Swappable Container Waterborne Transport Battery

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Reducing the Cost of Large Batteries for Waterborne Transport

D4.3

Composite Structure

2 April 2025

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GLOSSARY OF TERMS

Term	Definition
BMS	Battery Management System
CD	Current Direct
SoC	State of Charge
SoH	State of Health
TRC	Textile Reinforced Composite

DOCUMENT PROPERTIES

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REVISION HISTORY

Version	Issue Date	Changes Made / Reason for Issue
1.0	22 aug 22	**Initial Version Submitted**
2.0	1 Apr 25	Reviewed version. The comments from our PO were implemented. The summary has been updated. Details about the compositions were added. A section has been added on the simulations done on the composite structure.

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PROJECT SUMMARY

The transport sector contributes almost 25% of Europe's greenhouse gas (GHG) emissions. Compared to other sectors it is the only one with higher emissions than those of 1990. While minor emission reductions have been achieved, GHG emissions surged by 7% from 2014 until today. The European Commission adopted a low-emission mobility strategy in June 2016 to address this trend, which by 2050 aims to reduce GHG by 60% compared to 1990.

Waterborne transport (WT) emissions represent around 13% of the overall EU GHG from the transport sector. Moreover, they could increase between 50% and 250% by 2050 under a business-as-usual scenario, undermining the objectives of the Paris Agreement. The International Maritime Organization (IMO), in 2018, stipulated a strategy aiming to reduce GHG emissions from the WT sector by at least 50% by 2050.

Large-scale adoption of batteries for WT are mainly limited by the high costs of the battery systems and their integration. New innovative solutions need to be developed to drive down costs.

Together with high costs, the following challenges are identified as hampering the implementation of batteries in WT:

1. WT requires specific safety equipment leading to a higher CAPEX compared to other applications such as an automotive battery of equivalent capacity.

2. Port infrastructure for battery charging often require upgrades. In several WT sectors, fast chargers are necessary due to the short latency during operational schedules.

3. Specific regulations and training are required to ensure the safety of the battery system installation and operation.

4. There is a small market for maritime battery systems and thus a lack of drivers for cell producers to adapt their manufacturing to create cells optimized for maritime applications.

The Current Direct EcoSystem is shown in Figure 1.

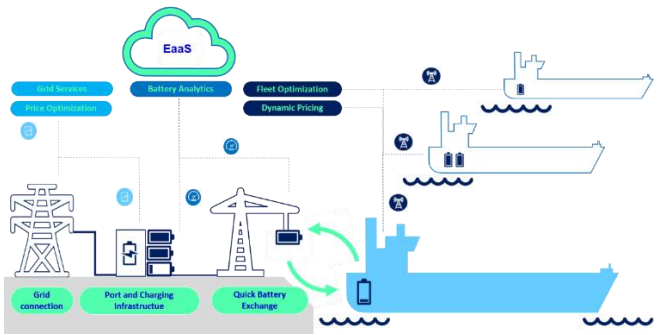


Figure 1. Current Direct EcoSystem

1. EXECUTIVE SUMMARY

In this updated deliverable, the comments from our PO were addressed by adding detailed information on the chemistry and types of fibers used. A section on the simulations done on the composites is added at the end (section 9).

The key properties to be considered in Composite Material development include anisotropic thermal properties, structural properties, design features (cell / assembly alignment to support automation), low cost, volume, and mass. The report presents the Composite Material' structure, development activities, requirement compliance, and outlook for activities to be conducted throughout the remaining duration of the project.

The composite is made of two thermally conductive layers (skin layers) and one core thermally insulating layer. The methodology adopted when assessing different materials to support the development of an optimized Composite Material consisted of establishing control groups and independent variables for each of the composite material's constitute elements. The variables were then integrated into different composite samples and tested to assess their impact on the material's performance metrics. The best performing complementary independent variables were then aggregated into an optimized composite material which was used to measure the requirement compliance. Some requirements were difficult to achieve, so one of the purposes of the Composite Material development was also to define at which level they could be achieved.

The composite skin was prepared using carbon textile and an inorganic polymer matrix, meanwhile, the core was prepared with an inorganic matrix and glass beads. Testing results and observation made during composite preparation showed that the skin with 400 g/m^2 C-fiber is one of the best options for the skin's composite configurations investigated. The composites prepared with this configuration and selected core composition also meet the material's thickness and surface density requirements. However, the flexural strength and in-plane thermal conductance was significantly lower than the requirements. However, there seems to be no reason for such a high flexural strength, meanwhile the cost will be significantly higher if better C-fibers are used (400 W/mK thermal conductivity). Based on the results, some requirements could be reviewed as they were too strickt**.** An overview of requirements and if they were reached or not is given below.

- Shall have an in plane thermal conductivity ≥400 W/mK : not reached. Will be done at subcontractor
- Shall have a mass less than 0.82g/cm^2. Reached
- Shall have an insulating capacity should be such that a temperature of <80 °C for >5 min can be maintained if the opposite surface is at 700 °C. not reached. Can only be reached with better C-fibers

- Shall have a flexural yield strength ≥ 100 MPa. Can be reached with another (more expensive) matrix, thus at higher cost. The importance of this requirement is however not clear.
- Shall maintain all required material properties with up to 700 °C surface temperature. Reached
- Shall be capable of exerting even pressure along the z/y plane ranging from 0.1 to 5 bar. Reached
- Shall not emit any electrically conductive FOD (foreign object debris). Reached
- Shall not absorb enough water to effect material physical / performance characteristics. Reached
- Shall survive a service a drop from 100 cm. Reached

2. SPECIFIC OBJECTIVES FOR WORK PACKAGE 4

This WP encompasses the design, prototyping, verification testing, and demonstration build of the Current Direct Waterborne Transport Battery optimized for inland and short sea shipping applications. It includes the development of key subsystems that improve safety, reduce cost, improve life, and increase energy density. Subsystem development will begin immediately at the start of the project, while the battery design will not start until milestone M2 with the requirements freeze.

Specific Objectives:

- Design a safe, low cost, long life, energy dense Current Direct Waterborne Transport Battery
- Develop and test ultrasound sensors for determining SOC and SOH
- Develop and test BMS single cell supervisor
- Develop and test composite structural and thermal plate battery module construction
- Create a thermal model of battery system to understand heat distribution and dissipation
- Produce prototype Current Direct battery modules
- Test Current Direct battery modules for performance and safety certification
- Design a marine, safety-certified, swappable container for the Current Direct battery
- Integrate and test the Current Direct battery, container, and subsystems

2.1. Task 4.4 Development of Composite Structural and Thermal Material

This task will develop fire resistant composite plates with high in-plane thermal conductivity on at least one side paired with significant insulating capabilities perpendicular to the plane of the plates. The task aims to reduce battery cell packaging cost and volume while maintaining the safety of current state of the art marine battery systems. Initial combinations of fibres and matrix properties will be evaluated via COMSOL Multiphysics simulations and subsequently verified with concept testing. The leading fibre/matrix combination for the textile reinforced composite (TRC) skin and the insulative core will be used in the T4.1 battery module design and incorporated in Vito's system thermal model. Reuse and recyclability of the plates will be design criterion from D2.1.

3. INTRODUCTION

The activity referenced "T4.4, Composite Material" is located under "Work Package 4. Battery". This report presents the work performed by VUB on developing the composite structure. The Composite Material is made of 2 thermally conductive layers (skin layers) and one core thermally insulating layer (Figure 1). Information related to methodology, Composite Material preparation, testing and properties, requirement compliance and prospects are presented. The properties determined were mainly those mentioned in material requirement of the CD project. Some information related to recyclability of the Composite Material is also presented.

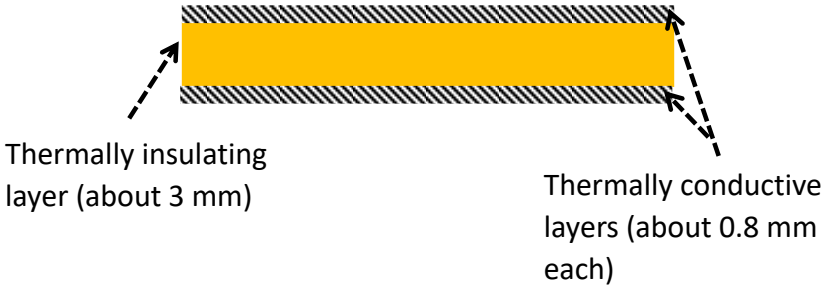


Figure 2. Sketch of the composite material

3.1. Objective

This task in the CD project was aiming to develop a Composite Material that could combine the properties of multiple components currently used in today's battery system to reduce both material and assembly costs. The composite should be fire resistant with high in-plane thermal conductivity and at least one side paired with significant insulating capabilities perpendicular to the plane of the plates and should meet the project requirements.

The most important target requirements are presented in Table 1. Some requirements are hard to achieve, so one of the objectives of the Composite Material development and testing was also to indicate to what level they could be reached

Table 1 Most Important Requirements

ID	Requirements
D2.1.1	Shall have a cost less than X Euro/kg
D4.3.1	Shall have a mass less than 0.82 g/cm^2.
D4.1.8	Have a total composite material thickness ≤ 4.8 mm
D5.1.1	Shall have an in plane thermal conductivity ≥ 400 W/m K
D5.2.1	Shall have an insulating capacity such that a temperature of <80 °C for >5 min can be maintained if the opposite surface is at 700 °C.
D5.3.1	Shall have a flexural yield strength ≥ 100 MPa

4. METHODOLOGY

The Composite Material is a sandwich panel with textile reinforced cementitious skins and a porous core comparable to the matrix of the skins to improve compatibility and recyclability.

The methodology adopted when assessing different materials to support the development of an optimized composite material consisted of establishing control groups and independent variables for each of the composite material's constitute elements. The variables were then integrated into different composite samples and tested to assess their impact on the material's performance metrics. The best performing complementary independent variables were then aggregated into an optimized Composite Material which was used to measure requirement compliance.

The methodology steps included:

- Raw materials selection and acquisition based on VUB expertise on composite materials and literature information.
- Design of experiments for fibre selection and core selection based on the change of one independent variable as shown in Table 2 and Table 3.
- Materials characterisation based on the most important requirements.
- Selection of the best fibre composite preparation based on the test results.
- Selection of the best core for composite preparation considering the test results and the project requirements.
- Suggestion of the composite structure considering the test results and the Current Direct requirements.

Table 2 Fibres configuration investigated

Fiber surface density (g/cm²)							
200	200	200	200	400	415	600	600
Type of woven/ Number of fiber layer in one skin							
Plain/2	Uni/2	Twill/2	Plain/ 1	Plain/ 1	Uni/ 1	Uni/ 1	Twill/ 1
Sample code							
CF200P_2L	CF200U_2L	CF200T_2L	CF200P_1L	CF400P_1L	CF415U_1L	CF600U_1L	CF600T_1L

Table 3 Core formulations investigated using the best/selected fibre configuration

Ref	MK1200 [g]	Potassium Silicate R :1.75 [g]	Glass beads 2 mm [g]	H_2O_2 50 % [g]	Al powder [g]	%vol Glass beads in core
1	25	38.5	0	1	0	0
2*	**25**	**38.5**	**5**	**1**	**0**	34
3	25	38.5	5	0	0	34
4	25	38.5	5	0	0.01	34
5	25	38.5	10	1	0	50
6	47	72	22	0	0	54

*Samples in bold with * in Tables 2 and 3 are control samples*

5. COMPOSITE RAW MATERAILS

5.1. Raw materials for the skin

The selection of raw materials for the Composite Material preparation was performed based on VUB's experience on cementitious materials, moreover non-traditional cements, and composite preparation. The materials used for the core are preferentially the same or comparable to the matrix of the skins to improve compatibility and recyclability. The raw materials used included copper slag, metakaolinite, glass beads and potassium silicate solutions. Both copper slag (Koranel, Aurubis) and metakaolinite were mainly X-Ray amorphous. Their chemical compositions are presented in Table 4. Hydrogen peroxide or aluminium powder were also used as pore forming agent. However, the use of these pore forming agents could be optional when using glass beads, hence is not detailed here.

Table 4 Chemical composition of koranel and metakaolinite

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Cr_2O_3	K_2O	TiO_2	P_2O_5	SO_3	Others
Koranel	24.8	8.9	53.6	2.6	0.9	0.7	0.2	0.2	0.7	0.8	0.06
MK1000	53.0	41.7	1.7	0.1	0.1	-	1.0	2.1	-	-	0.3

5.1.1. Copper slag

Copper slag (Koranel) was chosen because of the low reactivity at room temperature which is needed for the industrial impregnation. Koranel has good reactivity at moderate elevated temperature (80 °C), when mixed with the right alkaline solution. This property is interesting for industrial production as could allow to obtain a mineral matrix that is relatively stable during fiber impregnation step in the production line. Other advantages of copper slag include the availability and at present low cost; Koranel slag is an industrial by-product from Aurubis in Belgium .

5.1.2. Metakaolinite

Metakaolinite is a widely available and a broadly studied raw material for the preparation of alkali activated materials. Theoretically any metakaolinite could be used for the preparation of the composite. Moderate amount of MK1000 was used in the preparation of matrix for the skin. MK1000 was from Imerys in France . The main difference between MK1000 and MK1200 was the particle size which was finer for MK1200.

5.1.3. Activating solution

The most common activating solutions used for the preparation of alkali activated cementitious materials are potassium and sodium silicate solutions. The potassium silicate was chosen in preference to sodium silicate solution based on its better thermal stability after hardening and because of the lower viscosity, beneficial for the impregnation. The material was from Silmaco company, Belgium . The composition of the commercial potassium silicate solution is: 27.22 wt% SiO_2, 15.01 wt% K_2O and 57.77 wt% H_2O. The molar ratio SiO_2/K_2O was 2.84 and the density 1.42

g/cm^3. To achieve the SiO_2/K_2O molar ratios of 2.25 used in the experiments, 5.5 of commercial potassium hydroxide (85 % purity) was added to 100 g of the commercial potassium silicate solution.

5.1.4. Carbon fiber

Carbon fiber was chosen as reinforcement for the skin layer due to its good thermal conductivity and mechanical properties. The material was from Fibermax company . Different woven structures (plain, twill and unidirectional) and textile densities (from 200 g/m^2 to 600 g/ m^2) were investigated. The technical information details on the carbon yarn from the supplier web site are: tow tensile strength of 4410 MPa; tow tensile modulus of 235 GPa, density of 1.79 g/cm^3 and typical yield of yarn: 200 mg/m.

5.2. Raw materials for the core

5.2.1. Metakaolinite

The metakaolinite used in the composite core was MK1200, from Imery France as the MK1000. MK1200 is also amorphous, with a chemical composition similar to MK1000.

MK1200 was chosen for the preparation of the core layer because it is finer and could lead to better dissolution, better interface adhesion with the skin and better mechanical properties of the composite.

5.2.2. Activating solution

The commercial potassium silicate solution from Silmaco was also used for the core. To achieve the SiO_2/K_2O molar ratios of 1.75 and 1.5 used in the experiments, 13.1 g and 18.8 g of commercial potassium hydroxide (85 % purity) were respectively added to 100 g of the commercial potassium silicate solution.

5.2.3. Glass beads

Glass beads (1-2 mm) were selected considering their good thermal insulation (thermal conductivity about 0.07 W/mK) and low density (230 g/m^3). The material was from Poraver company, Germany .

5.3. Mix design

5.3.1. Selection of the potassium silicate solution

The reactivity of alkali-activated materials depends on the composition of the activating solution. 7 compositions of activating solution were investigated. These solutions presented different potassium to silica molar ratios ($R=SiO_2/K_2O$) ranging from 1 to 2.25 with 0.25 interval. The hardening reaction of the silicate solution with the powder, Koranel, is an exothermic reaction and the heat released by the fresh mixture is monitored with calorimetry to study the reaction kinetics (Figure 3 and Figure 4). In these figures, the heat flow is proportional to the reaction rate, thus the higher the heat flow, the faster the reaction. Large differences can be observed between the different mixtures.

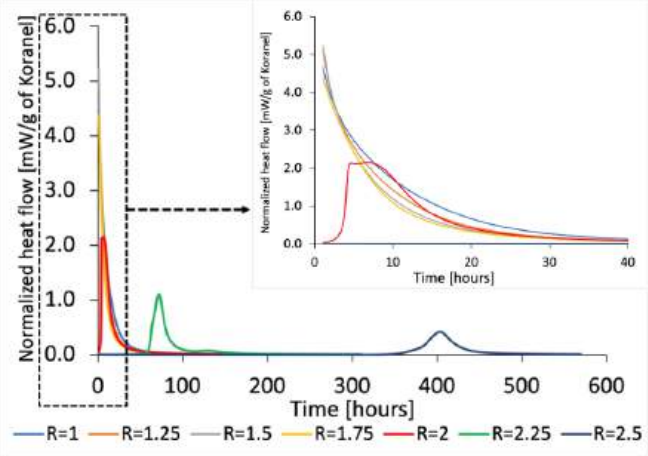


Figure 3. Effect of the silica to potassium molar ratio ($R=SiO_2/K_2O$) of the activating solution on the normalized heat flow of alkali activated Koranel. Isothermal calorimetry @ 20 °C.

The solution with R=2.25, which was stable for about 50 hours at 20 °C, but with relatively good reactivity after this period of time, was selected for the preparation of the composite. Indeed, this solution could allow sufficient time for carbon textile impregnation without hardening during the industrial scale production.

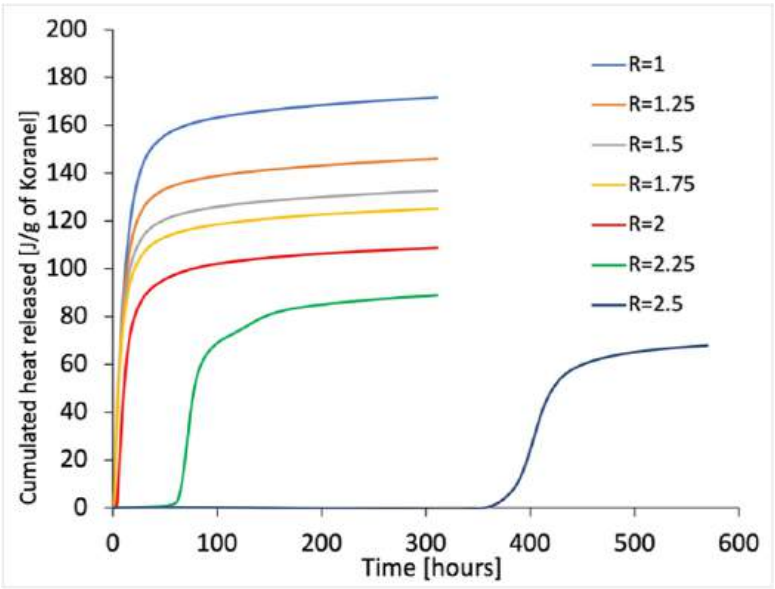


Figure 4. Normalized heat released by Koranel activated with potassium silicate solution at different molar ratios ($R=SiO_2/K_2O$). Isothermal calorimetry @ 20 °C.

Table 5. Composition of the samples

Reference	Koranel 2600 [g]	Metakaolinite 1000 [g]	Potassium silicate solution R:1.75 [g]
K100	100	0	70
K90MK10	90	10	70
K80MK80	80	20	70

5.3.2. Addition of metakaolinite in the mixture

Several mix designs aiming to improve the properties of the skin matrix were investigated. However, only those related to metakaolin addition in

Table 5 are presented in this report. The addition of metakaolinite was observed to increase the heat released without shortening the stability time of the matrix at 20 °C (Figure 5). However, metakaolinite is more expensive than Koranel, meanwhile its addition in large quantities will request a higher amount of the activating solution due to the higher fineness of metakaolin particles. Based on these results, 20 wt% of MK substitution was selected. The selected composition for the matrix for the skin is presented in Table 6.

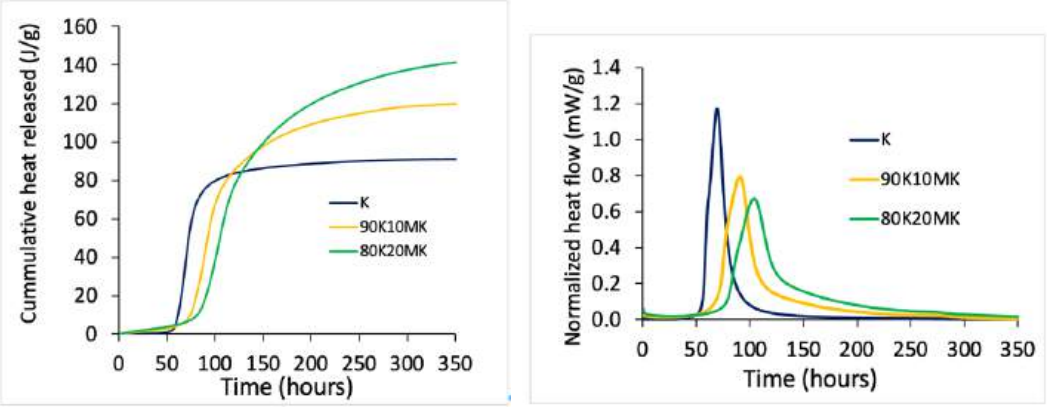


Figure 5. Effect of metakaolinite on the reactivity of Koranel based matrix

Table 6. Composition used for the skin preparation

Ref	Koranel 2600 [g]	Metakaolinite 1000 [g]	Potassium silicate solution R:1.75 [g]	K_2O/Al_2O_3
K80MK20	80	20	70	0.88

Further calorimetry investigations were performed in order to reduce the amount of chemicals input and minimize the composite cost. The results of these test have shown that the potassium silicate solution could be diluted up to about 20 wt% with water without alteration of the reaction heat. Water addition should however be minimized in the system as this could alter the mechanical properties. The results of these additional calorimetry investigations are presented in annex 1.

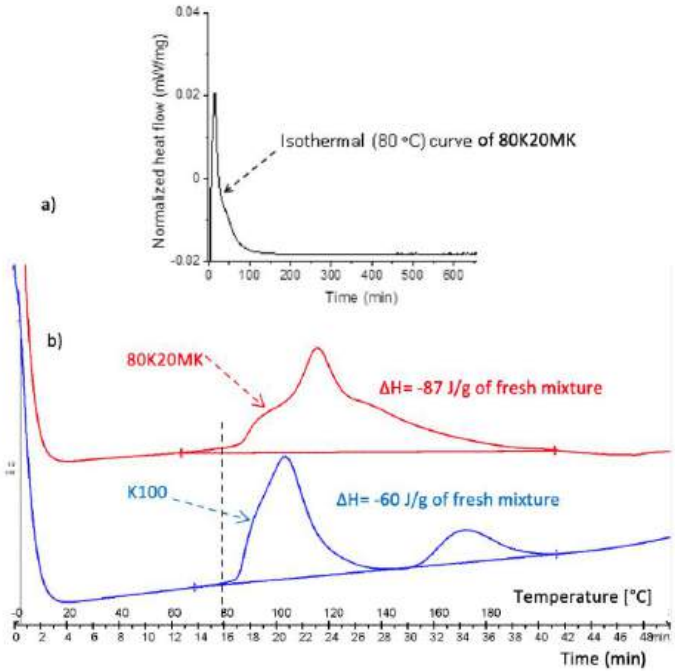


Figure 6. Isothermal (a) and differential scanning calorimetry (b) experiments of pure Koranel matrix and the one containing 20 wt% metakaolinite.

5.3.3. Selection of the curing temperature and time

Temperature is an important parameter affecting the hardening reaction. Differential Scanning calorimetry was used for the selection of the curing temperature. It could be seen from Figure 6 that 80 °C is a reasonable curing temperature of the skin matrix. Isothermal calorimetry at 80 °C also showed that the materials would need minimum 2 hours curing for the main part of the hardening reactions to complete. Addition of metakaolinite increases the heat released, thus a larger part of the matrix reacted.

5.3.4. Composition of the core

To obtain a thermal barrier, hollow glass beads, glued together by an alkali activated cement were used. The cement could have the same composition as the matrix for the skins, but in this case the reactivity can be higher and the viscosity lower. Several options have been tried. 2 main strategies are i) chemical foaming of the matrix in addition to hollow glass beads to decrease the thermal conductivity even more ii) maximize the amount of glass beads. From the point of view of upscaling, the chemical foaming might be cumbersome, thus this route might not be continued. At present, experiments are still going on to optimize the thermal barrier layer without chemical foaming. The composition of the core is given in Table 7. Trials with Koranel were performed, but the results are not yet as good as those with metakaolinite.

Table 7. Composition of the core for 15 cm^2 composite. The addition of H_2O_2 is optional

Sample	A	B	C	D
Koranel 2600 [g]	0	0	100	80
Metakaolinite 1000 [g]	25	25	0	20
Glass beads 1-2 mm [g]	5	5-15	33.4	70
Potassium silicate solution R :1.5 [g]	37.5	0	51	0
Potassium silicate solution R :1.75 [g]	0	38-45	0	0
Potassium silicate solution R :2.25 [g]			0	109
H_2O_2, 50% [g]	1	0		0
K_2O/Al_2O_3	1			

5.3.5. Preparation steps of the panel

The thermal conducting layers were prepared separately. One impregnated skin is placed on the bottom of the mold. A layer of core material is spread over. The second skin is placed on top of the core. The mold is closed and placed in a furnace at 80 °C for 12h. The configuration of the sandwich panel is presented in Figure 7. About 65 g of the thermal insulating layer was spread on top of the 15 cm^2 thermal conducting layer. Some images from the production steps at the laboratory scale are presented in Figure 8 and Figure 9 showing the final appearance of the composite prepared. About 40 g of matrix was used to impregnate 15 cm^2 of each layer of carbon fiber 200 g/m^2. For 400 g/m^2 carbon fiber, 50 g of matrix is used and for 600 g/m^2, 60 g of matrix is used. The rest of the procedure is the same as explained before.

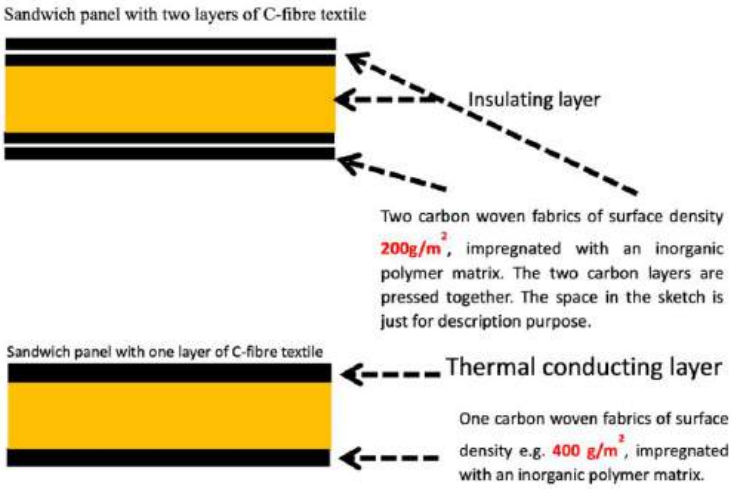
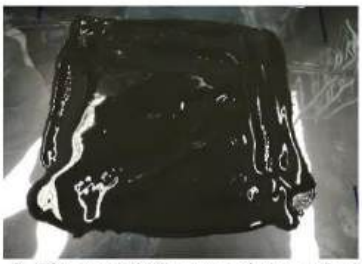
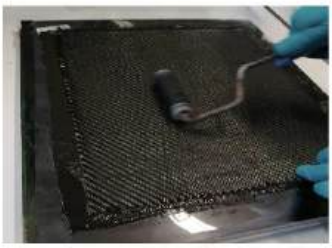


Figure 7. Sketch of cross section of panel with two and one layer carbon in the skin

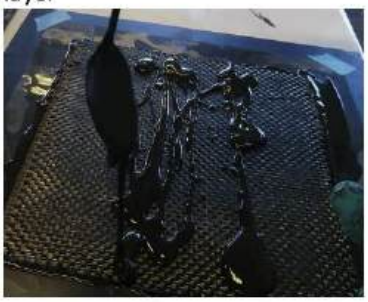
1- Prepared matrix for the skin layer



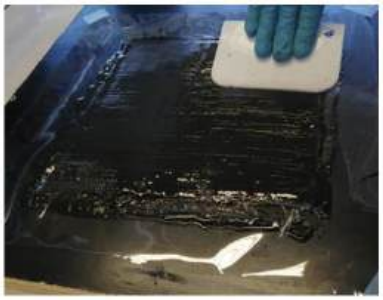
2- The matrix is spread on a plastic film placed on a wooden plate



3- A layer of carbon textile 200 g/m^2 is placed on the top of spread matrix. A roller is used to facilitate



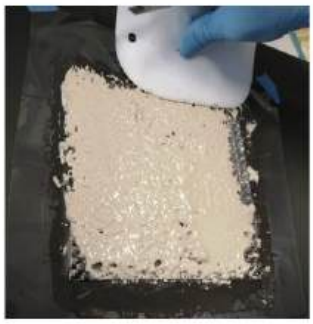
4- Matrix is added on the top of impregnated fiber.



5- Matrix is spread to facilitate impregnation of the second carbon layer.

6- The second layer of fiber is impregnated using a roller.

7- The core layer is prepared.



8- The core layer is spread on the top of two impregnated carbon fiber.

9- Two other impregnated carbon layers are placed on the top of the other which covered by the core.

10- The sample is sealed; a force of 50 N is applied on the top. Then, curing is performed at 80 °C for 12 hours.

11- Sample after cutting the edges

Figure 8. Some images of the production steps

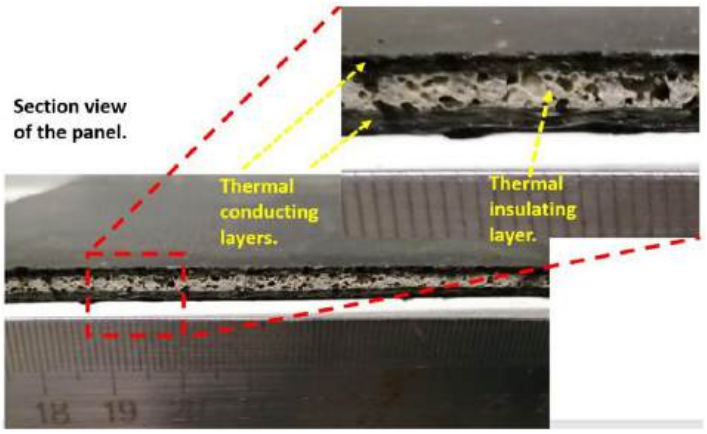


Figure 9. Cross section of the composite prepared in the laboratory

6. TESTS ON PREPARED SPECIMENS

6.1. Three point bending test, ability to manufacture and fibre cost indication

The three-point bending test was performed with a Universal testing machine Tinius Olsen 5ST. The instrument was equipped with a loadcell of 2.5 kN and the measurements were performed with a span of 8 cm and a displacement speed of 2 mm/min. The accuracy of this instrument is 5 N. The flexural strength was estimated assuming that the cross section of the composite is uniform, which is not correct considering the difference between the core layer and the skin layers, but it is an easy way to compare the composite materials with different compositions.

To estimate the flexural strength of the Composite Material,

Equation 1 was used:

$$\sigma = \frac{3\,F\,L}{2\,B\,D^2}$$

Where:

- σ: Flexural strength
- F: Maximum load
- L: span distance
- B: width
- D: thickness

The level of flexural strength in comparison to the requirement, cost related information and ability to manufacture of the different fibre configurations is presented in Table 8. The ability to manufacture is also related to the number of fibre layers in the composite 'skin; the composite 'skin with two fibre layers is requiring more preparation steps and about twice the time needed for the preparation of the composite 'skin with one fibre layer. The analysis of the results in Table 8 showed that the configuration "CF400P_1L" was a one of the best options of our tested configurations. However, the value of the flexural strength obtained was less than the target. A higher value of strength can be reached with a different matrix, but this will contain less or no

recycled materials and will be more expensive. The requirement of 100 MPa flexural strength was taken from the epoxy-glass fiber composites currently used to contain the cells. Now this is compared to the strength of a sandwich panel in which the core is a weak material, thus a lower strength is expected. The requirement for the strength should thus be adapted. The strength required to contain the cells is the one needed to keep them straight, thus only depending on the mass. From that perspective the strength does not need to be more than 1 MPa. The logic requirement would be that the plates would have a strength that can take up the forces exerted by the compression of the cells during a cycle of charging-discharging. This pressure is exerted on the complete surface of the panels, thus the flexural strength is not very relevant.

Table 8 Flexural strength compliance, cost related information and ability to manufacture of investigated configurations

Sample code						
CF200P_2L	CF200U_2L	CF200T_2L	CF200P_1L	CF400P_1L	CF415U_1L	CF600U_1L
Level of the flexural strength in comparison to the requirement						
17.6 ± 1.8	17.6 ± 2.0	13.8 ± 2.0	13.0 ± 1.9	27.5 ± 3.5	23.6 ± 2.9	24.0 ± 5.6
Cost of fiber in Euro for 1m² of Composite Material						
41.12	63	30.76	30.22	35.4	30.9	30.18
Ability to manufacture						
2	2	1	1	1	1	1

1=less production steps at laboratory scale; 2= more production steps at laboratory scale (twice time for fiber impregnation).

Considering the results obtained in Table 8, the sample "CF400P_1L" was chosen to assess the effect of different core changes. Indeed, since the fibres were made from the same type of material, they are expected to have the same thermal conductivity. Hence, the flexural strength, depending on the fibre density and woven type, was chosen as the elimination criterion for selecting the configuration "CF400P_1L" in the sandwich skin for the rest of experiments. The different core options in Table 3 were then tested with this configuration, but no significant difference was observed on the flexural strength results. For the rest of tests (mass, in-plane thermal conductivity and through plane thermal resistance), the skin configuration 'CF400P_1L' was associated with the core configuration "ref 2", which is theoretically expected to have one of the best through plane thermal resistance.

6.2. Thermal conductivity setup and thermal properties

A setup for measuring thermal conductivity has been developed. The reason for a home-made set-up is that commercially available instruments cannot perform all measurements needed, especially when dealing with non-isotropic materials. The set-up consists of a heating plate, in contact with the specimen to be measured, thermocouples at specific locations, rockwool to insulate the heater and specimen, a power supply, and heat sink for specific applications.

For the validation of the thermal conductivity setup, several experiments were performed on reference materials with known thermal conductivity (nylon 6, polystyrene, glass, Al and Cu plates), for both in-plane and through plane thermal conductivity. The error in the measurement varied from 4 to 20% in the experiments. The results are presented in Annex 1.

The photos and sketch of the experimental setup are presented in Figure 10 and Figure 11.

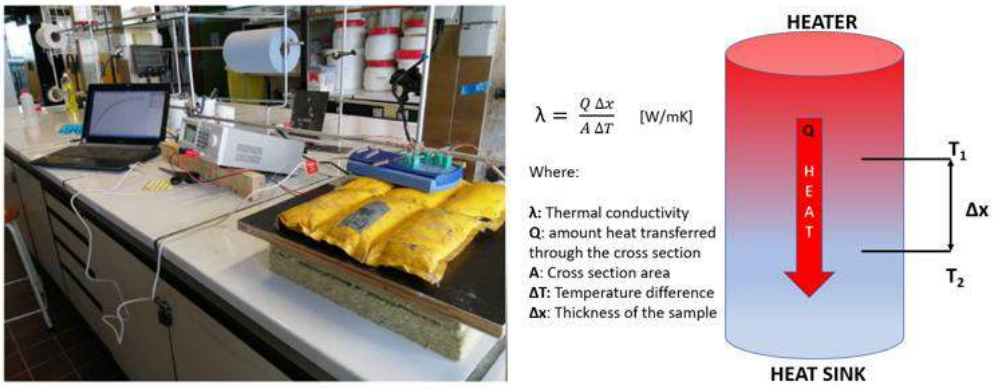


Figure 10 Thermal conductivity experimental setup and theory used for calculations

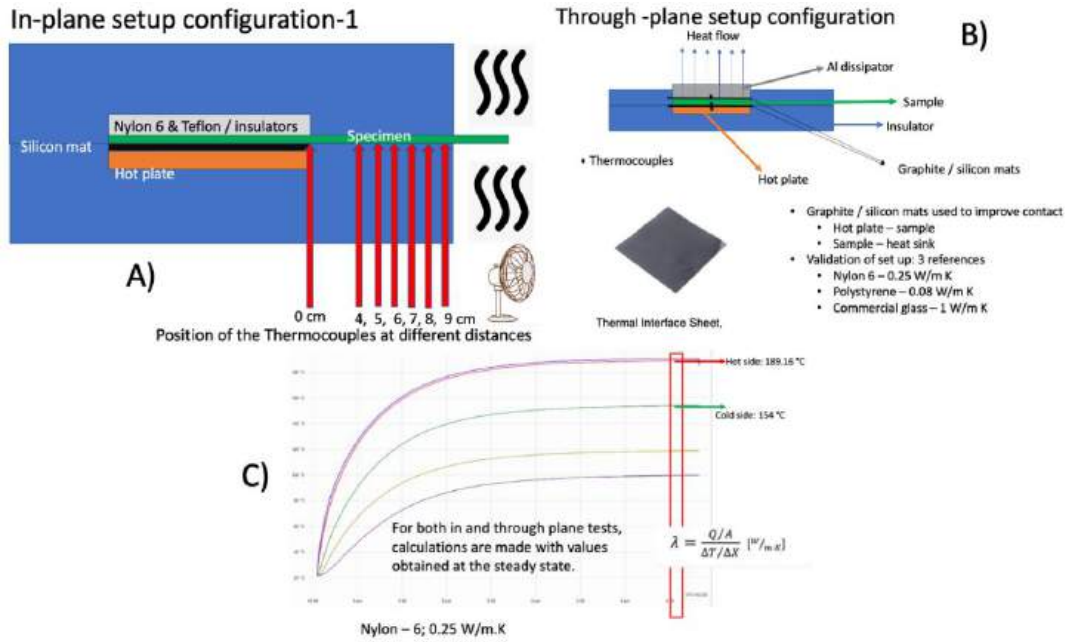


Figure 11 Sketch of experimental setup for the in plane (A) and through plane (B) thermal conductivity and sample of temperature curves collected (C).

The results of the in-plane and through plane thermal conductivity are presented in Table 9.

Table 9 Through plane and in-plane thermal conductivity results

Sample code in-plane thermal conductivity							
CF400P_1L	CF200U_2L	CF200T_2L	CF200P_1L	CF200P_4L	CF415U_1L	CF600U_1L	CF600T_1L
Level of the in-plane thermal conductivity in comparison to the requirement							

Sample code in-plane thermal conductivity							
Significantly less (65 W/mK)	Significantly less (30 W/mK)	Significantly less (31 W/mK)	Significantly less (54 W/mK)	Significantly less (24 W/mK)	Significantly less (36 W/mK)	Significantly less (28 W/mK)	Significantly less (35 W/mK)
Sample code through-plane thermal conductivity							
1	2*	3	4	5	6	/	/
Through plane thermal conductivity values (W/mK)							
0.18	0.21	0.31	0.25	0.22	0.3	/	/

The in-plane thermal conductivity values were all significantly lower compared with the requirement. However, some samples presented better performance in comparison to other. Based on the results obtained, CF400P_1L presented the highest thermal conductivity. Theoretically, the CF415U_1L and CF600U_1L should also present a relatively high thermal conductivity. The difference may be ascribed to the composite structure and the way matrix is distributed within the fiber. That may also explain the higher in-plane thermal conductivity for the composites made of one layer of fiber. An important repark is that the requirement at the start of the project was not clear and it took about 6 months to figure out what exactly was required.

The different core configurations only induced little difference on the through plane thermal conductivity, around 10% for the largest difference. There is some difference on the surface density of the samples prepared with the different core, but all of the masses or surface densities were in agreement with the requirement of the CD project requesting composite plate with a mass <0.82 g/cm². The core configuration 6 presented the higher mass, but will have the advantage of easy manufacturing because of the absence of foaming agent in the preparation. In terms of best insulating properties, the configurations 1, 2 and 5 presented the lowest thermal conductivity values.

6.3. Sample mass and dimensions

6.4. The mass test was also performed by weighing the sample. The mass of all the samples was below 150 g for a sample of 272 cm² surface, hence a surface density of 0.55 g/cm², meeting the requirement of the surface density. The Composite thickness requirement was achieved as well. Four real scale samples were sent to Spear for appreciation. The prepared composites were also found suitable to be cut in complex shape using laser or water jet cutting (Drop test

According to the requirements the drop test was performed on the sample at a height of 1 m. The samples survived to the tests, the two skins and the core remained together. However, a small damage was observed at the side of the sample that hit the floor during the drop (Figure 13b) without debris ejected during the test.

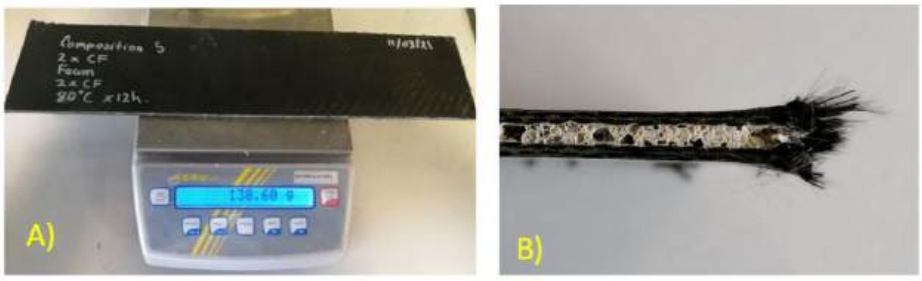


Figure 13. Weight test on real scale specimen (340 x 80 x 4.7 mm) (A) and sample after 1 m drop test (B)

).

Figure 12. Real scale panels cut in accordance with the design suggested by SPEAR

6.5. Drop test

According to the requirements the drop test was performed on the sample at a height of 1 m. The samples survived to the tests, the two skins and the core remained together. However, a small damage was observed at the side of the sample that hit the floor during the drop (Figure 13b) without debris ejected during the test.

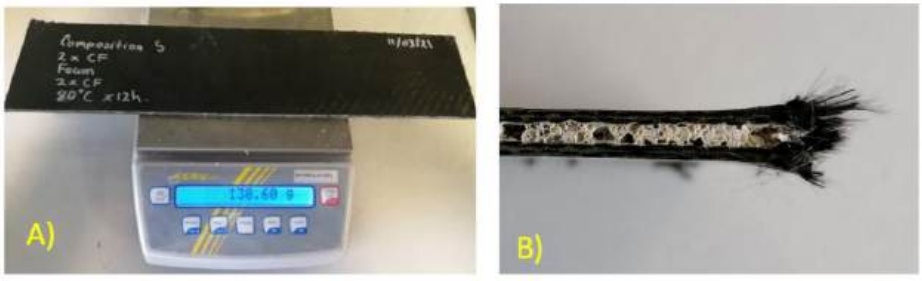


Figure 13. Weight test on real scale specimen (340 x 80 x 4.7 mm) (A) and sample after 1 m drop test (B)

6.6. Through plane thermal resistance

The Through plane thermal resistance test was performed on the Composite Material selected ("CF400P_1L" skin configuration with Ref 2 core configuration). The setup was made of a small furnace where the door was removed and replaced by a sample of the Composite Material. Thermocouples were installed inside the furnace and in the opposite face of the panel to monitor temperature evolution. An infrared camera was also used to monitor temperature evolution. The sketch of the experimental setup used is presented in Figure 14.

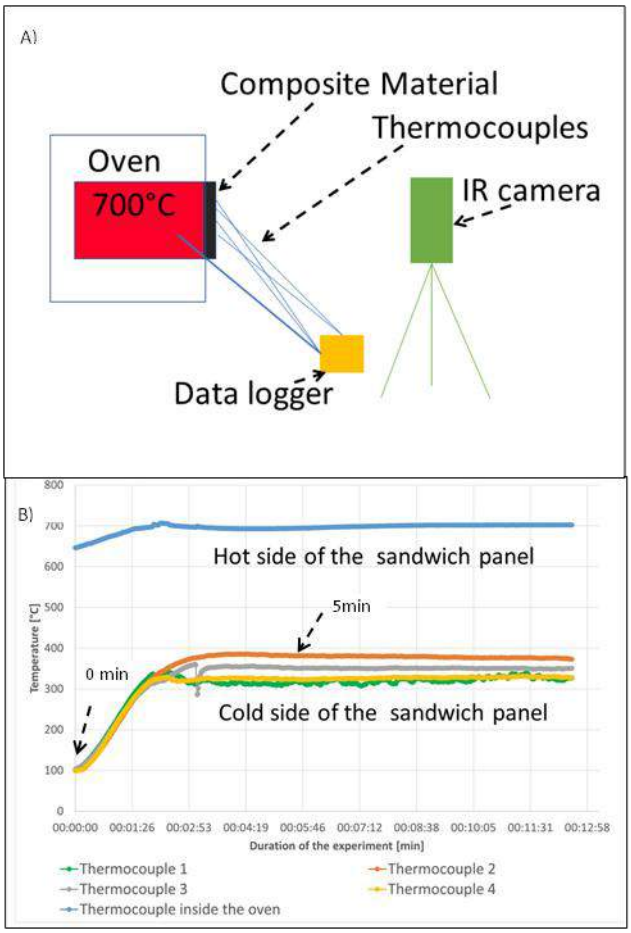


Figure 14 Flame test experimental setup (A) and temperatures recorded during the experiment (B)

The temperatures recorded during the experiment are showing that the panel was able to reduce the temperature from above 700 °C inside the furnace to about 380 °C for the face exposed outside. No heat sinks were used; thus, the cooling capacity of the conducting skins was not used. After about 20 min heating, some heating marks were observed on the face in contact with the higher temperature (Figure **15**), meanwhile the opposite face of the panel in contact with air outside the kiln remained unchanged. Future experiments will include testing Composite Materials with different core configurations.

Figure 15 **Face of the sample exposed at temperatures above 700 °C; The face of the sample in contact with** air outside the kiln remained unchanged.

7. SUMMARY OF RESULTS VERSUS REQUIREMENTS

A summary of obtained values versus initial requirements is presented in Table 10.

The requirement compliance in the Table 10 below is made with the sample that achieved the best performance so far. It is important to mention that results of flexural strength are lower than the requirement because the samples were tested in the form of sandwich structures, with 2 skin layers and 1 core material which is weaker and make the whole composite to fail under lower stresses.

Requirement D2.1.1 also needs to be adjusted as a material with lower mass is punished, while the low mass arises from the insulating part which is needed. A cost per panel would be more appropriate.

Table 10 Pass/% level of achievement of investigated requirements of sample prepared with "CF400P_1L" configuration and ref 2 core

ID	Requirement	Pass/less/higher than the requirement
D2.1.1	Shall have a cost less than 3 Euro/kg	Significantly high, around 9 euro/kg
D4.1.8	Have a total composite material thickness ≤ 4.8 mm	Pass, ~4.7 mm
D4.3.1	Shall have a mass less than 0.82 g/cm^2.	Pass, 0.55 g/cm^2
D5.1.1	Shall have an in plane thermal conductivity ≥ 400 W/m K	Significantly less, 65 W/m K
D5.2.1	Shall have an insulating capacity such that a temperature of <80 °C for >5 min can be maintained if the opposite surface is at 700 °C.	The experiment still needs to be improved by adding heat sinks. Current T: ~350 °C
D5.3.1	Shall have a flexural yield strength ≥ 100 MPa	Significantly less, 27.5 MPa

8. OTHER TRIALS, OPTIMIZATION POSSIBILITIES AND SIMULATIONS

8.1. Trials on materials from Promat

Asides from the developments performed with carbon fiber and metakaolin core matrices, other experiments were performed with other types of materials. One of the options tested by VUB was the core layer Dalfratherm®-1200 uls paper from Promat . The water sensitivity of the Promat material did not allow pressing the fresh skin with the core, thus, some knitting tests were also performed at Promat. However, this option may present difficulties when implemented due the water contained in the fresh skin matrix at the beginning of the production. Some materials and manufacturing steps are presented in Figure 16.

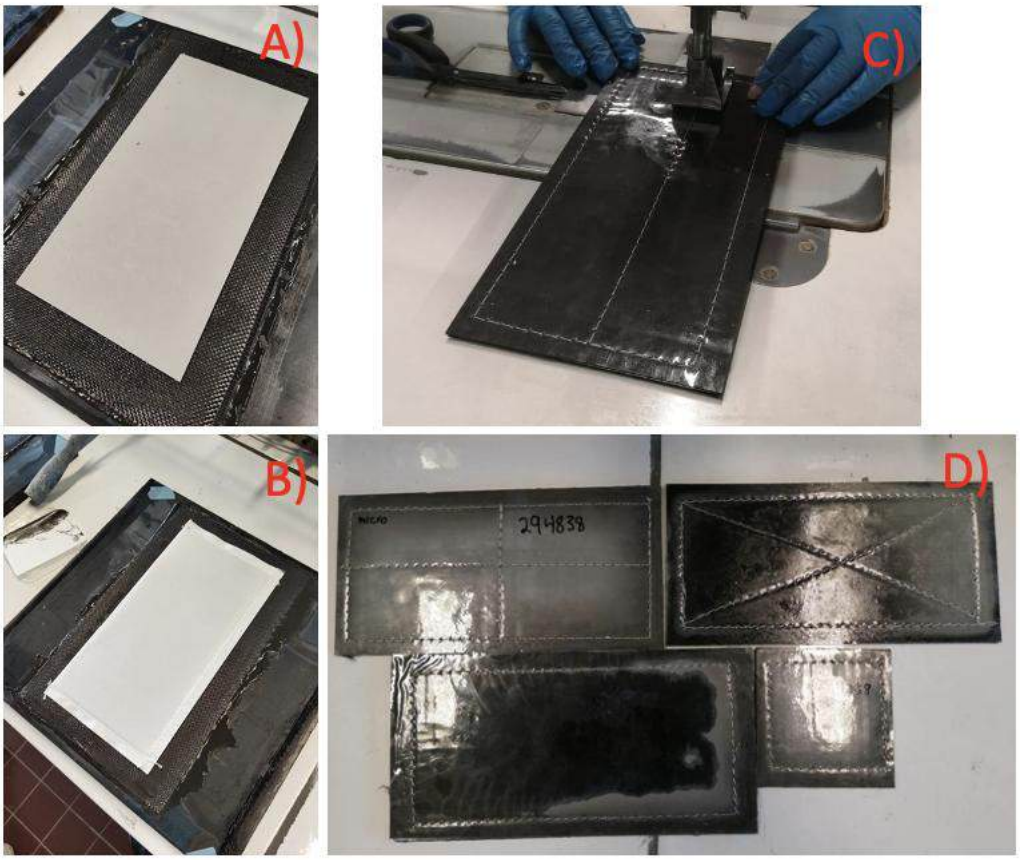


Figure 16. Samples with Promat core: A and B) preparation; C) knitting; D) cured samples

8.2. Trial with commercial copper and graphite layers

Albeit presenting a higher cost in comparison to carbon fiber, some experiments with copper and graphite sheet as skin were performed and it was observed that there was a relatively good adhesion between our actual core and these materials. Experiments with other type of skin should however consider their possible implication in the composite cost. Table 10 is presenting some cost comparison between carbon, copper and

graphite. It could be seen from Table 11 that carbon 400P is one the most cost effective option as skin element constituent.

Table 11. Cost related information of CF400P and some potential materials for the skin

MATERIALS	COST RELATED INFORMATION
Carbon Fiber 400P	15-19 Euro/m^2
Al 600 mm x 600 mm plate (L x W) 3 mm thickness:	19.87 Euro
Cu 300 mm x 300 mm plate (L x W)	0.35 mm thickness: 150.88 Euro 0.45 mm thickness: 21061 Euro
Brass (alloy copper and Zinc) 600 mm x 300 mm plate (L x W)	0.45 mm thickness: 110.57 Euro
Graphite 115 mm x 90 mm plate (L x W)	0.1 mm thickness: 29.46 Euro

8.3. Simulation heat spreader

This simulation of the heat spreader was carried out in the software Comsol Multiphysics V6.1. with the objective of evaluating/analyzing the feasibility of producing a heat spreader capable of keeping the temperature below 80 °C after an exposition for 5 minutes to 700 °C in the case of a thermal runaway in the battery while charging.

The heat spreader is a sandwich panel structure made of two skins and one insulating core. The skins are made of carbon fibers which are impregnated with an inorganic matrix. The core is a combination of glass beads with an inorganic foam. According to the drawing received, one of the skins (or both) would be connected to a heat sink through a feature in the geometry of the sandwich panel. This way part of the heat could be extracted thanks to the high thermal conductivity of the carbon fibers.

8.3.1. Geometry

The geometry of the heat spreader is defined in the drawing provided by Spears dated 13/07/2023 and presented in

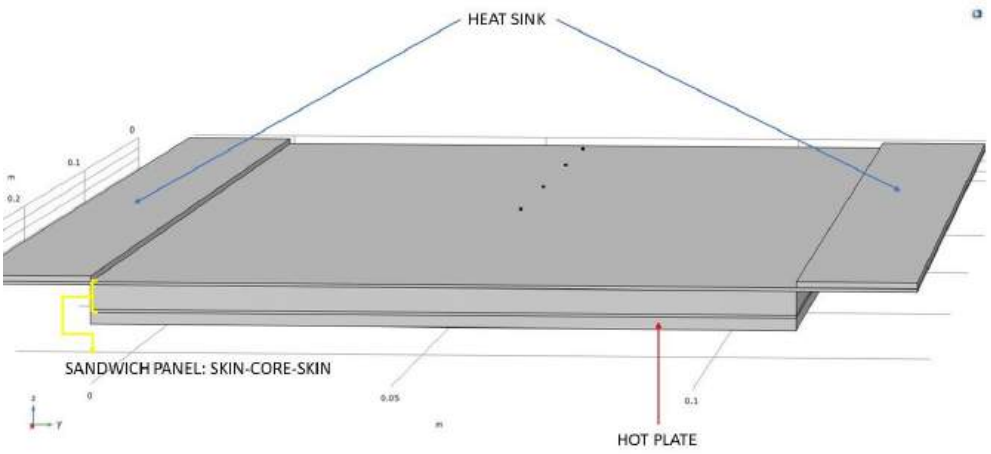
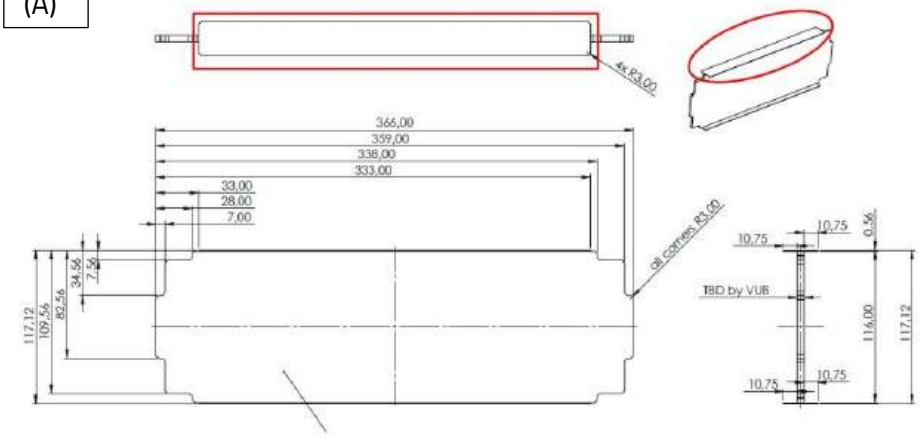


Figure 17a. The features on the composite that connect with heat sink are marked in in red. To simplify the simulation, the geometry was reduced to a simple rectangle the length and width as mentioned in the drawing, being 366 mm and 117.12 mm. The thickness of this element was fixed to 5 mm, from which 4 mm was for the insulating core and 0.5 mm for each skin. Additionally, 3 bodies extra can be seen on the drawing in the simulation, one corresponding to a hot plate or hot side of the battery and the two others which represent the heat sinks. The geometry of the sandwich panel in Comsol Multiphysics is presented in Figure 17b:

(A)



(B)

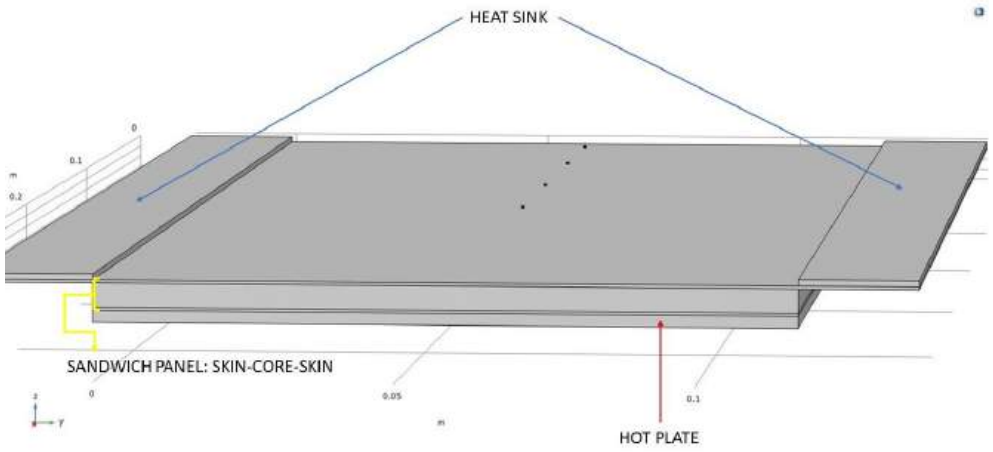


Figure 17. Drawing of the geometry proposed by SPEAR and representation of this geometry in Comsol Multiphysics

8.3.2. Assumptions and parameters

Some parameters were assumed, either to facilitate the simulation or because of the lack of information. These will be explained according to the geometry presented in Figure 17b from the bottom to the top.

▪Hot plate: This item has a fixed temperature of 700 °C, The material selected is copper with a thermal conductivity of 385 W/m K.

▪The skins of the sandwich panels were not defined with predefined material, but parameters such as the thermal conductivity was set at 0.06 w/m K, the heat capacity was 1 J/kg K, and the density was 1.5 g/cm^3.

▪The parameters of the insulation core were also defined manually: thermal conductivity 400 W/m K, heat capacity 0.8 J/kg K and density 0.9 g/cm^3.

▪The heat sinks were chosen to be made of copper with a thermal conductivity of 385 W/m K and a fixed temperature of 20 °C.

▪The system is perfectly insulated in all directions, the only place where there is heat flow is on the top.

▪The contact between the solids (hot plate-sandwich panel and sandwich panel-heat sink) is perfect and the bonding between the skins and the insulating core is also perfect.

▪The heat flowing to the top is released out of the system via radiation and natural convection.

▪The study is defined as Heat transfer in solids and time-dependent.

▪The mesh selected for this simulation was "Fine", this allows getting an accurate simulation without spending too much computational time, otherwise this would be very long and heavy.

▪The objective was also to try different values of the thermal conductivity of the insulating core (λ core) and the conductive skins (λ skins), for these reasons, two parametric sweeps were utilized, the first one varies the λ core from 0.01 to 0.1 with steps of 0.01. The λ skins was studied with the following values: 400, 100, 50, 25 and 5 W/m K.

▪The simulation was run from 0 to 800 seconds with a time step of 1 second.

8.3.3. Results of the simulation

The Figure 18 shows the temperature on the cold side of the sandwich panel after the thermal runaway. The result comes from the parametric sweep of the thermal conductivity of the core. It is noticeable that the heat transfer through the sandwich structure is quick and for thermal conductivities above 0.05 W/m K the cold side of the panel is more than 80 °C.

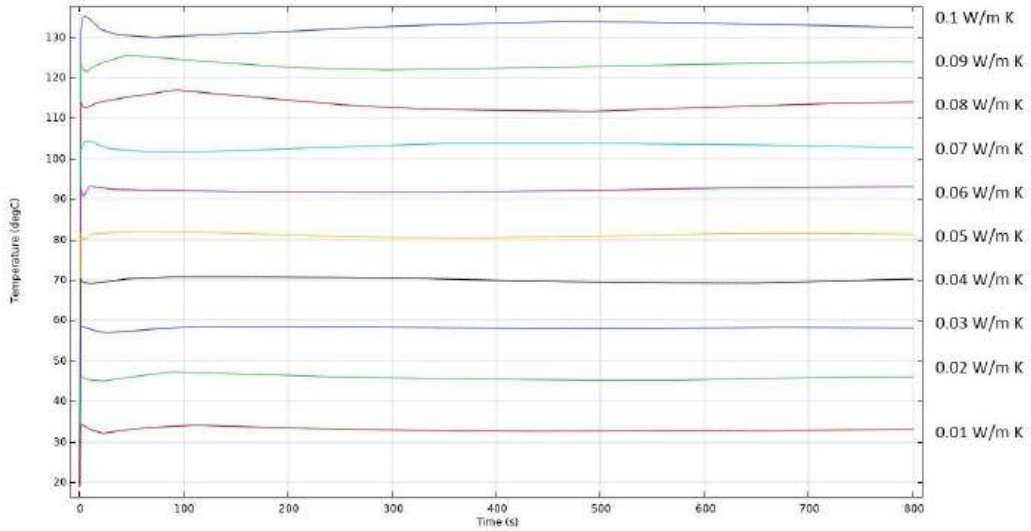


Figure 18. Parametric sweep of the thermal conductivity of the core, thermal conductivity of the carbon fiber layer is 400 W/m K

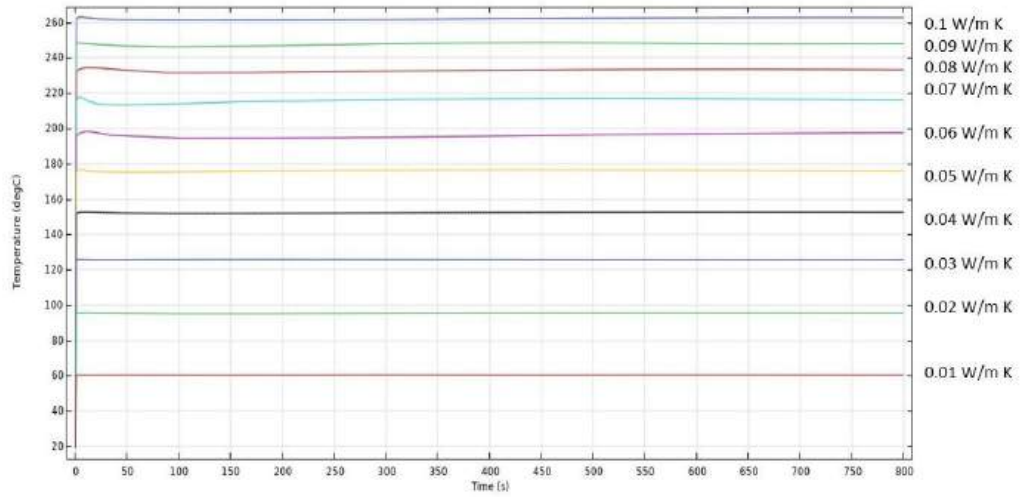


Figure 19. Parametric sweep of the thermal conductivity of the core, thermal conductivity of the carbon fiber layer is 50 W/m K

From the parametric sweeps presented in Figure 18 and Figure 19it is possible to observe how the temperature of the surface changes depending on the thermal conductivity of the carbon fiber layer. The higher the thermal conductivity of this, the more the heat that can be extracted towards the heat sinks. The case where the thermal conductivity is equal to 400 W/m K gives as result that the sandwich panel structure must be built with a material with a thermal conductivity lower than 0.05 W/m K. This is considering that the heat is perfectly removed to the heat sinks which are constantly at 20 °C. In the opposite case, Figure 19 shows that a thermal conductivity of 0.05 W/m k of the core and fibers conducting 50 W/m K leads to a temperature around 180 °C, this makes sense since less heat can be extracted to the sinks.

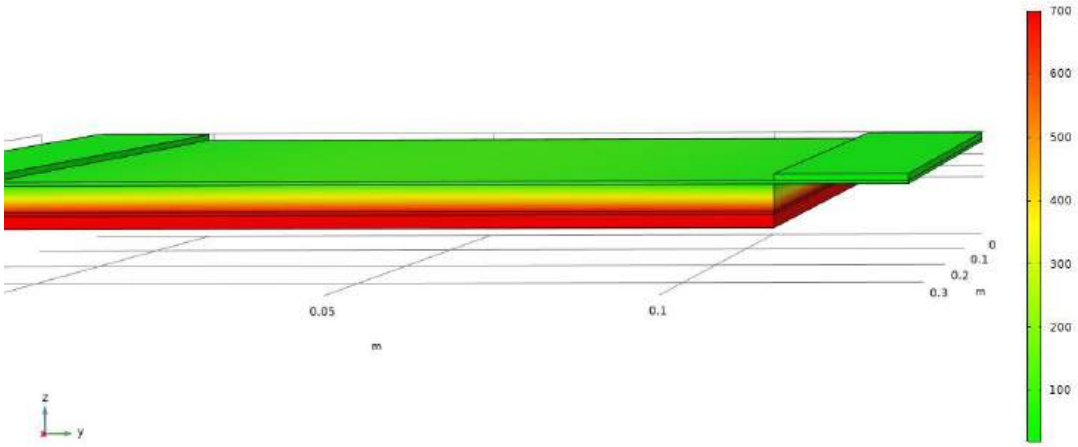


Figure 20. Result of the simulation thermal conductivity of the core is 0.06 W/m K and the thermal conductivity of the carbon fiber layer is 400 W/m K.

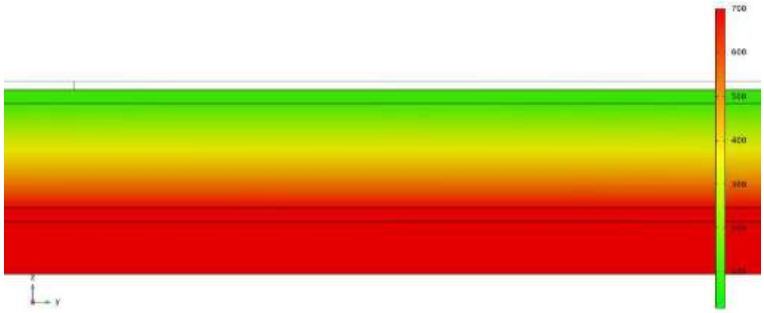


Figure 21. Cross section of the sandwich panel structure. Temperature on the surface 90 °C. λcore= 0.06 W/m.K and λcf= 400 W/m.K after 5 min.

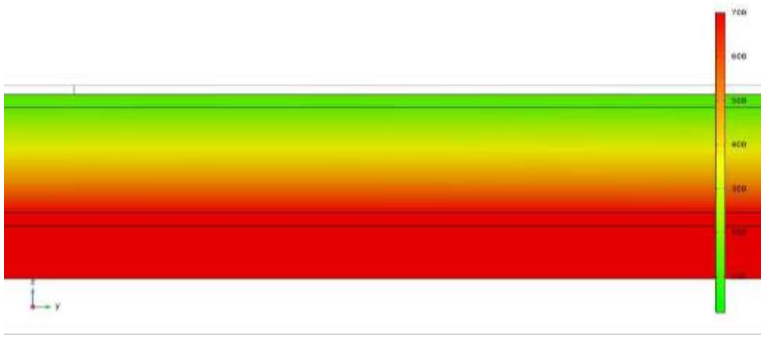


Figure 22. Cross section of the sandwich panel structure. Temperature on the surface 142 °C. λcore= 0.1 W/m.K and λcf= 400 W/m.K after 5 min.

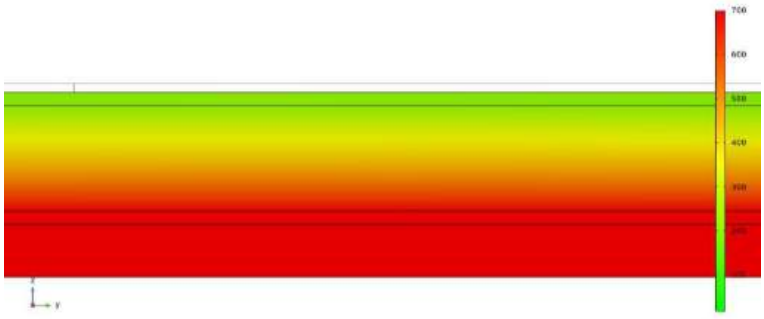


Figure 23. Cross section of the sandwich panel structure. Temperature on the surface 200 °C. λcore= 0.06 W/m.K and λcf= 50 W/m.K after 5 min.

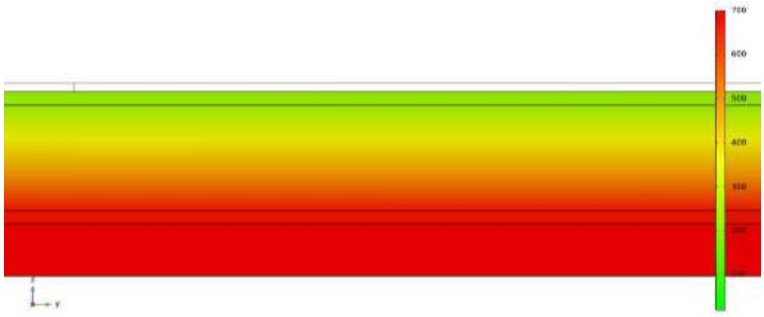


Figure 24. Cross section of the sandwich panel structure. Temperature on the surface 220 °C. λcore= 0.06 W/m.K and λcf= 5 W/m.K after 5 min.

In Figure 21-24, results from different studies are presented. It is possible to observe the change on the temperature on top of the sandwich panel structure. The first run of the simulation where the thermal conductivity for the core is set at 0.06 W/m K and the conductivity of the carbon fiber is 400 W/m K the top surface temperature is 90 °C after 5 minutes of exposition to 700 °C. One specific case was studied to compare the results with the experimental one obtained in the laboratory. For a sample with carbon fiber with thermal conductivity of 400 W/m K and insulation core with 0.1 W/m K, the top surface temperature is 142 °C after 5 minutes of exposition. This temperature is notoriously different from the one obtained experimentally with the infrared camera which was around 300 °C. This can be explained by the fact that experimentally, the heat sinks were not implemented due to the complexity of the setup to test it and the thermal conductivity of

the carbon fiber used to prepare the composites was lower than 400 W/m K. Moreover, the simulation was performed assuming perfect conditions which are different from what could be happening in a real experiment; on the other hand, the cell at the opposite side of the heat source (not present in our lab experiments) will also serve as a heat sink but is not taken into account in the simulations nor in the tests. This will have a positive effect, thus lowering the temperature at the opposite side. Figure 21-24 show the top surface temperature of the composite material in simulations with different conductivities, in summary: Higher thermal conductivity of the carbon fibers leads to higher heat extraction while lower conductivity of the core gives better insulation. Based on the simulations, the requirements could be met with C fibers with 400 W/mK thermal conductivity and an insulating core. In principle, an insulating core (e.g. glass wool 0.033 W/mK) can be found. The C-fibers also exist but could not be ordered due to shortage on the market. They will however be ordered for the final testing, by the subcontractor.

9. RECYCLABILITY INFORMATION

At the end of the life cycle, the sandwich panel could be reused. Alternatively, the panel could be crushed as a whole, or separated into the different layers; the skins could then be crushed to separate matrix and fibers. The fibers might be used as secondhand carbon fibers (market exists), the matrix could be mixed with other (construction and demolition waste) components, molten, quenched and turned into a new precursor for alkali activated cementitious materials. Comparable technology is developed in the ER1-MIN project 'SMARTG"

10. CONCLUSIONS AND PROSPECTS

10.1. Conclusions

Composite Materials with a thermally insulating core and thermally conductive skins were developed. Testing results and observations made during the composite preparation showed that the skin with Carbon fiber of 400 g/m^2 configuration 400 g/m^2 is one of the best options for skin's composite configurations investigated. The composites prepared with this configuration and a core composition with glass beads also meet the composite 's thickness and surface density requirements. However, the flexural strength was too low, but probably this is not important and was a requirement based on the currently used epoxy-glass fiber composites. The in-plane thermal conductance was below the requirement, which can only be improved via C-fibers with higher thermal conductivity, as will be done for the final testing in a module. Meanwhile the cost was significantly higher, due to the use of C-fibers.

10.2. Prospects

The developed composites will be tested after production of a larger amount at a subcontractor.

11. ANNEX

Information on the through and in-plane thermal conductivity test of the reference materials.

11.1. Through plane thermal conductivity

MATERIAL	Standard K value [W/mK]	Average K value [W/mK] (without silicon mat)	Error %	Average K value [W/mK] (with silicon mat)	Error %	COMMENT	RESPONSE
Polystyrene	0.08	0.08	0.62	-	-	Do not use silicon mat.	Do more experiments to validate comments
Nylon 6	0.25	0.25	0.00	0.30	22.4	Do not use silicon mat	Do more experiments to validate comments
Glass	1.00	0.50	49.8	0.94	5.55	Use silicon mat for good contact.	Do more experiments to validate comments
Teflon	0.25	0.38	52.0	0.23	6.00	Use silicon mat for good contact.	Do more experiments to validate comments

11.2. In plane thermal conductivity

MATERIAL	Standard K value [W/mK]	Average K value [W/mK]	Error %	COMMENT	Standard K value [W/mK]	Average K value [W/mK] (comparative study)	Error %	RESPONSE
Nylon 6	0.25	14.49	5696	Change set-up for good results.	0.25	0.26	4.0	Conduct more experiments.
Aluminium	235	90.89	61.32	Change set-up for good results.	235	257.5	9.5	Conduct more experiments.
Copper	370	346.2	6.415	Change set-up for good results.	370	396.9	7.2	Conduct more experiments.

11.3. Annex 1: Calorimetry experiments for chemical reduction in the mix design

We observed that the potassium silicate solution with the silica to potassium modulus (R=2.25) was a promising solution for the composite preparation.

Since the dissolution of Koranel is not total, a calorimetry study was performed on compositions prepared with the selected potassium silicate solution (R=2.25) with different liquid to solid ratios (0.3-1). The investigates compositions are presented in Table 12. Different compositions investigated to estimate the optimum amount of potassium silicate solution to be used.

Table 12. Different compositions investigated to estimate the optimum amount of potassium silicate solution to be used

Liquid Potassium silicate R :2.25/solid mass ratio	K2600 [g]	Potassium silicate solution R :2.25 [g]
0.3	100	30
0.4	100	40
0.5	100	50
0.6	100	60
0.7	100	70
0.8	100	80
0.9	100	90
1.0	100	100

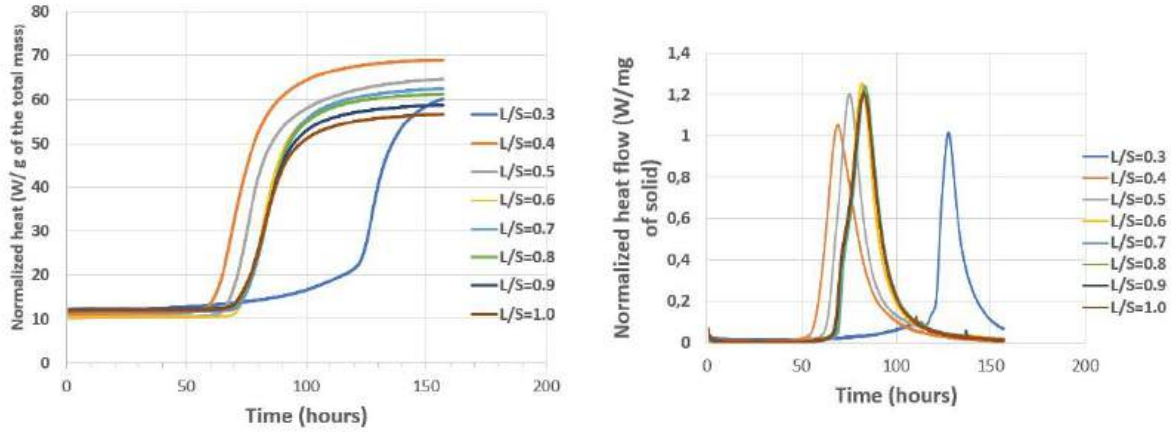


Table 13. effect of the Liquid to solid ratio (L/S) on the calorimetry of Koranel based matrix (L=potassium silicate solution; S=Koranel)

The composition with L/S=0.4 reacted earlier meanwhile the composition with L/S= 0.3 reacted late likely due to poor contact of liquid with solid particles. The effect of adding a moderate amount of water in the system in order to reduce the amount of potassium silicate used was then investigated. The investigated compositions are presented in Table 14. Different compositions investigated to assess the effect of moderate amount of water dilution in the system.

Table 14. Different compositions investigated to assess the effect of moderate amount of water dilution in the system.

Ref	K2600_2012 [g]	Potassium silicate R:2.25 [g]	Water [g]
1) K	100	70	0
2) K_A	100	40	0
3) K_B	100	40	13.5

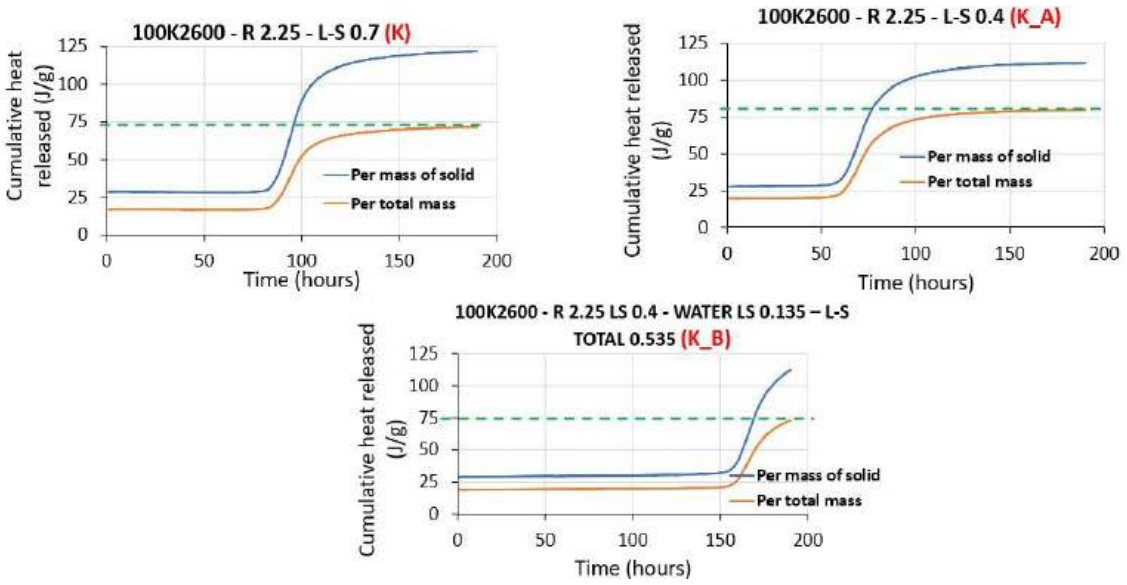


Figure 25. effect of addition of moderate amount of water in the calorimetry of Koranel based matrix

Based on the studies and experiments performed, it could be concluded that and presented in Figure 25:

Adding 10-20 wt% water in Koranel based matrix:

- No reduction of cumulative heat;
- The reaction rate goes down;
- Could help to reduce the amount of potassium silicate added;
- More economic and environmentally friendly composition.

Inconvenient:

- Higher risk for sample cracking and bending during drying;
- More caution needed for a homogenous drying;
- Negatively affect the mechanical properties.