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Rehabilitation of waterproofing coatings in flat roofs

An experimental study on the connection between new and aged membranes

- Extended Abstract -

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1. Introduction

Among the different layers used on flat roofs this study focus on waterproofing coatings, which are composed of materials that prevent the penetration of water inside of the rooftop. In this document the oxidized bitumen membranes, the bitumen-polymer membranes (APP or SBS) and plastic membranes are of particular importance. Membranes used in the waterproofing coating of rooftops are made of bitumen (in the case of bituminous membranes) or PVC resin (in the case of PVC membranes), reinforcement (s), and in most cases a material that provides the finishing of the membrane [1]. Each of these parameters influences the resistance of the coating and its capacity to bond with other materials.

Anomalies correspond to an unsatisfactory performance by any of the materials or solutions implemented, which in most cases results in the penetration of water to the layers underneath the waterproofing coating and causes varying degrees of damage. Anomalies may be caused by a variety of factors, which can be grouped into the following categories: design errors, application errors, accidental actions due to external mechanical factors, environmental actions, lack of maintenance and changes in the initially predicted in-service conditions. In turn, the anomalies can be grouped into two classes: those occurring in the general surface and in its singularities.

Detecting anomalies that compromise roof impermeability involves using diagnosis techniques in order to locate the precise location of the water penetration, so that the different options for repair or replacement of the existing coating can be considered. One of the usual methods for isolated repairs to the damaged area of the general surface requires overlaying and connecting a new membrane onto the existing one. When anomalies are located at singularities of the rooftop (such as upstands, movement joints and balustrades) the repair work requires the replacement of that element and, in some cases, repair of the membrane. Other techniques for isolated repairs of anomalies involve using liquid or pasty products.

However, little is known about the consequences of repair procedures and, particularly, about the effects of ageing on the performance of waterproofing systems because research in this field is still scarce. This was the reason for the development of this work – a dissertation mainly based on experimental data, focusing on the study of connections between new and aged membranes and seeking to contribute to optimizing repair methods and techniques.

The experimental campaign involved prefabricated oxidized bitumen membranes, APP and SBS-modified bituminous membranes and PVC membranes. These membranes are reinforced with fibreglass, and only in the case of APP-modified bituminous membranes a polyester felt reinforcement was used. Regarding the types of connections between the membranes, oxidized bitumen membranes were tested using gas torch welding and hot oxidized bitumen 90/40, APP-modified bituminous membranes were tested with gas torch welding and bituminous adhesive, PVC membranes were tested using hot air welding and bituminous adhesive, while SBS-modified bituminous membranes were tested with gas torch weldings only. Three periods of 4, 16 and 24 weeks were considered in order to determine the effects of ageing, inside a ventilated oven room at a temperature of 70°C. Specimens resulting from the combination of these variables were subjected to tensile, shear and peeling mechanical tests.

2. Experimental programme

2.1. Objectives

The motivation for the study of the connections arose from the need to determine through experimentation the performance of membranes in areas selected for intervention. In particular, the study focus on the connections between new membranes and between new and aged membranes in a context of rooftop refurbishment or repair. Specimens and joints were characterized according to their initial condition in order to establish a baseline for comparison in order to determine the effect of temperature in the ageing of membranes and joint resistance.

Tensile tests on the membranes and shear and peeling tests on the joints were chosen in order to characterize the types of connections, since these were considered the most relevant for this study. Some of the basic characteristics of membranes, such as mass, type of reinforcement and finishing, were defined aiming at reducing the number of random variables, thus limiting the number of potential combinations during the experimental programme.

The objectives of the experimental programme were the following: to determine the initial characteristics of the waterproofing membranes; to determine the effect of ageing on the characteristics of waterproofing membranes; to determine the performance of the connections between new membranes and between new and aged membranes through experimentation; to analyze the main performance parameters of the connection between membranes and compare those parameters with the specifications provided in the UEAtc technical guides [10-14].

2.2. MATERIALS

During the experimental programme 420 specimens were prepared and tested – their constant features, such as type of membrane, mass / thickness, type of reinforcement, type of finishing, joint width and test direction are listed in Table 1. All variables were kept constant except for the PVC membrane thickness and the reinforcement of the APP-modified bituminous membrane. The lower thickness of the PVC membrane was due to the unavailability of samples with a thickness greater than 2 mm in the market, and the fact that 1.5 mm membranes are considered to perform similarly to 4 kg/m^2 bituminous membranes. The choice for the APP-modified bituminous membrane with dual reinforcement was due to the fact that this was the only product available in Portugal with bituminous adhesive for joints, an aspect worth being studied.

The variable features are summarized in Table 2. These include the type of connection, the ageing period each specimen was subjected to and each respective type of test. The types of connections selected for the experimental programme involves a general overview of all the solutions available in the market, assessing the effect of ageing on their individual resistance and, therefore, allowing the best option for repairs to be determined. In what regards the types of mechanical tests to which the specimens were subjected, the tensile test provided information about the performance and resistance of the membranes, while the shear and peeling tests provided information about the resistance of the connections.

Table 1 – Constant features of specimens tested

Membrane type	Mass / thickness	Reinforcement	Finishing	Joint width	Test direction
Oxidized bitumen	4 kg/m^2	Glass fibre	Polyethylene film	10 cm	Transverse
APP-modified bituminous	4 kg/m^2	Glass fibre and polyester felt	Fine sand	10 cm	Transverse
SBS-modified bituminous	4 kg/m^2	Glass fibre	Polyethylene film	10 cm	Transverse
PVC	1,5 mm	Glass fibre	None	10 cm	Transverse

Table 2 – Variable features of specimens tested

Membrane type	Type of connection	Artificial ageing period	Test type
Oxidized bitumen	Hot oxidized bitumen 90/40	0 Weeks 4 Weeks 16 Weeks 24 Weeks	Tensile resistance of membrane Shear resistance of joint Peeling resistance of joint
	Gas torch		
APP-modified bituminous	Gas torch		
	Bituminous adhesive		
SBS-modified bituminous	Gas torch		
PVC	Hot air		
	Solvents adhesive		

2.3. TEST EQUIPMENT AND EXPERIMENTAL PROCEDURES

Experimental work involved the use of equipment for specimen preparation, an oven room, a standard atmosphere room, connection equipment and a testing machine. Pictures of different stages of the experimental programme can be seen in Figure 1 and are described in detail further below.

Figure 1 – Pictures illustrating different stages of the procedure

Specimens were prepared according to the NP EN 13416 [9] standard which defines sampling procedures. Using the preparation equipment (Stanley knife, ruler, tape measure, mechanical gauge and marker), membrane test samples were cut excluding a 10 cm of surrounding area so as to avoid the edge effect. The number of specimens and their sizes were defined by the respective standards for each type of test.

Standard NP EN 12311-1 [3] regarding tensile tests for bituminous membranes requires a series of 5 rectangular specimens 50±0.5 mm wide and 200±2 mm between grips that added to the 50 mm of each grip, results in specimens measuring 300±2 mm. For the PVC membranes tensile test, method A of standard EN

12311-2 [4] was applied. This standard requires testing 5 rectangular specimens 50±0.5 mm wide by 200±5 mm long.

In the case of shear test in bituminous membranes and PVC membranes, the standards NP EN 12317-1 [7] and EN 12317-2 [8], respectively, with that the test sample must be composed of 5 rectangular specimens, 50±1 mm wide and a length equivalent to the distance between grips, 200±5 mm, plus 50 mm for each grip, adding up to 300±5 mm. As mentioned before, the preestablished joint (W) measures 10 cm both for bituminous and PVC membranes, and must be performed before cutting the specimens.

In order to carry out the peeling test for bituminous membranes and PVC membranes, standards NP EN 12316-1 [5] and EN 12316-2 [6] respectively state that 5 specimens must be tested, 50±1 mm wide, with a total length of 200±5 mm and a free length of 100 mm between the grips. The connection is performed differently in this test, that is, specimens are T-shaped. However, the width of the joint (W) is still 10 cm, similarly to specimens used in the shear tests.

After cutting the test samples, the width of the joint was marked for applying aluminum tape. This tape served as a guide to align the joint and ensure a constant width, also avoiding that the connection of the joint should extend beyond 10 cm. This occurred with the T-shaped oxidized bitumen specimens, during the peeling test with hot oxidized bitumen 90/40 – where bitumen could easily spill outside the connection area. The test sample was divided into specimens only after the welding was made, thus ensuring better handling by the installer and, essentially, minimizing the edge effect.

Test samples were then placed in shelves inside a ventilated oven room at a constant temperature of 70±2 °C. These shelves were wrapped beforehand in tin foil and sprinkled with talcum powder in order to keep bituminous membranes specimens from sticking to the shelf, which could lead to a loss of bitumen. The NP EN 1296 [2] standard recommends a period of exposure of 4, 8, 16 and 24 weeks, depending on the conditions in which the waterproofing system is applied. In this dissertation, and bearing in mind the objectives set for this work, three periods of exposure – 4, 16 and 24 weeks – were adopted in order to obtain an overview of the changes in the quality of the connection, with particular emphasis on longer ageing periods that would be more likely to reveal problems in bonding new membranes to aged membranes, or other anomalies.

After the artificial ageing period was reached, specimens were removed from the oven room and left to cool down. Afterwards, compressed air was used to remove any talcum powder and placed in the standard atmosphere room until they were fully cooled.

Specimens subject to the shear and peeling tests were connected using the equipment specific for each type of membrane and respective joint, so that new membranes could be successfully connected together, as well as new membranes to old membranes.

In the case of oxidized bitumen membranes welded with hot oxidized bitumen 90/40, welding was achieved through cooling and cohesion of bitumen in the joint. The quality of the weld depends on the capacity of oxidized bitumen to fuse with the surfaces of the connecting membranes. It works much like an adhesive. The oxidized bitumen 90/40 was heated until it started to boil, and was then immediately applied to the surface of the lower membrane and spread evenly across the entire surface while pressing the membranes together in order to allow the bitumen to fill every gap and eliminate any excess bitumen. After the bitumen cooled off, the test sample was placed in the standard atmosphere room and only after a full week, the period of time required for the oxidized bitumen 90/40 to dry adequately, were the test specimens cut.

Gas torch welding the bituminous membranes, on the other hand, was achieved through fusing the bituminous layers of both membranes in the joint area. In order to achieve this, a gas torch with adjustable flame was used. While the specimen was still hot, a cloth was applied to exert pressure over the joint to improve the homogeneity of the connection and its cohesion. Finally, the edge of the joint was beveled with the help of a gas torch heated trowel, as is usual and appropriate at the worksite.

In general, APP-modified bituminous membranes may be connected using either gas torch or bituminous adhesive. Bituminous adhesive connection is achieved through adherence and cohesion, holding the membranes fixed together and maintaining the consistency of the joint. In order to execute the bituminous adhesive connection, the adhesive was applied using a caulking gun on the surface of the joint of the lower membrane, creating equidistant lines of adhesive, sufficiently close to each other preventing any unfilled spaces in the joint once the adhesive was pressed. The upper membrane was aligned with the aluminum strip to ensure the recommended joint width of 10 cm, and that area was pressed with a roller in order to spread the adhesive evenly across the surface and force any excess adhesive out of the test sample, allowing its removal. The test sample was placed in the standard atmosphere room for at least a week so as to allow the adhesive to dry and increase cohesion.

PVC membranes are usually welded with hot air. The hot air fuses the PVC of the two membranes together, which are therefore connected and consolidate after cooling. The manual welding equipment was left to heat and the welding precision nozzle was cleaned with a steel brush. Both membranes were placed with their joints aligned, the welding nozzle placed in the middle at a 45° angle, heating the PVC membranes while they were pressed against each other using the pressure roller.

Connecting PVC membranes with adhesives, on the other hand, is usually achieved through a chemical process that causes the membranes to adhere to each other. In order to connect the membranes using this technique, the area of the joint was first cleaned with a cloth. Adhesive was then applied using a brush over both sides of the membranes that make up the joint. Next, the membranes were made to overlap and after aligning the joint with the aluminum strip, pressure was applied. A bag of fine sand was placed on top of the joint to assist the connection. The test sample was left in the standard atmosphere room with the joint weighed down during a week. Finally, the test sample was cut into the specimens that were later tested.

Tensile tests, shear and peeling tests were performed inside the standard atmosphere room using a Lloyd universal testing machine, with a 10 kN load capacity. Test results were transmitted to a computer in order to be registered and displayed in tables and force-elongation plots.

3. RESULTS AND DISCUSSION

The analysis of results was complemented by verifying the minimum requirements defined in the UEAtc technical guides. This was performed by analyzing the requirements defined in the oldest (1984) and most recent (2001) guides. The values declared by manufacturers are shown in Table A1 of the appendix, while technical guide requirements can be consulted in Table A2.

Before analyzing the requirements provided in the previous table, it is worth saying that there are no requirements regarding oxidized bitumen membranes in the UEAtc technical guides. However, in order to evaluate the performance of this membrane and the resistance of its joint, it was decided to analyze the results based on the requirements set for a different bituminous membrane - the APP-modified bituminous membrane. This was due to the fact that they have less restricting requirements in what regards the peeling test, while requirements are similar for the remaining tests. Under the same conditions, the durability of an oxidized bitumen membrane is lower than that of an APP-modified bituminous membrane.

As for the other specimens (APP-modified bituminous, SBS-modified bituminous and PVC), when there are two conditions to be met in the requirements, for the purposes of this dissertation, if the connection complied with both conditions its quality was considered good; if it complied with only one of the conditions, the connection quality was considered satisfactory; if it failed to comply with both conditions, this would justify the need for further research. The introduction of this criterion in addition to those specified in the technical guides sought to avoid situations where, for example, tearing does not occur at the joint because the element limiting the resistance of the connection was the membrane and minimum test force was not reached.

3.1. MECHANICAL PERFORMANCE OF MEMBRANES

3.1.1. INITIAL CHARACTERISTICS

The results of tensile tests characterizing the membranes are illustrated in Figures 2 and 3 (Table A3 in the Appendix provide a full list of the values obtained). Among the specimens without ageing, the APP-modified bituminous specimens show the highest tensile strength, followed by the PVC specimens, the oxidized bitumen specimens and, finally, the SBS-modified bituminous specimens (Figure 2). The fact that the APP-modified bituminous specimens have the highest resistance is due to the addition of two reinforcements in their composition, one made of fibreglass and the other of polyester felt. In this way, after the fibreglass reinforcement is torn the membrane maintains its consistency due to the polyester felt reinforcement and it is only after the latter is torn that the specimen loses its consistency, leading to the rupture of the bituminous mixture. As far as the resistance of the PVC membranes is concerned, this was achieved essentially due to the resistance of the PVC mix, as after the fibreglass reinforcement is torn, the membrane continues to resist the forces applied until the maximum tensile resistance is reached, which corresponds to the rupture of the PVC membrane.

On the other hand, by analyzing the elongation of the specimens tested, Figure 3 and Table A3 shows that PVC specimens have the highest deformation capacity, with extensions above 300%. They are followed by the APP-modified bituminous specimens, the oxidized bitumen specimens and, finally, the SBS-modified bituminous specimens. The analysis of the series of specimens in which the membrane is made of a bituminous mix, shows that the APP-modified bituminous specimens, at maximum resistance, extend 16 times more on average than the other types of specimen, a characteristic that results from the inclusion of the polyester felt reinforcement. However, this reinforcement is unable to deform to the same extent as PVC.

With regard to the variability of results, variation coefficients for specimens in their initial condition are low, both in terms of maximum resistance and extension (all of them below 10%). For both parameters (maximum resistance and elongation), the SBS-modified bituminous specimens not subjected to ageing were those that registered the greatest variability.

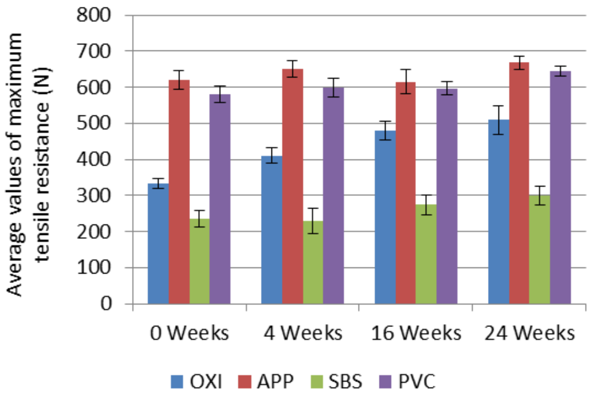

Figure 2 – Average values of maximum tensile resistance.

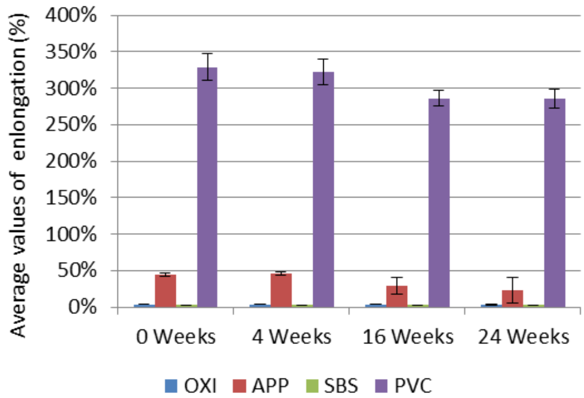

Figure 3 – Average values of elongation at maximum tensile resistance.

3.1.2. AGEING EFFECT ON MEMBRANES

Figure 2 (and Table A3) also reveal the effect of ageing on the characteristics of bituminous membranes. In theory, ageing the materials that make up the membrane should cause an increase in force and a decrease in extension, in view of the fact that ageing causes the evaporation of the volatile components of the membranes, increasing their stiffness and reducing their deformation capacity. However, only in the oxidized bitumen specimens there is, on average, an increase in force and a decrease of extension, as Table 3 shows. The remaining specimens show fluctuations in the maximum resistance throughout the ageing process. However, all the 24-week specimens showed maximum resistance higher than the initial value, which is consistent with what was expected. The fluctuations seen in the remaining specimens may be due to an increase in variability of results or to variables related to the execution of the specimens or, also, due to chemical changes in the structure of the mix (bituminous or synthetic) that the ageing may have caused.

Overall there is a reduction in extension with increased ageing (Table 3), except for SBS-modified bituminous specimens, that show a practically constant extension throughout the different ageing periods – the maximum variation registered was 3% as compared to the new specimens. In relative terms, there was no change in the order of the membranes in view of the results of the specimens not subjected to ageing, as shown in Figure 3. In this way, PVC membranes offered the greatest extension, followed by the APP-modified bituminous membranes, the oxidized bitumen membranes and the SBS-modified bituminous membranes.

Table 3 – Relative values (compared with unaged condition) of maximum resistance and elongation in tensile tests.

Membrane Type	Maximum tensile resistance				Elongation			
	0 Weeks	4 Weeks	16 Weeks	24 Weeks	0 Weeks	4 Weeks	16 Weeks	24 Weeks
Oxidized bitumen	100 %	123 %	144 %	153 %	100 %	96 %	92 %	81 %
APP-modified bituminous	100 %	105 %	99 %	108 %	100 %	102 %	65 %	50 %
SBS-modified bituminous	100 %	98 %	116 %	127 %	100 %	98 %	97 %	100 %
PVC	100 %	103 %	103 %	111 %	100 %	98 %	87 %	87 %

3.2. Mechanical performance of lap joints

3.2.1. Initial performance

3.2.1.1. Shear resistance tests

Regarding connection specimens not subject to ageing that were tested in shear, only in the APP-modified bituminous specimens failure was due to tear of the joint, while in the remaining specimens (oxidized bitumen and SBS-modified bituminous) tearing did not occur in the joint. Tearing of the joint in these APP-modified bituminous specimens occurred in 2 gas torch welded specimens, while this failure mechanism occurred in all 5 specimens bonded with bituminous adhesive that were not subjected to ageing. As to the PVC membranes, despite the fact that tearing did not occur along the joint, partial detachment of the joint did occur in 3 hot air welded specimens and in 5 specimens bonded with solvent adhesive.

The analysis of the results regarding maximum resistance, presented in Figure 4 (and in Table A4 of Appendix), shows that in contrast to the mechanical tensile test, the PVC samples welded with solvent adhesive (PVC.ADHESIVE) had higher resistance than the APP-modified bituminous samples welded by gas torch (APP.TORCH). The PVC specimens welded by hot air (PVC.HOTAIR) came next and then the APP-modified bituminous specimens welded with bituminous adhesive (APP.ADHESIVE). As to the oxidized bitumen specimens, both those welded with hot oxidized bitumen 90/40 (OXI.HOTBIT) and gas torch welded specimens (OXI.TORCH) have higher resistance than the gas torch welded SBS-modified bituminous specimens (SBS.TORCH), as occurred in the mechanical tensile test. Despite these conclusions regarding resistance, it is not possible to extrapolate them directly to the resistance of the welding, since only in the APP-modified bituminous specimens did tearing occur along the joint.

Both series of PVC specimens archived much higher values of elongation than the other types of specimens tested, a situation identical to what occurred with the extension in the mechanical tensile tests. They are followed by the gas torch welded APP-modified bituminous specimens, as seen in Figure 5. These APP-modified bituminous samples present a lower elongation compared with the PVC specimens bonded with solvent adhesive (83% reduction), while the APP-modified bituminous specimens welded with bituminous adhesive that come next, have an elongation below that of PVC specimens bonded with solvent adhesive (96% reduction). The remaining specimens exhibit an even lower elongation, with oxidized bitumen specimens following next, gas torch welded and those with bituminous adhesive and, finally, the gas torch welded SBS-modified bituminous specimens.

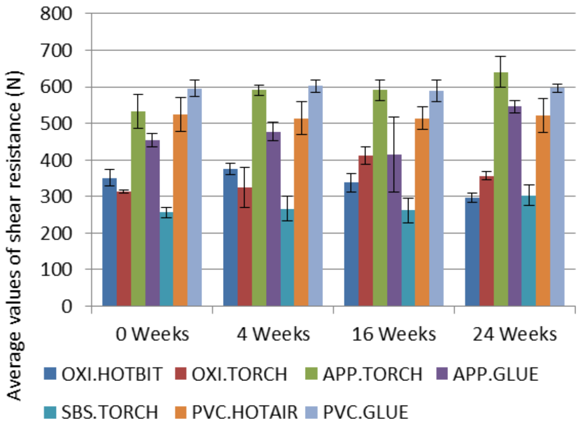

Figure 4 – Average values of maximum shear resistance.

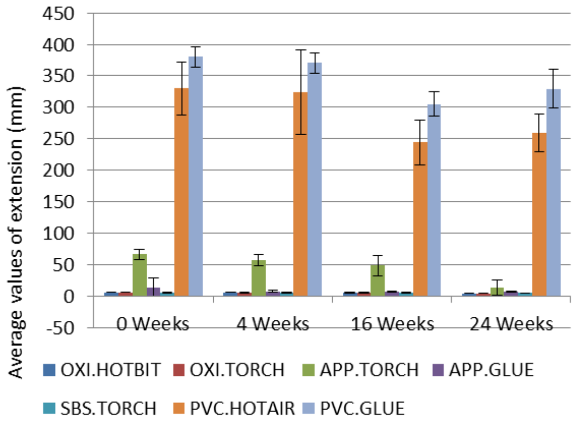

Figure 5 – Average values of extension at maximum shear resistance.

3.2.1.2. Peeling resistance tests

Figures 6 to 8 show a summary of the results obtained in the peeling test, namely the maximum peeling resistance and corresponding extension and the medium peeling resistance.

The complete results obtained in the peeling tests are listed in Table A5 of the Appendix. In this test, where the resistance of the welding was assessed directly, the solvent adhesive PVC specimens (PVC.ADHESIVE) in their initial condition exhibit the greatest resistance, as seen in Figure 6. In contrast to the shear test, the specimens that follow are the gas torch welded SBS-modified bituminous (SBS.TORCH), instead of the gas torch welded APP-modified bituminous specimens (APP.TORCH). The SBS-modified bituminous specimens had, in general, the worst performance in terms of resistance in the shear test. Also, in the peeling tests on SBS-modified bituminous specimens, tearing occurred outside the joint (the membrane was the limiting component). With regard to the remaining specimens in their initial condition, tearing always occurred along the joint.

Furthermore, hot air welded PVC specimens (PVC.HOTAIR) are in third place in the order of resistance to peeling, followed by the two types of welding regarding APP-modified bituminous specimens (APP.TORCH and APP.ADHESIVE), and the other two types of welding regarding oxidized bitumen specimens (OXI.HOTBIT and OXI.TORCH).

With regard to medium peeling resistance (Figure A1 of the Appendix), results are similar to what was described above for maximum resistance, only different to the extent that the gas torch welded SBS-modified bituminous specimens revealed a slightly higher level of resistance (3 N) than the solvent adhesive PVC specimens. Like for the SBS-modified bituminous specimens, tearing did not occur along the joint, and so it is not possible to directly extrapolate this increase of resistance to an improvement in the quality of the connection of these specimens. However, since it was the membrane that limited the resistance of the specimen, influencing the maximum and medium peeling resistances registered, it is possible to conclude that when the membrane is not a limiting factor (e.g. membranes reinforced with polyester felt) if tearing occurs along the joint this would, in principle, require greater force.

With regard to the peeling test of specimens under their initial condition, the most resistant connection was the solvent adhesive within the group of PVC specimens, while for APP-modified bituminous specimens gas torch welding was the most resistant method and, similarly, the gas torch welding was the most resistant within the group of oxidized bitumen specimens.

In what concerns the elongation of specimens under their initial condition that, in general terms, varies greatly, hot air PVC specimens have the greatest elongation (as well as a high level of variability). Figure A2 reveals the following order of elongation of specimens in the mechanical peeling test: hot air PVC, gas torch welded APP-modified bituminous, solvent adhesive PVC, oxidized-bitumen APP bonded with bituminous adhesive, gas torch welded oxidized bitumen, SBS-modified bituminous and oxidized bitumen bonded with hot oxidized bitumen 90/40.

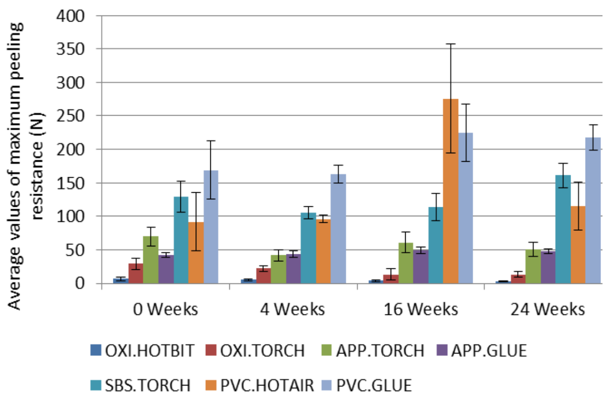

Figure 6 – Average values of maximum peeling resistance.

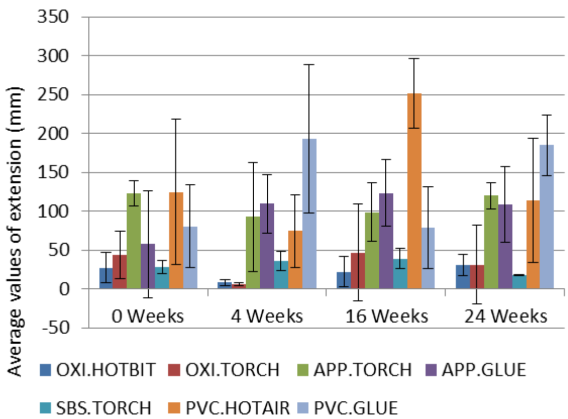

Figure 7 – Average values of extension at maximum peeling resistance.

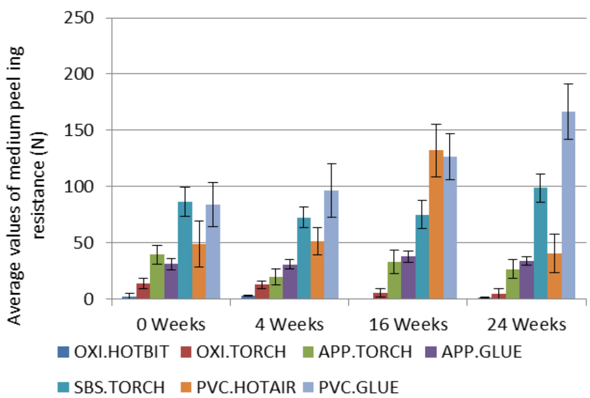

Figure 8 – Average values of medium peeling resistance.

3.2.2. AGEING EFFECT ON LAP JOINT

3.2.2.1. Shear resistance tests

In what regards the types of tear in the shear test, for most of the specimens (77%) tearing occurred outside the joint area, while in the remaining 23% tearing occurred along the joint or on the specimen but in the vicinity of the joint. This latter type of tear occurred in the APP-modified bituminous specimens both gas torch welded and bonded with bituminous adhesive, and also in the hot air PVC specimens.

The results shown in Figure 4 (and Table A4, Appendix) allows assessing the evolution in the resistance of specimens subject to the mechanical shear test with increased ageing, showing that, in general terms, the solvent adhesive PVC specimens were the most resistant. These specimens provide an average maximum resistance value that is practically the same throughout ageing, with a percentage variation of 1% in relation to the initial value (Table 4). In second place, in terms of resistance, are the gas torch welded APP-modified bituminous specimens, showing higher resistance than the hot air welded PVC specimens. However, these reveal a situation similar to what occurs with the solvent adhesive PVC specimens, with a percentage variation in the 4 and 16 weeks aged specimens of 2% in relation to the initial value, while with the gas torch welded APP-modified bituminous specimens there was an increase in resistance of 20% for 24 week specimens in relation to the original value (Table 4). In this APP-modified bituminous test sample, the results with 4 and 16-week specimens are practically the same and 11% above the initial value. The oxidized bitumen specimens are next, where the resistance regarding each type of welding alternates during the ageing periods and, finally, the gas torch welded SBS-modified bituminous specimens. Only the 24-week specimens are an exception to this order: for the gas torch welded SBS-modified bituminous specimens reveal slightly higher resistance than the oxidized bitumen samples welded using hot oxidized bitumen 90/40.

Regarding elongation in the shear mechanical tests, Figure 5 shows that the PVC specimens, both those connected with solvent adhesive and hot air, have the best performance. Out of these two types of connection, the solvent adhesive, in addition to providing a higher maximum resistance, also allow greater elongation. This performance is in line with what was stated above, as PVC membranes possess high deformation and elasticity capability, for which reason greater forces correspond to greater elongation. In this way, as with the hot air PVC specimens, when the force was lower, the elongation caused by the force was also lower. Within the group of bituminous specimens, it can be seen that the gas torch welded APP-modified bituminous have the greatest elongation, followed by APP-modified bituminous specimens using bituminous adhesive, while the remaining specimens, both oxidized bitumen and SBS-modified bituminous, register similar elongations. An examination of the percentage variation of the elongation reveals that increased ageing causes a reduction in elongation, except for the solvent adhesive PVC specimens after 24 weeks that show an increase in relation to 16-week samples (Table 4). This increase may be due to greater variability in the elongation results. Despite this increase, 24-week samples continue to reveal elongation below the initial value. The samples that present the highest percentage reduction were the gas torch welded APP-modified bituminous, for which a decrease of 80% occurred in relation to the initial value.

Table 4 – Relative values (compared to unaged condition) of maximum resistance and extension in shear tests.

Membrane type	Connection type	Shear resistance (N)				Extension			
		0 Weeks	4 Weeks	16 Weeks	24 Weeks	0 Weeks	4 Weeks	16 Weeks	24 Weeks
Oxidized bitumen	Hot oxidized bitumen 90/40	100%	107%	96%	84%	100%	98%	85%	69%
	Gas torch	100%	104%	131%	114%	100%	97%	96%	77%
APP-modified bituminous	Gas torch	100%	111%	111%	120%	100%	86%	73%	20%
	Bituminous adhesive	100%	105%	91%	120%	100%	56%	52%	50%
SBS-modified bituminous	Gas torch	100%	104%	102%	118%	100%	99%	98%	92%
PVC	Hot air	100%	98%	98%	100%	100%	98%	74%	79%
	Solvent adhesive	100%	101%	99%	100%	100%	97%	80%	87%

3.2.2.2. Peeling resistance tests

In what regards the types of tear in the peeling test, for most of the specimens tearing occurred inside the joint. The SBS-modified bituminous specimens were the exception, as tearing occurred generally outside the joint (only in two specimens partial tearing occurred inside the joint).

The results of the mechanical peeling test shown in Figure 6 (and Table A5, Appendix), show that solvent adhesive PVC specimens were, on average, the most resistant type of connection. Only in relation to 16-week specimens a higher maximum peeling resistance and medium peeling resistance was verified for hot air welded PVC specimens. This different result may be related to the variability parameters for the execution of the welding, i.e. the duration that heat was applied, the number of passages with the welding device, among others, that way have caused an added difficulty in the execution of the more aged PVC specimens. As far as concerns bituminous specimens, the gas torch welded SBS-modified bituminous specimens provide considerable resistance, which was made clear during the peeling mechanical test. This connection exceeded the maximum and medium peeling resistance of the other connection types involving bituminous specimen, including APP-modified bituminous membranes which had higher shear resistance, as can be seen in Figure 7.

Table 5 shows the percentage variations of maximum and medium peeling resistance for the specimens subjected to the mechanical peeling test, where it is possible to see the influence of ageing on the connections. In the oxidized bitumen specimens, whichever the type of connection, and in the gas torch welded APP-modified bituminous specimens, one can see that the resistances of the joints were affected negatively by ageing. As far as concerns the bituminous adhesive APP-modified bituminous specimens, resistance increased with ageing, which may be related to the relative invulnerability of the connection to ageing. In contrast, the SBS-modified bituminous specimens reveal a slight decrease in resistance, decreasing in the 4-week specimens and then increasing. This increase may be related to the variables in the execution of the welding; in fact, specimens become more rigid with ageing and require that the installer increase the number and duration of gas torch passes in order to increase adherence, thus increasing the resistance of the connection unintentionally. In relation to the PVC specimens, both types of welding show a substantial increase in resistance for 16 week specimens and, later, a decrease in 24 week specimens. Despite this decrease, the welding continues to present a resistance above the initial value, leading to the conclusion that the welding was not affected negatively to a great degree by ageing.

In the test results for both types of oxidized bitumen membrane connections, the resistance decreases with the increased ageing period due to the temperature. In general terms, both the maximum and the medium peeling resistance at 24 weeks decrease to values below half the initial value (Table 5). In order to improve the welding adherence when this is performed using hot oxidized bitumen 90/40, the polyethylene film should be removed from both sides of the membrane before the welding is performed. Even with the application of bitumen at boiling point this is unlikely to fuse the film, creating non-adhering areas that lead to detachment when the joint is subject to stress.

The resistance of connections using bituminous adhesives was below that of gas torch welding in APP-modified bituminous specimens. However, the connection with bituminous adhesive does not seem to have been as affected by ageing as the gas torch welding, taking into account that both the maximum resistance and the medium peeling resistance were always equal to or above the initial value as ageing increased, while regarding the gas torch welding specimens these forces always stood below the initial value. Even so, the resistance of the gas torch welding was, on average, higher than that of the bituminous adhesive connection (Figures 6 and 7).

Regarding the SBS-modified bituminous membranes and in contrast to the shear test where the SBS-modified bituminous membranes had the lowest resistances, these showed the highest resistance in the group of bituminous membranes in the peeling test (Figure 6). Despite the fact that this resistance cannot be extrapolated directly to the connection, seeing that tearing never took place due to the connection, it may be pertinent to place the hypothesis that for tearing to occur along the joint more force would be necessary in order to cause the connection to fail, in addition to the specimen not being the limiting factor. In order to verify this hypothesis it would be necessary to perform more tests. Tearing of the specimens almost never occurred along the joint, except for 2 specimens where there was partial tearing along the membrane in the joint area.

The connection of the solvent adhesive PVC specimens reveals a higher resistance, both average and maximum, compared to the same type of membrane using hot air welding; the medium peeling resistance of the former is almost the double of the latter, as seen in Figures 6 and 7. On the other hand, the quality of the solvent adhesive connection did not seem to decrease with ageing (at least during the defined periods), for which reason the chemical modifications that may occur in the PVC resin do not seem to affect the respective welding. The resistance of hot air welded specimens also seems not to have been affected by ageing. However, in specimens subject to more aging, taking into account the performance of the welding, the application of hot air had to be performed for longer periods, as well as more passes with the welding equipment for it to be successful. This increased need for heat to achieve the welding may lead to the deterioration the reinforcement and, consequently, the membrane itself.

As far as concerns elongation, Figure 8 shows that the PVC specimens register the largest elongations as well as the largest percentage variations, as shown in Table 5. The APP-modified bituminous specimens appear next, for which both types of welding exhibit elongations below those of PVC, but significantly higher than those of the remaining bituminous membranes. In contrast to the maximum and the medium peeling resistance, the elongation of the SBS-modified bituminous specimens was low, the initial and the 16-week specimen values were even lower than those of the oxidized bitumen specimens.

The percentage variations of the elongation in the mechanical peeling test are listed in Table 5, which shows that regarding the oxidized bitumen specimens, regardless of the type of connection, there is no clear trend for variations due to the ageing of the specimens. These high percentage variations may be due to the small elongation values obtained, as any minimal elongation variation corresponds to a very significant percentage variation. In the remaining samples, a similar situation occurs, in other words, the trend towards elongation according to ageing is not linear. However, regarding the APP-modified bituminous samples bonded using bituminous adhesive, despite the registered fluctuations, the elongation throughout all periods of ageing was always higher than the initial value. The variations observed in the elongation throughout ageing periods may be due to the chemical structure of the mix (bituminous or resin) that makes up the membrane. This structure suffers alteration due to temperature, losing the volatile elements that confer elasticity to the membrane, which certainly influences the elongation of the specimen.

Table 5 – Relative variation (compared to unaged condition) of resistance (maximum resistance and medium resistance in peeling tests).

Membrane type	Welding type	Resistance type	Peeling resistance (N)				Extension			
			0 Weeks	4 Weeks	16 Weeks	24 Weeks	0 Weeks	4 Weeks	16 Weeks	24 Weeks
Oxidized bitumen	Hot oxidized bitumen 90/40	Maximum	100%	79%	61%	36%	100%	30%	80%	112%
		Average	100%	125%	-	47%				
	Gas torch	Maximum	100%	75%	45%	45%	100%	14%	107%	71%
		Average	100%	92%	39%	33%				
APP-modified bituminous	Gas torch	Maximum	100%	60%	88%	72%	100%	75%	80%	98%
		Average	100%	51%	85%	68%				
	Bituminous adhesive	Maximum	100%	103%	117%	113%	100%	191%	214%	189%
		Average	100%	100%	122%	109%				
SBS-modified bituminous	Gas torch	Maximum	100%	81%	88%	124%	100%	127%	139%	63%
		Average	100%	83%	87%	114%				
PVC	Hot air	Maximum	100%	105%	302%	126%	100%	60%	202%	91%
		Average	100%	105%	270%	83%				
	Solvents adhesive	Maximum	100%	97%	133%	129%	100%	239%	98%	230%
		Average	100%	115%	151%	199%				

3.2.3. Comparison between the results and the requirements of the UEAtc technical guides

Table 6 provides a summary of the performance of each type of specimen, according to the requirements of the respective UEAtc technical guides. Since the technical guides do not always specify requirements for aged specimens, it was decided to compare these specimens with the requirements for new specimens, as was mentioned above. Failure to meet these requirements by the aged specimens does not imply that the welding is unsatisfactory, but that further studies are required.

The results obtained in this study were compared to the requirements defined in the UEAtc guides and in the tensile resistance tests only the PVC specimens failed to comply with requirements of guide 29:1984. The remaining specimens (oxidized bitumen, APP-modified bituminous and SBS-modified bituminous) without ageing complied with the corresponding requirements. In relation to aged specimens subject to the tensile resistance test, some specimens (such as the 24-week aged specimens of oxidized bitumen and of SBS-modified bituminous) did not comply with the requirements. In relation to the shear test, the APP-modified bituminous samples bonded using solvent adhesive did not reveal a satisfactory performance, while with regard to PVC specimens welded by hot air, further studies with a larger number of specimens were considered necessary; due to the level of uncertainty that resulted from the size of the sample it was not possible to check if the quality of the connection would be satisfactory. As far as the aged specimens that underwent the shear test are concerned, the APP-modified bituminous specimens bonded using bituminous adhesive and the PVC specimens with both types of connection failed to meet the requirements of the technical guide, the former in relation to the two guides (1984 and 2001) and the latter – hot air welding – also failed to meet the requirements of the two guides, while the solvent adhesive did not comply with the 1984 technical guide. Regarding the peeling test, neither specimen of oxidized bitumen met the requirements of the 2001 technical guide. This was similar to what occurred with the PVC specimens welded using hot air, except for the 16-week specimens. The remaining specimens complied with the requirements of the technical guides.

Table 6 – Summary of checklist with regard to the UEAtc technical guides.

Membrane type	Type of connection	Artificial ageing period (Weeks)	Tensile properties		Shear resistance of joint		Peeling resistance of joint	
			1984	2001	1984	2001	1984	2001
Oxidized bitumen	Hot oxidized bitumen 90/40	0	✓	✓	✓	✓	--[1]	✗
		4	✗	✓	✓	✓	--[1]	✗
		16	✗	✓	✓	✓	--[1]	✗
		24	✗	✗	✓	✓	--[1]	✗
	Gas torch	0	✓[2]	✓	✓	✓	--[1]	✗
		4	✗[2]	✓	✓	✓	--[1]	✗
		16	✗[2]	✓	✓	✓	--[1]	✗
		24	✗[2]	✗	✓	✓	--[1]	✗
APP-modified bituminous	Gas torch	0	✓	✓	✓	✓	--[1]	✓
		4	✓	✓	✓	✓	--[1]	✓
		16	✗	✗	✓	✓	--[1]	✓
		24	✗	✗	✓	✓	--[1]	✓
	Bituminous glue	0	✓[2]	✓	✗	✗	--[1]	✓
		4	✓[2]	✓	✗	✗	--[1]	✓
		16	✗[2]	✗	✗	✗	--[1]	✓
		24	✗[2]	✗	✗	✗	--[1]	✓
SBS-modified bituminous	Gas torch	0	✓	✓	✓	✓	--[1]	✓
		4	✓	✓	✓	✓	--[1]	✓
		16	✓	✓	✓	✓	--[1]	✓
		24	✗	✓	✓	✓	--[1]	✓
PVC	Hot air	0	✗	✓	✗	--[3]	✓	✗
		4	✓	✓	✗	✗	✓	✗
		16	✓	✓	✗	✗	✓	✓
		24	✓	✓	✗	✗	✓	✗
	Solvents glue	0	✗[2]	✓	✗	✓	✓	✓
		4	✓[2]	✓	✗	✓	✓	✓
		16	✓[2]	✓	✗	✓	✓	✓
		24	✓[2]	✓	✗	✓	✓	✓

[1] The 1984 technical guides do not provide requirements for APP-modified bituminous and SBS specimens. Since the results of the oxidized bitumen specimens were compared to the requirements of the technical guide regarding APP-modified bituminous membranes, no requirements are provided.

[2] In the tensile test, as the welding of the specimens does not occur, the two series were grouped together, so compliance with the requirements is the same for both series.

[3] Joint resistance in hot air welded PVC specimens was not classified, seeing that a study with a larger number of samples would be required.

4. Conclusions

The following main conclusions have been obtained based on the experimental programme performed in the scope of this dissertation:

1) In their initial condition, the APP-modified bituminous specimens showed the highest resistance in the tensile tests, followed by the PVC specimens, oxidized bitumen specimens and, lastly, the SBS-modified bituminous specimens.

2) The resistance of the connections when in new condition varies considerably depending on the type of membrane used. Those with the least resistance are the connections between oxidized bitumen membranes, irrespective of whether they are gas torch welded or bonded with hot oxidized bitumen 90/40. On the other hand, the membranes that possess the best connection characteristics are the PVC membranes, in general. However, taking into account only the bituminous membranes that were subjected to the peeling test, the SBS-modified bituminous specimens are those with the highest resistance. In general terms, PVC membranes offer the best performance levels, high elasticity, good bonding capacity, and may only require a smaller number of joints due to the width of some types of rolls.

3) In the analysis of the resistance of new specimens to shear and peeling, PVC membranes have the highest resistance, in both the mechanical tests. Furthermore, within the context of PVC membranes, solvent adhesive connections are clearly more resistant than hot air welding. For the remaining types of membrane the analysis is not straightforward, seeing that with regard to the shear test, the gas torch welded APP-modified bituminous specimens were the most resistant, but in the peeling test the SBS-modified bituminous specimen joints were the most resistant. In this way, both were considered satisfactory, particularly the connections with SBS-modified bituminous. Finally, the shear and peeling resistance of oxidized bitumen specimen connections were among the lowest among the types studied. For the oxidized bitumen 90/40 connections, resistance to peeling was practically inexistent. For the gas torch welded oxidized bitumen specimens, it was noted that the forces, both regarding shear and peeling, were higher than those of specimens connected using hot bitumen.

4) With regard to the effect of ageing on the resistance of connections, oxidized bitumen membranes, both hot bitumen and gas torch connections, the resistances were greatly reduced, in practical terms, but even so one can see that the connection resistance was influenced by increased age, more vulnerable to high temperatures. As far as regards gas torch welded APP-modified bituminous membranes, there was a decrease in connection resistance to peeling with age. Although there were variations, in terms of maximum and medium force of peeling at different periods of ageing, the values obtained were always lower than the initial value. On the other hand, the same type of membrane bonded using bituminous adhesive showed a practically constant resistance in the different ageing periods. Despite this advantage, bituminous adhesive connections had lower resistance than gas torch welding, throughout all ageing periods. It was not possible to directly characterize the resistance of gas torch welded SBS specimens at different stages of ageing, as tearing always occurred outside the area of the joint (both in the mechanical shear tests and in the mechanical peeling tests), except for two specimens that tore through the membrane in the joint area. The increase in the force of peeling and shear with ageing does not necessarily imply that the connections are more resistant, as the tensile resistance and shear tests revealed a trend to increase force with the stiffness of the membrane. As far as the hot air PVC specimens are concerned, in terms of maximum resistance, the resistance of the connection did not seem to be affected by the heat. However, at average force the membranes with 24-week ageing presented a slight decrease in resistance when compared to new membranes. In terms of performance, as the age of the membranes increased it was necessary to apply hot air for longer periods, as well as increase the number of passes of the pressure roller in order to make the membranes successfully adhere to each other. Similarly, the PVC membranes using solvent adhesive also showed this trend to increase resistance following ageing due to heat. However, in this situation the increase in resistance occurred through maximum and medium peeling

resistance in all periods, and it was this connection that proved the most resistant. In this way, solvent adhesive does not seem to be influenced by ageing of membranes due to heat.

5) In this way, one can conclude that the loss of properties exerts greater influence on the capability of the membranes to bond through welding processes, using gas torch or hot air. In the event that the connection is performed through adhesives, resistance is less affected or not affected at all by temperature. However, the resistance is lesser than that of the fused or welded connection.

6) Results obtained in the experimental campaign were compared with the requirements defined in the UEAtc guides. The majority of new specimens (66.2%) fulfilled those requirements. It was also concluded that the ageing did not affect the fulfillment of those requirements, as 64% of the aged specimens complied with UEAtc guides.

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8. APPENDIX

Table A1 – Manufacturer declared value (MDV) and minimum or maximum value stated by manufacturer (MLV).

Membrane	Characteristics	MDV	MLV
Oxidized bitumen	F_{max} tension (transverse direction)	----	300 N/50 mm
	ε on tear (transverse direction)	----	3 %
APP-modified bituminous	F_{max} tension (transverse direction)	650 N ± 20 %	> 520 N
	ε on tear (transverse direction)	45 ± 15 %	> 30 %
SBS-modified bituminous	F_{max} (transverse direction)	250 ± 100 N	> 150 N
	ε on tear (transverse direction)	----	----
PVC	F_{max} tension	----	> 500 N
	ε on F_{max}	----	> 2 %

Table A2 – Minimum requirements of UEAtc technical guide.

Test type	Membrane type	Requirement (1984 technical guide)	Requirement (2001 technical guide)
Tensile properties	APP-modified bituminous	F_{mean} : MDV ± 20%; ε on tear: MDV ± 15% (absolute value)	F_{mean}.: MDV ± 20%; ε on tear: MDV ± 15 % (absolute value)
		----	----
	SBS-modified bituminous	F_{avg}: MDV ± 15%; $\varepsilon \geq$ MLV[4]	F_{avg}. ≥ MLV[4]; $\varepsilon \geq$ MLV[4]
		----	----
	PVC	F_{avg}. and ε: variation less than or equal to 10% in relation to manufacturer specs.	$F_{avg} \geq$ 500 N / 50 mm; ε on $F_{avg} \geq$ 2%
		After 24 weeks ageing 80 °C: ΔF and Δ ε ± 15% of initial values.	After 24 weeks ageing at 70 °C: ΔF ± 20% and Δ ε ± 20% (absolute values in relation to initial values) [5]
Shear resistance	APP-modified bituminous	Tear outside joint area or $F_{avg} \geq$ 500 N / 50 mm.	Tear outside joint area or $F_{mean} \geq$ 500 N / 50 mm.
		After 8 weeks ageing at 70 °C [6]: Tear outside joint area or $F_{avg} \geq$ 500 N / 50 mm.	----
	SBS-modified bituminous	Tear outside joint area or $F_{avg} \geq$ 500 N / 50 mm.	Tear outside joint area or $F_{avg} \geq$ 500 N / 50 mm.
		After 8 weeks ageing at 70 °C[6] Tear outside joint area or $F_{avg} \geq$ 500 N / 50 mm.	----
	PVC	Tear outside joint area	Tear outside joint area or $F_{avg} \geq$ PVC membrane tensile resistance
		----	----
Peeling resistance	APP-modified bituminous		Tear outside joint area or F_{avg} [7] ≥ 40 N / 50 mm
		----	----
	SBS-modified bituminous		Tear outside joint area or F_{avg} [7] ≥ 100 N / 50 mm.
		----	----
	PVC	$F_{avg} \geq$ 80 N / 50 mm.	F_{avg} [7] ≥ 150 N / 50 mm ε $F_{min} \geq$ 80 N / 50 mm
		----	----

[4] MLV – In this case, the manufacturer did not specify a value for this parameter.

[5] Requirement in guide 65:2001 for non-reinforced PVC membranes with 24 week ageing.

[6] This 8 week ageing period at 70 °C was determined based on the requirement of the technical guide and of the Arrhenius formula.

[7] F_{avg} in the peeling test refers to the average maximum resistance and not the medium peeling resistance.

Table A3 – Tensile properties results.

Membrane type	Maximum tensile resistance (N)				Elongation (%)			
	0 Weeks	4 Weeks	16 Weeks	24 Weeks	0 Weeks	4 Weeks	16 Weeks	24 Weeks
Oxidized bitumen	333,0 ± 14,1	410,0 ± 21,8	480,3 ± 25,9	508,8 ± 38,5	3,6 ± 0,1	3,4 ± 0,2	3,3 ± 0,1	2,9 ± 0,4
APP-modified bituminous	619,3 ± 25,6	652,2 ± 23,0	615,1 ± 34,0	667,8 ± 18,7	45,0 ± 2,3	46,0 ± 2,0	29,1 ± 11,4	22,7 ± 17,7
SBS-modified bituminous	235,7 ± 23,2	230,3 ± 35,2	274,2 ± 28,0	299,2 ± 26,0	2,7 ± 0,2	2,6 ± 0,1	2,6 ± 0,2	2,7 ± 0,1
PVC	580,3 ± 22,9	599,4 ± 26,7	597,3 ± 19,3	644,5 ± 14,4	329,1 ± 7,2	322,7 ± 4,5	286,2 ± 8,2	285,8 ± 5,6

TableA4 – Joint shear resistance results.

Membrane type	Type of connection	Shear resistance (N)				Extension (mm)			
		0 Weeks	4 Weeks	16 Weeks	24 Weeks	0 Weeks	4 Weeks	16 Weeks	24 Weeks
Oxidized bitumen	Hot oxidized bitumen 90/40	351,1 ± 22,3	375,5 ± 14,7	337,8 ± 24,6	295,4 ± 12,4	6,2 ± 0,1	6,0 ± 0,1	5,2 ± 0,4	4,2 ± 0,3
	Gas torch	313,6 ± 5,3	325,0 ± 55,6	411,1 ± 23,4	356,3 ± 10,9	5,7 ± 0,2	5,5 ± 0,7	5,5 ± 0,3	4,4 ± 0,2
APP-modified bituminous	Gas torch	532,8 ± 46,9	590,7 ± 13,7	590,8 ± 27,6	640,9 ± 43,2	66,5 ± 8,3	57,3 ± 8,8	48,4 ± 15,6	13,1 ± 12,2
	Bituminous adhesive	454,4 ± 17,7	477,8 ± 26,1	414,1 ± 103,4	545,9 ± 16,7	13,8 ± 14,5	7,7 ± 1,3	7,1 ± 0,7	6,9 ± 0,6
SBS-modified bituminous	Gas torch	256,7 ± 14,2	266,7 ± 33,7	262,0 ± 34,2	303,6 ± 28,6	5,4 ± 0,4	5,3 ± 0,4	5,3 ± 0,4	4,9 ± 0,4
PVC	Hot air	523,1 ± 46,4	514,4 ± 43,6	513,3 ± 31,1	520,9 ± 46,8	329,9 ± 41,9	323,8 ± 67,5	244,5 ± 35,6	260,1 ± 29,9
	Solvents adhesive	595,7 ± 21,7	601,8 ± 17,8	589,1 ± 29,6	597,1 ± 11,1	380,3 ± 16,3	370,2 ± 16,2	305,4 ± 19,8	329,6 ± 30,8

Table A5 – Joint peeling resistance results.

Membrane type	Type of connection	Maximum peeling resistance (N)				Extension (mm)				Medium peeling resistance (N)			
		0 W	4 W	16 W	24 W	0 W	4 W	16 W	24 W	0 W	4 W	16 W	24 W
Oxidized bitumen	Hot bitumen oxidized 90/40	6,4 ± 2,3	5,0 ± 1,6	4,0 ± 1,6	2,4 ± 0,5	27,1 ± 19,7	8,1 ± 3,5	21,8 ± 19,5	30,5 ± 13,5	2,5 ± 2,4	3,1 ± 0,6	-	1,2 ± 0,5
	Gas torch	29,1 ± 8,7	22,0 ± 4,1	13,0 ± 8,4	13,1 ± 7,5	43,8 ± 30,5	6,1 ± 2,3	46,9 ± 62,8	31,3 ± 50,1	13,9 ± 4,7	12,8 ± 3,4	5,5 ± 4,0	4,6 ± 4,5
APP-modified bituminous	Gas torch	69,6 ± 14,3	41,7 ± 8,6	61,0 ± 15,1	50,4 ± 10,4	123,3 ± 16,2	92,5 ± 70,5	98,7 ± 37,9	120,3 ± 16,9	39,4 ± 8,5	19,9 ± 7,0	33,4 ± 10,4	26,6 ± 8,4
	Bituminous adhesive	42,3 ± 3,7	43,5 ± 4,8	49,3 ± 4,7	47,6 ± 3,5	57,5 ± 68,9	109,7 ± 37,6	123,0 ± 42,9	108,6 ± 48,2	31,0 ± 5,2	30,9 ± 3,9	37,7 ± 4,8	33,9 ± 3,7
SBS-modified bituminous	Gas torch	129,2 ± 23,1	104,8 ± 9,3	113,7 ± 20,5	160,8 ± 18,5	28,2 ± 8,9	35,7 ± 12,7	39,1 ± 12,4	17,7 ± 0,9	86,7 ± 13,1	72,4 ± 9,2	75,1 ± 12,5	98,7 ± 12,6
PVC	Hot air	91,4 ± 43,5	95,8 ± 5,5	275,7 ± 81,9	115,4 ± 36,1	124,7 ± 93,2	74,3 ± 46,5	251,9 ± 44,5	113,9 ± 79,4	49,0 ± 20,3	51,3 ± 12,2	132,0 ± 23,5	40,6 ± 16,9
	Solvents adhesive	169,1 ± 44,1	163,3 ± 13,2	224,6 ± 42,1	218,0 ± 19,2	80,6 ± 53,5	192,9 ± 95,2	79,1 ± 52,9	185,2 ± 39,1	83,8 ± 19,6	96,3 ± 23,6	126,8 ± 20,3	166,7 ± 24,7