Multilayered Lamination for Acoustic Board Manufacturing

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MASTER THESIS

Multilayered Lamination for Acoustic Board Manufacturing

Sound Circularity

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Abstract

Saint-Gobain Ecophon manufactures acoustic ceiling tiles made primarily of glass wool and are interested in exploring the idea of a new manufacturing technique – using thinner layers of material and laminating these together. The possible benefits are, amongst others, the ability to use different kinds of material where they are the most useful, reduced costs, larger amounts of recycled material, less material waste, and more customizability.

The objective is to design concepts and produce prototypes of multilayered panels that could prove to be more beneficial than the current panels, seen to one or more aspects that are presented in this report (cost, mechanical stability etc.). The goal is also to explore if and how the different aspects affect each other and if some of the aspects are possible to predict with calculations.

A pre-study is carried out in order to get a better idea of the current products, materials and testing methods. This also provides the aspects that need to be taken into consideration for the concept development. The concepts are generated and brought into reality by making prototypes in several steps with increasing knowledge regarding the materials used. Each layer, as well as different combinations of layers with or without glue in between the layers, is analyzed using air flow resistance equipment. The Young's modulus for the prototypes is obtained through the use of a quasi-static mechanical analyzer and the sound absorption coefficient curve through the use of an impedance tube.

The results show that consideration of the dominant fiber direction is of importance. Combination of layers with different densities seems promising and incorporation of Refiber board and/or stone wool points to some interesting acoustic properties to use in further development.

Keywords: Acoustic panels, lamination techniques, sound absorption, insulation

Sammanfattning

Saint-Gobain Ecophon tillverkar akustiska takplattor, till största delen gjorda av glassfiberull, och är intresserade av att utforska idén av en ny tillverkningsteknik – att använda tunnare lager av material och laminera ihop dessa. De möjliga fördelarna med detta är, bland annat, att kunna utnyttja olika typer av material där de gör mest nytta, reducera kostnader, ha större mängd återvunnet material, mindre materialspill och mer anpassningsbarhet.

Syftet är att ta fram koncept och producera prototyper av paneler gjorda av flera lager, som skulle kunna visa sig vara mer fördelaktiga än de nuvarande produkterna sett till en eller flera aspekter som presenteras i den här rapporten (kostnad, mekanisk stabilitet etc.) Målet är också att utforska om och hur de olika aspekterna påverkar varandra och om vissa av aspekterna är möjliga att förutsäga med beräkningar.

En förstudie genomförs för att få en bättre förståelse för de nuvarande produkterna, materialen och testmetoderna. Här presenteras också de aspekter som måste tas hänsyn till vid konceptutvecklingen. Koncepten genereras och förverkligas genom tillverkning av prototyper i flera steg, med ökande kunskap om materialen som används. Varje lager, såväl som kombinationer av lager med eller utan lim mellan skikten, analyseras med utrustning som mäter luftflödesmotstånd. E-modulen för prototyperna tas fram genom användning av en kvasi-statisk mekanisk analysator och ljudabsorptionskoefficientkurvor tas fram genom användning av ett impedansrör.

Resultaten visar att det är viktigt att ta hänsyn till den dominanta fiberriktningen. Kombinationer av skikt med olika densiteter verkar lovande och inkludering av Refiber board och/eller stenull kan bidra med intressanta akustiska egenskaper som kan utnyttjas i vidareutveckling.

Nyckelord: Akustiska paneler, lamineringsteknik, ljudabsorption, isolering

Acknowledgments

I want to thank my supervisors Tommy Månsson at Ecophon and Per-Erik Andersson at LTH for their continuous support and encouragement throughout this project. Your feedback has been invaluable, and I have appreciated the efficient communication between us greatly.

A special thank you to Emma Arvidsson at Ecophon, who has taken the time to teach me about acoustics and how to use the testing equipment. I could not have done this without you.

Getting a better understanding for the production of glass wool has been a great help in this project, so thank you Marie Jay and Isover for guiding me through the facilities in Billesholm.

Making prototypes has been a large part of this project, and Borut & Pia at the Design department at Ecophon have made this a breeze. Thank you for your help and flexibility with finding the time to do so.

A general but huge thank you to everyone at Ecophon, and especially those of you involved in the Sound Circularity Project, who have made me feel very welcomed at the company. Thank you for the valuable input and for the interest you've shown in my work.

Lund, March 2019

Angelica Madeland

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1 Introduction

1.1 Background and Objective

Saint-Gobain is a global company that focuses on the design, production and distribution of functional materials within the building industry.

Saint-Gobain Ecophon is a company, stationed in Hyllinge, Sweden, that manufactures acoustic panels for ceilings and walls, but what they are selling is rather the positive working environment that comes from having beneficial room acoustics. The main focus lies on the fields of healthcare, education and workplace, where, as their promise says, Ecophon aims to provide *a sound effect on people*.

Ecophon is actively working with sustainability in several ways. The glass wool in their panels consists of more than 70% recycled glass. The latest generation of the glass wool is bound together with a green binder made from on biobased components and they claim to have the lowest CO2 emissions in the business. One of the most recent projects is called “The Sound Circularity Project” in which Ecophon attempts to create a more circular business model. Old, used or discarded panels can be returned to Ecophon and be made into new panels through one of several different processes depending on the quality of the panel.

The objective is to design multilayered panels that are more beneficial than the current panels, seen to one or more aspects covered in this report. The goal is also to explore if and how the different aspects affect each other and if some of the aspects are possible to predict with calculations.

The Master Thesis project in this report is a “spin-off” from the Sound Circularity project. The incorporation of Refiber board, which is almost completely recycled from acoustic products, as one of the layers is one example that will be taken into consideration. However – the introduction of the lamination technique is happening with or without the products from the Sound Circularity project and other material combinations are also investigated.

1.2 Disposition

1.2.1 **Chapter 1 - Introduction**

The introduction provides background information about the company and the project, as well as a description of the disposition used throughout this report.

1.2.2 **Chapter 2 - Method**

Chapter 2 describes the methods used in the project, the general structure of the workflow and the limitations/delimitations that apply.

1.2.3 **Chapter 3 - Pre-study**

A pre-study is carried out to generate a better understanding of what the common problems are and what aspects need to be taken into consideration when designing the product. The current materials and testing methods are presented here.

1.2.4 **Chapter 4 - Concept development**

Chapter 4 presents the main theoretical concepts that have been generated from internal and external sources of inspiration.

1.2.5 **Chapter 5 - Prototypes**

Chapter 5 describes the process of making the prototypes and presents the different waves/generations of prototypes made throughout this project. Evaluations after a completed wave of prototypes are also presented here.

1.2.6 **Chapter 6 – Results**

Chapter 6 presents selected results from the measurements and tests done for the final prototypes and their sub-layers.

1.2.7 **Chapter 7 – Discussion and Conclusions**

The results are discussed and some conclusions about recommended concepts for future development and production are reached.

1.2.8 **Appendix A – Time Plan**

The project plan and outcome is presented here.

1.2.9 **Appendix B – Workshop**

The planning, execution and evaluation of the workshop held at Ecophon is presented here.

1.2.10 **Appendix C – Detailed Results**

The detailed results from the material testing using *Air Flow Resistance*, *Quasi-static Mechanical Analyzer* and *Impedance Tube* equipment are presented here.

2 Method

The methods used to achieve the objective is presented below. Inspiration is taken from the established product development process taught at LTH, as well as from the process used at Saint-Gobain.

2.1 Methods

Ecophon has a wide variety of products that all have different requirements. These must be reached, but it is unnecessary for them to be overly exceeded. By investigating interesting new materials and incorporating them as layers in the design and by making physical prototypes that can be subjected to testing it can be determined what kind of product, within Ecophons product line, that can be substituted for the new laminated design, alternatively be presented as a new product.

The innovation and product development process from ideation to realization used by Ecophon can be seen in figure 2.1 below. This thesis will focus on the first part, circled in green, from the ideation through the preliminary investigation and ending up in the concept validation stage. [1]

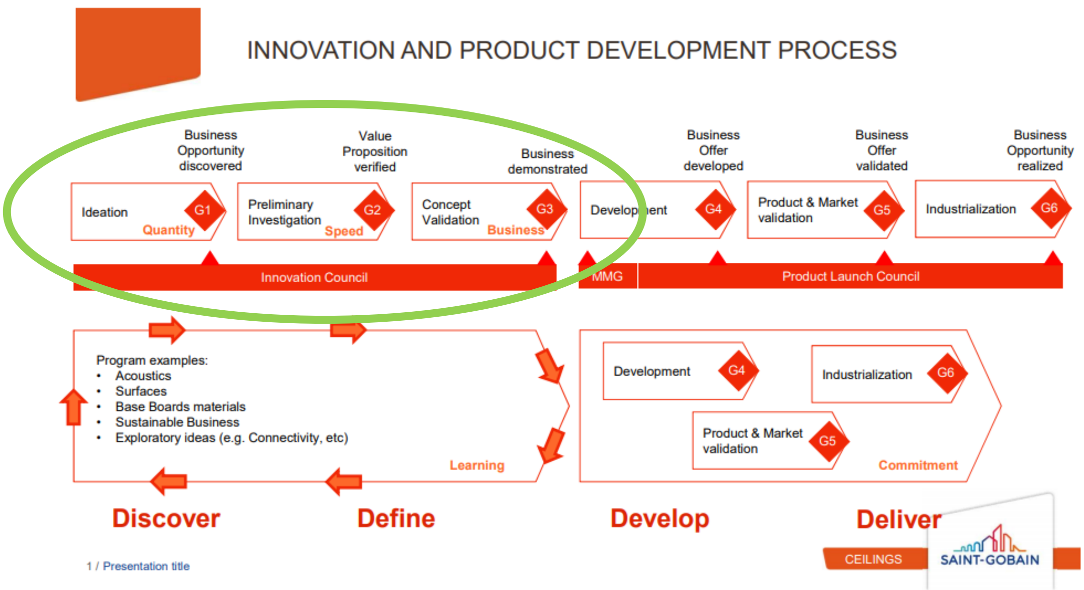

Figure 2.1 Ecophon innovation and product development process. [1]

Inspiration is also taken from the familiar Ulrich and Eppinger product development process which is being taught at LTH. This process is suitable mainly for more advanced products [2, p.30] but parts of it can be applied on a product such as this. The generic product development process as presented by Ulrich and Eppinger can be seen in figure 2.2 below.

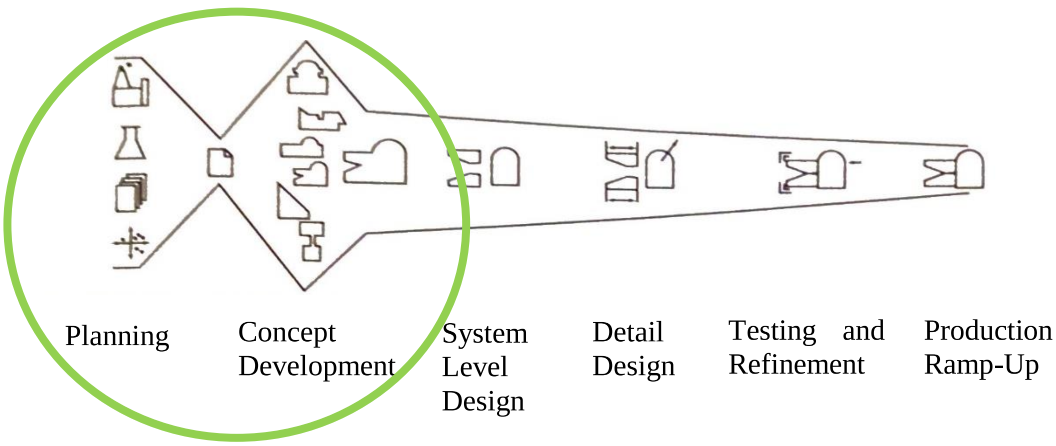

Figure 2.2 The generic product development process by Ulrich and Eppinger. [2, p.45]

This project is confined to the first two stages in this process. These are described to include the following sub-steps:

- **Planning**
  - **Marketing**
    - Articulate market opportunity
    - Define market segment
  - **Design**
    - Consider product platform and architecture
    - Assess new technologies
  - **Manufacturing**
    - Identify production constraints
    - Set supply chain strategy
  - **Other Functions**
    - Research: Demonstrate available technologies
    - Finance: Provide planning goals
    - General Management: Allocate project resources.

- **Concept development**
  - **Marketing**
    - Collect customer needs
    - Identify lead users
    - Identify competitive products
  - **Design**
    - Investigate feasibility of the product
    - Develop industrial design concept
    - Build and test experimental prototypes
  - **Manufacturing**
    - Estimate manufacturing cost
    - Assess production feasibility
  - **Other Functions**
    - Finance: Facilitate economic analysis
    - Legal: Investigate patent issues

The steps marked in grey will not be explored in greater detail.

The general workflow of the concept development process that will be followed in this project is captured in figure 2.3 below.

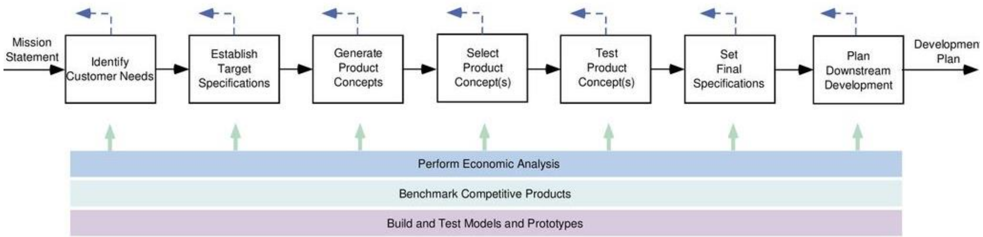

Figure 2.3 The concept development process by Ulrich and Eppinger. [2, p.140]

A pre-study is carried out where information about the different design aspects that are taken into consideration are identified, as well as the market segment that Ecophon is directed towards. A greater understanding for the product platform, current materials and current testing methods is developed and presented to the reader. Basic technologies of lamination are explored to see if there are any limitations before the concepts are developed.

Concepts are developed and evaluated – narrowing the ideas down to more feasible ones in different steps. Prototypes are also made and evaluated in parallel with the concept development.

The final round of prototypes is made with known materials and are tested using the current testing methods. These results are analyzed and compared with some of Ecophon’s current products.

2.2 Limitations

The nature of the materials used in the product, combined with the laminated design of the product makes it difficult to analyze using standard calculations and computer aided analyses such as the finite element method, where both the material properties and the boundary conditions between the layers are unknown. Therefore, the making of physical prototypes will provide the information needed.

2.3 Delimitations

The larger project which this Master Thesis is a part of consists of the introduction of a new way of manufacturing acoustic boards through lamination. This includes, but is not limited to:

- Material input
- Machine specifications
- Lamination parameters and
- Product output

This thesis, which only contributes to a part of the larger project, will focus on the "product output". This means that some of the steps presented in the planning and concept development stages from Ulrich and Eppinger will not be explored in greater detail (marked in gray).

3 Pre-study

The product that Ecophon manufactures can seem very simple, however, a lot of things are taken into consideration when designing the product. The following chapter gives the reader a crash course into what these aspects are.

3.1 Design Aspects

The following is taken from source [4].

The size and shape of a room and the choice of interior materials and furniture in it affect the perception of the sound. When the sound waves encounter a wall one/several of four things can happen:

- Transmission: the sound goes straight through the wall.
- Reflection: the sound "bounces" off the wall.
- Absorption: the energy of the sound gets absorbed in the wall in the form of thermal energy.
- Diffusion: the sound scatters off the wall in multiple directions.

Background noise, late reflections and reverberations increase the perception of "bad sound".

The goal is not to absorb as much sound as possible, but to create an environment where people feel comfortable and able to focus on the tasks at hand. In a lecture room, for example, the sound coming from the lecturer needs to be able to travel all the way to the back of the room. If not – the message will not get through to the students or the lecturer will strain his/her voice in order to make sure that it does. The higher spectra of frequencies contain the information of speech, music and sounds from nature that are pleasant and expected for the receiver, whereas the lower spectra is more unsettling. Unfortunately, it is easier to absorb the higher frequencies than the lower ones with a longer wavelength that often passes right through a porous material. In order to absorb lower frequencies, it is possible to use "membrane absorbers" or "resonance absorbers" to transform the sound energy into kinetic energy.[3] The Eigen frequency of the boards can also change the properties of the sound absorption for certain wavelengths.

Diffusors - objects that scatter the sound waves in a room and reducing direct echoes and reverberations - can be designed to create a positive sound environment. They can angle the sound either towards the ceiling to be absorbed, or towards the back of the room to increase susceptibility.

The ceiling can be subjected to different kinds of contamination, often because of the ventilation in the room, and therefore needs to be able to be cleaned repeatedly throughout its lifetime and/or be resistant to stains. Different products offered by Ecophon provide different levels of cleanability depending on where the product is to be used.

The surface of the product is also responsible for the perception of the lighting of the room. If the ceiling is brightly colored (white) and provides a good amount of scattering/diffusion and reflection of the light shone on it, the comfort level, as well as the energy efficiency, is increased (due to lesser need for complimentary lighting).

The ceiling also often covers aesthetically displeasing installations such as ventilation, pipes and cords. These need to remain accessible for maintenance and the boards might need to be constructed in such a way as to be dismountable without harming the product.

The product also must be resistant to environmental effects, mainly from moisture, heat and microbiological activity. The product is tested in accordance with ISO 4611 when it comes to moisture, and in accordance with ASTM G 21-96 when it comes to microbiological growth. Criteria vary for different products offered by Ecophon depending on the intended applications.

When the products are in place it is important that emissions from the products in the form of ammonia, formaldehyde, volatile organic compounds, particles and fibers are low. Today Ecophon’s products meet the strictest requirements set up by the Danish Indeklima Mærkning (DIM). Some products are intended for use in cleanrooms and therefore need to live up to the US Federal Standard 209E and EN ISO 14644-1.

To ensure a pleasant working environment the product should not give off any smell in a disturbing quantity.

The materials used in the product should be environmentally sound. The glass fiber wool used in the boards today is made of over 70% recycled glass. The thickness and weight of the boards affect resource management when it comes to materials and transportation, and it also affects the ease of installation. The lifespan of the product should be on par with the building.

One of the most critical aspects is that of fire safety. The ceilings are designed not to noticeably contribute to fire development and smoke production, not fall down during the time when evacuation and rescue operations can take place, and prevent involvement of the material behind the panels in the fire, to prolong the time to flashover. This is evaluated in accordance with Euroclass standard EN 13501-1 and is performed by RISE (Research Institute of Sweden)

The boards need to be structurally adequate to withstand the mechanical stresses and strains caused by its own weight, the installation process and the possible additional fittings and armatures put in place (no more than a maximum of 300-500 g, depending on the type of product). Some of Ecophon's products are also to be impact resistant in accordance with SS-EN 13964.

To be able to fit spotlights and the like into the boards, they might have to be easily cut/altered.

As always, the cost and price of each product is of importance both for the customer and for Ecophon. To be able to finally sell the product it must be successfully marketed to the customers.

In conclusion, the following needs to be considered for a complete product:

- The acoustic properties
- The hygienic properties
- The light scattering properties
- Dismountability
- Resistance to moisture, heat and microbiological activity
- Indoor air quality
    - Harmful emissions from the product
    - Smell of the product
- Environmental aspects
- Fire safety aspects
- Mechanical properties
- Ability to make alterations to the product on site
- Cost and marketability

3.2 Current materials

The main component in the products Ecophon is manufacturing today is, as stated earlier, glass wool. This is manufactured at Isover in Billesholm, not far from Hyllinge. Isover is also a company in the Saint-Gobain group. The glass wool is manufactured using the process that is illustrated in figure 3.1 below. [5]

Figure 3.1 Schematic of the manufacturing process for glass wool. [5]

1. The batch is made, consisting of mainly recycled glass, sand, limestone and soda-ash in measured proportions.
2. The mixture is melted in a furnace, exceeding 1400 degrees C.
3. The liquid glass reaches a fiberizing machine – very similar to what is used when making cotton candy. The melt is propelled through tiny holes measuring only 1 mm in diameter. This creates the fibers which are then coated with a binder and formed into a blanket.
4. The blanket passes through a curing oven and is formed into shape. The density and thickness of the final product depends on how much the blanket is compressed in this stage.
5. The cured product is cut into the appropriate width and length. This is the product that Ecophon is using as their baseboard.
6. The boards are packaged (not rolled as the image shows, just laying on top of one another)
7. The product is made ready for delivery.

The manufacturing process causes the product to have anisotropic (direction dependent) properties. The "blanket" is made up of layers upon layers of glass fibers, making it easier to pull apart using a force that is perpendicular to the layers than one that is parallel with the layers. The fibers are also oriented more in line with the direction of the conveyor belt´s movement and is therefore easier to bend around the directional axis than it is around the cross-directional axis.

The acoustic properties of the board also depend on the direction of the fibers. If the fibers are perpendicular to the surface it allows for less air flow resistance, which in turn indicates more sound absorption. One way to achieve this is by crimping the glass wool – creasing it in the manufacturing process makes the fibers go from parallel with the surface to a more perpendicular, although wavy shape, see figure 3.2 below.

Figure 3.2 Cross section crimped glass wool.

Plaster board is used as a sound insulating material on the back of a product called “Combison”.

The previously mentioned Refiber board is made of recycled material and is currently being developed. The smoothness of the surface is being improved but is thought of in this project as being somewhat rough or bumpy.

3.3 Possible Materials

The companies within Saint-Gobain are producing materials used for the building industry and could therefore be suitable in this application as well. These materials should already live up to the standards set by/for the building industry and thereby, perhaps, meet the requirements of some of the aspects presented earlier. Several companies are looked into and are presented in table 3.1.

Table 3.1 Materials produced within Saint-Gobain

Material	*Producing Company within SG*	*Comments*
Glass wool board	Isover	Used today, Sound absorbing [5]
Loose glass wool	Isover	"Waste product" [6]
Polystyrene/Polyurethane	Isover	Expanded/extruded [7]
Stone wool	Isover, Eurocoustic	Sound absorbing, already used for the same application [8] [9]
Plasterboard	Gyproc	Sound insulating [10]
Industrial fabrics *Non-woven/ woven*	Adfors	Strengthening. Available with adhesives already applied to the fabrics [11]
PIR-foam	Celotex	Used for insulation. Rigid and fire resistant [12]
Wood products	Decoustics	MDF and veneer. Already used for the same application [13]
High performance polymeric films	Chemfilm	FEP, PFA, PTFE, UHWM PE etc. [14]

These materials are considered when developing the concepts. Glass wool is commonly used as a thermal insulator, which is also true for the polystyrene/polyurethane, PIR-foam and stone wool, the idea being that these might also have interesting acoustic properties. However, incorporating polymers in the products might not be of interest seen to the environmental aspects of mixing completely different kinds of materials together. PIR-foam has also been studied to release considerably higher levels of toxic products when exposed to higher temperatures and flames. [15]

3.4 Lamination Techniques

Since the lamination machine is yet to be specified in the project it is possible to explore several ways of laminating. In order to get an idea of what kind of materials are feasible to use when it comes to the lamination process, different lamination techniques have been researched and the basic concepts are presented below.

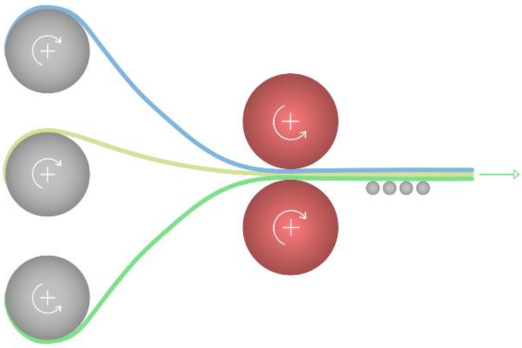

Figure 3.3 Lamination using flexible materials.

One of the most common ways is shown in figure 3.3 above. All materials that are being laminated together are flexible enough to be stored rolled up in long sheets. The materials pass through the laminator which uses pressure and/or heat to bind the layers together. The bonding can be caused by some of the material melting together, or by having a layer of adhesive coated on one or more of the layers. This process allows for continuous production of the laminate. The technique is often used for lamination of polymer-coated fabrics, packaging etc. [16]

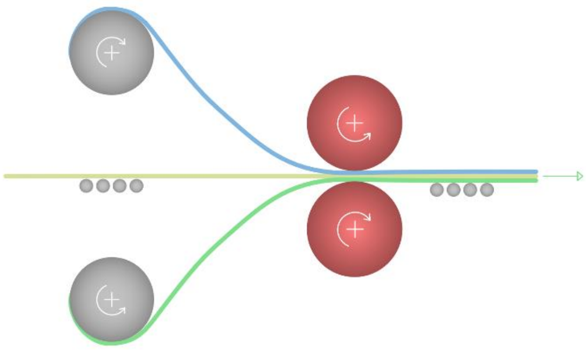

Figure 3.4 Lamination using both flexible and non-flexible materials.

Using the technique shown in figure 3.4 above it is possible to incorporate stiffer and thicker materials as one of the layers. This allows for a semi-continuous production of the laminate, depending on the possible size of the stiffer material. This technique is used in Ecophon's production today when applying surface layers to the baseboard.

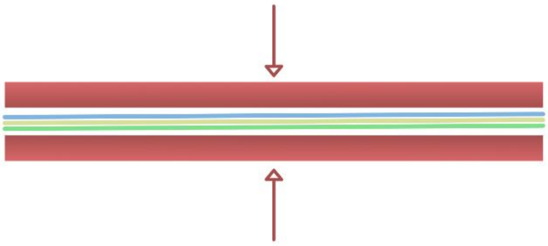

Figure 3.5 Lamination using sheets of material.

Lastly, figure 3.5 shows a lamination technique using sheets of material stacked on top of one another. The laminate is exposed to pressure and heat in a hot press, bonding the layers together. This technique is used for making plywood and other laminates where the materials do not allow for excessive bending. [17]

Considering these three lamination techniques there seems to be few constrictions to what kind of materials that are possible to use.

3.5 Current Testing Methods

The products are tested with respect to acoustics, fire/combustibility, emissions and climate. More information can be found in table 3.2 below.

Table 3.2 Testing equipment and methods

Product/ raw material	***Testing method***	***Property***
Wool layer (glass, stone, Refiber board)	Loss on Ignition	Fire
All layers	Thermogravimetric Analysis	Fire
Adhesives	Thermogravimetric Analysis	Fire
All layers except the surface layers	Air Flow Resistance	Acoustics
All surface layers	Air Permeability	Acoustics
Final product	Air Flow Resistance	Acoustics
Final product	Bending test	Mechanical
Final product "Solo"	Pull-out test	Mechanical
Surface layer	-	Aesthetics

3.5.1 Air Flow Resistance (AFR)

The air flow resistance is an important parameter that is used to describe porous materials in the aspect of its acoustic properties. This is done in accordance with ISO 9053: *Acoustics – Materials for acoustical applications – Determination of airflow resistance.* A specimen is cut out using the die seen in figure 3.6 t.t.l below. This ensures a precise diameter of the specimen such that it provides a tight seal when placing it into the AFR equipment seen in the figure 3.6 t.t.r below. The specimen is weighed, and the thickness is measured. This provides the information needed to get a value for the density of the material.

Figure 3.6 T.t.l: Die punch used to get the appropriate size of the sample. T.t.r: AFR measuring equipment Nor1517A from Norsonic. Image taken from [18]

The specimen is placed into the AFR machine where a piston creates an oscillating movement that causes an alternating flow of air at a frequency of 2Hz through the material. The pressure modulation inside the cylinder is measured by a condenser microphone connected to a sound analyzer which displays the air flow resistance directly in the unit (Pa*s/m). Dividing this value by its thickness provides the resistivity in the unit (Pa*s/m^2). The resistivity is what can be compared between different materials. [19]

The resistivity of a standard low-density baseboard is around 37 kPa*s/m2, medium-density is around 52 kPa*s/m2 and high-density is around 84 kPa*s/m2.

Each sub-layer is first tested on its own and later also as combined layers with or without glue in between the layers. The results from the sub-layers are used to create a theoretical combination value that can be compared to the measured result. This can be used to indicate whether the end result will be easy to predict or not.

3.5.2 **Quasi-static Mechanical Analyzer (QMA)**

Using an automatic quasi-static mechanical analyzer, it is possible to get values for Young’s modulus for poroelastic materials in accordance with the ISO 18437-5 standard. Compression tests are performed at low frequencies where the interstitial air has a limited (ignorable) effect on the elastic parameters. When used on anisotropic materials, as in this case, the properties found are the apparent axial elastic properties. The testing equipment is shown in figure 3.7 below. A vibrating plate is fixed to a shaker and an accelerometer measures the vibrations of the plate.

This vibration is converted into a displacement using software. The sample is harmonically compressed by the vibrating plate against a rigid motionless plate. The reaction force is measured by a force transducer that is placed between the rigid plate and the rigid frame of the machine. This allows the software to calculate the transfer function (reaction force / displacement) which yields the mechanical impedance/rigidity of the tested sample. [20]

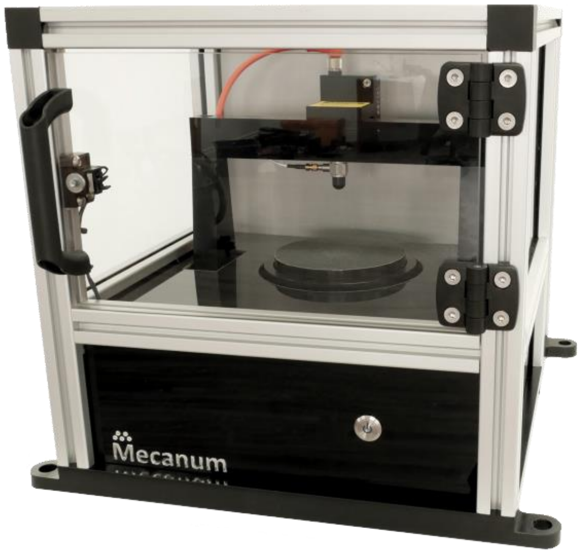

Figure 3.7 Mecanum Automatic QMA testing equipment. [21]

3.5.3 Impedance Tube and TubeCell

An impedance tube, seen in figure 3.8, can be used to characterize several different acoustical properties in a sample. In this case it is used to get values of the sound absorption coefficient. This parameter indicates how much of the frequency wave energy is absorbed in the material, and how much is reflected back. This is done in accordance with ISO 10534-2. [22]

Figure 3.8 Impedance tube from Mecanum. [23]

The impedance tube requires an interpretation software called TubeCell. This allows for calibration of the equipment and plotting of the data. To measure surface properties, such as the sound absorption, two microphones are needed. The schematic of the setup can be seen in figure 3.9 below.

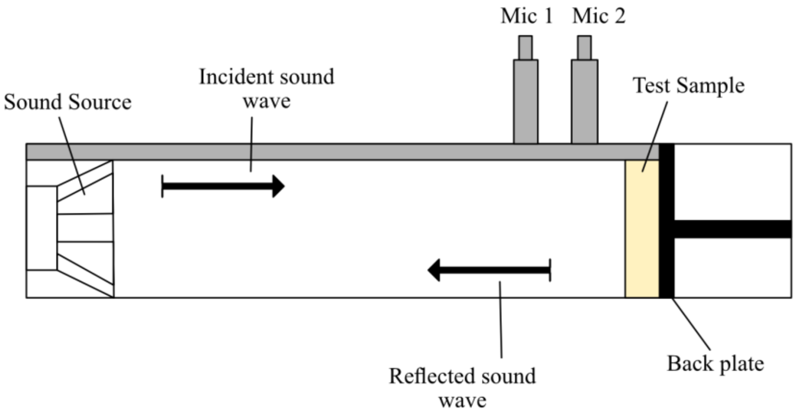

Figure 3.9 Schematic of the impedance tube setup. [24]

The samples are prepared for testing by cutting out smaller cylinders from the samples previously used for the AFR and QMA testing, using the metal cylinder seen in figure 3.10 below.

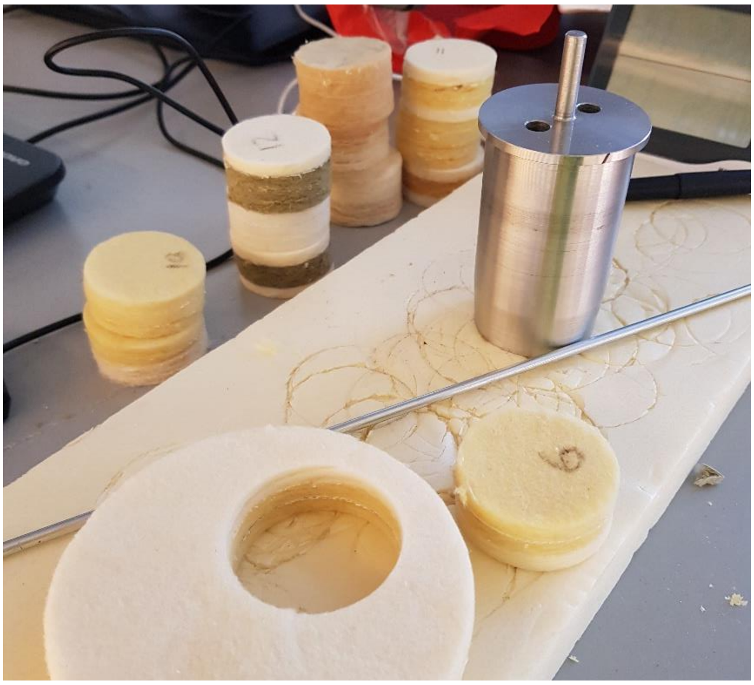

Figure 3.10 Sample preparation for the Impedance tube testing.

A typical result for porous materials such as glass fiber wool can be seen in figure 3.11 below. As stated earlier in this chapter, lower frequencies are more difficult to absorb, and this is confirmed by this graph. The “dip” in the curve corresponds to the materials eigen frequency, meaning it goes into a resonance state and does not absorb that frequency as well as what the trend would have you predict.

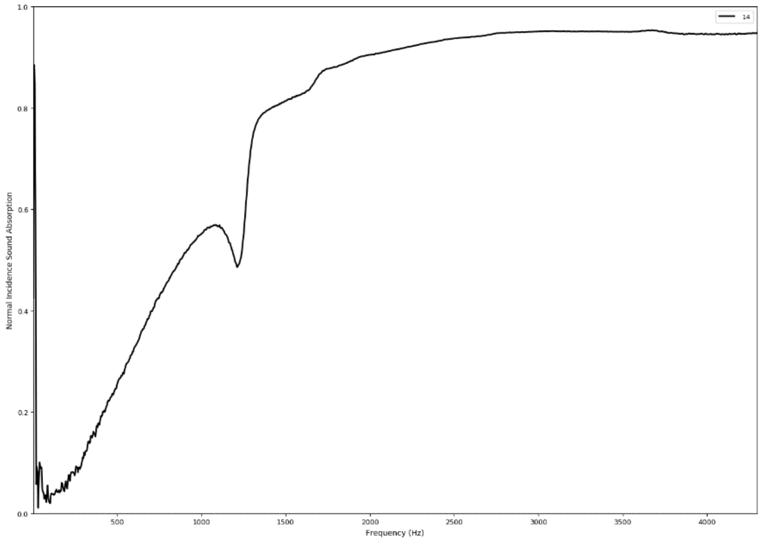

Figure 3.11 Typical sound absorption curve for glass fiber wool.

3.5.4 **Climate Chamber**

The product is placed into a chamber with a consistently high temperature and humidity for a prolonged period of time. The damage done to the product after such a test can be seen in figure 3.12 below. The amount of time needed for this test could not be found in the timeframe for this thesis project.

Figure 3.12 Acoustic board after being subjected to a warm and humid environment for a prolonged period of time.

4 Concept Development

Main concepts for the new products generated from internal and external sources of inspiration. Acoustic behavior is difficult to predict. These general concepts are therefore made to get an idea of the structures that would be interesting to explore further. Chosen concepts are used to create prototypes that can later be evaluated by material testing.

4.1 General Concepts

Figure 4.1 shows how the following concepts in figures 4.2-4.9 are meant to be interpreted.

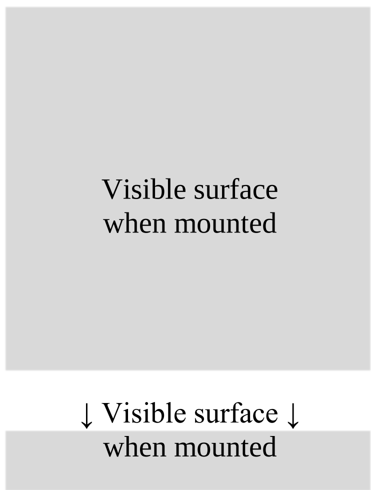

Figure 4.1

Concept 1:
Using the developed Reboard (or Refiber board) as a middle layer and virgin material as the visible surfaces. See figure 4.2.

Figure 4.2 Concept 1

Concept 2:
Using the developed Refiber board or other material as a thicker middle layer and virgin material as the visible surfaces. See figure 4.3.

Figure 4.3 Concept 2

Concept 3:
Frame of virgin material filled with rectangular rods or Reboard. Thin virgin material as the visible surfaces. See figure 4.4.

Figure 4.4 Concept 3

Concept 4:
Reboard as the middle layer, wider surface layers with higher mechanical properties could be laminated to directly get the desired edge profile on at least 2 of the edges without milling. See figure 4.5.

Figure 4.5 Concept 4

Concept 5:
Strengthening fabric or other performance enhancing material just below the visible surface. See figure 4.6.

Figure 4.6 Concept 5

Concept 6:
Loose material inside a frame. Thin virgin material as the visible surfaces. See figure 4.7.

Figure 4.7 Concept 6

Concept 7:
Reboard or other anisotropic material laminated perpendicular to each other in several layers to increase the stiffness in all directions. See figure 4.8.

Figure 4.8 Concept 7

Concept 8:
Harder material on the back of the board to achieve sound insulation. See figure 4.9.

Figure 4.9 Concept 8

4.2 Evaluation of the General Concepts

The reason for using a frame of virgin material in concepts 3 and 6 is to ensure good and trustworthy results from milling/painting/other manufacturing processes. This does, however, raise the question of how this frame is manufactured. Unless there is a need for smaller products that would allow the material within the frame to be used in a good way, there seems to be a lot of material waste. There is also the aspect of scaled up manufacturing to take into consideration, where these concepts seem more complicated to manufacture in greater quantities. These concepts are not explored further in this project but could be interesting to take another look at in the future.

Using recycled material or other thicker material in the middle, and virgin surfaces, as in concepts 1, 2 and 4, could prove very beneficial, both from an environmental perspective, and from an economical perspective. This could further increase the attractiveness of the company and give Ecophon a competitive edge. These will be explored further. (See later concepts “10Cr10s”, “GwSwGw”, “GwCGw”, “GwRP”, “GWR1” and “GWR2”.)

Incorporating a performance enhancing material, as in concept 5, perpendicular arrangement, as in concept 7, and insulating materials, as in concept 8, will also be explored further. (See later concepts “PB,4”, “GB,4”, “55IIII”, “55ILIL”, “GwSw”, “GwSwGw”, “GwP”, “GwRP”, “GwAGw1”, “GwAGw2”, “Gw1”, “Gw2”, “GwA” and “GwAGwSwAGwCA”.)

To allow for better comparisons, more efficient prototype-making and less material waste it is decided to only make the baseboard material, meaning the surface materials will be taken out of the equation for the final prototypes.

5 Prototypes

The following chapter explains the process of making the prototypes at the facilities at Ecophon and presents the different waves/generations of prototypes made throughout this project. Evaluations after a completed wave of prototypes are also presented here.

5.1 Initial Prototype

The first question that needs to be answered is: Is it possible to glue several layers of glass wool together?

5.1.1 Making the first prototype

From previous experiments at Ecophon involving sawing boards horizontally, thin boards of different thicknesses, seen in figure 5.1 below, are available.

Three of these layers, each measuring about 5 mm thick, are sprayed with a water-based glue that is usually used in the process of adhering the surface layer to custom-made products of varying shapes and sizes.

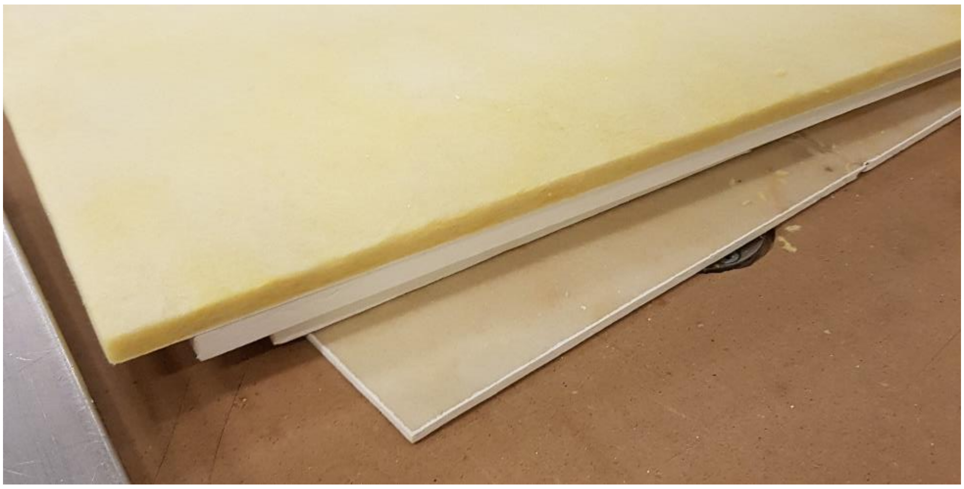

Figure 5.1 Horizontally cut baseboards.

The layers are placed on top of each other and placed into the lamination machine, seen in figure 5.2 below. The glue dries quickly with the help of heat and pressure.

Figure 5.2 Small scale lamination machine used for custom made products.

The edges of the laminate are trimmed using a band saw, seen in figure 5.3 below.

Figure 5.3 Band saw rig

The laminate is again sprayed with glue and finished off with a surface layer of “staple fibers, 50g” and glass fiber weave before being placed in the lamination machine yet again. The surface layer is larger than the glass fiber laminate and is therefore trimmed off using a blade cutter. Figure 5.4 below shows the laminate after the edges have been trimmed.

Figure 5.4 Finished prototype

The edges can be painted using standard methods such as applying thick paint by hand with a paintbrush or using spray/airbrushing. This is supposed to be done before laminating the surface layer to get crisp edges, but due to the amount of time the paint takes to dry this is done, in this case, afterwards and attempted only on one edge using a brush. When the paint is dry the edge can be sanded down and painted again repeatedly to get a nice finish. For this first prototype the edge was only painted and sanded down once to see if the different layers affect the appearance of the edge after painting. Figure 5.5 shows the close-up of the unpainted edge.

Figure 5.5 Close-up of the unpainted edge for the initial prototype, ca 10 mm thick

5.1.2 Evaluation of the first prototype

The different layers are almost nondetectable with the naked eye when looking at the trimmed edge, see figure 5.5 above. When trying to pull apart the layers it seems that the glued interface is at least as resilient as the wool itself, even with this preliminary choice of glue.

5.2 Further prototypes

Using the same approach as with the initial prototype the following prototypes are made.

5.2.1 Phenolic Binder, 4 layers - "PB, 4"

Four layers of horizontally cut glass wool with phenolic binder are laid on top of each other with the dominant fiber orientation rotated 90 degrees in relation to the next layer. The close-up of the unpainted edge can be seen in figure 5.6 below.

- Standard surface layer
- Staple fibers
- 10 mm thick glass wool with phenolic binder
- 10 mm thick glass wool with phenolic binder
- 15 mm thick glass wool with phenolic binder
- 5 mm thick glass wool with phenolic binder
- Staple fibers

Figure 5.6 Close-up of the unpainted edge for prototype "PB, 4" ca 40 mm thick

5.2.2 **Green Binder, 4 layers - “GB, 4”**

Four layers of horizontally cut glass wool with green binder are laid on top of each other with the fiber orientation rotated 90 degrees in relation to the next layer. The close-up of the unpainted edge can be seen in figure 5.7 below.

- Staple fibers
- 10 mm thick glass wool with green binder
- 5 mm thick glass wool with green binder
- 5 mm thick glass wool with green binder
- 10 mm thick glass wool with green binder
- Staple fibers

Figure 5.7 Close-up of the unpainted edge for prototype “GB, 4”, ca 30 mm thick

5.2.3 **Crimped Sandwich**

A thicker board of crimped glass wool is sandwiched between two layers of horizontally cut glass wool with phenolic binder. The close-up of the unpainted edge can be seen in figure 5.8 below.

- Staple fibers
- 10 mm thick glass wool with phenolic binder
- Staple fibers
- 20 mm thick glass wool with phenolic binder
- 10 mm thick glass wool with phenolic binder
- Staple fibers

Figure 5.8 Close-up of the unpainted edge for prototype "Crimped Sandwich", ca 40 mm thick

5.2.4 **Evaluation of the second round of prototypes**

All of the prototypes made in this round seem relatively sturdy and the adherence between the layers, even with the increased total thickness of the prototypes, seems to be appropriate. The sandwiched crimped glass wool bonded well to the laminar glass wool and provided a nice, even surface to the prototype. It is decided to continue making prototypes with better known parameters to arrive at a more accurate evaluation, but the results from this round appears to be promising.

5.3 Final Prototypes

The next round of prototypes requires known materials with determined/ determinable properties. The material is gathered at Ecophon and brought to Isover in Lübz, Germany, to be horizontally cut into approximately 5 mm slices. Each type of material is tested using Air Flow Resistance equipment described earlier in this report. The detailed results can be found in Appendix C. After each layer has been tested, combinations of the layers are also prepared and tested, se figure 5.9 below.

Figure 5.9 Combinations of 5 mm layers prepared for AFR-testing

The prototypes were then glued together as 600 by 600 mm boards in the same way as described earlier in this chapter. The adhesive used was substituted for what is used in the industrial production today. The amount of adhesive used is about 1.4 grams / square meter.

Below follow explanations of the prototypes made, together with an image of the cross section of the prototype. Most of them are made of four layers, adding up to about the same thickness to more easily compare the different results. The prototypes are named in a way to make it possible for the reader to more easily keep in mind which is which when looking at the results. The names follow the order of material appearance through the cross section, where **Gw** = Glass wool, **Sw** = Stone wool, **A** = Advanced material (Tedlar or glass fiber weave), **C** = Crimped glass wool, **P** = Plasterboard and **R** = Refiber board. If two prototypes follow the same order, these are separated by a number at the end. The first two prototypes presented below are exceptions to the rule. By "IIII" refers to the layers being stacked with the dominant fiber direction oriented the same way, meaning parallel. "ILIL" instead refers to the layers being stacked with the dominant fiber direction being rotated 90 degrees between each layer, meaning perpendicular.

Figure 5.10 Prototype "55IIII"

Prototype 55IIII, seen in figure 5.10, is made up of 4 layers of glass wool where the dominant fiber direction in each layer is oriented the same way. This prototype is made for comparison in the tests that follow.

Figure 5.11 Prototype "55ILIL" / "Gw1"

Prototype 55ILIL, seen in figure 5.11, is made up of 4 layers of glass wool where the dominant fiber direction is rotated 90 degrees for each layer. This prototype is made for comparison in the tests that follow.

Figure 5.12 Prototype "Gw2"

Prototype Gw2, seen in figure 5.12, is made up of 4 layers of glass wool. 2 with high-density, top and bottom layer, and 2 with low-density, in the middle. This prototype is made for its potential in cost and density reduction while maintaining nice and even surfaces and visible edges. Some soundtrap possibilities.

Figure 5.13 Prototype "GwA"

Prototype GwA, seen in figure 5.13, is made up of 4 layers of glass wool, two high-density on top, followed by two low-density on the bottom, and one layer of Tedlar foil, seen as a very thin layer on the bottom.

Figure 5.14 Prototype "GwAGw1"

Prototype GwAGw1, seen in figure 5.14, is made up of 3 layers of glass wool, 2 of lower density and 1 of high-density seen at the bottom, and 1 layer of glass fiber weave "Super G" that can be seen as the "dashed line" between the low-density layers. This prototype is made for its potential in strengthening the solo panels in the pull-out tests.

Figure 5.15 Prototype "GwAGw2"

Prototype GwAGw2, seen in figure 5.15, is made up of 3 high-density layers of glass wool and 1 layer of glass fiber weave that can be seen as the dashed line between two of the layers. This prototype is made for its potential in strengthening the solo panels in the pull-out tests.

Figure 5.16 Prototype "GwCGw"

Prototype GwCGw, seen in figure 5.16, is made up of two high-density layers of glass wool, top and bottom, and two layers of crimped glass wool in the middle. This prototype is made for its acoustic (sound trap) possibilities. Better visible surfaces when it comes to painting.

Figure 5.17 Prototype "GwP"

Prototype GwP, seen in figure 5.17, is made up of 3 layers of low-density glass wool and one layer of plasterboard. This prototype is made for its sound insulation properties.

Figure 5.18 Prototype "GwRP"

Prototype GwRP, seen in figure 5.18, is made up of one layer of low-density glass wool, followed by two layers of Refiber board and lastly one layer of plasterboard. This prototype is made for its sound insulation properties. It also takes environmental aspects in mind by using recycled material as the middle layers, while maintaining a smooth visible surface.

Figure 5.19 Prototype "GwR1"

Prototype GwR1, seen in figure 5.19, is made up of two layers low-density glass wool and two layers of Refiber board. High proportion of recycled material while maintaining a smooth visible surface. Could have interesting acoustical properties.

Figure 5.20 Prototype "GwR2"

Prototype GwR2, seen in figure 5.20, is made up of two layers of high-density glass wool and two layers of Refiber board. High proportion of recycled material while maintaining a smooth visible surface. Could have interesting acoustical properties.

Figure 5.21 Prototype "GwSw"

Prototype GwSw, seen in figure 5.21, is made up of one layer of high-density glass wool and three layers of stone wool. This prototype is made to compare the properties of stone wool to glass wool and could have interesting acoustical/insulating properties.

Figure 5.22 Prototype “GwSwGw”

Prototype GwSwGw, seen in figure 5.22, is made up of two layers of high-density glass wool, top and bottom, and 2 layers of stone wool in the middle. This prototype is made to compare the properties of stone wool to glass wool and could have interesting acoustical/insulating properties.

Figure 5.23 Prototype “GwAGwSwAGwCA”

Prototype GwAGwSwAGwCA, seen in figure 5.23, is made up of materials in this order: High-density glass wool, Glass fiber weave, Medium-density glass wool, Stone wool, Glass fiber weave, Low-density glass wool, Crimped glass wool x2, Tedlar foil. This prototype is mostly made to see if it is possible to laminate many layers together without issues.

6 Results

Selected results from the measurements and tests done on the final prototypes and their sub-layers. Detailed results can be found in Appendix C. The tests are performed for the materials and prototypes that are suitable for each test.

Table 6.1 Selected results from AFR-measurements of each sub-layer

Name	***Density (kg/m3)***	***Resistivity (kPa*s/m2)***
GW Low density 1	56,1	36,5
GW Low density 2	64,5	44,3
GW Low density 3	65,4	44,7
GW Low density 4	60,1	39,3
GW Medium density 1	99,6	96,8
GW Medium density 2	93,8	87,3
GW Medium density 3	91,7	87,2
GW Medium density 4	94,3	88,8
GW High density 1	113,5	116,0
GW High density 2	116,7	116,7
GW High density 3	113,9	111,0
Refiber 1	117,4	81,8
Refiber 2	134,0	97,8
SW 1	185,8	228,3
SW 2	208,9	260,0
SW 3	159,2	175,0
Crimped 1	162,0	258,0
Crimped 2	146,2	226,0

In table 6.1 above, the AFR measurements have been carried out for each porous sub-layer that are later used in different combinations. Table 6.2 shows the results from the combined layers where no glue has been added between the layers. The theoretical combination value is simply the average resistivity of the different layers.

Table 6.2 Selected results from AFR-measurements with combined layers (no glue)

Name	***Density (kg/m3)***	***Resistivity (kPa*s/m2)***	***Theoretical combination value (kPa*s/m2)***	***Accuracy***
4 x GW MD IIII	94,9	85,8	90,0	0,953
4 x GW MD ILIL	94,9	85,4	90,0	0,949
4 x GW LD IIII	61,5	37,6	41,2	0,913
4 x GW LD ILIL	61,5	38,2	41,2	0,926
Crimped II	154,1	234	242	0,967
Crimped IL	154,1	237	242	0,980
HD/LD/HD/LD	86,5	76,1	78,4	0,971
HD/LD/HD/LD	86,5	74,3	78,4	0,948
HD/HD/LD/LD	86,5	74,8	78,4	0,954
GwRP (-P)	102,5	68,9	72,1	0,956
GwSwGw	158,0	170	180	0,943
GwCGw	133,7	171	179	0,957
Gw2	86,5	76,1	78,4	0,971
GwSw	168,0	183	195	0,939
GwR1	93,0	62,5	65,1	0,960
GwR2	120,6	98,7	103	0,957
			Mean accuracy [0,913 , 0,980]:	**0,951**

(HD = High density, MD = Medium density, LD = Low density)

Figure 6.1 shows the accuracy of the theoretical vs the measured values graphically.

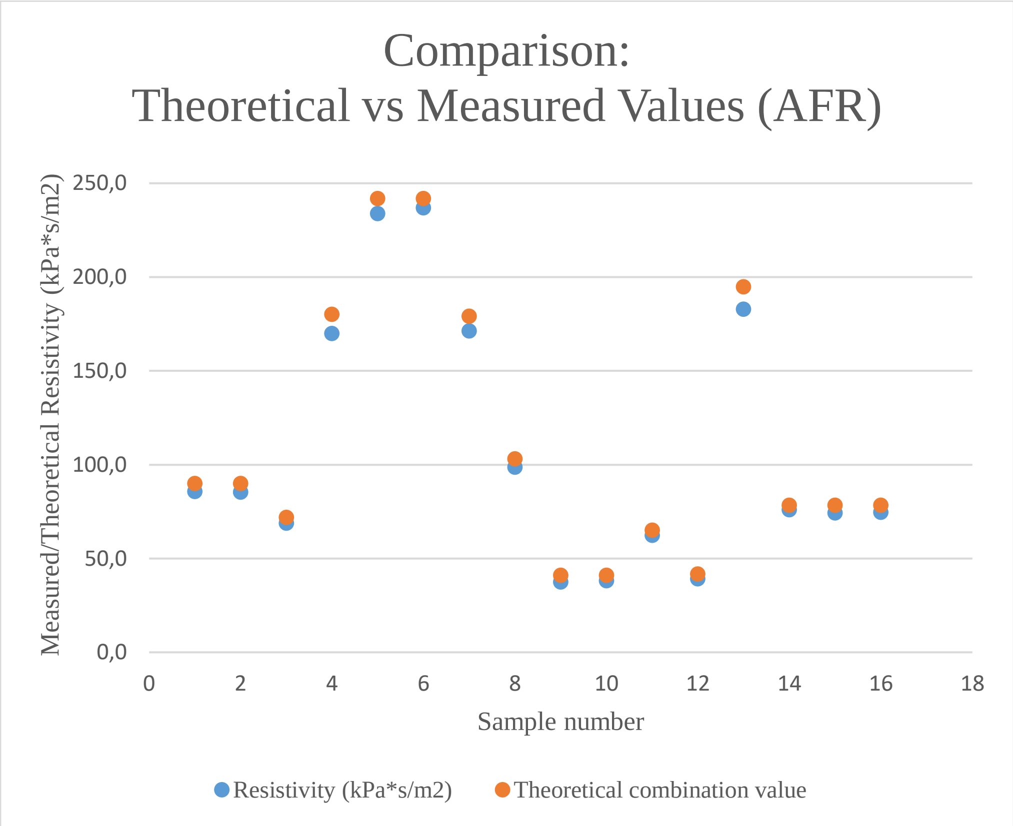

Figure 6.1 Graphical illustration of the accuracy of the measured/theoretical resistivity

Table 6.3 shows the selected results from the AFR measurements where glue has been added between the layers.

Table 6.3 Selected results from AFR-measurements with combined layers (with glue)

Name	*Density (kg/m3)*	*Resistivity (kPa*s/m2)*	*Ranking of Resistivity*	*Ranking of Density*
55 IIII	71,7	40,4	11	9
55 ILIL	68,4	40,7	10	11
GwSwGw	145,1	140,0	2	2
GwAGw1	107,4	112,2	4	5
Gw1	60,2	39,8	12	12
GwAGw2	135,0	137,9	3	3
GwCGw	110,2	108,2	5	4
GwP(-P)	71,6	56,7	8	10
Gw2	92,8	82,2	6	7
GwSw	162,9	182,6	1	1
GwR1	81,0	56,4	9	8
GwR2	101,9	75,0	7	6

Table 6.4 shows the comparison between the samples with glue between the layers and the ones without glue between the layers. Red numbers mark the values below 1, meaning that the resistivity became lower with glue than without.

Table 6.4 Comparison between glue/no glue results

Name	*Resistivity no glue (kPa*s/m2)*	*Resistivity with glue (kPa*s/m2)*	*Difference with glue*
55 IIII	37,6	40,4	1,074
55 ILIL	38,2	40,7	1,065
GwSwGw	170	140,0	0,824
GwAGw1	82,3	112.2	1,363
Gw1	38,2	39,8	1,042
GwAGw2	124,4	137,9	1,109
GwCGw	171,4	108,2	0,631
Gw2	76,1	56,7	1,443
GwSw	183	182,6	1,080
GwR1	62,5	56,4	0,998
GwR2	98,7	75	0,902
		mean difference: [0,631 , 1,443]	**1,024**

Figure 6.2 and 6.3 show the results from the Quasi-static Mechanical Analyzer testing where the apparent Young’s modulus for each tested frequency can be observed. Table 6.5 shows the ranked order from high to low seen to the performance in the QMA test. Red markings indicate the reference values.

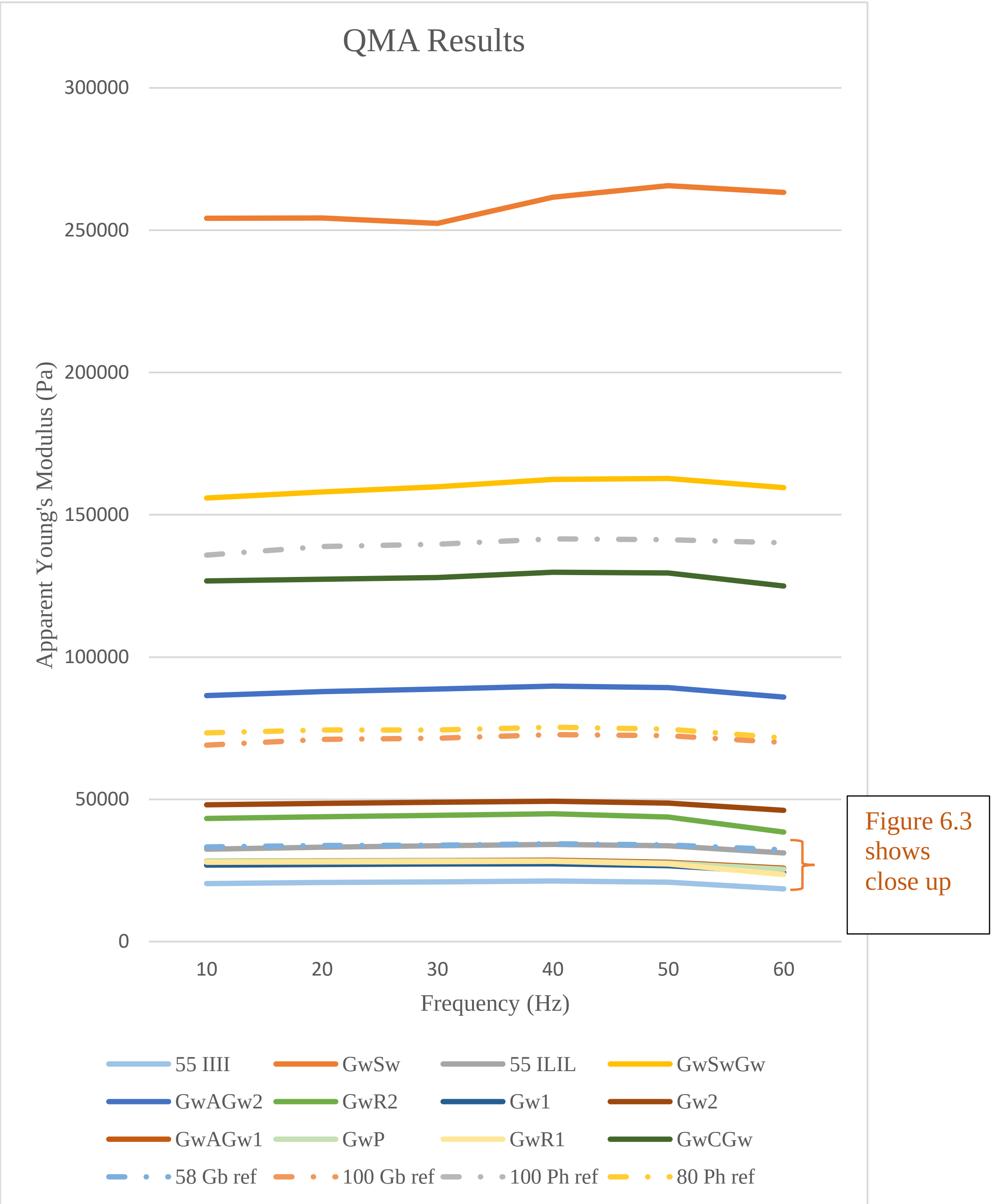

Figure 6.2 Apparent Young's modulus from the QMA results. Observe the scale. Dashed/dotted lines mark the reference values.

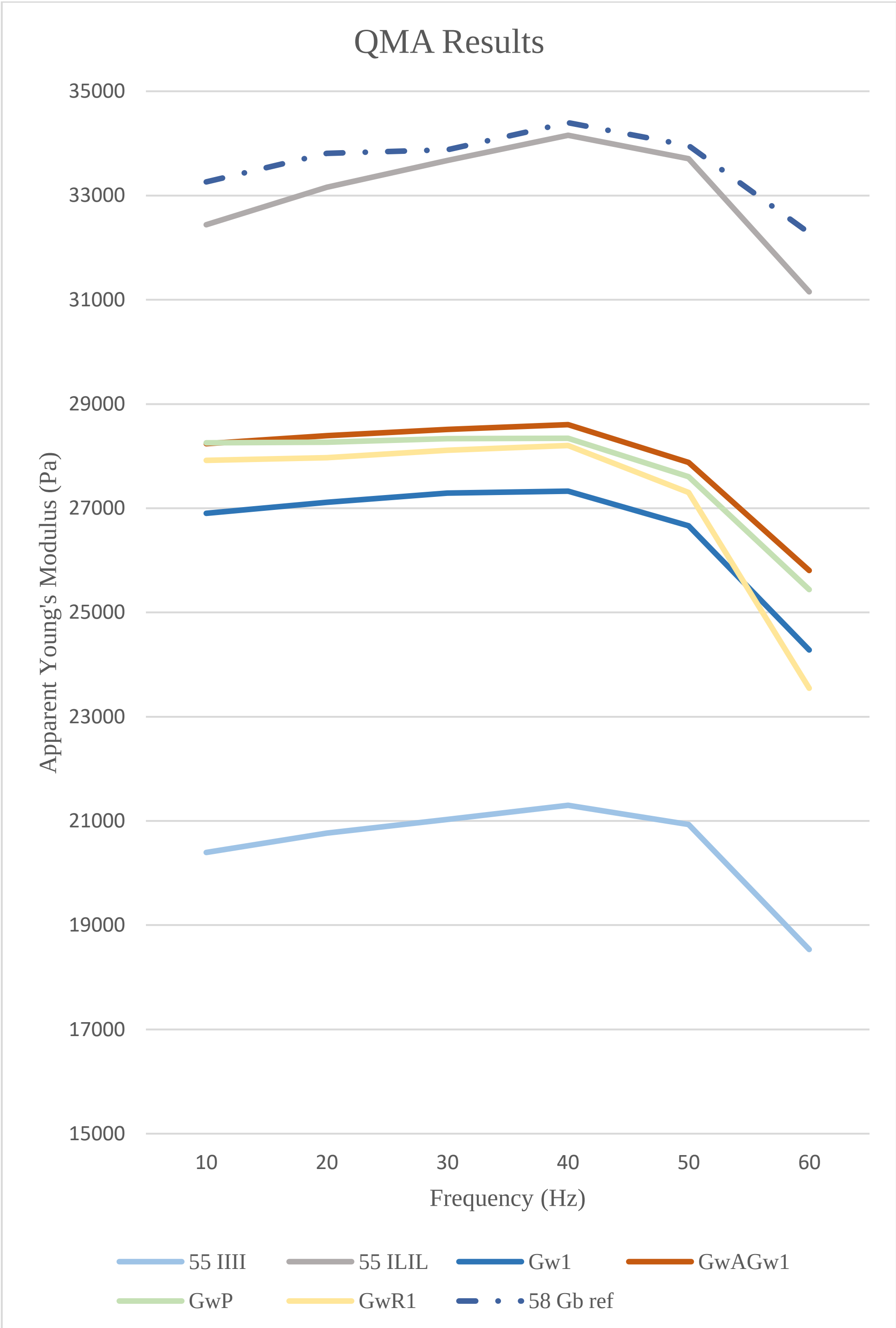

Figure 6.3 Apparent Young's modulus from the QMA results zoomed in on the bottom results. Observe the scale.

Table 6.5 Ranked results from QMA

Placement	*Name*	*Mean value (Pa)*
1	GwSw	258564
2	GwSwGw	159733
3	100 Ph ref	139550
4	GwCGw	127742
5	GwAGw2	87995
6	80 Ph ref	73932
7	100 Gb ref	71099
8	Gw2	48292
9	GwR2	43126
10	58 Gb ref	33598
11	55 ILIL	33046
12	GwAGw1	27906
13	GwP(-P)	27707
14	GwR1	27175
15	Gw1	26596
16	55 IIII	20493

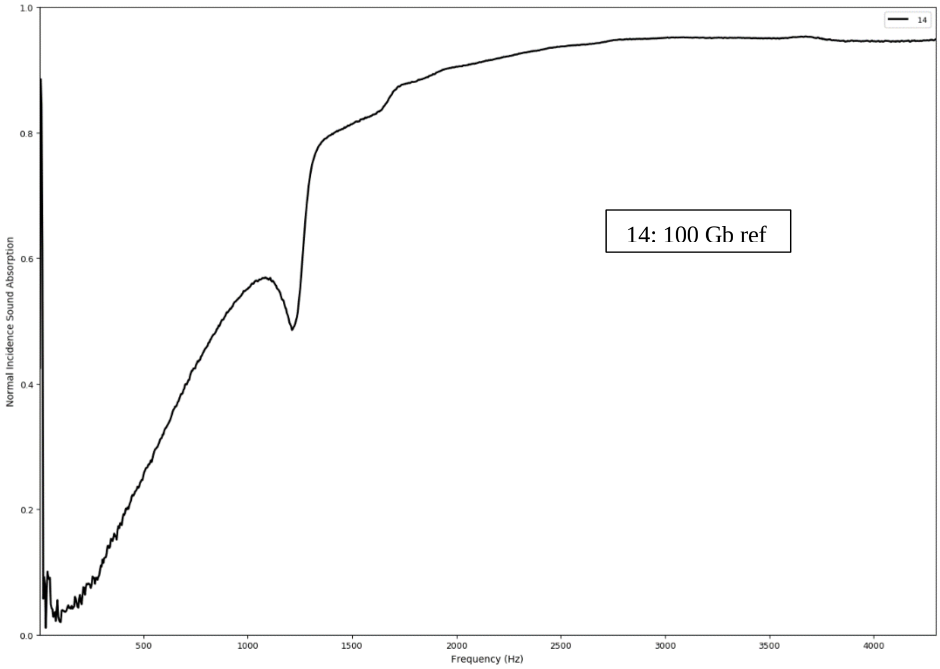

Figure 6.4 Absorption curve for the high-density glass wool reference sample.

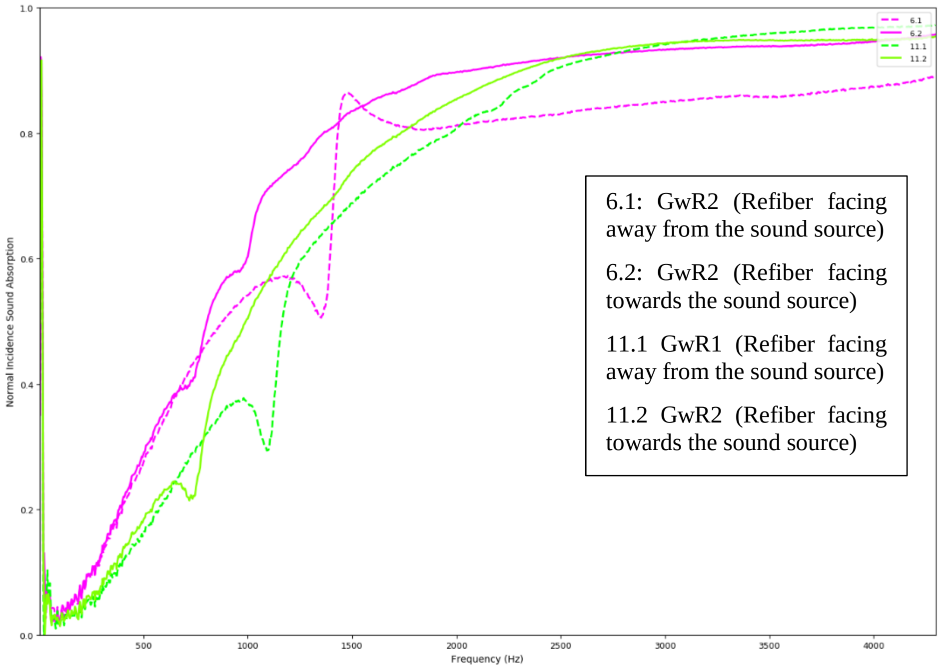

Figure 6.5 Absorption curve for the samples that include Refiber board.

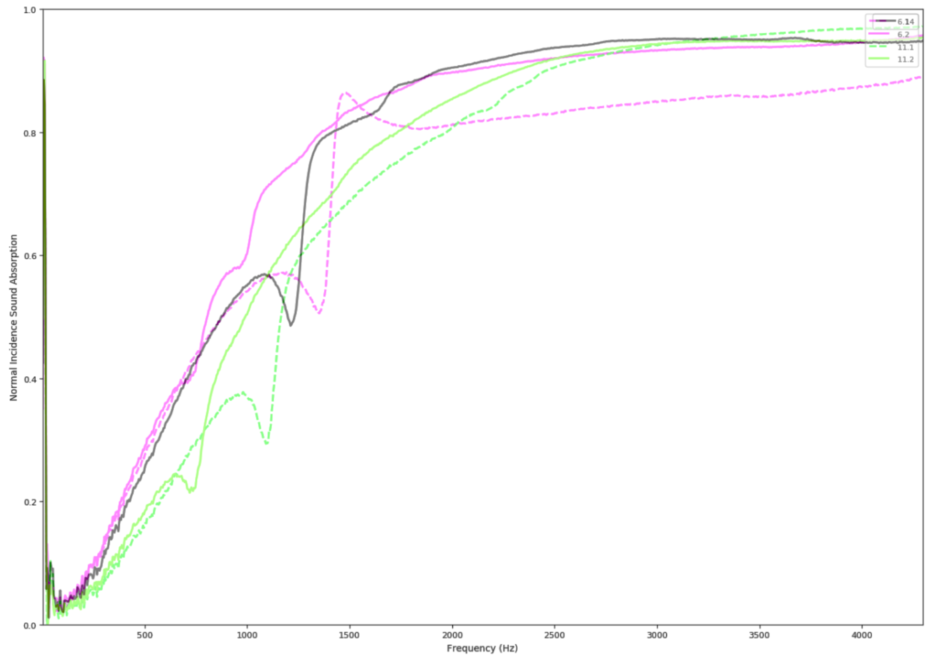

Figure 6.6 Comparison between figure 6.4 and 6.5

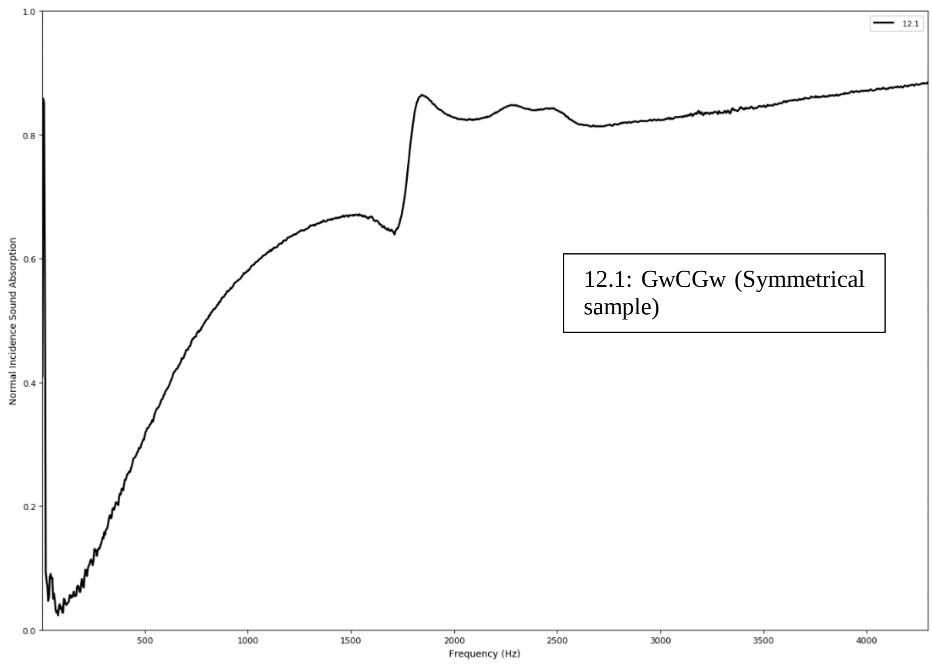

Figure 6.7 Absorption curve for the sample including crimped glass wool.

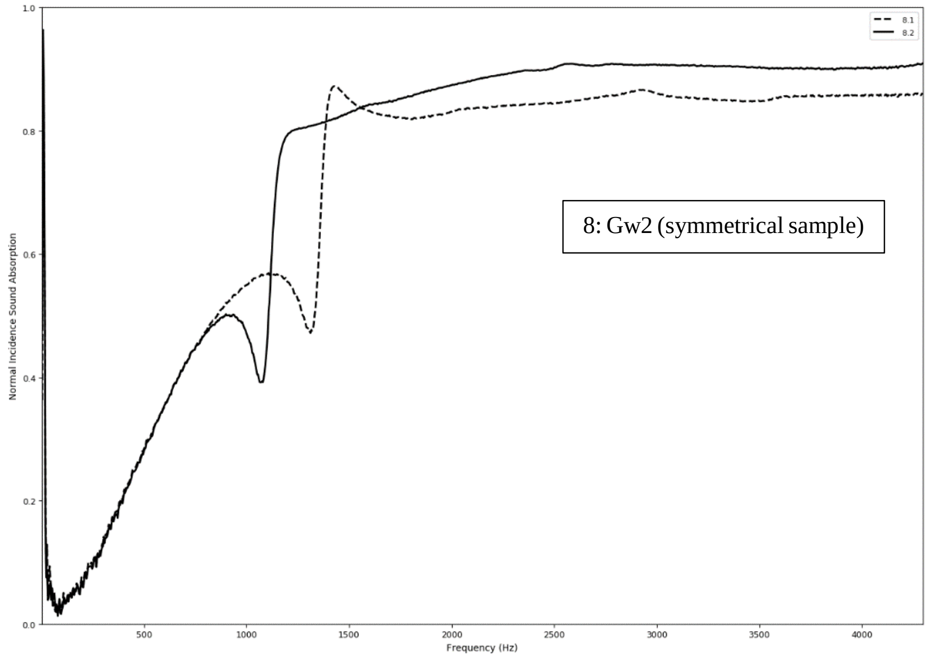

Figure 6.8 Absorption curve for sample Gw2.

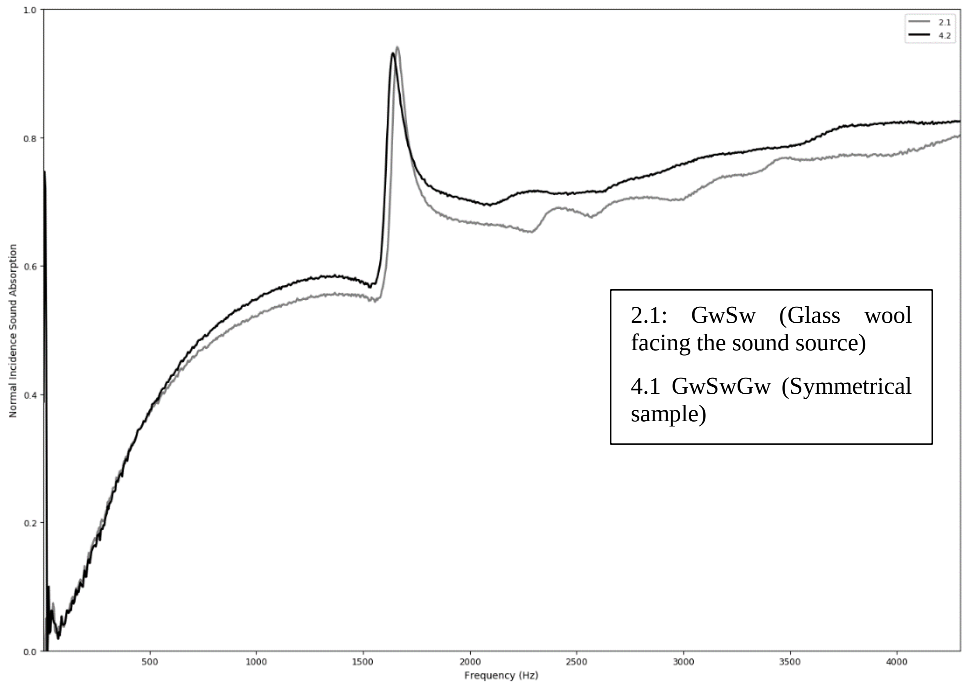

Figure 6.9 Absorption curves for the samples including stone wool.

7 Discussion and Conclusions

7.1 AFR Results

To no surprise, the density of the single layer sample correlates quite well with the resistivity, as can be interpreted from table 6.1. The materials that provide the most sound absorption are the ones with the lowest resistivity, meaning the low density glass wool, followed by the medium-density and Refiber board. The crimped glass wool and the stone wool are in the same range at the other side of the spectra, leaving the high-density glass wool somewhere in the middle.

Three different sets are tested to see if there is any difference when the dominant fiber direction is rotated 90 degrees between each layer, or if they are all in the same direction. These results are found in table 6.2. We can see that there is no significant change in the resistivity (85,8 vs 85,4, 37,6 vs 38,2 and 234 vs 237), which is interesting to note, since that would mean that prediction of the results would be simplified.

Three samples consisting of the same four layers are tested to see if the order of the layers play a part in the resistivity. The values here (76,1, 74,3 and 74,8) indicate that it does not.

The theoretical combination value, shown in the same table and graphically in figure 6.1, is simply the average value of the resistivity for each sub-layer (the thickness is already taken into consideration at that point). The accuracy for this value ranges between 91.3% and 98,0%, with the average being 95,1%. This is not a bad approximation seeing as the resistivity of the single layers in table 6.1 range from, for example, 56,1 to 65,4 (16,6% difference) for the same material taken from the same 5 mm board.

Table 6.3 shows the ranking of the resistivity results for the tested samples with glue in between the layers. Unsurprisingly, the ones with stone wool have the highest values, followed closely by the two samples containing glass fiber weave and the one with crimping. The effect of the glass fiber weave on the resistivity is quite high in some samples, GwP(-P) consists of three low density layers and is almost comparable to what GwAGw1 would be without the glass fiber weave (although the higher density layer also affects the higher value) and the resistivity is almost doubled.

When comparing the results from glue vs no glue in table 6.4 we see the mean difference being 2,4% off, which would be a great result. However, the values range from -39,9% off to +44,3% off, which certainly makes it more difficult to predict the results. It is also worth noting that the layers that have been glued together are not exactly the same as the ones that have been tested individually and in the no glue tests. The material isn't homogenous, and results would vary somewhat between different samples, even from the same board, which we have seen before. There might not have been such a difference between the values if we had had a larger sample size of each material, but it's difficult to say with certainty.

The AFR value for a standard low-density baseboard is around 37 kPa*s/m2, medium-density is around 52 kPa*s/m2 and high-density is around 84 kPa*s/m2. This means that 55IIII, 55ILIL and Gw1 approximate low-density baseboard, GwP(-P) and GwR1 approximate medium-density baseboard and GwR2 and Gw2 approximate high-density baseboard. The rest of the samples (GwSwGw, GwSw, GwAGw1, GwAGw2 and GwCGw) are outside of the spectra of what is used as baseboard today.

7.2 QMA Results

The QMA gives the values of the apparent Young's modulus, which is used to get an idea of the correlating sound-insulating property of the sample. The top two results are, again, the samples containing stone wool, see figure 6.2 and table 6.5. Many of the samples are in very close proximity of each other, around 28 000 Pa and these are better observed in figure 6.3. GwCGw can be seen approximating the reference sample of high-density glass wool with phenolic binder the closest, and the same could be said for the GwAGw2 and the references of high-density glass wool with green binder, and the medium-density glass wool with phenolic binder. The closest resemblance is seen in figure 6.3 as being the 55ILIL sample and the 58 Gb reference. This is not strange since they are made of basically the same material. Noteworthy is the fact that so is 55IIII, which is the lowest value of them all. This result seems to indicate that rotating the dominant fiber direction increases the apparent Young's modulus by, in this case, 61%.

7.3 Sound Absorption Results

In figure 6.4 we see the reference curve for high-density glass wool. Comparing this to figure 6.5 in figure 6.6 we can notice some interesting results. When the sample is placed with the Refiber board facing away from the sound source the curve looks very similar to the reference curve. However, when the Refiber board is facing towards the sound source there is little to no resonance dip in the curve. Otherwise, the GwR2 prototype in particular is following the reference curve very closely and it can be argued that this is a better result even if it is slightly below the reference at the higher frequencies. Even better, considering the high amount of recycled material in the product!

The resonance dip in the GwCGw prototype, see figure 6.7, seems to be significantly smaller than the reference, but it also has a lower absorption capability of the higher frequencies. Figure 6.8 shows two curves from the same, symmetrically stacked sample, with somewhat different characteristics. It is interesting to compare this to figure 6.9, where there are instead 2 different samples but a much closer resemblance between the curves. This is especially the case in the area of the curve where there is a high peak that can not be observed in any of the other curves shown here. Not necessarily a good thing when it comes to room acoustics, but interesting to note.

7.4 Design Aspects

The design aspects presented in the prestudy are what need to be considered for the complete product. Since we have only looked at the baseboard, we have been unable to check some of them. The hygienic and light scattering properties have to do with the surface material, the dismountability with the edge profiles and the mechanical properties with the product as a whole. There was no time to try out the products in the climate chamber. The acoustic properties have been investigated, environmental aspects have been considered, no material with any type of sharp smell has been introduced in the prototypes and neither has any materials that would be considered an obvious fire hazard.

All of the materials used are already being used within the building/acoustic industry and should not give off any harmful emissions, but it could be worth checking the amount of dust that is given off from the products. When making the prototypes it was noticed that the sliced layers gave of more fiber dust than a non-sliced layer would have. This was especially the case for the crimped glass wool.

The ability to make alterations to the products on site in order to install fittings etc. has not been compromised for most of the prototypes. The ones with glass fiber weave would be more difficult to cut through, but not impossible, and the ones with plaster board would probably require nothing more than what would be used if there was no acoustic board in front of it to begin with.

Seen to the environmental aspects, mixing different kinds of materials together makes recycling more difficult. This should also weigh into the decision of which concepts should be continued. Mixing stone wool and glass wool together is not detrimental if new products would be made from them once their lifetime as an acoustic panel is up. This could be something for Ecophon or other companies in search for more environmental solutions to look into.

7.5 Adhesives

A part of the project from the beginning was to explore different adhesive solutions. However, because of problems with approving new chemicals to use at Ecophon, this ended up being scrapped from the project and all of the prototypes were made using the same glue that is used in the production today. Time was spent on researching different alternatives, but it was decided to not include the details in this report. An example of an interesting alternative to use in further development is “water glass”, which is widely used in different industries.

7.6 Material Testing

Some of the prototypes made have not undergone the testing and are therefore not part of the results. This is simply because it was not possible to cut through the plasterboard with the die-cutter and when trying to do so with the Tedlar foil it ripped in such a way as for the sample to be useless for testing. Strong stuff.

7.7 Prototype Conclusions

According to the results, there seems to be no downsides to rotation of the dominant fiber direction when compared to leaving them parallel. The 55ILIL prototype closely resembles the 58 Gb reference for both the AFR and QMA results. It is therefore unclear if there would be any benefit to make this laminate when the reference performs just as well.

The Gw2 prototype seems to perform very similar to the reference curve when comparing figure 6.4 to curve 8.2 in figure 6.8. This is interesting since half of the high-density glass wool is substituted for low-density glass wool in the middle of the board, leaving the surfaces and visible edges smooth and easily painted. It would also mean a total density reduction as well as a lower material cost.

For prototype GwA no tests were performed because of the die-punch problems so it is difficult to draw accurate conclusions here.

The GwAGw1/GwAGw2 prototype results have been discussed above. In conclusion: The use of a glass veil strengthens the product, but perhaps to a degree where delamination would become a problem when trying to modify the product on site. Could have potential in the Solo panels and baffles. A layer that is tightly woven also seems to affect the sound absorption negatively, which should be kept in mind.

The results for prototype GwCGw are quite similar to the high-density references, but has a higher resistivity, higher total density and lower sound absorption at higher frequencies. The positives would be the decreased resonance dip and higher insulative properties, perhaps there are applications for this.

Prototype GwP and GwRP were also not subjected to testing because of the die-punch problems, but as they are similar to the product Combison it can be assumed that they would perform well in the sound insulation aspect. GwP could probably be expected to perform in an almost identical fashion, seen to the results from the 55ILIL prototype (the layers in GwP are also rotated). GwRP turned out looking great and the low-density layer managed to live up to its purpose of giving the prototype a nice surface. This is a good use for the Refiber board if you do not want it to be seen, but if the surface parameters of the Refiber board are improved it might be interesting to try this with only the Refiber board, or add a high-density layer in between the plaster board and the Refiber board to approximate the results from figure 6.6 when it comes to sound absorption.

The other prototypes containing Refiber board, GwR1 and GwR2, showed interesting results throughout the testing. Appropriate values for the AFR, corresponding to references, as well as for the QMA. Perhaps the most interesting results showed up in the impedance tube testing, which showed that the orientation of the dominant fiber direction matters significantly. Overall positive results.

The stone wool prototypes, GwSw and GwSwGw, contributed with off the charts results when it came to density, resistivity, and apparent Young’s modulus (insulation). Perhaps adding only one or two layers on the back of a product would contribute to sound insulation (similar to the plasterboard) but not interfere as much with the sound absorption. This would also probably simplify on-site alterations to the products.

For prototype GwAGwSwAGwCA, what can be said is that it is possible to laminate this many layers together without issues. No tests could be performed for the same reason as the others.

The prototypes and concepts that I would recommend primarily continuing with based on these results are:

- All prototypes including Refiber board for the acoustic results and the environmental aspects
- Combining high-density and low-density glass wool as in Gw2 to reduce density and material cost
- Rotating the dominant fiber direction – more testing needed
- Trying out substitution of plaster board for stone wool as an insulating backing

7.8 Further Work

Some aspects in the prestudy of this report were not possible to test within the timeframe of this project. Fire property tests (cone calorimeter) are scheduled to take place at RISE with selected prototype samples. Here it is interesting to see if a material with better fire properties could protect another (worse performing) material laminated behind it, as one example. Mechanical testing, such as the pull-out test for the solo panels – especially with regards to the GwAGw1/GwAGw2 prototypes - could be carried out. When cutting these samples by hand for the impedance tube testing, they were very difficult to cut through. This could cause more of a problem with getting the fixing into the panel to begin with, and risk delamination problems when trying to do so. If that is not a problem however, it could strengthen the panel greatly.

Different adhesives need to be put to the test, as well as patterns when distributing the glue between the layers. The Combison panels manages to use dots of glue between the plaster board and the glass wool and still get a very strong bond.

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Appendix A Time plan

The time plan and execution of the project is presented here, along with explanations of some deviations from the plan.

A.1 Project plan and outcome

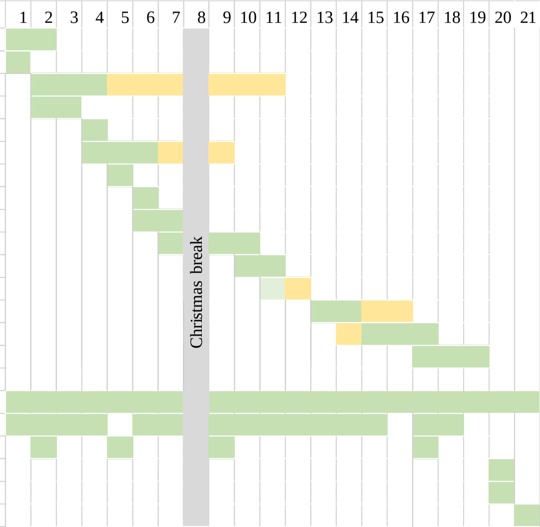
When doing a project in research and development it is difficult to know where the project is going to end up ahead of time. The project was first thought to cover more ground, but due to difficulties with scheduling, getting go-aheads and getting the materials needed for the prototypes, plans were postponed and the project more focused. The Gantt-schedule, seen in figure A.1 below, was not completely planned from the very beginning, but rather filled out as the project progressed and the results from the different stages allowed for planning on what to do next.

The "Prestudy" task took longer than expected since new information had to be brought into the project as the different stages of concept development and material testing evolved.

The "Lamination & Adhesive Research" continued longer than expected because of uncertainties with the approval of new chemicals. The solution for this ended up being too late to being able to use in this project, which is why no testing of different adhesives could be carried out, and why all of the prototypes are made with the adhesive that is already used by Ecophon today.

The trip to Germany was made to slice the material into thinner sheets and this was postponed due to a high workload and scheduling difficulties for Tommy. The third round of prototypes also took longer that expected due to scheduling and coordination with different departments and people. This time was spent instead on beginning the "Material Testing" earlier with the prototypes and material that were already made.

Activity	Planned start	Planned length	Actual start	Actual Length	Week:
Planning & Introduction	1	2	1	2	
Isover Study Visit	1	1	1	1	
Prestudy	2	3	2	10	
Concept Development 1	2	2	2	2	
1st Round of Prototyping	4	1	4	1	
Lamination & Adhesives Research	4	3	4	5	
Presenting Concepts	5	1	5	1	
2nd Round of Prototyping	6	1	6	1	
Workshop	6	2	6	2	
Evaluation and Concept Development	7	3	7	3	
Gathering Material	10	2	10	2	
Lübz, Germany	11	1	12	1	
3rd Round of Prototypes	13	2	13	4	
Material Testing	15	4	14	4	
Analyzing Data	17	3	17	3	
Writing Report	1	21	1	21	
Meetings with Tommy					
Meetings with Per-Erik					
Opposing Report	20	1	20	1	
Presentation at Ecophon	20	1	20	1	
Presentation at LTH	21	1	21	1	



Planned but not begun

Planned and Executed within time frame

Extra/other time needed for the task

Figure A.1 Gantt schedule for the project

Appendix B Workshop

A workshop was held with the Sound Circularity team where new ideas and prototypes were shown to other departments at Ecophon.

B.1 Purpose and Plan

The purpose of contributing to the workshop was to get some input into the concept development from the different departments at Ecophon and to present more of what my project would be about. By arranging the available material of different thicknesses in more manageable sizes, the participants could assemble a layered board and motivate why the different materials were chosen. The most promising/interesting concept were to be included in this project.

B.2 Preparations

B.2.1 Material

Most of the material could be found at Ecophon, some new materials of interest were purchased and made into the right size and shape. For the material to manageable it was cut into 30 cm squares, seen in figure B.1

One material consisted of puffed rice, seen in figure B.2. The rice was combined with a small amount of water and carefully kneaded to activate the natural starch within the rice to act as a binder. The rice was then made into the correct shape and pressed between two plates and left to dry.

Figure B.1 Assortment of materials for the workshop

Figure B.2 Puffed rice board

B.2.2 Poster

A poster was made to explain the purpose of the station and to provide a list of the available materials, see figure B.3 below

Figure B.3 Poster made for the workshop

B.3 Result

In figure B.4 below the Build-A-Board workshop station is visible, complete with the assortment of materials, gloves, pens and paper for the participants to use, and the poster printed out. Leaning against the board is the 4 initial prototypes made in this project. I was also constantly present at the station to explain more about the project and answer any questions that they had, as well as to take in additional feedback.

Figure B.4 Stations at the workshop.

Figure B.5 shows some of the participants that came to the workshop and in figure B.6 you can see active participation in the Build-A-Board workshop station. Some concepts were constructed individually and some in teams. The proposed concepts were documented through photographs and the written motivations, as can be seen in the example in figure B.7.

Figure B.5 Participants at the workshop.

Figure B.6 Participation in the Build-A-Board station.

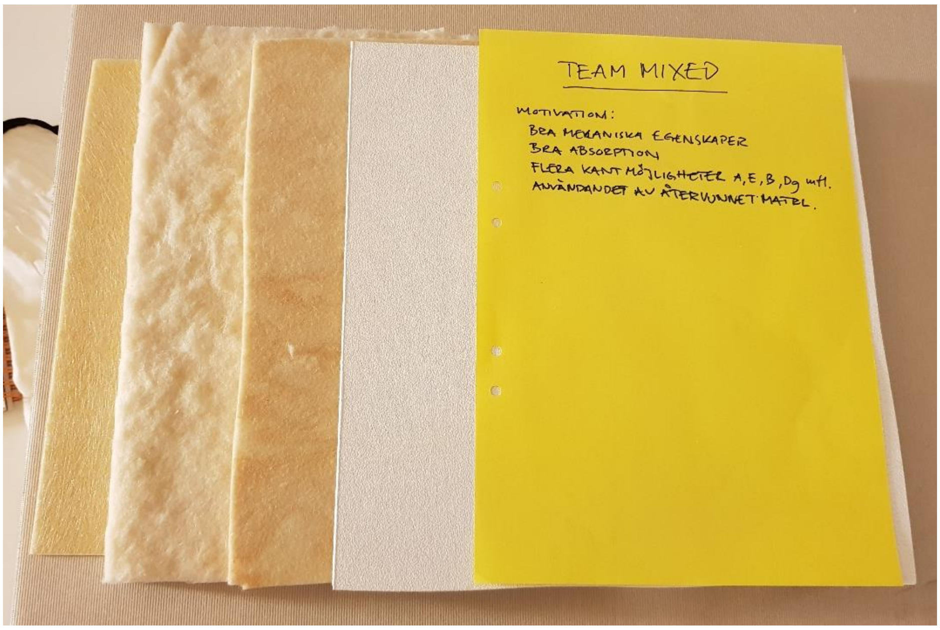


Figure B.7 Concept example. Backside – Refiber – High-density glass wool – Akutex surface.

All of the proposed concepts from the workshop are listed in table B.1 below.

Table B.1 Proposed concepts

Submitter	*Layers (back → surface)*	*Motivation*
"Frida"	Refiber 25 mm 10 mm glass wool Akutex T	Uses recycled material while maintaining a nice surface
"Katrin Bergmark"	High-density back side 2 mm High-density glass wool 5 mm x2 Low-density Akutex T 10 mm	Only materials already within Ecophon. 2 boards of glass wool assembled so that the fiber direction is perpendicular between them for higher stability
"No name"	Non-woven back Reused baseboard 20 mm Reused baseboard 20 mm New Akutex surface	2 boards of glass wool assembled so that the fiber direction is perpendicular between them Stiffness Fewer suspense points Focus on use for "Solo" model
"Mak"	Refiber Moisture absorbent Non-woven glass fiber Low-density glass wool Akutex surface	Refiber as a base, followed by "wettex" to even out the surface of the refiber. Non-woven and low density glass wool to get a nice, even surface
"Johan"	Non-woven backside Refiber Low-density glass wool 10 mm Akutex T	Evens out the surface of the refiber. Uses recycled material
"KRL"	Crimped 25 mm Refiber 25 mm Surface	Good acoustic properties
"Team Mixed"	Non-woven backside Refiber High-density glass wool Akutex surface	Good mechanical properties Good absorption Several edge possibilities (A, E, B, Dg etc.) Uses recycled material

B.4 Evaluation

The workshop yielded the desired results of receiving more feedback and concept proposals. The idea of having the Build-A-Board itself as a separate workshop more dedicated to coming up with concepts in group constellations was brought up more than once. Some were hesitant to propose a concept on such short notice and with so much else going on around them. It was also noticeable that the participants were influenced by the previous stations they had visited, as well as the Build-A-Board station itself with the finished prototypes laid out and explained before they were to propose something of their own. This was most noticeable in that six out of seven concepts included the recycled material that they had been informed about in the previous station. This in itself is certainly not a bad thing, but it is likely that it would have produced a wider variety of ideas if more time and group discussions would have been possible to allow for.

The proposed ideas of the most relevance for this project was decided to be the ones using refiber combined with low/high-density glass wool ("Johan" and "Team Mixed"). It was later in the project decided to only produce only the baseboards as the prototypes, which is why the backside and the Akutex T surface are not included in the prototypes.

Appendix C Detailed Results

Results from AFR measurements and calculated values for the combined layers.

Table C.1 Separate layer testing AFR

Name	Thickness (m)	Area (m2)	Weight (g)	Density measure (kg/m3)	Resistance	Resistivity (kPa*s/m2)
R225 55	0,006	0,00785	2,93	62,2	0,316	52,7
R225 80	0,0055	0,00785	4,81	111,4	0,527	95,8
R225 100	0,0055	0,00785	4,73	109,6	0,644	117,1
GB3b 55 1	0,006	0,00785	2,64	56,1	0,219	36,5
GB3b 55 2	0,006	0,00785	3,04	64,5	0,266	44,3
GB3b 55 3	0,006	0,00785	3,08	65,4	0,268	44,7
GB3b 55 4	0,006	0,00785	2,83	60,1	0,236	39,3
GB3b 80 1	0,006	0,00785	4,69	99,6	0,581	96,8
GB3b 80 2	0,006	0,00785	4,42	93,8	0,524	87,3
GB3b 80 3	0,006	0,00785	4,32	91,7	0,523	87,2
GB3b 80 4	0,006	0,00785	4,44	94,3	0,533	88,8
GB3b 100 1	0,0055	0,00785	4,9	113,5	0,638	116,0
GB3b 100 2	0,0055	0,00785	5,04	116,7	0,642	116,7
GB3b 100 3	0,005	0,00785	4,47	113,9	0,555	111,0
GB4+ 55	0,005	0,00785	2,86	72,9	0,228	45,6
GB4+ 100	0,006	0,00785	4,96	105,3	0,519	86,5
Refiber 1	0,006	0,00785	5,53	117,4	0,491	81,8
Refiber 2	0,006	0,00785	6,31	134,0	0,587	97,8
SW 1	0,006	0,00785	8,75	185,8	1,37	228,3
SW 2	0,006	0,00785	9,84	208,9	1,56	260,0
SW 3	0,006	0,00785	7,5	159,2	1,05	175,0
Crimped 1	0,005	0,00785	6,36	162,0	1,29	258,0
Crimped 2	0,005	0,00785	5,74	146,2	1,13	226,0

Table C.2 Combined layer testing (no glue)

Name	Thickness (m)	Area (m2)	Weight (g)	Density measure (kg/m3)	Resistance	Resistivity (kPa*s/m2)	Theoretical combination value	Accuracy
80 IIII	0,024	0,00785	17,87	94,9	2,06	85,8	90,0	0,95326
80 ILIL	0,024	0,00785	17,87	94,9	2,05	85,4	90,0	0,94863
GwRP	0,018	0,00785	14,48	102,5	1,24	68,9	72,1	0,95605
GwSwGw	0,023	0,00785	28,53	158,0	3,91	170,0	180,3	0,94306
Crimped II	0,01	0,00785	12,1	154,1	2,34	234,0	242,0	0,96694
Crimped IL	0,01	0,00785	12,1	154,1	2,37	237,0	242,0	0,97934
GwCGw	0,021	0,00785	22,04	133,7	3,6	171,4	179,2	0,95673
GwR2	0,023	0,00785	21,78	120,6	2,27	98,7	103,1	0,95729
55 IIII	0,024	0,00785	11,59	61,5	0,903	37,6	41,2	0,91304
55 ILIL	0,024	0,00785	11,59	61,5	0,916	38,2	41,2	0,92619
GwR1	0,024	0,00785	17,52	93,0	1,5	62,5	65,1	0,95969
55 ILI (GwP)	0,018	0,00785	8,76	62,0	0,707	39,3	41,8	0,93891
GwSw	0,0235	0,00785	30,99	168,0	4,3	183,0	194,8	0,93916
Gw2	0,023	0,00785	15,62	86,5	1,75	76,1	78,4	0,97062
100/55/ 100/55	0,023	0,00785	15,62	86,5	1,71	74,3	78,4	0,94843
100/100/ 55/55	0,023	0,00785	15,62	86,5	1,72	74,8	78,4	0,95398
							mean accuracy: (0,91304, 0,97934)	**0,95071**

Table C.3 Combined layer testing (with glue)

Name	Thickness (m)	Area (m2)	Weight (g)	Density measure (kg/m3)	Resistance	Resistivity (kPa*s/m2)
55 IIII	0,025	0,00785	14,07	71,7	1,01	40,4
55 ILIL	0,024	0,00785	12,88	68,4	0,977	40,7
GwSwGw	0,023	0,00785	26,2	145,1	3,22	140,0
GwAGw1	0,018	0,00785	15,18	107,4	2,02	112,2
Gw1	0,025	0,00785	11,81	60,2	0,995	39,8
GwAGw2	0,019	0,00785	20,14	135,0	2,62	137,9
GwCGw	0,022	0,00785	19,03	110,2	2,38	108,2
GwP	0,017	0,00785	9,56	71,6	0,964	56,7
Gw2	0,023	0,00785	16,75	92,8	1,89	82,2
GwSw	0,023	0,00785	29,42	162,9	4,2	182,6
GwR1	0,022	0,00785	13,99	81,0	1,24	56,4
GwR2	0,026	0,00785	20,79	101,9	1,95	75,0

Table C.4 Comparison between glue/no glue results

Name	Resistivity no glue (kPa*s/m2)	Resistivity with glue (kPa*s/m2)	Difference with glue
55 IIII	37,6	40,4	1,074
55 ILIL	38,2	40,7	1,065
GwSwGw	170	140,0	0,824
GwAGw1	82,3	112.2	1,363
Gw1	38,2	39,8	1,042
GwAGw2	124,4	137,9	1,109
GwCGw	171,4	108,2	0,631
GwP	39,3	56,7	1,443
Gw2	76,1	82,2	1,080
GwSw	183	182,6	0,998
GwR1	62,5	56,4	0,902
GwR2	98,7	75,0	0,760
		mean difference: (0,631 , 1,443)	**1,024**

Table C.5 QMA and Apparent Young's modulus results

Name	Frequency (Hz):	10	20	30	40	50	60	Mean
55 IIII		20395,8	20763,6	21031,8	21299,9	20932,6	18534,2	**20492,98**
55 ILIL		32436,5	33156,9	33672	34155,7	33704	31152,2	**33046,22**
GwSw		254166	254311	252402	261548	265644	263313	**258564**
GwSwGw		155882	158061	159785	162387	162753	159527	**159732,5**
GwAGw2		86420,9	87807,4	88747,7	89777,8	89295,8	85920,6	**87995,03**
GwAGw1		43291,2	43855,7	44406,6	44923,8	43783,9	38494,5	**43125,95**
Gw1		26901,8	27111,7	27290,2	27327,6	26665,4	24280,8	**26596,25**
Gw2		48082,5	48602,4	48983,9	49323,1	48627,5	46129,5	**48291,48**
GwAGw1		28239,5	28392,2	28513,5	28603,8	27881,3	25805,4	**27905,95**
GwP (-P)		28225,2	28265,2	28334,2	28342,2	27606,4	25439,3	**27707,08**
GwR1		27917,7	27969,3	28110,8	28203,5	27302,9	23546,4	**27175,1**
GwCGw		126779	127390	127989	129802	129534	124959	**127742,2**
58 Gb ref		33260,7	33809,9	33877,2	34396,8	33960,2	32280,9	**33597,62**
100 Gb ref		69038,1	71093,3	71441,4	72738,9	72339	69942,1	**71098,8**
100 Ph ref		135818	138872	139650	141534	141256	140172	**71570,8**
80 Ph ref		73336,2	74398,3	74324,9	75347,4	74612,6	71570,8	**73931,8**