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Bio(and)**C**ircular **I**nsulation for **R**esourceful **C**onstruction

Prototype Deployment Report (UK)

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Review and Input from Bio-Circ Partners

EUROPEAN UNION
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nomadéis

ASBP The Alliance for Sustainable Building Products

thermafleece Nature's finest insulation

backtoearth

Abstract of the project

The BIO-CIRC Project, Bio(and)Circular Insulation for Resourceful Construction, intends to tackle the building sector's high carbon, energy and resources dependencies while taking advantage of an unused waste resource: polyester from waste bedding.

The project aims to conceive, develop and deploy 3 prototypes of innovative low-carbon thermal insulation material made from polyester and combined with natural fibres. It intends to promote the emergence of a bespoke waste polyester valorisation industry and the use of virtuous Natural and Recycled Fibre Insulation products.

This project is carried out by a cross-channel partnership of 4 key and complementary links in the building sector's value chain:

- Nomadéis (lead partner)
- Alliance for Sustainable Building Products
- Eden Renewable Innovations
- Back to Earth

Planned over 2 years, the BIO-CIRC project receives funding from the European Regional Development Fund (ERDF). The ERDF's contribution amounts to €399,600 for a total budget of €499,500.

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Summary

As part of the BIO-CIRC project, the partner Eden Renewable Innovations Limited produced a sample for each of the three prototypes of insulation products. These were made from duvet waste and recycled polyester, as well as from sheep's wool for two of the three prototypes. Then, the prototypes were tested for thermal conductivity, reaction to fire, water activity and hygrothermal properties under the supervision of Nomadéis.

In addition to the initially planned deployments, two prototypes (P2 and P3) were installed in an operational setting in East Grinstead (East Sussex).

Finally, all prototypes performed sufficiently to show good potential as commercial products. The prototypes that contained sheep's wool performed better across all measures and the prototype containing the highest proportion of wool performed the best. The additional deployment in the loft of an existing property in showed that prototypes 2 and 3 could be successfully used in service with no operational issues of concern.

Prototype Description

Four fibre components were utilised to produce the prototypes:

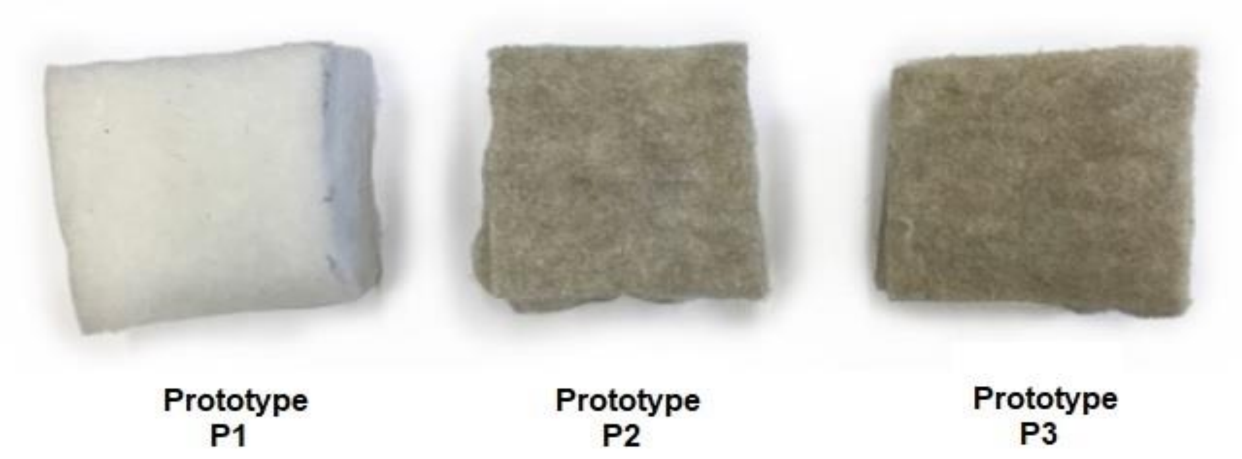
1. Reclaimed and refiberised polyester sourced from waste duvets (**rcPET**) – fibres created by cutting duvets and pulling to open the fibres apart.
2. Scoured sheep's wool (**Wool**) – loose wool fibres that were cleaned and degreased.
3. Recycled polyester staple fibre made from waste polyester packaging (**rPET**) – an extruded fibre created from cleaned waste polyester (PET) bottles and other packaging.
4. Polyester bi-component binder fibre (**bi-co**) – a binder fibre commonly used in non-wovens comprising a high melting point core fibre surrounded by a low melting point polyester sheath that adheres to surrounding fibres.

3 prototypes were produced in line with the prototype concept. The specification of each is outlined below.

Table 1: Prototype composition

	Content (% w/w)			
Prototype	**rcPET**	**Wool**	**rPET**	**bi-co**
P1	65%	-	25%	10%
P2	25%	65%	-	10%
P3	39%	51%	-	10%

Figure 1: Prototypes



Thermal testing

Thermal Conductivity

Thermal conductivity measures the amount of heat transported through a material. This property is largely independent of thickness: measuring this value at a certain thickness provides a value that can relate to a wide range of different product thicknesses. Thermal conductivity defines the U-value of a building element and is the most important property of an insulation product.

Thermal conductivity was measured on a sample of each prototype in line with **ISO 8301:1991** Thermal insulation — Determination of steady-state thermal resistance and related properties — Heat flow meter apparatus.

Samples of insulation (60mm in depth) were tested under the following settings:

Table 2: Thermal measurement settings

Setting	Value
Mean temperature [°C]:	10.1
Mean temperature difference [°C]:	12.12
Density of heat flow rate [W/m²]:	7.599
Setpoint Duration [hours]:	30.33

A single thermal conductivity measurement is insufficient to determine the consistency of the property with respect to multiple samples. It was not possible to conduct multiple measurements. To estimate the likely thermal conductivity, **ISO 10456** was used to determine thermal conductivity value that 90% of production should equal or outperform with a 90% confidence limit.

Table 3: P1 Thermal conductivity

PROTOTYPE 1				VALUES				
Assumed number of Samples	3	4	5	6	7	8	9	10
Tolerance interval coefficient (90%)	2.02	1.92	1.86	1.81	1.77	1.74	1.71	1.69
Estimated Standard deviation	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001
Measured Thermal Conductivity (single sample) (W/mK)	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038
Thermal Conductivity (90/90) (W/mK)	0.043	0.042	0.042	0.040	0.040	0.040	0.040	0.040

Table 4: P2 Thermal conductivity

PROTOTYPE 2				VALUES				
Assumed number of Samples	3	4	5	6	7	8	9	10
Estimated interval coefficient (90%)	2.02	1.92	1.86	1.81	1.77	1.74	1.71	1.69
Assumed Standard deviation	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001
Measured Thermal Conductivity (single sample) (W/mK)	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036
Thermal Conductivity (90/90) (W/mK)	0.041	0.040	0.040	0.038	0.038	0.038	0.038	0.038

Table 5: P3 Thermal conductivity

PROTOTYPE 3				VALUES				
Assumed number of Samples	3	4	5	6	7	8	9	10
Estimated interval coefficient (90%)	2.02	1.92	1.86	1.81	1.77	1.74	1.71	1.69
Assumed Standard deviation	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001
Measured Thermal Conductivity (single sample) (W/mK)	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038
Thermal Conductivity (90/90) (W/mK)	0.043	0.042	0.042	0.040	0.040	0.040	0.040	0.040

Thermal conductivity values indicate that the prototypes will be within the specified thermal conductivity range. This will be contingent on testing more samples and achieving a material consistency to achieve a standard deviation of 0.001 W/mK across results from at least 6 samples.

Hygrothermal testing

Methods

Conditioning

The specimens were unwrapped and transferred to a climate control room with conditions of 23 °C and 50% RH for a minimum of two weeks prior to testing. During this time the mass of random specimens of the samples were measured to ensure stability in mass was achieved prior to testing.

Porosity

ISO 15901-1:2016 was used to demine the **porosity of the specimens** by mercury porosimetry. Mercury Intrusion Porosimetry (MIP) is a widely accepted method for pore size analysis of various materials such as building materials, mainly because it allows pore size/porosity analysis to be undertaken over a wide range of pore sizes from meso- to macropores. A progressive increase in hydrostatic pressure is applied to enable the mercury to enter the pores in decreasing order of width. Accordingly, there is an inverse relationship between the applied pressure and the pore diameter.

The test specimens were all nominally 20 mm x 10 mm x 10 mm and tested using a Thermo Scientific Pascal 140 and Thermo Scientific Pascal 440.

Water Absorption

EN ISO 15148: 2002 was used to demine the **water absorption coefficient** by partial immersion. The water absorption by partial immersion is determined by measuring the change in mass of the test specimen, the bottom surface of which is in contact with water, over a period which is usually at least 24 h.

The test was conducted on two samples for each different material (Figure 1) to investigate the absorption through the 'surface' and through the 'edge' of the material. When testing the 'surface' absorption, three specimens were tested with an exposed area of nominal 100 mm x 100 mm squares with the thickness of the insulation: approximately 50 mm. When testing the 'edge' absorption, six specimens with an exposed surface area of approximately 100 mm x 50 mm (representative of the thickness) and which thickness in this orientation measure approximately 100 mm were used. The sides of the specimens were sealed to prevent bypassing with aluminium tape.

Water Vapour Diffusion Resistance

EN ISO 12572 :2016 was used to determine the **water vapour permeability** of building materials under isothermal conditions. A test specimen is sealed to the open side of a test cup containing either a desiccant (dry cup) or an aqueous saturated solution (wet cup). The assembly is then placed in a temperature and humidity-controlled test chamber. Due to the different partial vapour pressure between the test cup and the chamber, a vapour flow occurs through the insulation materials. Periodic (daily) weighing's of the assembly are made to determine the rate of water vapour transmission.

Six specimens of each insulation material (Figure 1) were tested; three under 'wet' cup conditions and three under 'dry' cup conditions. An aqueous solution of ammonium dihydrogen phosphate was used to give a 93% RH at 23 °C for the 'wet' cup and calcium chloride was used to give a 0% RH at 23 °C for the 'dry' cup. Each assembly was within an environmental chamber at 50% RH at 23 °C. Nominal 100 mm x 100 mm and 50mm-thick squares were used.

Vapour Sorption

EN ISO 12571:2013 was used to demine the **hygroscopic sorption properties** using the climatic chamber method (§7.3). While maintaining a constant (23 ± 0,5°C) temperature, the specimen is placed consecutively in a series of test environments, with relative humidity increasing in stages. The moisture content is determined when equilibrium with each environment is reached. Equilibrium with the environment is established by weighing the specimen until constant mass is reached (two measurements at 24 hours apart with the mass differing by less than 0.1%).

While the specimens' size is not crucial, the specimens were approximately 100mm x 100mm squares with a given thickness of the insulation being approximately 50mm. Prior to testing, the specimens were dried out in an oven at 105 ± 1 °C until constant mass was achieved.

Results

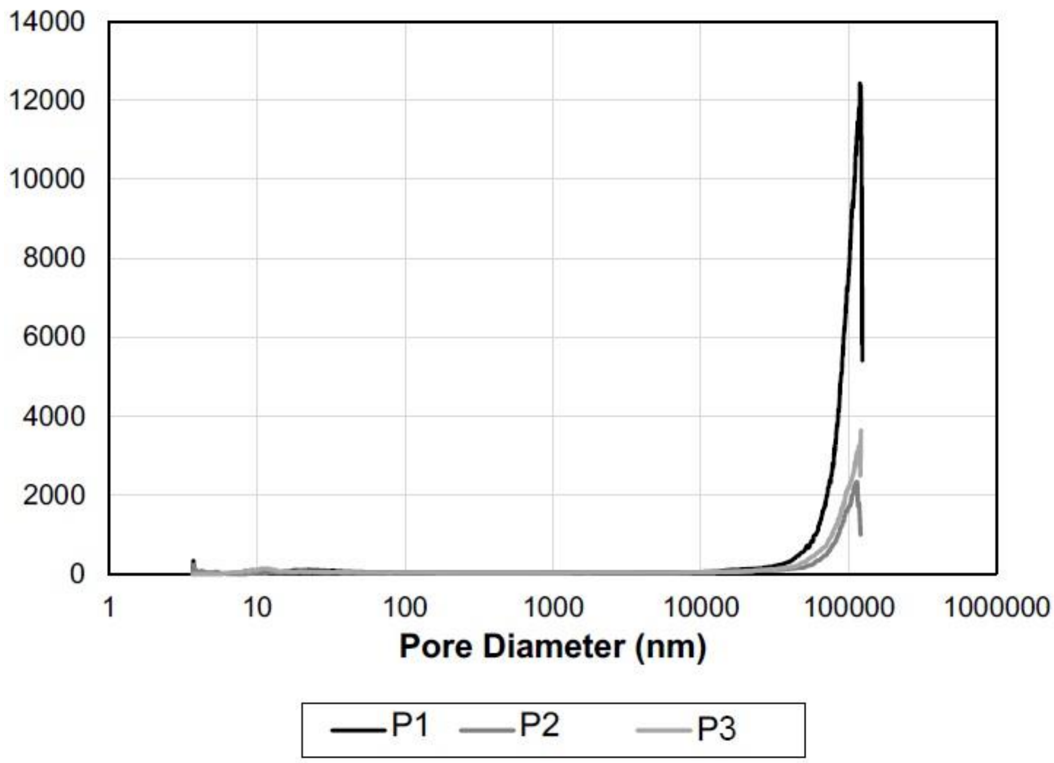
Porosity

The porosity characteristics are provided in Table 6 and Figure 2. As expected from insulation materials, there is a relatively large number of large pores.

Table 6: Porosity measurements

Sample	Porosity (%)
P1	76.30%
P2	45.60%
P3	55.20%

Figure 2: Pore diameter distribution



Water Absorption

The water absorption coefficient as given in Table 7 was based on a 24-hour period. Figure 3 and Figure 4 are assumed to be of Type B, according from ISO 15148. The results show clear anisotropy, likely due to the manufacturing process.

Table 7: Water absorption coefficients

Sample	Average Water Absorption Coefficient (W_w)	
	Surface Water Absorption Coefficient (kg/m² · h^0.5)	**Edge Water Absorption Coefficient (kg/m² · h^0.5)**
P1	0.04	1
Coefficient of variation	8.30%	12.50%
P2	0.46	0.41
Coefficient of variation	13.70%	8.60%
P3	0.22	0.47
Coefficient of variation	10.50%	9.30%

Figure 3: Surface Water Sorption

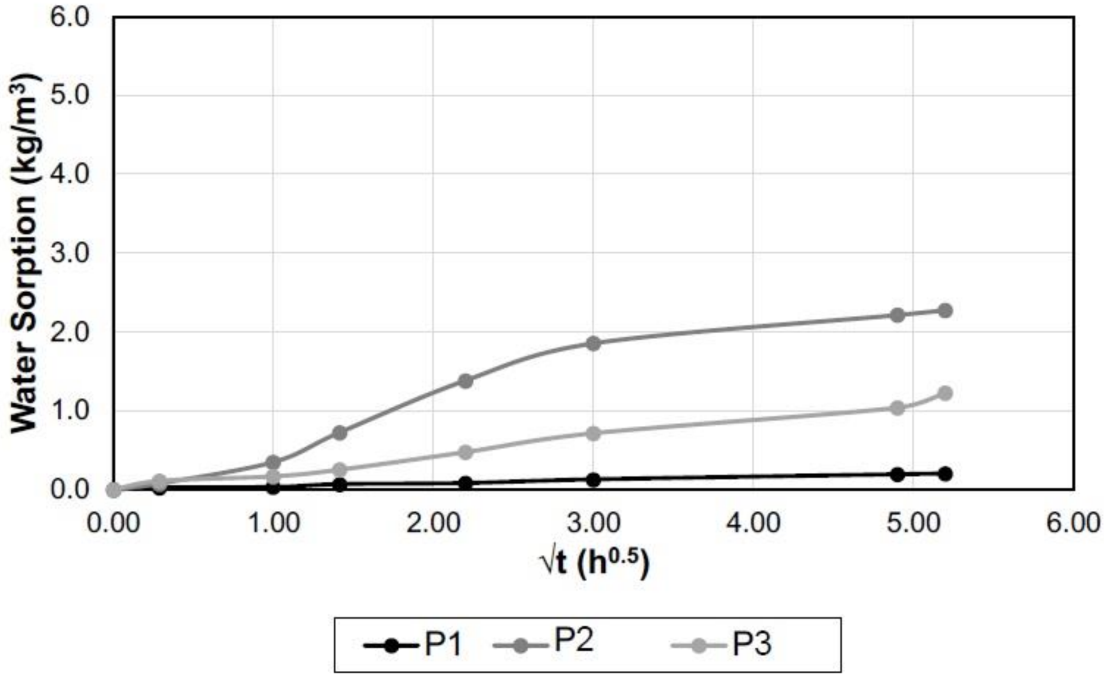
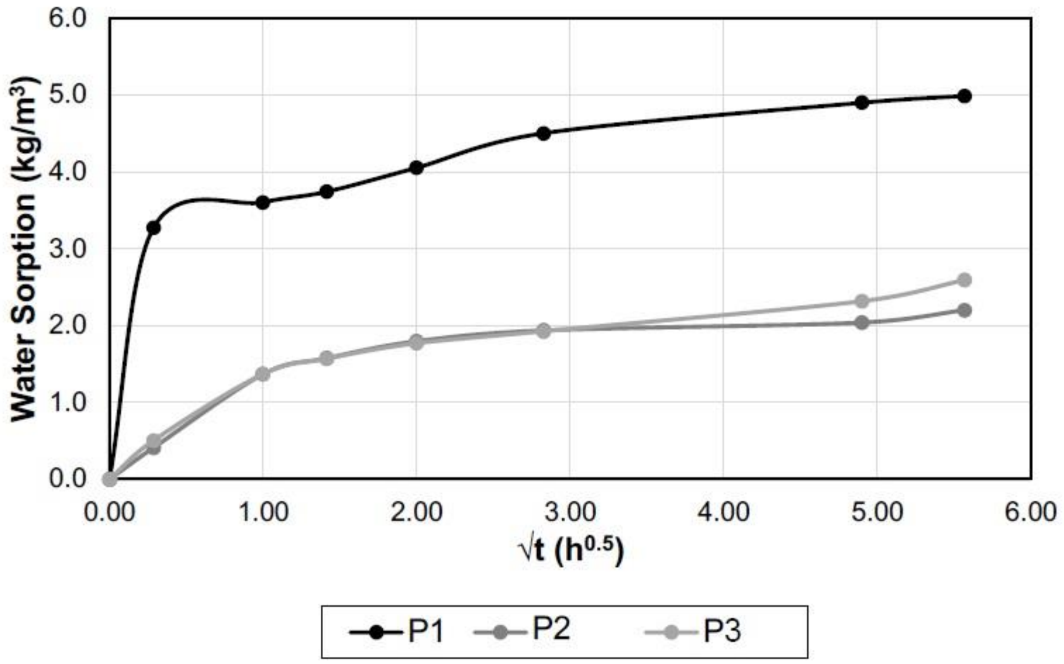


Figure 4: Edge Water Sorption



Vapour Sorption

The hygroscopic sorption properties are provided in Table 8, Table 9 and Figure 5.

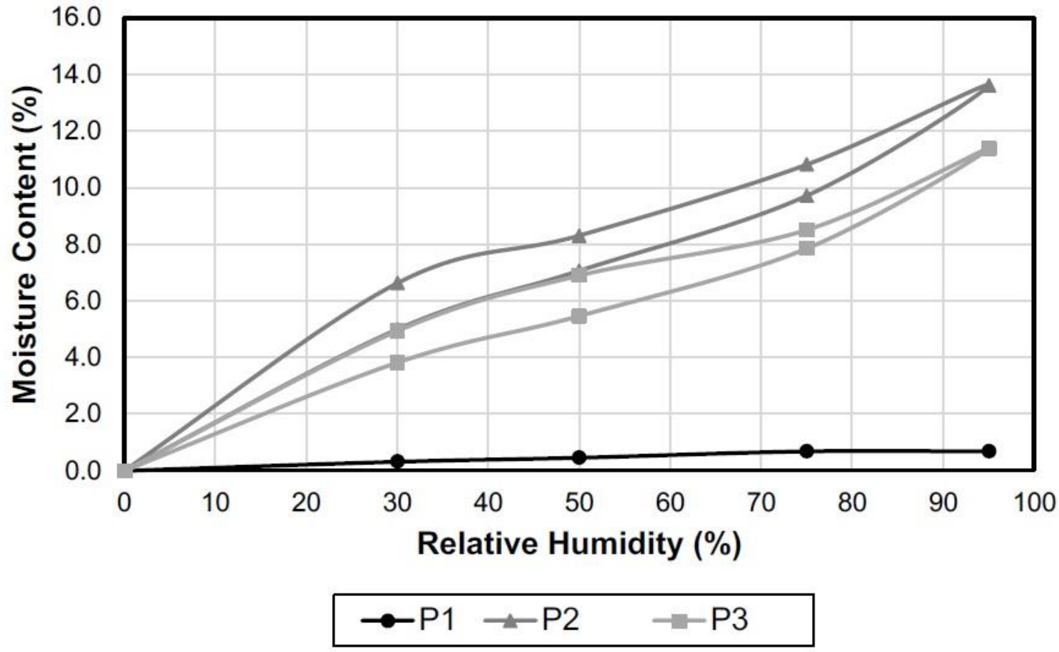
Table 8: Average moisture content of specimens at different relative humidities during sorption.

Sample	**Relative Humidity**				
	0%	**30%**	**50%**	**75%**	**95%**
P1 Coefficient of Variation	0%	0.32% (20.20%)	0.46% (21.80%)	0.69% (18.20%)	0.69% (17.20%)
P2 Coefficient of Variation	0%	4.99% (8.50%)	7.07% (0.50%)	9.72% (0.40%)	13.63% (3.70%)
P3 Coefficient of Variation	0.00%	3.82% (16.80%)	5.47% (8.80%)	7.85% (5%)	11.39% (20.10%)

Table 9: Average moisture content of specimens at different relative humidities during desorption.

Sample	**Relative Humidity**				
	95%	**75%**	**50%**	**30%**	**0%**
P1 **Coefficient of Variation**	0.69% 33.20%	0.69% 33.20%	0.86% 2.30%	0.73% 22.70%	0.00%
P2 **Coefficient of Variation**	13.63% 3.70%	10.82% 2.20%	8.31% 4.80%	6.63% 5.00%	0.00%
P3 **Coefficient of Variation**	11.39% 20.10%	8.51% 1.40%	6.90% 3.80%	4.94% 1.60%	

Figure 5: Sorption Isotherms



Bulk Density

Bulk density (mass per unit volume) is an important property because it influences most of the properties of an insulation material. A consistent bulk density is thus important to ensure consistent performance of an insulation product.

The bulk density (mass per unit volume) was determined in accordance with **EN 1602:2013** Thermal insulating products for building applications – Determination of apparent density. For the purposes of this study, apparent density and bulk density are terms for the same property.

Apparent overall density Pa, is the mass per unit volume of a product, including all surface skins formed during production but excluding any facings and/or coatings.

Table 10: Bulk density

Item	Bulk Density (kg/m3)	Deviation
P1	16	15%
P2	21	15%
P3	18	15%

Water Activity

Water activity (a_w) is the vapour pressure of water within a material, divided by the vapour pressure of pure or salt-free water measured at the same temperature. Pure water has a water activity of 1.0 (100%), so any material containing unbound pure water is likely to have an a_w of 1.0 if the water in the material can evaporate or condense. If a material is capable of binding water, then the vapour pressure exerted by the water within the material is lower than pure water so a_w reduces to below 1.0.

Water activity is a measure of the availability of water for deleterious reactions, metabolic activity, and growth of microorganisms. Different species of microorganisms have different minimum levels of aw that permit growth. The growth of most bacteria and fungi occurs at aw values above

0.90 and if the a_w is below 0.8, then only xerophilic moulds and osmophilic yeasts are likely to grow. For most organisms, too much energy is required to capture water from materials below 0.8.

All insulation prototypes pass through a bonding oven during the final stages of product manufacture. The bonding oven is designed to ensure that a temperature of at least 100ºC is achieved throughout the insulation. As a result, water evaporates from within the insulation. The insulation is then immediately sealed in LDPE packaging, which ensures that the insulation maintains its post-oven moisture content and water activity, until after the packs have been opened.

The relative humidity of each pack of insulation was measured using a relative humidity probe which was inserted into a small hole cut in the packaging.

Figure 6: Water activity measurement

Table 11: Maximum water activity values

Item	Number of Measurements	Maximum Water Activity (a_w)
Prototype 1	18	< 30%
Prototype 2	18	< 10%
Prototype 3	18	< 10%

Reaction to Fire

An ad-hoc **ISO 11925-2** ignitability test was conducted on multiple specimens from each prototype to assess their reaction to fire. This test is used to determine the ignitability of materials (such as insulation) when exposed to direct impingement of flames. It is not designed to measure any other parameter, such as spread of flame.

The specimen (250mm x 90mm) was mounted vertically, and a flame was applied to the lower edge of the specimen. The flame was applied to the bottom edge of each specimen for 15 seconds. The height of the flame tip was then measured: if the flame tip spread more than 150mm above the tip of the flame source, the specimen was deemed to have failed.

Figure 7: Reaction to fire

Table 12: Reaction to fire P1

Prototype 1	**Ignition**	**Extent of flame spread**
Specimen 1	Yes	< 150mm
Specimen 2	Yes	< 150mm
Specimen 3	Yes	< 150mm
Specimen 4	Yes	< 150mm
Specimen 5	Yes	< 150mm
Specimen 6	Yes	< 150mm

Table 13: Reaction to fire P2

Prototype 2	Ignition	Extent of flame spread
Specimen 1	No	< 100mm
Specimen 2	No	< 100mm
Specimen 3	No	< 100mm
Specimen 4	No	< 100mm
Specimen 5	No	< 100mm
Specimen 6	No	< 100mm

Table 14: Reaction to fire P3

Prototype 3	Ignition	Extent of flame spread
Specimen 1	Yes	< 120mm
Specimen 2	Yes	< 120mm
Specimen 3	No	< 120mm
Specimen 4	Yes	< 120mm
Specimen 5	No	< 120mm
Specimen 6	Yes	< 120mm

The above results indicate that the prototype specifications would all be capable of passing an ISO 11925-2 test. This in turn would ensure the insulation would meet a Euroclass E fire classification.

Additional Testing in Operational Setting

In addition to the initially planned deployment tests described above, a complementary testing in the loft of an existing property in East Grinstead (East Sussex) was performed.

The property chosen was a standard brick construction, built in the 1950's. Timber ceiling joists were installed at 400mm centres, and the ceiling was lined with a standard 12.5mm plasterboard. A high vapour resistance membrane was installed over the rafters with clear ventilation around the perimeter.

Three layers of Prototype 2 and three layers of Prototype 3 were installed in different sections of the loft.

Figure 8: Operational loft setting

U-values were calculated for each prototype deployed. U values are as follows:

Table 15: U-value P2

	mm	W/mK	m²K/W	Bridge Details
Outside surface resistance	-		0.04	
Loft Space	-		0.2	
Prototype 2 - unbridged	200	0.04	5	
Prototype 2 - bridged	100	0.04	2.5	11.75%
Plasterboard	12.5	0.17	0.074	
Inside surface resistance	-	-	0.1	
Total Thickness	**312.5**			
U-value (W/m²K)	**0.133**			

Table 16: U-value P3

	mm	W/mK	m²K/W	Bridge Details
Outside surface resistance	-		0.04	
Loft Space	-		0.2	
Prototype 3 - unbridged	200	0.042	4.75	
Prototype 3 - bridged	100	0.042	2.35	11.75%
Plasterboard	12.5	0.17	0.074	
Inside surface resistance	-	-	0.1	
Total Thickness	312.5			
U-value (W/m²K)	**0.139**			

Both values are **below the recommended U-value of 0.16 W/m²K** listed in Part L of the UK Building regulations.

Discussion

The measured thermal conductivity for each prototype was lower than specification. However, predictions for performance at scale indicate that a standard deviation of 0.002 W/mK would ensure that thermal conductivity would be within specification with 90% confidence ($\lambda_{90/90}$). This level of standard deviation provides a target for consistency on scale up. The largest variable influencing standard deviation is density.

Reaction to fire improved with increasing proportions of wool. This is unsurprising given the relatively high ignition point for wool (>600°C). Nonetheless, all prototypes showed the potential to pass fire tests sufficient to achieve the Euroclass E fire rating. Further tests to determine consistency of material across separate production runs would be essential for commercialisation.

From a hygrothermal perspective, performance improved as the proportion of wool in the prototypes increased. Prototype 2 (65% wool) showed better results than prototype 3 (51% wool) although both showed a marked difference with prototype 1 which contained no natural fibres. The difference between P2 and P3 was less marked and the hygrothermal properties of each would be sufficient to class both as breathable insulation.

Deployment of P2 and P3 in an operational setting demonstrated that both prototypes could be handled and installed on site and could perform as well as conventional products. The very low water activity in the insulation packs prior to opening would indicate that the level of microbial activity within the pack would be negligible.

Standards

- **EN ISO 15148: 2002** Hygrothermal performance of building materials and products - Determination of water absorption coefficient by partial immersion.
- **EN ISO 12571:2013** Hygrothermal performance of building materials and products - Determination of hygroscopic sorption properties.
- **EN ISO 12572 :2016** Hygrothermal performance of building materials and products - Determination of water vapour transmission properties. Cup method.
- **ISO 15901-1:2016** Evaluation of pore size distribution and porosity of solid materials by mercury porosimetry and gas adsorption — Part 1: Mercury porosimetry.
- **EN ISO 12572 :2016** Thermal performance of building materials and products. Determination of thermal resistance by means of guarded hot plate and heat flow meter methods. Products of high and medium thermal resistance.
- **ISO 11925-2:2020** Reaction to fire tests – Ignitability of products subjected to direction impingement of flame – Part 2: Single-flame source test.
- **EN1602:2013** Thermal insulating products for building applications - Determination of the apparent density.
- **ISO 10456: 2007** Building materials and products - Hygrothermal properties - Tabulated design values and procedures for determining declared and design thermal values.

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