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Interaction between plasticized polyvinyl chloride waterproofing membrane and extruded polystyrene board, in the inverted flat roof

A. Pedrosa ✉, M. Del Río, C. Fonseca

Universidad Politécnica de Madrid (Madrid, Spain)
✉a.pedrosa@alumnos.upm.es

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ABSTRACT: The inverted flat roof is a constructive system widely used in flat roof construction. In this constructive solution, the insulation is placed over the waterproofing material as a protection. It is believed that this solution provides a longer life cycle; given the fact that it limits the thermal variation the waterproofing material bears up to the end of its life cycle. Consequently, the result will be providing a longer life to the waterproofing membrane. This constructive solution always incorporates polymers or other materials with a thermoplastic addition in their composition. Some polymers show interactions between them that can affect their integrity, and, at the same time, the bulk of the polymeric materials are incompatible. The extruded polystyrene board is always present in the inverted flat roof, and although it is an unbeatable product for this use, it presents incompatibilities and interactions with other materials, and these can affect their properties and therefore the durability of them.

KEYWORDS: Inverted flat roof; Extruded polystyrene board; Waterproofing; Plasticizers migration; Single ply membrane

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RESUMEN: *Interacción entre las membranas de policloruro de vinilo plastificado y el poliestireno extrusionado, en la cubierta plana invertida*. La cubierta plana invertida es un sistema constructivo muy utilizado en las cubiertas planas. En esta solución constructiva, el aislamiento se coloca sobre el material impermeabilizante a modo de protección. Se cree que esta solución proporciona un ciclo de vida más largo; dado que se limita la variación térmica de la impermeabilización hasta el final de su ciclo de vida. En consecuencia, el resultado proporciona una vida más larga a la membrana impermeable. Esta solución constructiva siempre incorpora polímeros u otros materiales con adición termoplástica en su composición. Algunos polímeros muestran interacciones entre ellos que pueden afectar a su integridad, además, la mayor parte de los materiales poliméricos son incompatibles. La plancha de poliestireno extrusionado está siempre presente en la cubierta plana invertida, y aunque es un producto inmejorable para este uso, presenta incompatibilidades e interacciones con otros materiales, y estos pueden afectar a sus propiedades, y por lo tanto a la durabilidad de los mismos.

PALABRAS CLAVE: Cubierta plana invertida; Plancha de poliestireno extrusionado; Impermeabilización; Migración de plastificantes; Membrana monocapa

1. INTRODUCTION

Nowadays, building for long-term sustainability is essential, and therefore, establishing mechanisms for preserving the materials included in this constructive solution has become crucial.

In this paper, the inverted flat roof will be analyzed, focusing and studying the possible interactions between extruded polystyrene board (XPS) and plasticized polyvinyl chloride (PVC-P) waterproofing membranes. Figure 1 shows a detail drawing (cross section) of the materials make up this constructive solution.

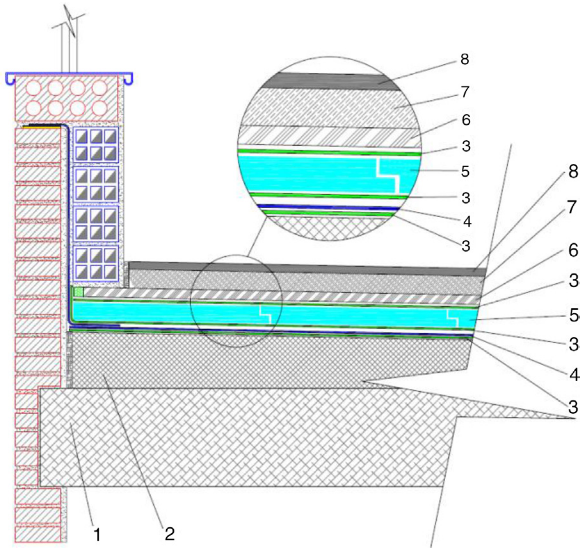

Figure 1. Detail drawing (cross section) of an inverted flat roof. 1 – Slab; 2 – Slope formation; 3 – Auxiliary separating sheet; 4 – Waterproofing membrane; 5 – XPS; 6 – Mortar protection layer; 7 – Mortar; 8 – Pavement.

This is not, however, a chemical study; this paper intends to analyze some interactions that can affect the materials involved in this constructive solution, and the consequences that placing them improperly in a flat roof might have; PVC-P waterproofing membranes have been used in flat roofs for more than 35 years; this material has undergone a great improvement along this time, adding better internal reinforcements to stabilize the dimension of the membrane, and including new additives to withstand weathering, the ultraviolet radiation of the sun, and other inconvenient factors, in order to make gradually a more reliable and durable material. Thus, nowadays PVC-P waterproofing sheets are materials with a great deal of additives in their composition, and composed by different layers in the cross section. To carry out a general study of the behavior of these materials in specific circumstances is a complex task, even more so, if the many different manufacturers are considered, that obviously vary the composition of their waterproofing single ply.

Several tests were carried out in the laboratory to have a clearer outcome on the performance of these materials in pre-established circumstances, and a research work carried out on PVC-P waterproofing membranes installed in flat roofs, with the condition of being part of an upside down flat roof.

2. OBJECTIVE

The main goal in this study is to detect interactions and incompatibilities between PVC-P waterproofing sheets and XPS board, to research if these processes can happen in a common inverted flat roof in use for several years, and to find out how can they affect the integrity of the materials involved in this constructive system. In addition, a wide variety of PVC-P waterproofing membrane brands of common use were tested in the laboratory to check whether this can occur as a general rule. On the other hand, the effectiveness of some frequent auxiliary separating sheets for safeguarding the integrity of these materials was to be analyzed.

3. STATE OF THE ART

Most polymers are incompatible with each other; and in fact, the interactions and incompatibilities between them have been widely studied. One of the fields of study in this matter is the compatibility of incompatible polymer blends. This research line tends to create stable polymer combinations, in order to combine the properties of theoretically incompatible polymers (1, 2) and to take advantage of the better qualities of each one.

PVC-P can contain an ample variety of additives, as for example plasticizers that increase the plasticity of a material. The main applications of plasticizers are as additives for plastics. The ASTM D883 standard defines plasticizer as: *a substance incorporated into a plastic or elastomer to increase its flexibility, workability or distensibility* (3). There is a great deal of plasticizers can be incorporated into a plastic however, those with a greater molecular weight, are more appropriated to increase the durability of the PVC-P waterproofing membranes (4). Phthalates are broadly used in PVC-P laminas, the physical characteristics of these plasticizers are rather diverse. The boiling point can fluctuate from 160 °C of the Diallyl Phatalate to 384 °C of the Di-sec-Octyl Phatalate (5). Other physical data, such as the melting point can oscillate from 5.5 °C of Dimethyl Phatalate to −58 °C of Disiobutyl Phatalate (6).

The interactions between PVC-P and XPS might be summarized as a transference process of plasticizers, commonly named by the term: plasticizers migration, which is a widely studied phenomenon in other industries, such as health and food industries (7). Plasticizers can migrate from PVC-P to any adjacent absorbent material, if the strength and the interface between these materials is not too high, and if the plasticizer is compatible with the receiving material (8, 9). Plasticizers of plastic materials can migrate to another substance or material, such as food products, liquids, or even to another plastic (10). Nevertheless, plasticizer migration from plasticized PVC into other polymeric materials has not been studied as extensively as plasticizer migration into air (i.e., volatile loss) and liquid.

There is a wide variety of plasticizers, and each of them presents a similar behavior when a PVC-P containing some of them is exposed to heat. Time and temperature have influence in the plasticizer migration (11), furthermore, the rate of plasticizer loss increases when the temperature rises (12), and this does occur even with bio-based plasticizers (13). In addition, heat it is an important factor to study this process in the short term, and to make a prediction about the behavior of a polymer in specific circumstances. On the other hand, polystyrene (no foams of this material) is frequently used in chemical studies or tests, as an absorbent material, and as a vehicle for accelerating the speed of the plasticizer loss in a PVC-P sheet (14). Thus, in favorable conditions, crude polystyrene is capable of taking plasticizers contained in other plastics.

XPS is basically manufactured, by extruding molting polystyrene containing a blowing agent (nitrogen gas or chemical blowing agent) under elevated temperature and pressure, into an atmosphere where the mass expands and solidifies into rigid foam (15). There is no evidence that XPS cannot absorb plasticizers. Additionally, once polystyrene has been transformed into plastic foam the thermal conductivity (XPS) lies in a range between 0.03 and 0.04 W/mK (16).

Plasticizers loss has an important consequence for the waterproofing membranes. The amount of plasticizers in a PVC-P might reach the 50% of the total mass, and in the case of some PVC geomembrane already studied the initial content percentage of plasticizers was between 31% and 40% (17). The mass loss of a waterproofing sheet implies a loss of volume, which brings a variation of the membrane dimension (18), and moreover, a gradual reduction of the flexible properties of the sheet. This process will end up marking the end of the life cycle of the waterproofing sheet, causing eventually moisture and leaks.

The plasticizers loss in synthetic waterproofing membranes has been studied in the civil engineering industry. There are works based on the analysis of some materials placed in reservoirs, but not on the interactions previously described. The amount of plasticizers contained in some synthetic membranes was studied, the additives and plasticizers were identified, and their behavior through time was analyzed (19). The phthalates used as additives in PVC-P waterproofing sheets were examined in a geomembrane placed in another reservoir (20). In contrast, another study abounded in the performance of a PVC geomembrane after five years of service, used as a final cover system for the Dyer Boulevard Landfill in West Palm Beach, Florida. In this case, the sheet lost 13% of the initial plasticizer content (21). The conditions a synthetic waterproofing sheet has to bear in the construction field are different, and involve usually more variable factors and singularities, such as roof shape, –whether it has a great number of corners or right angles– services (air conditioning, gas pipes, antennas, solar hot water and electro voltaic panels), sheet areas permanently exposed to the open air, etc. And the most important factor to be considered is: contact or proximity with XPS.

When these waterproofing sheets began to be used in the building industry, after several years of being placed, they brought some problems, at was the case of some unreinforced PVC roof membranes (22). The concern about the effect of the plasticizers loss for the durability of PVC-P membranes generated some studies as well (23). In the case of the properties evolution of these sheets installed on roofs, the performance of them through time has also been researched, and several samples were removed for laboratory testing characterization of selected mechanical and physical properties (24).

PVC-P waterproofing membranes have been studied from various and interesting points of view, but this is not the case of the inverted flat roof in the building industry.

4. MATERIALS AND METHODS

The methodology of this study is divided in three parts; the first part of the study is devoted to analyze an inverted flat roof in use for 10 years with a PVC-P membrane placed on it, looking for possible interactions between polymeric materials. The following two parts of this research article are the experimental tests performed in the laboratory analyzing the possible interactions between XPS board and PVC-P.

An established standard test was partially used to check the response of these materials in the laboratory, the ISO 177:1998 standard: Plastics – Determination of migration of plasticizers. It describes an experiment, based on exposing plastic materials to heat through time. Following this, it is possible to determine the tendency of the plasticizers to migrate from plastic materials (into which they have been incorporated), towards other absorbent materials or plastics placed in touch with them. This is possible by analyzing the mass loss of the samples after several days in the draft furnace. The standard indicates that the samples have to be placed in close contact with two sheets capable of absorbing plasticizers, under defined conditions of pressure, temperature, and time. The mass loss of the test specimen becomes a measure of the plasticizer migration. In order to accurately adapt this experiment to the materials placed in an inverted flat roof with a waterproofing membrane of PVC-P, the absorbent material was the XPS board, which would take the plasticizers from the PVC-P waterproofing sheet.

The interactions between these materials, if they finally occur, can be appreciated after a week in the draft furnace. These interactions show a perfectly visible degeneration in at least one of the materials involved in the test. In the Figure 2 can be appreciated the interaction between XPS and a sample

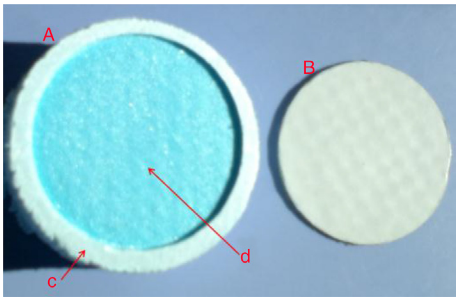

FIGURE 2. Degradation of XPS in direct contact with a PVC-P waterproofing membrane tested after 15 days in the draft furnace (50 °C). Nomenclature of the image: A – XPS sample; B – PVC-P waterproofing membrane sample; c – Edge of the XPS sample with no contact with the PVC-P lamina during the experiment; d – Degraded area of the XPS in contact with the PVC-P sheet during the test.

of PVC-P waterproofing lamina, after one of the tests carried out in the draft furnace. Two experiments were done simulating small inverted flat roof in different situations, and formed by different configurations. Figure 3 shows an image of the samples (in the left part of the image "A"), and a detail drawing of the composition of them (in the right part of the image "B"). The samples were disposed on a tray especially made to carry and to handle the specimens. Every single case (configuration) was tested three times, as the standard advices.

4.1. Testing an inverted flat roof in use

Testing an inverted flat roof in use for 10 years, removing the protection layers of the roof in different positions was carried out and the state of the PVC-P sheet was analyzed, looking for interactions between materials. The studied areas were chosen depending on the orientation of the place, choosing one with an important amount of solar radiation, especially in summer, and another shady area (with no direct sun radiation). In every position at least two parts of the sheet were analyzed; one of them in the vertical edge of the sheet, and another completely covered by the protection layers, with and without contact with XPS if possible, in order to study any kind of degradation of the materials.

4.2. Test in a draft furnace at 70 °C

The second part of this paper analyzes the results offered by a test in the draft furnace working at 70 °C. The test was repeated during seven and during fifteen days. Seventy two samples of three different commercial brands were tested, thirty six samples for every part. This experiment intends to detect interactions between XPS and PVC-P waterproofing laminas, and to test the behavior of the most common separating auxiliary barriers used in the inverted flat roof. These separating sheets are within the requirements of some current and not mandatory standards, with a weight greater than 250 g/m^2 (25). The temperature used for the test was the reference one considered by the ISO 177 standard; however, temperatures between 50 °C and 85 °C are allowed by the standard (26).

The waterproofing PVC-P materials tested were: Novanol 1.5 mm polyester fiber- Basf; Danopol FV 1.2 – Danosa; Sikaplan®-SGMA 1.2 (Trocal SGMA 1.2). Every brand was shaped by four different configurations, and everyone was tested

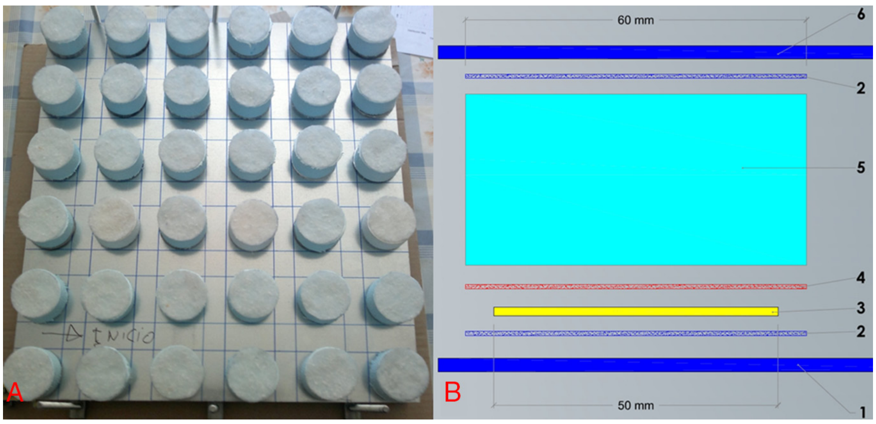

FIGURE 3. Image of the samples for the experiment in the draft furnace (in the left part of the image, "A"), and a detail drawing of the composition of the specimens (in the right part of the image, "B"). "A" – Image before the experiment, the samples were disposed on the tray. Space between samples: 32 and 28 mm, in order to make easier the ventilation in the draft furnace. Afterwards, another plate of galvanized steel (same dimensions of the inferior one) was placed on the samples. The system (before the introduction in the furnace) was finally compressed with a stainless steel frame, using threaded bars. "B" – Detail of the composition of the samples. Nomenclature of the image: 1 – Metallic tray to dispose the samples; 2 – Auxiliary separating layer of Polyester geo-textile of 150 g/m^2 (same for all the samples); 3 – PVC-P waterproofing membrane (variable); 4 – Auxiliary separating layer (variable), no layer in configuration with direct contact; 5 – Extruded Polystyrene Board (XPS) IV Type; 6 – Plate of galvanized steel.

three times. The configurations of the samples were: first, direct contact between PVC-P and XPS; and later, separating PVC-P and XPS, the following materials were used: polyester geo-textile 300 g/m^2, polypropylene geo-textile 300 g/m^2, and aluminum foil, a metallic barrier in order to guarantee no chemical interactions. All waterproofing samples were weighed before placing them in the furnace, and after removing them. However, before being weighed, every sample passed the conditioning process described in the standard ISO 291:2008; Plastics – Standard atmospheres for conditioning and testing.

The brands and types of the rest of the materials involved in this experiment were; XPS IV Type ROOFMATE SL - 30 mm; polyester geo-textile Sika® Geotex PES 300; polypropylene geo-textile Tex Delta 300 g/m^2; and a common alimentary aluminum foil of 0.013 mm thick.

4.3. Test in a draft furnace at 50 °C

The study also performed a new test in the draft furnace, but in this case running at 50 °C, and only during fifteen days (the analysis of the evolution of the plasticizers loss was not the objective of this test, that is why the test during seven days was discarded). The purpose of this experiment was to have a wide view of the results of plasticizers migration that is why, a high amount of brands used to waterproof roofs were tested. In fact, fifty four samples of nine different commercial brands were tested. However, in this case, the samples were placed with only two configurations, and again as it occurred in point 4.2, every sample was analyzed three times. The PVC-P materials tested in the 4.2 point were also checked in this part. The waterproofing PVC-P materials tested were: Novanol 1.5 mm polyester fiber- Basf, Danopol FV 1.2 – Danosa, Sikaplan®-SGMA 1.2 (Trocal SGMA 1.2) – Sika; Sikaplan®- 1.2 G – Sika, Danopol HS 1.2 – Danosa; Sikaplan® W P 5160 -12H (light gray) – Sika; Sarnafil® G410 -12 – Sarnafil, Rhenofol CV 1.2 – Braas Gmbh, Flagon SP – 1.2 – Flag. The configurations of the samples were; direct contact between PVC-P and XPS, and aluminum foil between both. The conditioning process was followed in this case as well, in the same way it was done in point 4.2. On the other hand the other materials involved in this point were: XPS IV Type ROOFMATE SL - 30 mm; and a common alimentary aluminum foil of 0.013 mm thick.

5. THEORY – CALCULATION

The procedure exposed in section 4.1 of this study is a visual overseen section. Thus, following the criterion previously developed, XPS and plasticized polyvinyl chloride are going to interact when placed in specific conditions and circumstances. Therefore, the roof finally chosen will be reviewed looking for traces of interactions.

The results of the two following parts were estimated by calculating the average of all mass loss values of the three samples tested in every configuration, brand and time placed in the draft furnace. The mean of the results had to follow certain norms; for instance, in the case of the three samples analyzed of Sikaplan®-SGMA 1.2 (Trocal SGMA 1.2) tested for 7 days in the draft furnace working at 70 °C, and placed in direct contact with the XPS board, the mean deviation of the three weights could not be greater than 10% when compared to each single weight. All the samples had to comply with this rule regarding each corresponding mean, and if this requirement was not fulfilled, because weights were too dissimilar, the test would have to be repeated until reaching correct result.

In order to weigh all the samples, a balance with a 0.001g of precision was used, the difference between the previous and the final mass will be the mass loss of this material in these conditions and with this configuration.

The final mass loss results are later shown in graphs to simplify and clarify the broad amount of data finally obtained.

6. RESULTS AND DISCUSSION

6.1. Testing an inverted flat roof in use

After finding an inverted flat roof with all the parameters needed to carry out this part of the study, located in Madrid - Spain, it was found that the roof studied did not have any geo-textile or auxiliary separating layer between XPS board and PVC-P sheet. Consequently, in the case of this inverted flat roof, only two areas of the sheet were analyzed: one on the vertical an exposed zone of the sheet, and another area under the XPS board. In the shady area of the roof (with no direct solar radiation), neither PVC-P nor XPS presented any trace of interactions or incompatibilities, however, in the area of the roof with a great deal of direct solar radiation, evident traces of tension were observed on the vertical and exposed area of the sheet. The movement of the horizontal area of the sheet can be appreciated in Figure 4, where red arrows are included to show the shrinkage of the membrane.

Shortly after, the PVC-P waterproofing sheet of this roof was identified as RHENOFOL CG – FDT and the entire roof is formed by this sheet. The XPS boards of the roof were: IV Type ROOFMATE SL - 50 mm, over it, a 300 g/m^2

Figure 4. Arrows show the waves produced by the movement of the horizontal area (shrinkage) of the PVC-P waterproofing membrane.

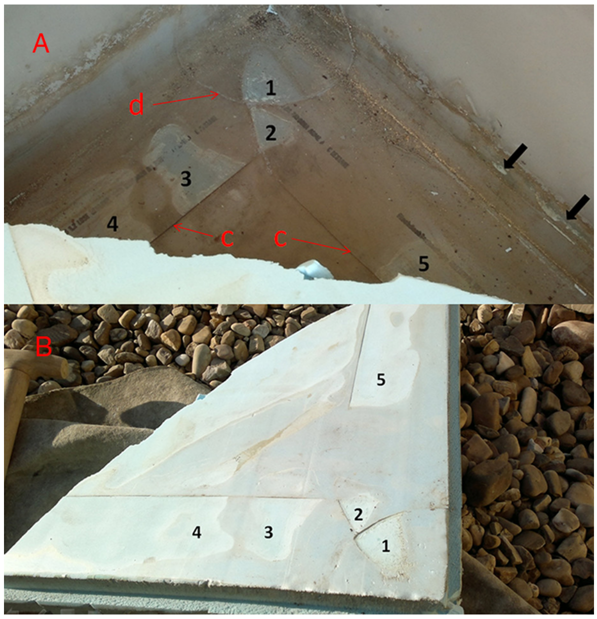

Figure 5. Detail of some possible evidences of chemical interactions between XPS and PVC-P membrane produced in the sunny area of the roof (high levels of solar radiation). In the superior part of the image (A), the front side of the PVC-P waterproofing sheet, numbers and arrows identify some possible interactions and remains of it. The inferior part of the image (B) shows the backside of the XPS board (previously in direct contact with the PVC-P membrane), numbers identify interactions with lack of material. Letter “c” points out the edges of the two overlaps of the vertical finishing of the waterproofing membrane over the horizontal area of the lamina. Letter “d” points out the edge of a specific piece of reinforcement for corners (extra overlap).

polyester geo-textile, and finally a layer of gravel, five centimeters thick.

After removing the XPS board, possible evidences of chemical interactions between both materials could be observed. As a matter of fact, the surface of the XPS board had evident traces of the effect that PVC-P close contact, temperature, and pressure have had on the material. Furthermore, this effect had consequences on the dimension and mass of the PVC-P sheet, and moreover in the amount of plasticizers contained in it. In Figure 5 the marks of these possible chemical interactions can be seen, there is lack of material on the XPS board (visible in the inferior part of the image “B”), and the resultant material of these interactions is adhered on the surface of the PVC-P sheet (in the superior part of the image “A”). As can be seen in Figure 5, arrows show interactions in the vertical finishing of the sheet, and numbers show zones where degradation took place on the horizontal area of the membrane, which coincides perfectly with the lack of material pointed out in the inferior part of the Figure 5 (B). In other words, there is match between the backside of the XPS material, and the front side of the PCV-P waterproofing membrane. The numbers are a reference to make easier find the connection between the two parts of the Figure. Due to the area from which the photographs were taken, these traces were specially located in the areas where the waterproofing membrane had more relief, such as the overlap of the vertical finishing of the membrane over the horizontal part of it. That is why, on the surface of the XPS board, numbers 3, 4 and 5 point out traces with some straight lines, which matches perfectly with the end of the overlaps of the PVC-P waterproofing membrane (“c” letter on the Figure) visible in the superior part of the image “A”. Furthermore, in the corner of the roof, there were other traces (1 and 2 numbers), which were the consequence of higher reliefs on the waterproofing membrane they were produced by consecutive overlaps.

Number 2 is pointing out an area where coincide two overlaps coming from two directions (one over the other, “c” letter on the Figure 5). Number 1 has additionally a special piece of reinforcement over the two previous overlaps (“d” letter shows the edge of this piece). Furthermore, other traces can be appreciated, especially on the surface of the XPS board.

As it was predictable, the more insulation thickness, less interaction possibility, because of the higher thermal protection, or in other words, the heat that would reach the PVC-P waterproofing membrane would be minimized. However, even five centimeters of insulation cannot be enough for safeguarding these interactions. On the other hand, there is a troublesome area, which is the edge of the XPS board all around the perimeter of the roof, and in every area susceptible of contact with the vertical finishing of the sheet, this area has a high risk of interactions due to the absence of thermal protection.

It is important to place a proper auxiliary separating sheet to cut down these interactions. Moreover, it is essential to protect the contact of the vertical finishing of the sheet and the edge of the XPS board. The Figure 6 shows a close-up of these areas, with a detail

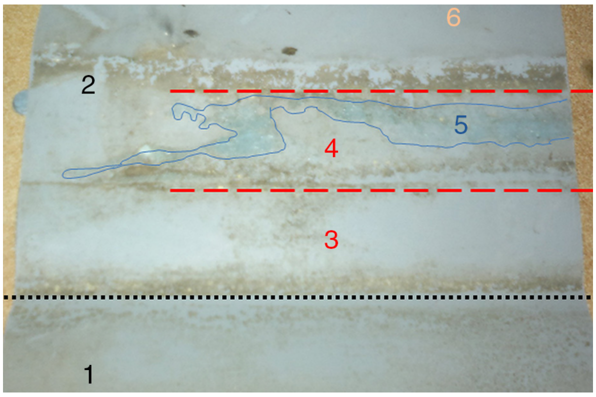

FIGURE 6. Sample of PVC-P waterproofing membrane extracted from the roof (sunny area) including traces of possible interactions with the XPS board; Dotted line - Right angle line between the horizontal and the vertical area of the waterproofing sheet; 1 – Horizontal area of the sample (the remaining of the interactions in this area were removed); 2 – Vertical area of the sample; 3 – Vertical area with no contact with XPS board, due to the rabbet of the edge of the XPS board; 4 – Vertical area with contact with XPS board; 5 – Remaining of interactions stuck on the sheet; 6 – Exposed vertical area (to the open air, and in contact with the gravel).

of the possible interactions in a sample extracted from the roof (sunny area). The dotted line marks the right angle between the horizontal and the vertical area of the roof; the region between broken lines, points out the area in which XPS and PVC-P contacted. As a matter of fact, in this part, remains of interactions stuck on the sheet can be seen (number five). In the area between the broken line and the dotted line, indicated with the number three, there was not any contact with the XPS due to the rabbet of the board edge.

6.2. Test in a draft furnace at 70 °C

This test was carried out in two different phases, by testing samples for seven and for fifteen days in order to quantify the evolution of the mass loss of the samples. The results of the experiment show a similar behavior of the different brands of PVC-P sheets tested. Every sheet and every configuration of the samples presented a mass loss in the draft furnace after the experiment. Big differences in the mass loss can be observed between the expositions of direct contact and the samples shaped with auxiliary separating sheets or a metallic barrier.

The samples shaped with direct contact between XPS and PVC-P, after the first week in the draft furnace show a perfect visible degradation in the XPS board. Additionally the polystyrene foam suffered a transformation in contact with the PVC-P. Figure 7 (in the left part of the image - A) shows an image of polystyrene transformed (with the appearance of a blue gel), which appeared partially stuck on the surface of the sheet in the case of some samples tested (i.e. B part of the Figure 7), as had occurred

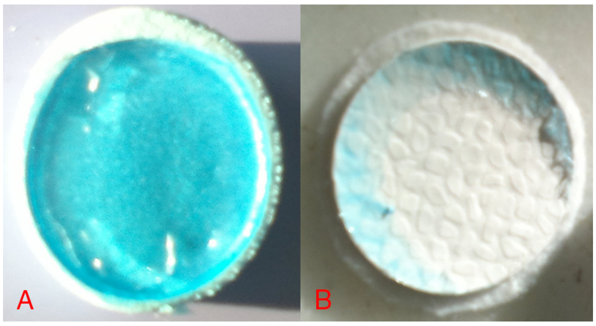

FIGURE 7. Image of samples of XPS and PVC-P waterproofing membrane after the experiment in the draft furnace 7 days 70 °C (configuration - direct contact between them). In the left part of the image (A) XPS sample with the resultant material of possible chemical interactions (similar to a blue gel) in its surface. In the right part of the image (B) a PVC-P sample with the resultant material of the interaction stuck on the surface of the sheet.

in the case of the inverted flat roof analyzed in point 6.1. XPS can be altered by the contact with PVC-P under certain conditions.

After the experiment, every sample had a similar reaction, however, some of them did not have the remains of the interaction stuck on the PVC-P sheet. The behavior of every brand of waterproofing membrane is obviously particular, and it depends on the composition of every sheet.

On the other hand, it is necessary to control the stability of the XPS samples, when the experiment is carried out at 70 °C. This temperature produces thermal degradation in the XPS samples, nevertheless, this is completely different to the deterioration of this material when it is tested in direct contact with PVC-P laminas. Thermal degradation varies the shape, the dimensions and consequently the density of the foam material (Figure 8). Despite being

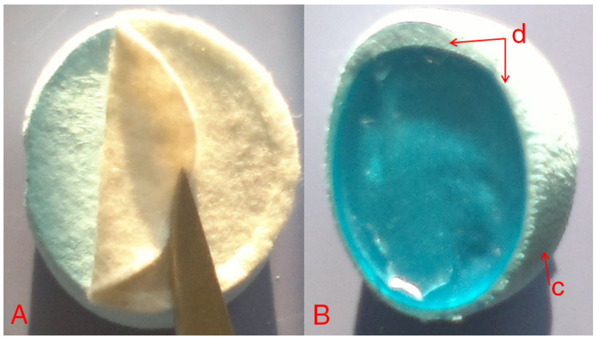

FIGURE 8. Image of samples of XPS after the experiment in the draft furnace 15 days 70 °C. In the left part of the image (A) a XPS sample with thermal degradation and no interaction (formed with an auxiliary separating lamina). In the right part of the image (B) a XPS sample with thermal degradation and interaction; "c" letter shows the edge of the XPS sample deformed by thermal degradation (slight frustoconical shape); "d" letter shows the perimeter of the face of the XPS tested, showing thermal degradation (variation of dimension, but no interaction).

the temperature of reference in the ISO 177 standard, lower temperatures are more convenient to performance these experiments with foam materials.

The results of the auxiliary separating sheets checked as plasticizers barrier, offered a reasonable response to the test, both geo-textiles tested had the same weight, 300 g/m^2. The Figure 9 shows the mean results of mass loss in percentage, offering a comparison between geo-textiles and the metallic barrier, which can guarantee the absence of chemical interactions, and shows the effectiveness of the auxiliary separating sheet tested as a plasticizer barrier.

Volatiles substances of a PVC-P waterproofing membrane can be approximately quantified by analyzing the mass loss of the samples formed with the metallic barrier in between.

6.3. Test in a draft furnace at 50 °C

After testing the PVC-P waterproofing membranes in the draft furnace, the mass losses of the samples were lower than the ones shown in section 6.2, as it was predictable due to the lower temperature. Plasticizers migration took place also at this temperature with every sample. Indeed, the interactions between XPS and PVC-P in the configurations with direct contact occurred also at this temperature. Polystyrene foam suffered a transformation in contact with the PVC-P as it happened in section 6.2, but clearly to a lesser extent.

Figure 10 shows a photograph of different materials from distinct specimens tested. In this image is visible the effect of every particular configuration on the surface of the XPS boards. Notice the absence of interactions in the XPS sample formed with a metallic barrier (4′).

The mass loss of the different brands of PVC-P sheets tested was similar for every configuration. Thus the Figure 11 shows a reliable and simplified way of presenting the mass loss results independently of the brand of the PVC-P membrane. This figure also shows findings from the test at 70 °C, to appreciate better the mass losses obtained in the entire study. Results are presented comparing data of mass losses between the two configurations.

In spite of the fact that the PVC-P membranes tested show a similar behavior for every configuration, as it was shown in Figure 9 and 11, the results are varied considering all the brands. The response is slightly different, depending on the brand. There are a wide variety of plasticizers that can be chosen to make these sheets, and this is also the case of additives; every combination of plasticizers and additives is going to offer the sheet a slightly dissimilar behavior in specific conditions.

PVC-P waterproofing membranes are polymers made with a great deal of additives such as antioxidants, fillers, plasticizers, heat and light stabilizers, pigments, etc. The composition of every PVC-P waterproofing brand is different, and as a consequence, the response of every PVC-P is only similar

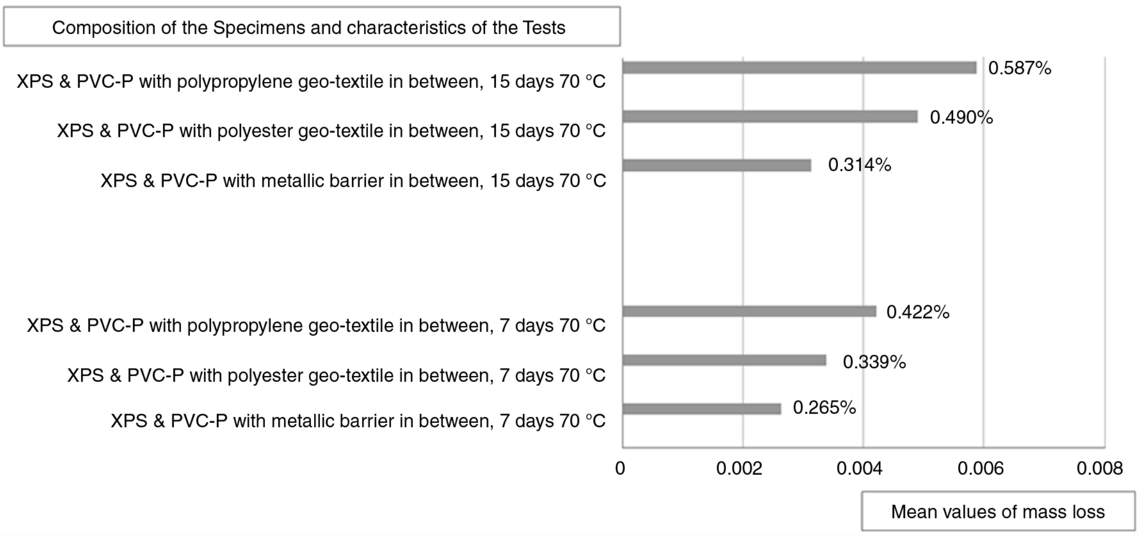

FIGURE 9. Comparison of mass losses between the configuration with auxiliary separating sheets, and the metallic barrier, test in draft furnace during seven and fifteen days at 70 °C; measurement unit - mean of the results of mass loss percentage. RSD% values: Configuration XPS & PVC-P with polypropylene geo-textile in between, 15 days 70 °C – 1st Brand: ± 7.512%. 2nd Brand: ± 9.750%. 3rd Brand: ± 7.050%. Configuration XPS & PVC-P with polyester geo-textile in between, 15 days 70 °C - 1st Brand: ± 7.512%. 2nd Brand: ± 4.225%. 3rd Brand: ± 9.116%. Configuration XPS & PVC-P with metallic barrier in between, 15 days 70 °C -1st Brand: ± 4.681%. 2nd Brand: ± 6.928%. 3rd Brand: ± 5.263%. Configuration XPS & PVC-P with polypropylene geo-textile in between, 7 days 70 °C – 1st Brand: ± 5.882%. 2nd Brand: ± 9.091%. 3rd Brand: ± 7.692%. Configuration XPS & PVC-P with polyester geo-textile in between, 7 days 70 °C - 1st Brand: ± 7.692%. 2nd Brand: ± 6.186%. 3rd Brand: ± 5.088%. Configuration XPS & PVC-P with metallic barrier in between, 7 days 70 °C -1st Brand: ± 5.094%. 2nd Brand: ± 7.873%. 3rd Brand: ± 8.660%.

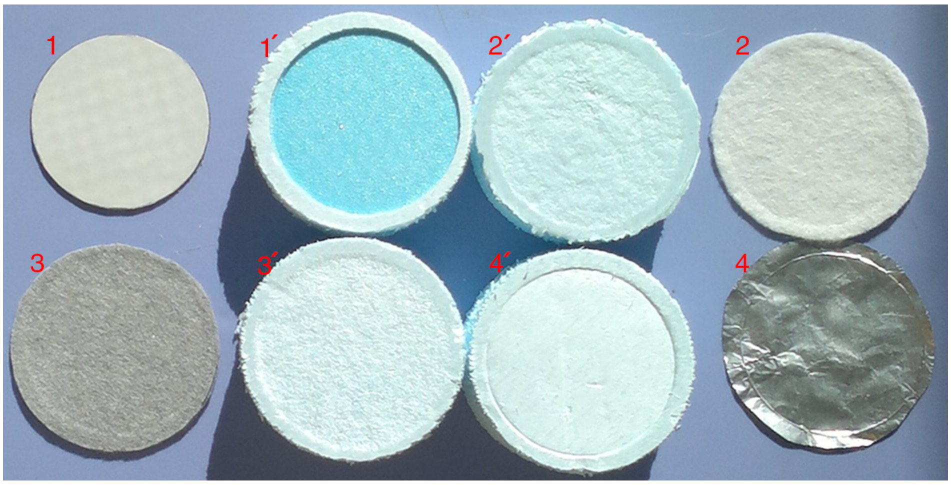

Figure 10. Image of some materials involved in the experiment, after the test in the draft furnace (50 °C – 15 days). Nomenclature of the materials: 1 - PVC-P waterproofing lamina; 1´- XPS in direct contact with the PVC-P waterproofing membrane; 2 - Auxiliary separating layer of Polyester geo-textile of 300 g/m^2; 2´- XPS separated from the PVC-P waterproofing lamina with Polyester geo-textile of 300 g/m^2; 3 - Auxiliary separating layer of Polypropylene geo-textile of 300 g/m^2; 3´- XPS separated from the PVC-P waterproofing lamina with Polypropylene geo-textile of 300 g/m^2; 4 - Auxiliary separating layer of aluminum foil of 0.013 mm thick; 4´- XPS separated from the PVC-P waterproofing membrane with an aluminum foil of 0.013 mm thick.

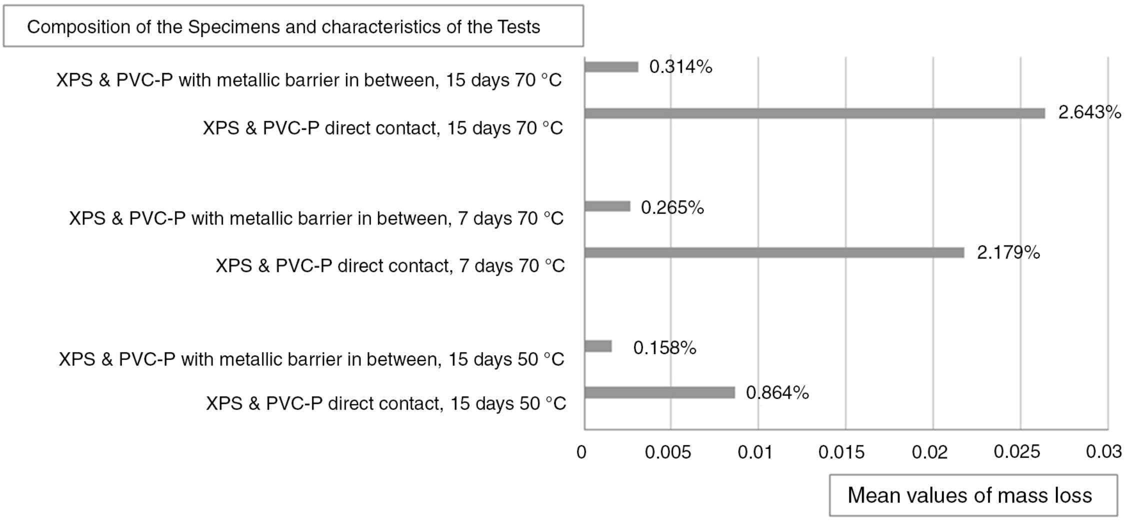

Figure 11. Comparison of mass losses between the configuration with direct contact, and with the metallic barrier, test in draft furnace during seven, fifteen days, at 50 °C and 70 °C; measurement unit - mean of the results of mass loss percentage. RSD% values: Configuration XPS & PVC-P with metallic barrier in between, 15 days 70 °C -1st Brand: ± 4.681%. 2nd Brand: ± 6.928%. 3rd Brand: ± 5.263%. Configuration XPS & PVC-P direct contact, 15 days 70 °C -1st Brand: ± 2.577%. 2nd Brand: ± 3.726%. 3rd Brand: ± 5.556%. Configuration XPS & PVC-P with metallic barrier in between, 7 days 70 °C -1st Brand: ± 5.094%. 2nd Brand: ± 7.873%. 3rd Brand: ± 8.660%. Configuration XPS & PVC-P direct contact, 7 days 70 °C -1st Brand: ± 5.094%. 2nd Brand: ± 7.873%. 3rd Brand: ± 8.660%. Configuration XPS & PVC-P with metallic barrier in between, 15 days 50 °C - 1st Brand: ± 8.056%. 2nd Brand: ± 8.056%. 3rd Brand: ± 9.445%. 4th Brand: ± 8.585%. 5th Brand: ± 9.116%. 6th Brand: ± 9.207%.7th Brand: ± 9.116%. 8th Brand: ± 8.479%. 9th Brand: ± 8.248%. Configuration XPS & PVC-P direct contact, 15 days 50 °C - 1st Brand: ± 8.898%. 2nd Brand: ± 2.440%. 3rd Brand: ± 7.050%. 4th Brand: ± 6.250%. 5th Brand: ± 8.696%. 6th Brand: ± 3.125%.7th Brand: ± 8.206%. 8th Brand: ± 6.415%. 9th Brand: ± 7.873%.

in every configuration tested in this research. There are materials, which show a better behavior to the direct contact with the XPS, but for instance, they can lose more volatile substances, or react better or worse with a specific geo-textile. However it can be assured as a general rule, that PVC-P waterproofing sheets show interaction or incompatibilities with XPS board, and the response of them for every brand, is close to the results presented in Figure 9 and 11.

6.4. Summary of the results

This section is going to show the results of the tests performed at 70 °C, moreover, mean values, standard deviation and RSD% of the results are going to be presented. On the other hand, the range of response of the sheets tested in sections 6.2 and 6.3 of this study can be seen in Figure 12, showing maximum and minimum values of mass loss (mean percentage) for every configuration.

In Table 1 can be seen the results of the test in the draft furnace during 7 days at 70 °C, additionally, Table 2 shows the results of the test in the draft furnace during 15 days at 70 °C.

The mean values of every brand tested show a different behavior for every brand after the experiment in the draft furnace. It becomes evident, making a comparison between the mean values of mass loss of the brands tested. The second brand of PVC-P waterproofing membrane got the lowest values of mass loss for every configuration and temperature. Nevertheless, it does not mean that this brand have better quality than others. To stay this, additionally, other factors have to be taken into a consideration.

The values of standard deviation obtained are not related with the brand tested, in other words, there is no relation between the characteristics of the waterproofing lamina and the standard deviation values finally obtained. However, this is not the case of the configuration of the samples.

The configuration with the greatest values of standard deviation is: direct contact between XPS and PVC-P, followed by Polypropylene geo-textile, Polyester geo-textile, and finally, the lowest values are offered by the metallic barrier. This is also the case of the results of mass loss, which follow the same rule. The effectiveness of the auxiliary separating lamina used produces a significant decrease of mass loss in the samples tested and consequently, the results values are closer between each other. The mean values offered by the configuration with the metallic barrier are more precise than others.

Analyzing the RDS% values showed in Table 1 and 2, it can be said, that the precision of the results is higher for the configuration with direct contact (they are the lowest RDS% values). Other configurations offered higher, but quite similar RSD% values (between 5% and 9% approximately). Nevertheless, from an experimental point of view, the precision of the results in the configuration with the metallic barrier have to be much higher, in order to achieve data within the requirements of the ISO 177 standard. A balance with a 0.0001g of precision is more appropriated, or even with higher precision if possible.

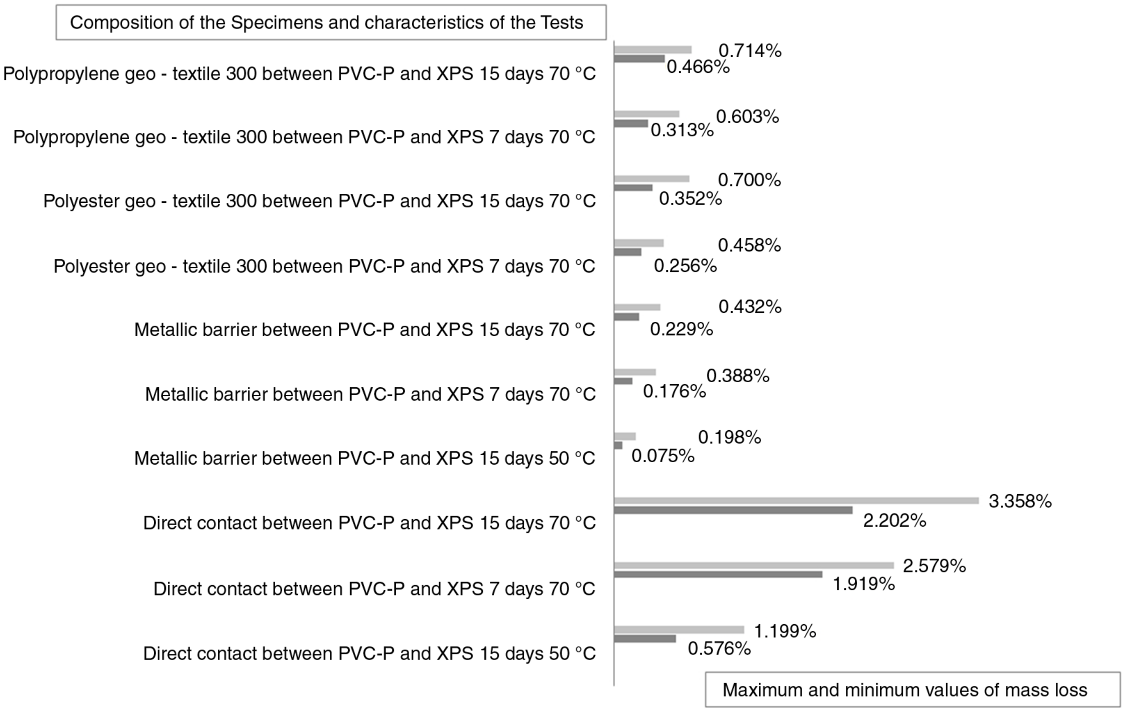

FIGURE 12. Range of response of the sheets tested; maximum and minimum values of mass loss (mean percentage) for every configuration. The RSD% values are the same presented in Figure 9 and Figure 11.

TABLE 1. Test in the draft furnace 7 days 70 °C

Configuration of the samples							
Direct contact between XPS and PVC-P							
PVC-P Membranes		**Initial Mass**	**Final Mass**	**Mass loss**	**Average**	**σ**	**RSD%**
1st Brand	1st Sample	2.907	2.832	0.075			
	2nd Sample	2.873	2.798	0.075			
	3rd Sample	2.867	2.794	0.073	0.074	0.00115	1.553%
2nd Brand	1st Sample	3.213	3.151	0.062			
	2nd Sample	3.184	3.120	0.064			
	3rd Sample	3.192	3.134	0.058	0.061	0.00306	4.981%
3rd Brand	1st Sample	3.796	3.720	0.076			
	2nd Sample	3.787	3.707	0.080			
	3rd Sample	3.795	3.719	0.076	0.077	0.00231	2.986%
Auxiliary separating layer of Polypropylene Geo-textile 300 g/m^2							
PVC-P Membranes		**Initial Mass**	**Final Mass**	**Mass loss**	**Average**	**σ**	**RSD%**
1st Brand	1st Sample	2.948	2.932	0.016			
	2nd Sample	2.950	2.933	0.017			
	3rd Sample	2.890	2.872	0.018	0.017	0.00100	5.882%
2nd Brand	1st Sample	3.189	3.177	0.012			
	2nd Sample	3.172	3.161	0.011			
	3rd Sample	3.229	3.219	0.010	0.011	0.00100	9.091%
3rd Brand	1st Sample	3.803	3.791	0.012			
	2nd Sample	3.802	3.789	0.013			
	3rd Sample	3.811	3.797	0.014	0.013	0.00100	7.692%
Auxiliary separating layer of Polyester Geo-textile 300 g/m^2							
PVC-P Membranes		**Initial Mass**	**Final Mass**	**Mass loss**	**Average**	**σ**	**RSD%**
1st Brand	1st Sample	2.924	2.912	0.012			
	2nd Sample	2.941	2.928	0.013			
	3rd Sample	2.872	2.858	0.014	0.013	0.00100	7.692%
2nd Brand	1st Sample	3.170	3.160	0.010			
	2nd Sample	3.171	3.162	0.009			
	3rd Sample	3.180	3.171	0.009	0.009	0.00058	6.186%
3rd Brand	1st Sample	3.779	3.769	0.010			
	2nd Sample	3.784	3.774	0.010			
	3rd Sample	3.781	3.770	0.011	0.010	0.00053	5.088%
Auxiliary separating layer of Metallic barrier							
PVC-P Membranes		**Initial Mass**	**Final Mass**	**Mass loss**	**Average**	**σ**	**RSD%**
1st Brand	1st Sample	2.902	2.890	0.012			
	2nd Sample	2.947	2.936	0.011			
	3rd Sample	2.909	2.898	0.011	0.011	0.00058	5.094%
2nd Brand	1st Sample	3.189	3.182	0.007			
	2nd Sample	3.209	3.202	0.007			
	3rd Sample	3.184	3.176	0.008	0.007	0.00058	7.873%
3rd Brand	1st Sample	3.828	3.822	0.006			
	2nd Sample	3.759	3.752	0.007			
	3rd Sample	3.786	3.779	0.007	0.007	0.00058	8.660%

TABLE 2. Test in the draft furnace 15 days 70 °C

Configuration of the samples							
Direct contact between XPS and PVC-P							
PVC-P Membranes		**Initial Mass**	**Final Mass**	**Mass loss**	**Average**	**σ**	**RSD%**
1st Brand	1st Sample	2.881	2.781	0.100			
	2nd Sample	2.934	2.836	0.098			
	3rd Sample	2.911	2.816	0.095	0.098	0.00252	2.577%
2nd Brand	1st Sample	3.288	3.215	0.073			
	2nd Sample	3.193	3.125	0.068			
	3rd Sample	3.193	3.121	0.072	0.071	0.00265	3.726%
3rd Brand	1st Sample	3.815	3.730	0.085			
	2nd Sample	3.778	3.688	0.090			
	3rd Sample	3.804	3.709	0.095	0.090	0.00500	5.556%
Auxiliary separating layer of Polypropylene Geo-textile 300 g/m^2							
PVC-P Membranes		**Initial Mass**	**Final Mass**	**Mass loss**	**Average**	**σ**	**RSD%**
1st Brand	1st Sample	2.872	2.850	0.022			
	2nd Sample	2.912	2.893	0.019			
	3rd Sample	2.899	2.879	0.020	0.020	0.00153	7.512%
2nd Brand	1st Sample	3.184	3.168	0.016			
	2nd Sample	3.225	3.208	0.017			
	3rd Sample	3.239	3.225	0.014	0.016	0.00153	9.750%
3rd Brand	1st Sample	3.777	3.755	0.022			
	2nd Sample	3.803	3.780	0.023			
	3rd Sample	3.774	3.754	0.020	0.022	0.00153	7.050%
Auxiliary separating layer of Polyester Geo-textile 300 g/m^2							
PVC-P Membranes		**Initial Mass**	**Final Mass**	**Mass loss**	**Average**	**σ**	**RSD%**
1st Brand	1st Sample	2.897	2.877	0.020			
	2nd Sample	2.948	2.929	0.019			
	3rd Sample	2.869	2.847	0.022	0.020	0.00153	7.512%
2nd Brand	1st Sample	3.252	3.239	0.013			
	2nd Sample	3.223	3.209	0.014			
	3rd Sample	3.292	3.278	0.014	0.014	0.00058	4.225%
3rd Brand	1st Sample	3.816	3.804	0.012			
	2nd Sample	3.777	3.763	0.014			
	3rd Sample	3.784	3.770	0.014	0.013	0.00121	9.116%
Auxiliary separating layer of Metallic barrier							
PVC-P Membranes		**Initial Mass**	**Final Mass**	**Mass loss**	**Average**	**σ**	**RSD%**
1st Brand	1st Sample	2.848	2.835	0.013			
	2nd Sample	2.853	2.841	0.012			
	3rd Sample	2.860	2.848	0.012	0.012	0.00058	4.681%
2nd Brand	1st Sample	3.190	3.181	0.009			
	2nd Sample	3.244	3.236	0.008			
	3rd Sample	3.196	3.188	0.008	0.008	0.00058	6.928%
3rd Brand	1st Sample	3.788	3.779	0.009			
	2nd Sample	3.801	3.791	0.010			
	3rd Sample	3.788	3.778	0.010	0.010	0.00050	5.263%

7. CONCLUSIONS

Heat is an important factor in the mass loss of a PVC-P waterproofing membrane; even without any possibility of interactions, heat produces mass loss (volatiles substances are lost in this process).

XPS can be altered by the contact with PVC-P waterproofing membranes under certain conditions. Interactions between these materials can occur in a common inverted flat roof. This phenomenon might be especially significant in latitudes with hot summers.

The amount of heat that can reach the PVC-P membrane in a conventional inverted flat roof is clearly minimized by the thermal protection that XPS board offer to the constructive solution. However, it is not enough, even despite the five centimeters thick insulation board of the roof.

In the long term, the mass loss observed, implies a dimension loss in the waterproofing sheet. This process makes the waterproofing membrane become brittle. The shrinkage of the membrane brings internal strong stresses that will end up producing leaks by tearing the sheet, or by producing failures in the weakest points of the welding.

Every PVC-P waterproofing sheet used in an inverted flat roof has to have an internal reinforcement to minimize this shrinkage effect, but even though, the dimension loss occurs, as in the case of the sheet studied in sections 4.1 and 6.1 of this study.

PVC-P waterproofing membranes and XPS are remarkable materials, with excellent waterproof and insulating roofs properties, but they have to be placed with an appropriate auxiliary separating sheet, and covering the edges of the XPS board everywhere in which the vertical finishing of the membrane can be in contact with the edge of the XPS board, i.e. in the perimeters of the roof.

The direct contact between both materials (tested in the draft furnace) produces five to nine times more mass loss that those configurations with a proper barrier placed in it. This mass loss produced, in turn, a loss of membrane dimension, which brings internal stress, and increases the pressure between PVC-P waterproofing membrane and XPS on the perimeters of the sheet (which raises the plasticizers migration).

The geo-textile tested with the best behavior as an auxiliary separating layer was the polyester geo-textile of 300 g/m^2. On the other hand, polypropylene geo-textile of 300 g/m^2 can offer a good response to reduce the transference of plasticizers in a PVC-P waterproofing sheet. Nevertheless, plasticizers migration does occur, even with these materials placed as auxiliary separating sheets.

There are many factors to assess the quality of a PVC-P waterproofing sheet. And, the stability of the plasticizers after the test in the draft furnace cannot only be taken into consideration. The quality of the internal reinforcement of the membrane, among other factors, can also be important.

For the study of interactions and incompatibilities between XPS and PVC-P in a draft furnace, the temperature of 50 °C is more appropriated. The plastic foam material remains stable along these experiments at this temperature.

The behavior of the materials placed in an inverted flat roof depends on many factors, such as heat, pressure, composition of the PVC-P waterproofing membrane, the auxiliary separating layer placed in, etc. Additionally, another important factor is the composition and the manufacturing system of the XPS board. Thus, it is really difficult to predict the global behavior of the materials involved in this constructive system.

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