RECYCLED PLASTIC FOR RESILIENT ROOFS

AN EXPERIMENTAL RESEARCH ON INSULATION PANELS OF HDPE

Maud Houterman
Faculty of Architecture & the Built Environment, Delft University of Technology
Julianalaan 134, 2628BL Delft

ABSTRACT

The Caribbean deals with hurricanes every year, in these storms roofs are often damaged. In this paper a solution to use recycled HDPE for resilient roofs on Sint Maarten is discussed. The following research question is answered: "What are the potentials of HDPE plastic waste as material for hurricane resilient sandwich panels that improve the insulation value on Sint Maarten?" Roofs mostly common on the island are wooden gable and hip roofs. The current highest insulation value is from a concrete roof with a value of 0, 31 m2 K/W. Insulation material is based on the principle, the more air it is containing in relation to its own weight, the better it insulates. Formability of the plastic makes it possible to form the material in shapes that captures air inside. A thicker sandwich panel is equal to a higher insulation value. Some guidelines are made for future implementation of plastic in resilient roofs. In broader aspect HDPE can potentially bring a social-economic waste strategy to Sint Maarten and generate income.

KEYWORDS: *HURRICANE-RESILIENT ROOFS, PLASTIC-WASTE, INSULATION,*

I. INTRODUCTION

Sint Maarten is an island in the Caribbean which lies in the North Atlantic Ocean. This ocean is one of the six main tropical areas of the earth where hurricanes develop each year. Hurricanes Irma and Maria did strike in 2017 which caused 90% of buildings left damaged. These where mostly due to loss of roof covering and damage to windows and doors. Most of the severely damaged houses were built of zinc roofs with tinder or plywood walls (Williams, 2018, pp. 10).

The capital of the island is Philipsburg and is the second most visited port in the Caribbean. Yearly the country receives 1.7 million cruise visitors and 530.000 stopover visitors. These visitors combined spend about 820 million a year (Williams, 2018), making the tourism and commerce sectors the most important income generation. The rebuilding process of the tourism sector takes a long time. Since this sector relies heavily on rebuilding hotels, cleaning beaches etc. A long rebuilding process leaves a large group of the population unemployed after a hurricane.

Plastic is with 80% the main marine litter in the Caribbean Sea. This litter mainly comes from poor household collection services. An estimated 322,745 tons of plastic goes uncollected each year in Caribbean (World Bank Group, n.d. pp. 15). Sint Maarten stays behind in banning single used plastics like plastic bags in the supermarket (Nature foundation St. Maarten, 2019). Single use plastic are abundantly littered on Sint Maarten. With a population of 42.575 people (Worldometers, n.d.), Sint Maarten generates 0.25 kg of plastic per person every day (Our World in Data, n.d.). This means that the yearly plastic waste generation of Sint Maarten is 3.751 kg. Worldwide there are seven groups of plastic polymers used for packaging applications. These are PET, HDPE, PVC, LDPE, PP, PS and Other (including acrylic and polycarbonate). Because these plastics are coded, it is easy for the local community to recycle them. Of these types High Density Poly Ethylene (HDPE) is the only one that is UV and water resistant. HDPE is used to make plastic bags, shampoo bottles, milk jugs, toys etc. When Sint Maarten integrates a recycling system, a HDPE roof panel can be a good example of recycling in the built environment.

The idea is to decrease the unemployment rate after a disaster by implementing a waste collecting system on Sint Maarten and build resilient housing with these materials. The research is focused on roofs because roofs are often damaged by high wind speeds. Previous research on TU Delft show that sheets from recycled plastics can be produced (van den Berg, 2019). With a hydraulic press air bubbles are pushed out. These air bubbles can be seen as thermal insulation that is created by captured dry air, preventing it from moving. In a hot climate such as the one Sint Maarten deals with, a cavity in a panel can improve the insulation value of roofs. The following question arises: *"What are the potentials of HDPE plastic waste as material for hurricane resilient sandwich panels that improve the insulation value on Sint Maarten?"*

METHODOLOGY

The general objective of this research is to make resilient roofs for houses on Sint Maarten. The research is supplemented with a field research of 3 weeks on the island. This research gave an overall inside on local needs, main problems with roofs, governmental needs and waste management. The field research formed the starting point of defining the problem and refining the research question. This paper will go deeper into three aspects: improving the indoor climate by insulation of the roof, the use of HDPE plastic elements and producing these elements low tech. The research question is: *"What are the potentials of HDPE plastic waste as material for hurricane resilient sandwich panels that improve the insulation value on Sint Maarten?"*
This paper is further divided into two parts; literature research and experimental research. First, a thorough literature and analysis has been conducted in order to comprehend the effect of high wind speeds on roofs. The following sub-questions are investigated:

- What makes a roof resilient to hurricanes?
- Which roof structures are most common on Sint Maarten?

The literature research will help formulating criteria for a sandwich roof element on Sint Maarten. These criteria will help developing the prototype in the second part of the research, experimental research. While performing the experiments, the use of machines has been minimalized because the objective of this research is to produce elements low tech. It will answer the following sub-questions:

- How to create captured still air in a roof panel with recycled HDPE?
- How to connect a plastic sheet to a cavity layer, which can wind-stand weather conditions?

The hypothesis for this research is that recycled plastic has the potential to make a sandwich panel which comprises of 2 elements. Shredded plastic can form a sheet and a structure that captures air inside. These two elements can be molt together to create a resilient roof (figure 1).

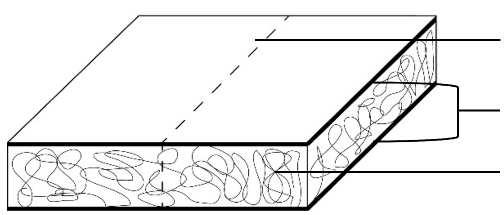


Figure 1. Sandwich panel (Own work)

II. RESILIENCE

3.1. Effects of high winds on roofs

The definition of a hurricane, according to Chambers, is a high wind speed formed by warm, moist air over an ocean (Chambers, 2006). These wind speeds can reach to 252 km/h or higher, known as the highest category 5 (NOAA, n.d.). For roofs these high winds are problematic because flying debris, like a piece of wood, can cause damage, and suction at edges and corners can create a Bernoulli Effect

(Prevatt, 1994). The roofs are pulled upwards because the air pressure drops on the top surface of the roof due to fast moving air across its surface. To add, pressure inside an enclosed building pushes the roof up. A large roof has more surface and therefore has more negative pressure. Wind pressure is highest at ridges, overhangs and eaves because air flow separates at angles. However, overhangs in hot climates like Sint Maarten are crucial to cool the walls and create shade.

The shape of the roof is important for the level of resistance. Pyramid roofs are proven to be the most resilient shape for the Caribbean. It creates less uplift of air because of four sloped surfaces (figure 2). For example, the negative pressure on a gable roof can be 50% greater than those on the hip roof. In addition, Meecham discusses that the performance of a roof under extreme winds relies mostly on the spatial distribution of the pressures relative to the structural framing. In the case of hurricanes as explained by T. Gibbs: God is in the connections (Gibbs, 1994).

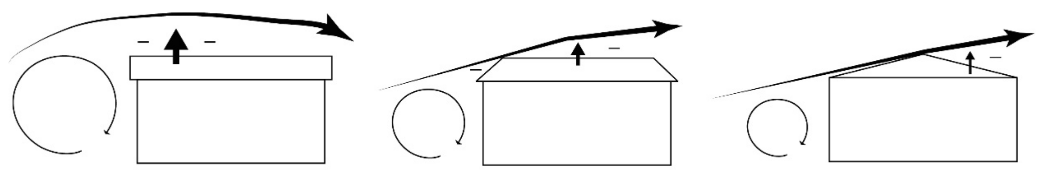
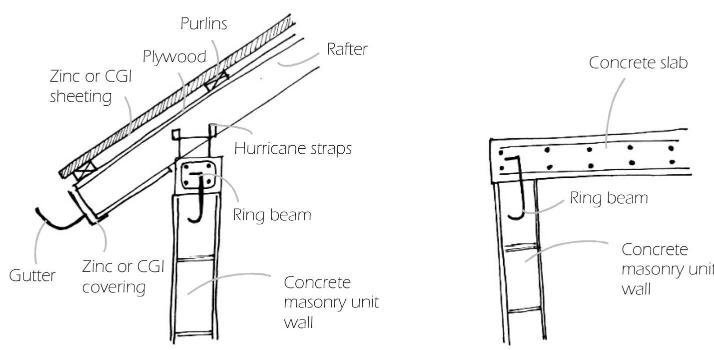


Figure 2. Wind forces on gable, hip and pyramid roof (Own work)

3.2. Roof types on Sint Maarten

The most common roof-shapes in the Caribbean are gable, double lean-to, hip and mono pitched. As discussed earlier, a pyramid roof is the most resilient. The roofs of Sint Maarten are mainly gable and hip roofs and can be categorized in the materials wood and concrete (figure 3). The wooden roof consists of rafters with or without plywood on top, then purlins and roof sheeting. To evenly distribute the forces to the structure, rafters are placed each 600 mm.



Wooden roof with plywood: 0,28 m2 K/W Without plywood: 0,17 m2 K/W	Concrete roof slab: 0,31 m2 K/W

Figure 3. Roof types on Sint Maarten with calculated insulation values (Own work)

During a fieldtrip to Sint Maarten the author has visited 11 houses with Build Change (Build Change, 2015). These houses were low to medium damaged by hurricane Irma. After category 5 hurricane Luis in 1995, word got out to protect yourself by making a concrete roof. Nevertheless, concrete is expensive so people did build back in wood (Arroyo, Corbella, & Poveda, n.d.). From the visited houses, 72% had a gable roof and 82% had a roof with timber structure with CGI (zinc) and T1-11(plywood). The insulation value of a wooden structure (with and without T1-11) and the concrete roof has been calculated. The highest insulation value is of the concrete roof slab, 0, 31 m2 K/W. From the interviews conducted on Sint Maarten it is concluded that electricity is expensive and people therefore leave the air-conditioning off. People are in need of cheaper insulation or ventilation methods for their house.

III. EXPERIMENTAL RESEARCH

4.1. Design criteria

Weather: The roof should serve as protection for future disasters. The wind resiliency of a roof is of big importance on Sint Maarten. A resilient roof includes good connections. The roof should be water resistant as the island copes with +/- 1.000 millimeter rainfall per year (Klimaatinfo, n.d.). Therefore the roof should be watertight water penetration is not allowed. The roof is UV-resistant as the island has yearly 3.000 hours of sun light. Locals experience a hot indoor climate caused by the sun and the use of concrete walls and concrete or metal roofing. The insulation of the roof panel should improve the existing insulation value of concrete slab roofs (thickness 150mm) of 0, 31 K/W m2.

Shape: Pyramid roofs are proven to be the best workable shape in the Caribbean, After all, the plastic roof panels can be placed on pyramid and hip roofs. The roof should have no to minimum seams because they are sensitive for high wind speeds (Meecham, Surry, & Davenport, 1991).

Dimensions: It should be able to lift one roof element by a little crane truck. Current concrete masonry unit walls are 6 or 8 inches (150mm – 200mm) in width (Build Change, 2015).

Strength: The elements should be strong enough to hold 2 people walking on it, because the elements need to be put together on the roof itself. The roof cladding should wind-stand most (>75%) of the flying debris.

Costs: Replacing the existing roof materials for plastic will reduce material costs. Costs which can be invested into the community.

4.2. Process of testing textures

Density	0,95	Gr/cm3
Thermal conductivity	0,42	W(k.m)
E. Modulus	1079	N/mm2
Melting point	125	Celsius
Shrinkage	1.5-4.0	%

Table 1: Characteristics HDPE (Kruse Training inc., n.d.)(van boxtel volkel, elektro & kunststof, n.d.)

In this experimental research the author manipulates the following value: air pockets in panels. Still air is a good insulator with a lambda value of 0,024 W/mK. In comparison, concrete has a lambda of 1, 85 W/mK. Insulation material is based on the principle, the more air it is containing in relation to its own weight, the better it insulates. This concept of still air is also used in plastic bag insulation in Kathmandu (Nienhuys, 2004) and polyethylene insulation (Ingrao et al., 2014).

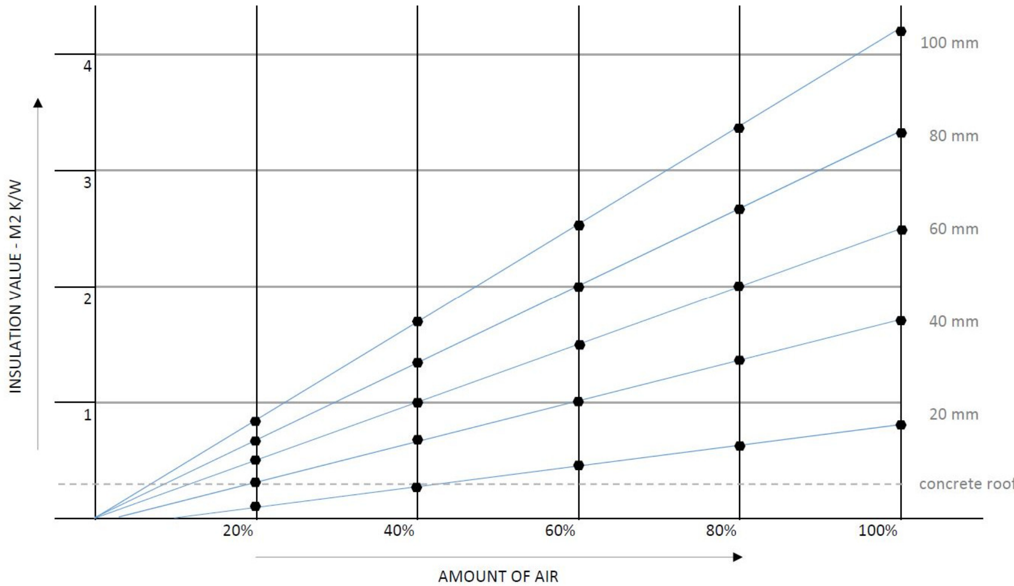


Table 2. Impact of increasing the amount of air in different size of panels on the insulation value (Own work)

To prevent the air to move inside the panel the air should be captured inside a texture. The amount of air that is captured influences the insulation value, seen in table 2. The following tests are done on textures, creating air:

Test 1.1. First a plastic bag (800x1250mm) is melted for 5 minutes in a regular kitchen oven on 170 degrees Celsius. In previous research melting a plastic bag creates air pockets (van den Berg, 2019). On the other hand, the piece is still solid. A further look into how to create more captured air pockets is needed.

Test 1.2. To create more pockets of air, shredded plastic is put in the oven and melted for 5 minutes in a regular kitchen oven on 170 degrees Celsius. Every 5 minutes more plastic is added till one plastic bag is used. The plastic at the bottom layer is pushed by the top layer to a dense structure. HDPE shrinks and forms a dense spider web. The small pieces of HDPE stay up straight because the melting process is shortened. When put longer in the oven, it will melt into one solid piece and this minimizes the amount of air pockets.

Test 1.3. In this test ribbons of 20mm are cut out of the plastic bags which are used to make plastic roles. These will function as a sheer wall seen in corrugated sheets made of Poly Carbonate, used for roofs or walls (GmbH, 2019). These walls are used to distance the two sheets and create air chambers. When the ribbons are heated for 5 minutes in a regular oven on 170 degrees Celsius the plastic hardens. The top and bottom surface is irregular making it hard to connect it to sheets.

Test 1.4. To create a regular distance and surface, plastic is put into a waffle iron between two baking sheets. The temperature of the waffle iron is not known. It creates an irregular surface because of the baking paper which withhold the plastic to fully go into the frame of the iron.

Figure 4. Test 1.1 (Own work)

Figure 5. Test 1.2 (Own work)

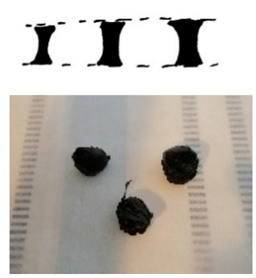


Figure 6. Test 1.3 (Own work)

Figure 7. Test 1.4 (Own work)

These tests show some requirements of the infill of the panel. It should be stiff enough to improve the strength of the panel and create an air cavity. The percentage of air in the cavity has influence on the insulation value, seen in table 2. The calculations of the weight and insulation value can be seen in the appendix. Shredded plastic decreases the strength because the linking surfaces are small. The shape of the inner layer has influence on the amount of plastic that is used and the interface with the top- and bottom sheet.

4.3. Sheet forming

As could be seen in the research of Stijn (van den Berg, 2019), sheets of plastic can be produced in a hydraulic press. A sheet can also be produced by melting the plastic by a hot surface. For example, using an iron or sheets press. A following test is conducted to see if a sheet can be pushed into a frame by thermoforming. Thermoforming is a manufacturing process in which a plastic sheet is heated and molded to a shape using vacuum and compressed air (Bridgewood, n.d.). The material of the used molt is MDF. The design of the mold is carefully chosen looking at the form of u-type sheet pile and the structure of cardboard (Talbi, Batti, Ayad, & Guo, 2009). The structure gives the sheet his strength. The height of 15mm is chosen because of easy manufacturing of the mold during the research. The outer surfaces have draft angles of 4 degrees.

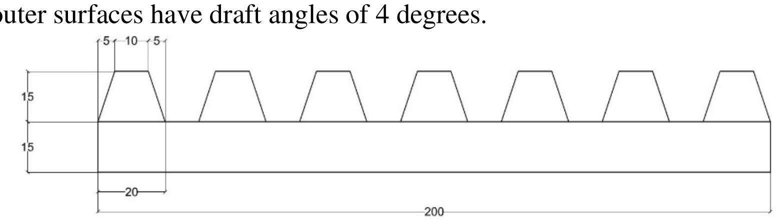


Figure 8. Measurements mold.(Own work)

The vacuum press has a heating element which heats the plastic. For HDPE, 100 seconds of heating is suggested (Formech Inspire, n.d.). When the plastic moves it indicates it is weak. The mold is pressed upwards into the plastic sheet. Meanwhile the plastic is pushed downwards by the vacuum. Because the corners of the mold pressed holes into the plastic it loses the pressure of the air. The mold has been adjusted by making little holes in each row to increase the suction. The machine and molt is then verified by using a sheet of Vivak (figure 11). The sheet of Vivak flowed in the mold. Then, a last sheet of recycled HDPE is tested to thermoform. The plastic sheet burst in the middle, this can be a result of pollution in the recycled plastic. Looking at the formability of the two plastics, Vivak has a higher formability than HDPE (Formech Inspire, n.d.).

Over time a wooden mold will show visible degradation. Moreover, a wooden mold stays cold during the process which can influence the end product. A steel mold is made to see if a HDPE corrugated sheet can be formed in an oven. It is important to make draft angles at each side of the mold, otherwise it can be hard to remove the plastic from the mold (figure 14). The cavity formed by the corrugated sheet has an insulation value of 0,625 m2 K/W. The total weight of the element is 4 kg per m2.

4.4. The connection of HDPE sheets

Because of the high wind speeds on Sint Maarten the connection between inner layer and top layer is of high importance. HDPE can be connected by using a solder shown in figure 15. But with the corrugated sheet it is difficult to reach all interfaces. The sheets are connected by pointing the solder and melt the plastic sheets together. It is not possible to glue HDPE sheets together (AWA Molding, n.d.). Poly Carbonate corrugated sheets are sheets with top and inner layer connected true pushing the plastic through an extruder machine (Perlaplast Kunststofshop, n.d.). These plates can only be manufactured with virgin plastic and not with recycled. Because recycled plastic cannot be extruded in thin layers.

Figure 9. Mold (Own work)

Figure 10. Vacuum machine (Own work)

Figure 11. Vivak (Own work)

Figure 12. Sheet after vacuum press (Own work)

Figure 13. Steel mould. (Own work)

Figure 14. Melted HDPE capturing mould. (Own work)

Figure 15. Solder connection. (Own work)

Figure 16. Final element. (Own work)

4.5. Discussion of Results

To understand the strength of each structure, that influences the insulation value, a pressure test needs to be conducted. Furthermore, an additional research can be done to calculate the precise insulation value.

The tests that are discussed in this paper are made by minimum use of machines. Making the process more reliable on machines will give a consistent result. Nonetheless, this research is focused on the low tech solutions. This way a lot more jobs will be accessible on Sint Maarten.

Further research to polyethylene insulation would be interesting. However this is not stiff, one can look into how to manipulate the characteristics of this material to develop a roof panel. In the end, this paper only discusses a few design possibilities with HDPE.

IV. Conclusions

"What are the potentials of HDPE plastic waste as material for hurricane resilient sandwich panels that improve the insulation value on Sint Maarten?"

HDPE is a plastic that can easily be formed when heated. This short research showed that a lot can be done with limited tools. However, making the plastic sheets has some tool, design and knowledge requirements. From this research the following guidelines for designing with HDPE are formulated:

Melting HDPE

- Plastics need to be divided by sort to overcome quality differences in processing the material.
- HDPE has a melting temperature of 125-135 degrees
- Plastic burns at temperatures above 180.
- The cooling process should be controlled so the element does not bend in undesirable ways.

Mold

- A mold should be heated beforehand.
- Sharp edges in a mold can cause plastic to break, make sure there are no 90 degrees angles.
- The mold should have draft angles because HDPE shrinks 1.5-4.0% during cooling.

Air gap size

- Increasing the airgap size will increase the insulation value. It is needed to analyze the local construction methods to decide which measurement fits.

Amount of plastic versus size of panel

- To produce a sheet with granulate
  Material usage *6 kg/m2*
  Average thickness *4-8 mm*
- To fill a cavity with granulate
  Material usage *412 kg/m3*
- To fill a cavity with shredded plastic bags
  Material usage *30, 25 kg/m3*

Connection options

- HDPE cannot be glued or solder.
- It can be weld. In this case it is important to see if one can reach the seam or melt linking surfaces.
- It can be screwed to each other or to a structure.

In broader aspect HDPE can potentially bring a social-economic waste strategy to Sint Maarten and generate income. The circular process of production and the operators can be seen in figure 17.

Figure 17. Factory on SXM.(Own work)

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FIGURES

1 – 17 Houterman, M.M. (2019). Own work

Tables:

1 – 2 Houterman, M.M. (2019). Own work

APPENDIX A:

Wood without plywood

Zinc lambda: 113

Thickness Zinc: 1, 1 mm

0, 0011 / 113 = 9, 7x10^-6

0, 04 (Rse) + (9,7x10^-6) + 0,13 (Rsi) = <u>0,17 m2 K/W</u>

Wood with plywood

Zinc lambda: 113

Thickness Zinc: 1,1 mm

0,0011 / 113 = 9,7x10^-6 m2 K/W

Plywood lambda: 0,17

Thickness wood: 16 mm

0,016 / 0,17 = 0,094 m2 K/W

Insulation value of air between zinc and plywood: 0,015 m2 K/W

0, 04 (Rse) + (9,7x10^-6) + 0,015 + 0,094 + 0,13 (Rsi) = <u>0,279 m2 K/W</u>

Concrete

Lambda: 1,85
Thickness: 250mm

0,250 / 1,85 = 0,135

0,04 (Rse) + 0,135 + 0,13 (Rsi) = <u>0,305 m2 K/W</u>

APPENDIX B:

Test 1.1

0,060 kg per 20mmx70x80 → 0,000112 m3
0,000112 / 0,015 = 0, 0075 m2
0,060 kg per 0, 0075 m2
7,99 kg per 1 m2

Test 1.2

0,059 kg per 10mmx90x110 → 0,000099 m3
0,000099 / 0,015 = 0,066 m2
0,059 kg per 0,066 m2
0,89 kg per 1 m2

Test 1.3

0,012 kg per 15mmx100x100 → 0, 00015 m2
0,012 kg per 0,01 m2

1,2 kg per 1 m2

Test 1.4

0,029 kg per 10mmx70x60 → 0,000042 m3
0,000042 / 0,015 = 0,0028 m2
0,029 kg per 0,0028m2
10,36 kg per 1 m2

Final element:

0,147 kg per 22mmx175x175*
0,147 kg per 0,03675 m2
3,99 kg per 1 m2
* including one top sheet

APPENDIX C:

Calculation of insulation value of test 1.1-1.4.

	Thickness in m	Lambda	RC in m2 K/W
HDPE sheet	0,005	0,42	0,012
Cavity 100%			0,625
Cavity 80%			0,5
Cavity 60%			0,375
Cavity 40%			0,25
Cavity 5%			0,03125
Surface interior			0,13
Surface exterior			0,04
Total			0,819*
Test 1.1 (5%)			0,22525 *
Test 1.2 (40%)			0,444 *
Test 1.3 (80%)			0,694 *
Test 1.4 (60%)			0,569 *
* Calculation based on a bottom and top sheet of HDPE			

APPENDIX D:

Calculation prototype sandwich panel.

	Thickness in m	Lambda	RC in m2 K/W
HDPE sheet	0,005	0,42	0,012
Cavity	0.015	0,024	0,625
HDPE sheet	0,005	0,42	0,012
Surface interior			0,13
Surface exterior			0,04
Total insulation value			0,819 m2 K/W

APPENDIX E:

	100 %	80%	60%	40%	20%
100mm	0,1,/0,024 = 4,17 m2 K/W	3,33 m2 K/W	2,5 m2 K/W	1,67 m2 K/W	0,83 m2 K/W
80mm	0,08,/0,024 = 3,33 m2 K/W	2,66 m2 K/W	2 m2 K/W	1,33 m2 K/W	0,66 m2 K/W
60mm	0,06,/0,024 = 2,5 m2 K/W	2 m2 K/W	1,5 m2 K/W	1 m2 K/W	0,5 m2 K/W
40mm	0,04,/0,024 = 1,67 m2 K/W	1,33 m2 K/W	1 m2 K/W	0,67 m2 K/W	0,33 m2 K/W
20mm	0,02,/0,024 = 0,83 m2 K/W	0,66 m2 K/W	0,5 m2 K/W	0,33 m2 K/W	0,17 m2 K/W
Lambda air 0,024					

APPENDIX F:

Sheet with granulate

Material usage 6 kg/m2
Average thickness 4-8 mm

To fill a cavity with granulate:

In a tray of 115x115x40mm goes 218 grams of plastic granulate.
0,115 x 0,115 x 0,04 = 0,000529 m3
1/0,000529 = 1.890
1.890 x 218 gram = 412 kg/m3

To fill a cavity with shredded plastic bags:

In a tray of 115x115x40mm goes 16 grams of shredded plastic.
0,115 x 0,115 x 0,04 = 0,000529 m3
1/0,000529 = 1.890
1.890 x 16 gram = 30,25 kg/m3

1 bag is 3 grams.
30250 / 3 = 10.080 bags /m3