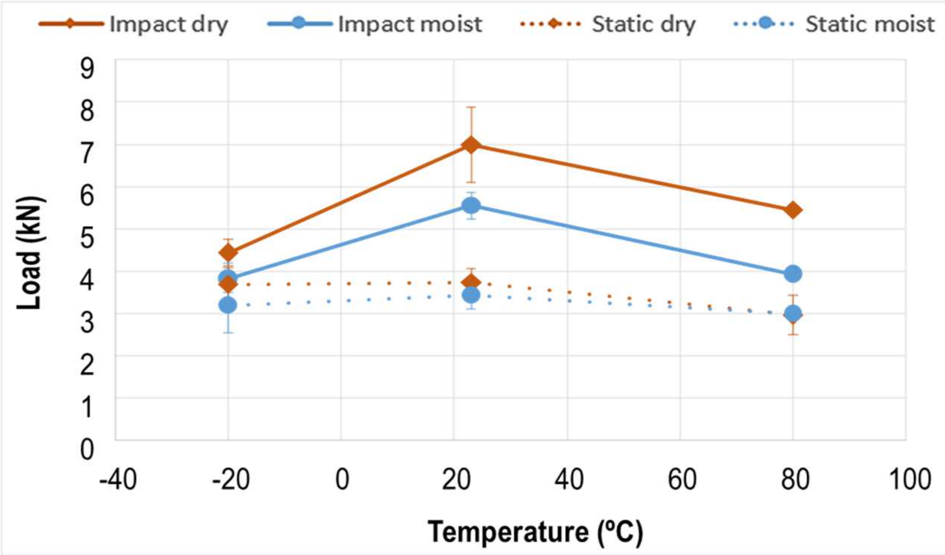

Fig. 9. Maximum loads obtained from all the tests – Nagase XNR 6852E-2 with 2 mm adherends.

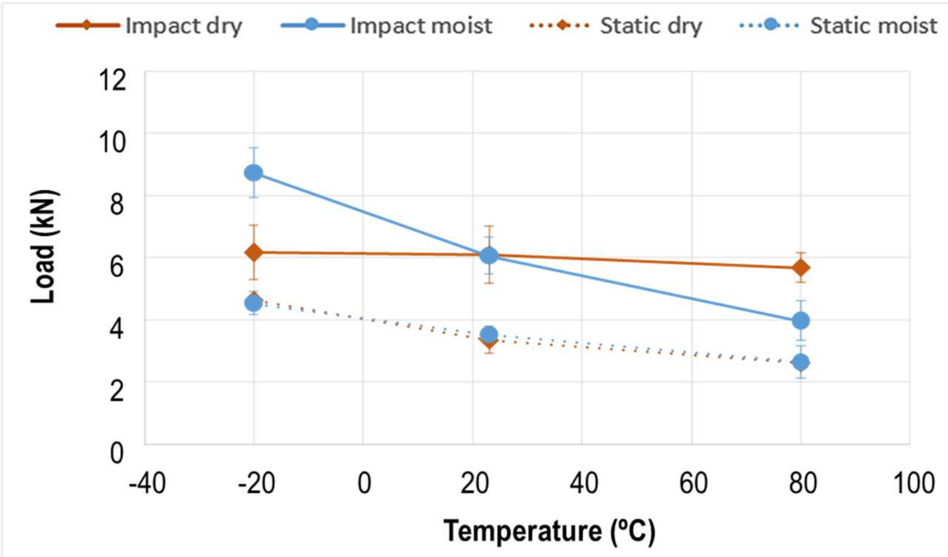

Fig. 10. Maximum loads obtained from all the tests – Nagase XNR 6852E-2 with 5 mm adherends.

Fig. 11. Adherend yielding after quasi-static testing of a SLJ using SikaPower 4720 with 2 mm adherends (-20 °C; moist).

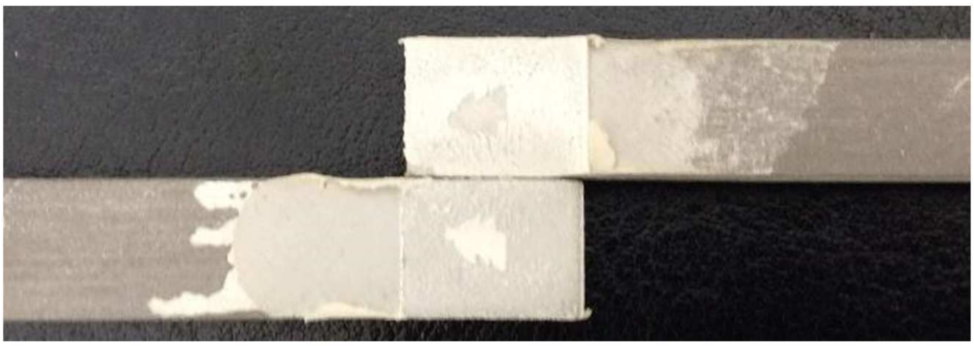

Fig. 12. Failure mode after quasi-static testing of a SLJ with XNR 6852E-2 at low temperature (5 mm adherends; moist).

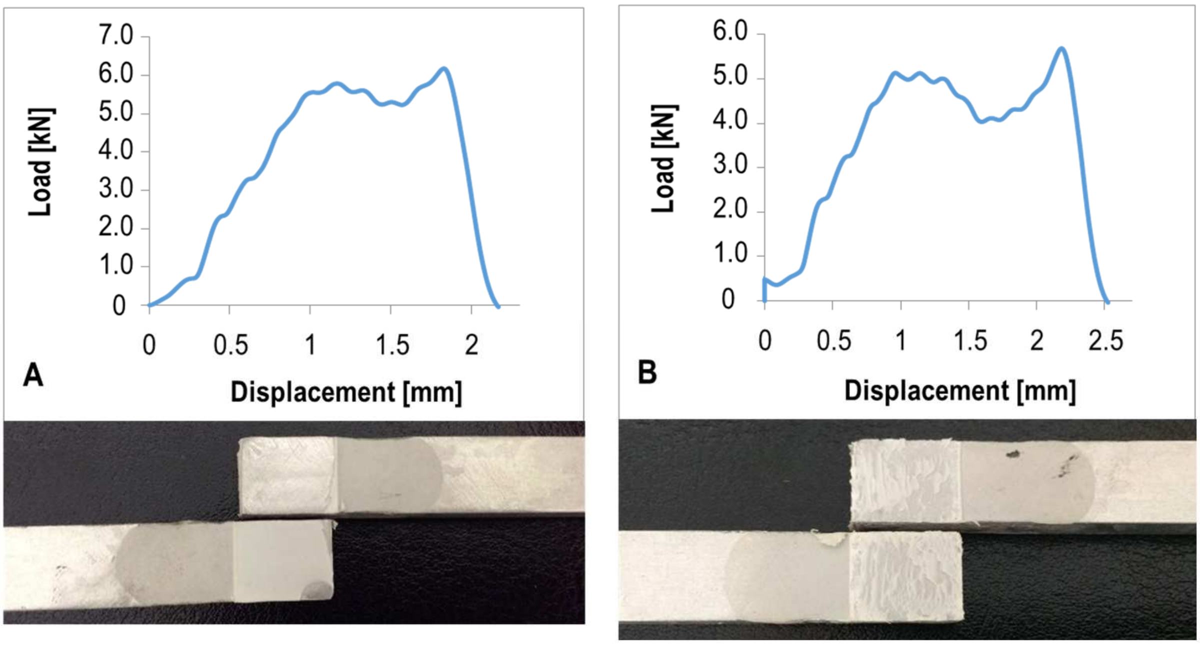

Fig. 13. Load-displacement curves of SLJs under impact using XNR 6852E-2 with 5 mm adherends under dry conditions and (A) -20 °C and (B) 80°C.

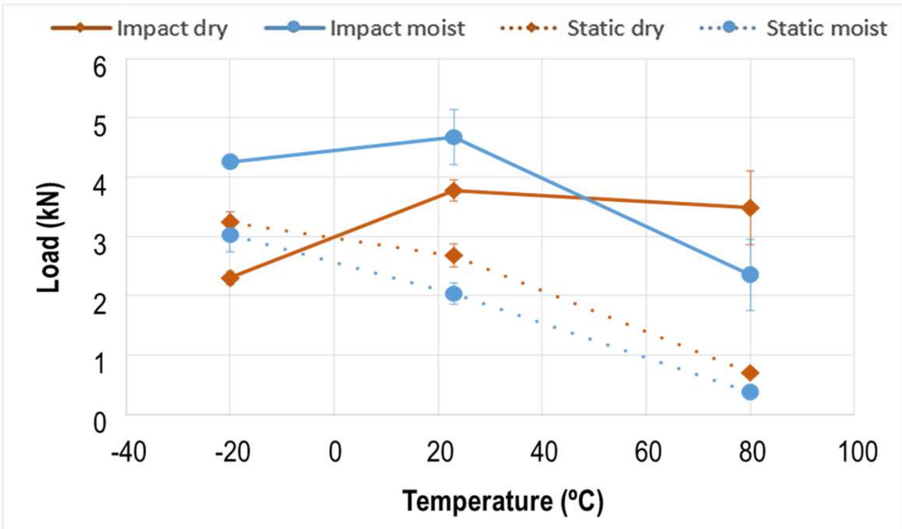

Fig. 14. Maximum loads obtained from all the tests – SikaPower 4720 with 2 mm adherends.

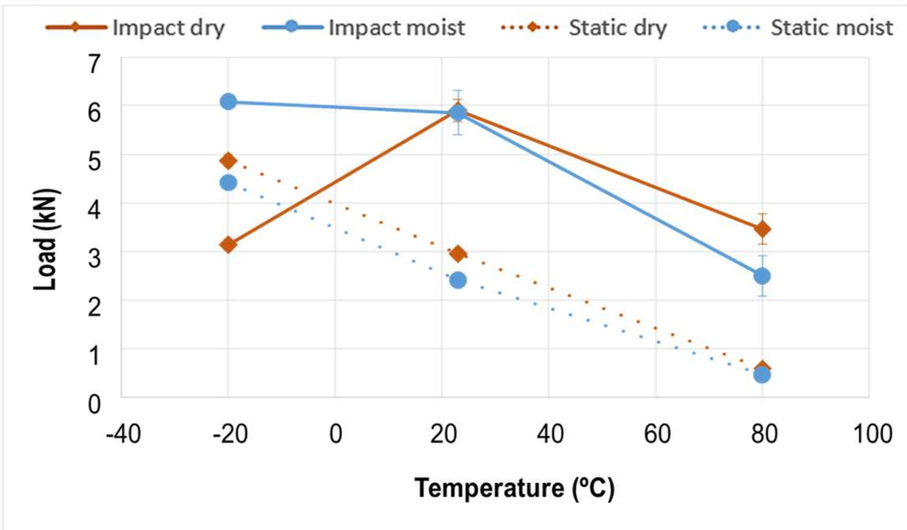

Fig. 15. Maximum loads obtained from all the tests – SikaPower 4720 with 5 mm adherends.

Results show that, for the joints with 2 mm thick adherends, the relation between maximum loads is linear – the joints support a higher load before failure under impact than quasi-static conditions and the dry joints are stronger than the moist ones. It is also noticeable that at room temperature the joints are the strongest since at low temperature the adhesive loses ductility and at high temperature, closer to its Tg, it loses mechanical performance. These effects from temperature variation are most noticeable at a higher loading rate. In both the quasi-static and impact tests, the adherend yielding is clearly visible (Fig. 11) for the dry tests performed at room temperature as well as low temperature, which increases the yielding of the aluminium. For these conditions, the failure is solely controlled by the adherend.

For the joints with 5 mm thick adherends (Fig. 12), where the stress distribution throughout the joint is more linear due to limited elastic deformation of the aluminium, the relation between results is different, but the maximum loads are generally higher. In this case, the strongest joints are the low temperature moist ones, an effect that becomes more apparent as the testing rate goes up. However, the dry joints, under impact, show no variation in behaviour as temperature varies. The Nagase adhesive generally has fails nearer the interface as temperature varies – higher temperature results show plenty of mixed failure modes and lower temperatures usually result in failures closer to the interface or even some mixed failures. Figure 12 shows an example of a failure at low temperature on a wet joint, where the effect of the moisture distribution throughout the layer is clearly visible.

The increase in ductility with temperature is very noticeable in both the load-displacement curves and the failure modes of the joints, as seen in Fig. 13.

The behaviour obtained from a ductile failure is noticeable from the increase in displacement before failure, as well as a less uniform distribution of the remaining adhesive. Fig. 14 and 15 show the results for the SLJs with the SikaPower 4720 adhesive.

An initial analysis shows that both graphs are much more similar to each other than the XNR 6852E-2 ones. This means the SikaPower 4720 adhesive is not as dependent on the adherend thickness due to the generally lower maximum loads, which lead to a decrease in elastic deformation of the aluminium and a more uniform stress distribution. At low temperatures, the abnormal adhesive failures do not allow to draw significant conclusions, even though the joints seem to be strong at low loading rates or with moisture. Figure 16 shows an interfacial failure where the adhesive is completely separated from the adherends.

At high temperature, the adhesive is operating above its Tg, and the maximum load the joints can withstand is reduced. The effect of working at a temperature higher than its Tg is a very loading rate dependent behaviour, although under impact loads the joints still returned a relatively high failure load. The effect of a joint working above its Tg on the load-displacement curve is clear, as the failure is not as abrupt and the load reduction after failure is more gradual due to its rubbery behaviour, as seen in Fig. 17. Due to the lower maximum loads, no yielding of the adherends was found in any test using the SikaPower 4720 adhesive.

3.1.2 Maximum Load Predictions – Quasi-Static

Using the Adams et al. [3] model the values obtained for maximum load can be predicted. This was done for the joints tested at room temperature and at a dry state, where the materials' properties are either accessible or easily determined. The yield strength used for the adherends was 300 MPa, and the shear strength of the adhesives, obtained from other studies, were 22.9 MPa and 27.8 MPa for the Sika and Nagase adhesives, respectively. The comparison between the experimental and predicted loads is presented in Table 5.

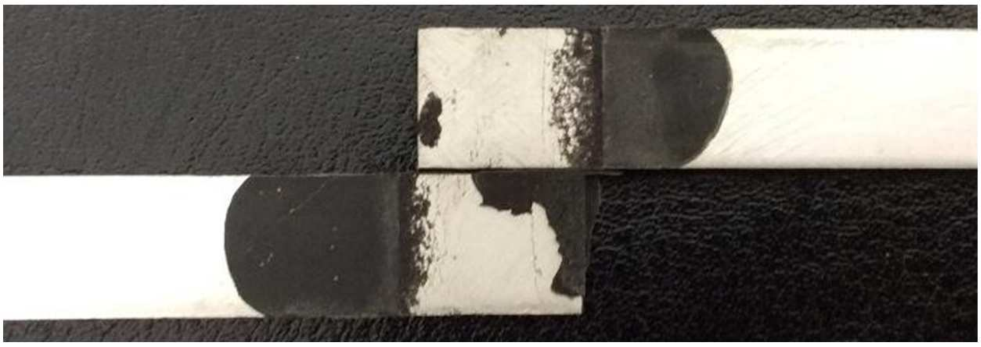

Fig. 16. Adhesive failure after quasi-static testing of a SLJ with SikaPower 4720 at low temperature (2 mm adherends; dry).

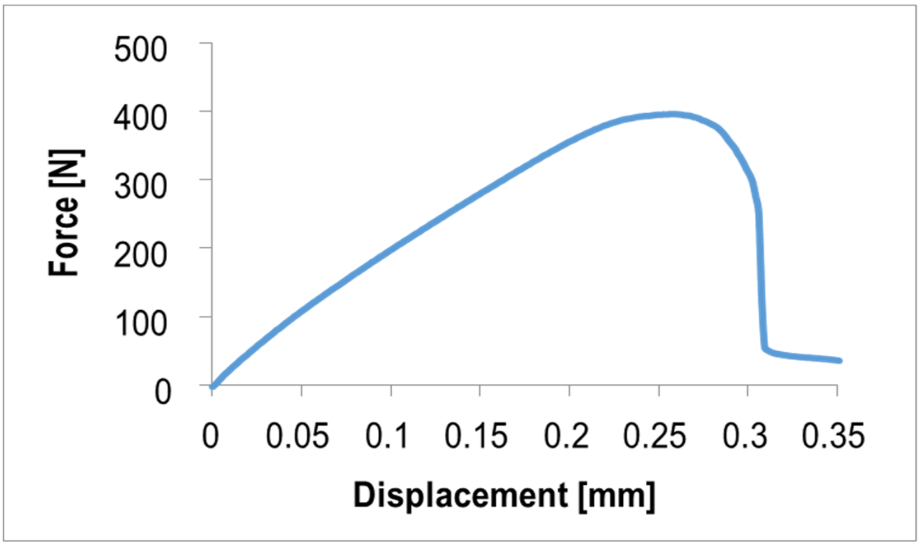

Fig. 17. Load-displacement curve of a quasi-static test of a SLJ with SikaPower 4720 at high temperature (2 mm adherends; moist).

Table 5. Experimental and predicted maximum loads under quasi-static conditions.

Adhesive	Adherend thickness (mm)	Experimental max. load (N)	Predicted max. load (N)
Nagase XNR 6852E-2	2 mm	3893	2906
	5 mm	3355	3475
SikaPower 4720	2 mm	2718	2863
	5 mm	2953	2863

Table 6. Experimental and predicted maximum loads under impact conditions.

Adhesive	Adherend thickness (mm)	Experimental max. load (N)	Predicted max. load (N)
Nagase XNR 6852E-2	2 mm	6981	3778
	5 mm	6100	5201
SikaPower 4720	2 mm	3777	3778
	5 mm	5904	4028

It can be concluded that this predictive model, applied to the quasi-static tensile tests, does indeed correctly forecast if the failure will be caused by the adherend yielding or solely by the adhesive's properties. In the latter case, the predicted values correspond correctly to the amounts verified experimentally, but there is some inconsistency when it comes to the maximum load at which the yielding will cause failure.

3.1.3. Maximum Load Predictions – Impact

The same predictive model could be used for the same joints under impact conditions, but the properties for the high strain rate of 1.24 m/s are not directly available in literature. The tensile strength of the aluminium adherends was obtained by performing impact tests on specimens made out of the same aluminium alloy. By measuring the maximum applied load and the respective deformation, its tensile strength at the same strain-rate it was submitted to in the impact tests could be directly determined. This value was found to be equal to 390 MPa. For the adhesives' properties, a different method was used. Using the relation between the available values for 1 mm/min and 100 mm/min, their shear strength was obtained by logarithmic extrapolation. The obtained strengths were 41.6 and 32.2 MPa respectively for the Nagase and the Sika adhesives. The comparison between the experimental and predicted loads is presented in Table 6.

Under impact, the properties of the materials are not the only parameters that must be changed. As the strain-rate increases, so do the stress distributions along the adhesive layer, a change that is not accounted for by the Adams et al. [3] predictive model. This results in predicted failure loads that are significantly lower than the experimental values. The strength of the aluminium at high strain-rate also seems to be quite inaccurate since higher values of load for adherend initial yielding are to be expected (the SLJs with the Sika adhesive and 2 mm adherends should not fail by adherend yielding, for instance), so additional tests should be performed to properly obtain this value. When this is combined with the fact that the extrapolations were made from two rates which are very far from the impact test speed, suggests that these predictions are too imprecise to be of practical use. The only accurate prediction (SLJs with the Sika adhesive and 2 mm adherends) was purely coincidental since the cause of failure should be the adhesive as opposed to what the predicted results show.

3.2. Absorbed Energy under Impact

Focusing on the impact tests, this section summarizes the amounts of energy absorbed in the impact tests, comparing the effect of each combination of properties on the joint failure parameters. The results show that the XNR 6852E-2 adhesive joints are capable to absorb a significantly higher amount of energy than those bonded with SikaPower 4720 (Figs. 18 and 19).

With moisture, the toughness seems to decrease as the temperature increases, as the highest value is found at low temperature. This happens because of the plasticization of the adhesive and, with thick adherends where their yielding is not a factor, the low temperature, moist joints are capable of absorbing the most energy. With 2 mm thick adherends, where the stress peaks at the edges of the overlap are higher, the amount of absorbed energy was similar between the dry and moist joints. This is evident on the results of the Nagase adhesive but, while the pattern is still somewhat noticeable with Sika, it performed poorly at low temperatures, presenting adhesive failures (Fig. 20) for which no conclusions could be accurately made.

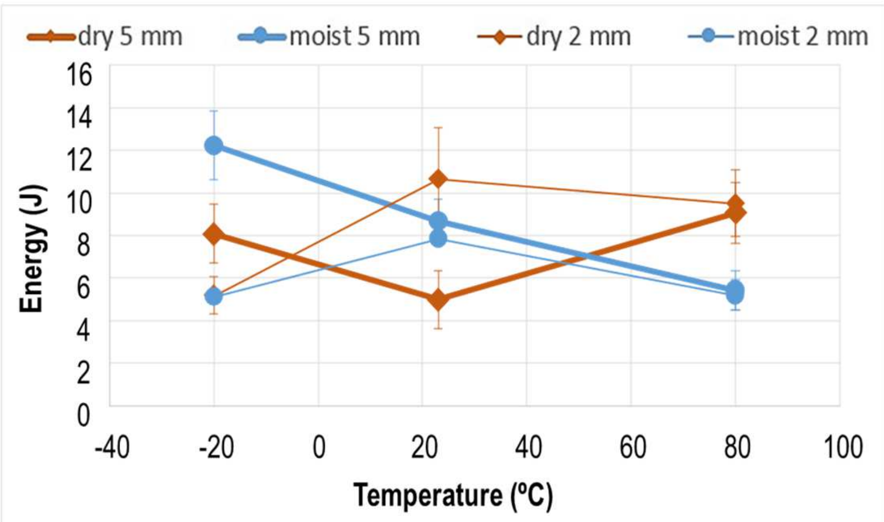

Fig. 18. Energy absorbed under impact for the joints with the XNR 6852E-2 adhesive.

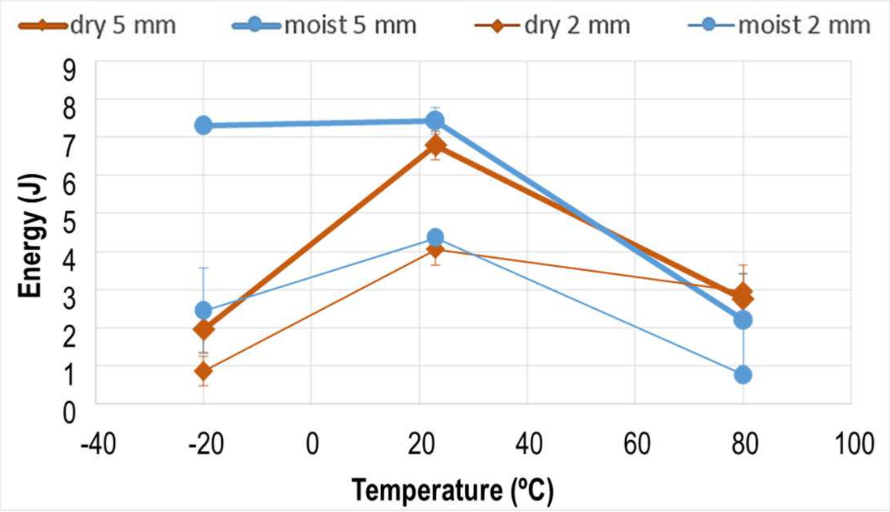

Fig. 19. Energy absorbed under impact for the joints with the SikaPower 4720 adhesive.

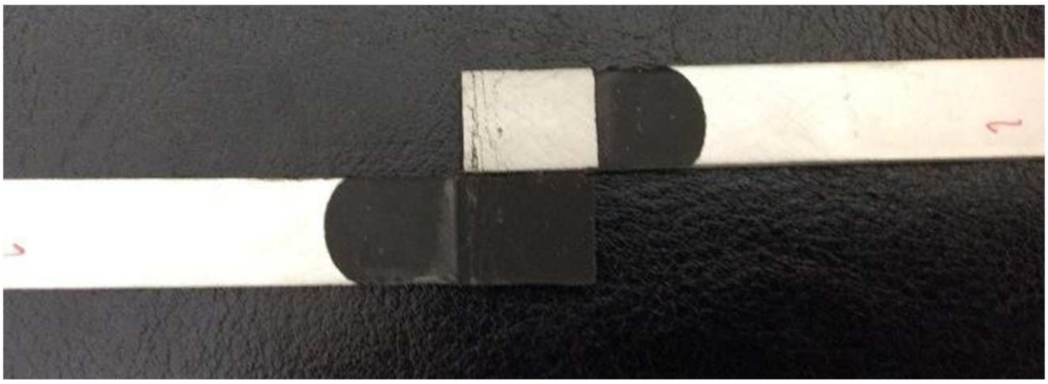

Fig. 20. Adhesive failure under impact of a SLJ with SikaPower 4720 at low temperature (2 mm adherends; dry).

Fig. 21. Adherend yielding after impact on a joint made with the Nagase XNR 6852E-2 adhesive (2 mm adherends; dry; room temperature)

At room temperature the joints with thick adherends absorb more energy than their thin adherend counterparts (when adherend yielding is not perceptible) due to the difference in maximum stress in the adhesive layer. The moist joints absorb more energy than their dry counterparts due to the significantly higher elongation resulting from the higher ductility of the moist adhesive. Another reason is that the adhesive in the moist joints is more ductile at the ends of the overlap (where it has absorbed more water), resulting in a more uniform stress distribution, which is similar to what happens in a functionally graded joint. One clear exception to this rule is found in the dry joints made with 2 mm thick adherends and the Nagase adhesive. These present the highest load and therefore the highest adherend yielding which in turn absorbs an additional amount of energy relative to the other conditions (Fig. 21).

At high temperature, the high level of plasticization of the adhesive causes the adherend thickness to lose relevance. The dry joints also absorb a higher amount of energy than their moist counterparts for both adhesives. This happens since a higher moisture level decreases the adhesives' Tg along with its mechanical properties at high temperature.

4. Conclusions

The objective of this work was to verify how adhesively bonded joints made with two different adhesives used in the automotive industry behave under impact. The joints were tested under diverse temperatures, moisture levels and loading rates. To study the effect of adherend yielding, two different substrate thicknesses were also used.

The geometry of the joints allowed to correctly judge the effect of adherend yielding on the joint's behaviour, showing that the amount of energy absorbed may drastically increase. The joint thickness was correctly selected according to their geometry, although the small overlap length was not ideal to study the effect of the adhesives on the joints. A larger overlap would allow for a bigger variation in results and a better analysis of the joints' behaviour.

The systems implemented to heat up and cool down the joints before testing under different temperature conditions successfully allowed them to reach the required temperatures. At low temperature, the Sika adhesive failed at the interface and the Nagase adhesive had both interfacial and mixed failure modes. The brittle behaviour of the adhesives leads to a poor performance at low temperature when dry. At high temperature, the adhesives presents a ductile behaviour and have a generally lower resistance and tensile strength.

Due to the reduced dimensions of the joints, it was possible to introduce a significant moisture level in the adhesive layer, which allowed to study its effects on the joint performance. The surface preparations also allowed for good adhesion even under moist conditions. The joints that were submerged showed a more plastic, ductile behaviour, withstanding generally lower maximum stresses but allowing for higher strains before failure, ultimately increasing the energy absorbed. At low temperature, combined with thick adherends, the moist joints absorbed a good amount of energy and sustained high failure loads despite their bad adhesion. At high temperature, however, moisture lowered the adhesives' Tg, greatly harming the joints' performance. The amount of water content on an adhesive joint appears to have greater effect on its behaviour if the testing rate is also increased.

As the testing rate increases, so does the maximum load that the joints resist before failure. Under impact, the joints showed a generally better performance, although this may change with bad adhesion. It is important to understand how the adhesives' properties change with strain-rate and tests should be performed to quantify these changes. The strong sensitivity of the adhesives to high loading rates make it more difficult to predict their behaviour, while leads to higher values than those expected from analytical models.

Lastly, the Nagase adhesive, besides having better mechanical properties, proves to behave better under different conditions. Its adhesion is better, even with moisture and it has a higher working temperature before it begins to degrade. Considering its performance alone, the Nagase XNR 6852E-2 adhesive can be considered as more adequate for the automotive industry than the SikaPower 4720.

Author Contributions

The authors through this study evaluated the effect of temperature and moisture on performance of aluminium adhesive joints subjected at different rate tests, behaviour essential to automotive industry. All authors discussed the results, reviewed and approved the final version of the manuscript.

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Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

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Nomenclature

Tg:	Glass transition temperature [ºC]	DC2D4 SLJs:	4-node linear heat transfer quadrilateral element type single lap joints

References

[1] da Silva, L.F.M., Öchsner, A., Adams, R.D., *Handbook of Adhesion Technology: Second Edition*. vol. 1–2. Springer, 2018.
[2] Adams, R.D., *Adhesive Bonding: Science, Technology and Applications*: Elsevier Science, 2005.
[3] Adams, R.D., Comyn, J., Wake, W.C., *Structural Adhesive Joints in Engineering: Vol. Second Edition*. London: Chapman & Hall, 1997.
[4] Bryant, R., Strength of Adhesive Joints. *Nature*, 202, 1964, 1087–1088.
[5] Naskar, A., Keum, J., Boeman, R., Polymer matrix nanocomposites for automotive structural components. *Nature Nanotech*, 11, 2016, 1026–1030.
[6] Liu, M., Guo, Y., Wang, J., Yergin, M., Corrosion avoidance in lightweight materials for automotive applications. *npj Mater Degrad*, 2, 2018, 24.
[7] Naskar, A., Keum, J., Boeman, R., Polymer matrix nanocomposites for automotive structural components. *Nature Nanotech*, 11, 2016, 1026–1030.
[8] da Silva, L.F.M., Adams, R.D., Adhesive joints at high and low temperatures using similar and dissimilar adherends and dual adhesives. *International Journal of Adhesion and Adhesives*, 27, 2007, 216-226.
[9] Deb, A., Malvade, I., Biswas, P., Schroeder, J., An experimental and analytical study of the mechanical behaviour of adhesively bonded joints for variable extension rates and temperatures. *International Journal of Adhesion and Adhesives*, 28, 2008, 1-15.
[10] Grant, L.D.R., Adams, R.D., da Silva, L.F.M., Effect of the temperature on the strength of adhesively bonded single lap and T joints for the automotive industry. *International Journal of Adhesion and Adhesives*, 29, 2009, 535-542.
[11] Owens, J.F.P., Lee-Sullivan, P., Stiffness behaviour due to fracture in adhesively bonded composite-to-aluminum joints II. Experimental. *International Journal of Adhesion and Adhesives*, 20, 2000, 47-58.
[12] da Silva, L.F.M., Adams, R.D., Measurement of the mechanical properties of structural adhesives in tension and shear over a wide range of temperatures. *Journal of Adhesion Science and Technology*, 19, 2005, 109-141.
[13] Adamson, M., Thermal expansion and swelling of cured epoxy resin used in graphite/epoxy composite materials. *Journal of Materials Science*, 15, 1980, 1736-1745.
[14] Zhang, Y., Adams, R.D., da Silva, L.F.M., Absorption and glass transition temperature of adhesives exposed to water and toluene. *International*

Journal of Adhesion and Adhesives, 50, 2014, 85-92.
[15] Bao, L.-R., Yee, A.F., Effect of temperature on moisture absorption in a bismaleimide resin and its carbon fiber composites. *Polymer*, 43, 2002, 3987-3997.
[16] Machado, J.J.M., Marques, E.A.S., da Silva, L.F. M., Adhesives and adhesive joints under impact loadings: An overview. *The Journal of Adhesion*, 94(6), 2018, 421-452.
[17] Lin, Y.C., Chen, X., Moisture sorption–desorption–resorption characteristics and its effect on the mechanical behavior of the epoxy system. *Polymer*, 46(25), 2005, 11994-12003.
[18] Avendaño, R., Carbas, R.J.C., Chaves, F., Costa, M., da Silva, L.F.M., Fernandes, A.A.. Impact Loading of Single Lap Joints of Dissimilar Lightweight Adherends Bonded With a Crash-Resistant Epoxy Adhesive. *ASME. J. Eng. Mater. Technol*., 138(4), 2016, 041019.
[19] Avendaño, R., Carbas, R.J.,C., Marques, E.A.S., da Silva, L.F.M., Fernandes, A.A., Effect of temperature and strain rate on single lap joints with dissimilar lightweight adherends bonded with an acrylic adhesive. *Composite Structures*, 152, 2016, 34-44.
[20] Machado, J.J.M., Nunes, P.D.P., Marques, E.A.S., da Silva, L.F.M., Adhesive joints using aluminium and CFRP substrates tested at low and high temperatures under quasi-static and impact conditions for the automotive industry. *Composites Part B: Engineering*, 158, 2019, 102-116.
[21] Machado, J., Hayashi, A., Nunes, P., Marques, E., Carbas, R., Sato, C., da Silva, L., Strain rate dependence of a crash resistant adhesive as a function of temperature for the automotive industry. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 233(11), 2019, 2189–2203.
[22] Saldanha, D.F.S., Canto, C., da Silva, L.F.M., Carbas, R.J.C., Chaves, F.J.P., Nomura, K., Mechanical characterization of a high elongation and high toughness epoxy adhesive. *International Journal of Adhesion and Adhesives*, 47, 2013, 91-98.
[23] Hussain, N.N., Regalla, S.P., Rao Y.V.D., Dirgantara, T., Gunawan, L., Jusuf, A., Drop-weight impact testing for the study of energy absorption in automobile crash boxes made of composite material. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 235(1), 2021, 114-130.
[24] da Silva, L.F.M., Dillard, D. A., Blackman, B., Adams, R.D., *Testing Adhesive Joints: Best Practices*: Wiley, 2013.
[25] Deb, A., Malvade, I., Biswas, P., Schroeder, J., An experimental and analytical study of the mechanical behaviour of adhesively bonded joints for variable extension rates and temperatures. *International Journal of Adhesion and Adhesives*, 28, 2008, 1-15.
[26] Varajão J.F., *Impact of CFRP adhesive joints for the automotive industry*, MCs thesis, Department of Mechanical Engineering, University of Porto, Porto, Portugal, 2015.
[27] Viana, G., Costa, M., Banea, M.D., da Silva, L.F.M., Behaviour of environmentally degraded epoxy adhesives as a function of temperature. *The Journal of Adhesion*, 93(1-2), 2017, 95-112.
[28] Costa, M., Viana, G., da Silva, L.F.M., Campilho, R., Effect of humidity on the mechanical properties of adhesively bonded aluminium joints. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 232(9), 2018, 733-742.

ORCID iD

Ricardo Carbas https://orcid.org/0000- 0002-1933-0865
Eduardo Marques https://orcid.org/0000- 0002-2750-8184
Lucas da Silva https://orcid.org/0000- 0003-3272-4591

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