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Lightweight Eco-composites Based on Renewable Raw Materials

by

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Abbreviations

AD - Anaerobic Digestion
ADep - Abiotic Depletion
CBL - Compression Bonded Loosefill
EPS - Expanded Polystyrene
GHG - Greenhouse Gas
GWP - Global Warming Potential
HDPE - High Density Polyethylene
LCA - Life Cycle Assessment
LDPE - Low density Polyethylene
MAM - Microwave Assisted Moulding
ODP - Ozone Depletion Potential
PE - Polyethylene
POCP - Photochemical Oxidant Creation Potential
PP - Polypropylene

RH - Relative Humidity
RPS - Regular Packing and Stacking
WBF - Wheat Based Foam

Consortium members

BH - Buro Happold
Biffa - Biffa Waste Services
BRE - Building Research Establishment
BU - Brunel University, the leading research partner
CD - Caledonian Ferguson Limited
FE - Foam Engineer
GLP - Greenlight Products Ltd, the leading partner
HG - Heygates Limited
HGCA - Home-Grown Cereals Authority
IC - Imperial College, London
KP - Kingspan Panels
PIRA - PIRA International
SCA - SCA Industrial

Abstract

The aim of the project was to develop novel technologies for industrial production of lightweight eco-composites applicable in many industrial sectors. Wheat flour foam eco-composites are renewable and natural materials which are more sustainable than oil-based plastics. They can be made fully biodegradable and compostable which facilitates waste management by composting and helps reduce waste sent to landfill. A further environmental benefit of using wheat-based eco-composites is that the processing technologies utilise water as both blowing and bonding agents. This prevents the emission of hazardous chemicals that are currently used to manufacture oil-based polymer foams.

Wheat flour-based lightweight eco-composites have good mechanical, thermal insulation and sound barrier properties which may also be improved by: 1) using appropriate additives during extrusion foaming; 2) applying different coatings; 3) lamination of the foams with other renewable materials. Case studies demonstrated the potential of the materials for many applications in construction, packaging and consumer goods sectors including:

- Cool box thermal insulation panels for shipping chilled foods, beverages and pharmaceutical products without using refrigerated vehicles.
- Display boards for exhibitions.
- Cushioning planks/blocks and wrapping sheets in protective packaging.
- Antistatic packaging for electronic products.
- Fugitive foam for void creation in novel cast concrete structures.

In addition, wheat-based foams can be utilised in durable construction applications such as ceiling and partition panels for sound and thermal insulation. These applications require resistance to fire, mould growth and insect attack. The consortium developed a range of treatments suitable for modifying the properties of wheat-based foams used for the above construction applications.

A life cycle analysis study demonstrated the environmental impact of wheat-based foam materials compared with oil-based foams. The results indicated that wheat-based foams have a lower global warming potential than oil-based polymer foams.

By scaling up a novel processing line, the foam manufacturer established preliminary industrial production capacity of the wheat-based foams. In addition, a test-of-market trial of chilled food thermal packaging was successfully carried out.

Currently, wheat-based foams represent over 25% of the loosefill packaging market in the UK. The consortium anticipated that within five years, wheat-based foams will capture 15-25% of the UK plastic packaging and thermal insulation foam markets (worth approximately £50 and £70 million per annum, respectively). This will provide a significant increase in the use of wheat as an industrial feedstock.

Summary

This project took a holistic approach to address the challenges in the development of new wheat-based foams and composites for industrial applications in the packaging and construction industries. These included: 1) R&D in foam processing technology and industrial scale-up; 2) characterisation of foam physical properties (e.g. mechanical, thermal, fire resistance and antistatic properties); 3) characterisation of foam insect and microbial stability (i.e. insect attack and mould growth); 4) enhancement of material properties by inclusion of additives, lamination with other materials or surface modifications; 5) assessment of the performance of prototype products (e.g. cool boxes for thermal and cushion packaging, sandwich composites for ceiling panels and partitioning, fugitive foams for void creation in cast concrete structures); 5) assessment of the environmental impact of wheat-based eco-composites using a life cycle assessment method.

The project enabled in-depth technical understanding of the requirements in design of solutions using new wheat-based foam materials. It was demonstrated that the wheat-based foams and sandwich composites from the foams have many desirable properties comparable to oil-based polymer foams and thus can be used as environmentally-friendly alternatives. These include suitable characteristics for: 1) cushion or protective packaging; 2) thermal insulation packaging for chilled foods or pharmaceuticals; 3) antistatic packaging for electronic products; 4) core in sandwich panels for construction and display boards; 5) water soluble foam for void creation in cast concrete.

Wheat-based foams are suitable for short-term applications due to their water solubility and compostability. Both of these features enable the foams to either be recycled in existing cardboard recycling systems (when combined with paper boards in the form of sandwich panels) or simply composted. For more durable applications, wheat-based foams can be modified by the incorporation of additives or by application of coatings to enhance moisture, insect and mould growth resistance.

Flame tests of the wheat-based foams identified that they give off less heat and smog than equivalent oil-based plastic foams making them relatively safer materials.

A novel process known as regular packaging and stacking was successfully scaled up for commercial production of block wheat-based foams. A technique known as compression bonded loosefill was studied as a complementary technique. This enabled

the establishment of industrial production of an alternative type of wheat-based foam. This paved the way for further commercialisation of novel wheat-based foam materials.

A life cycle assessment study provided useful information on the environmental impact of wheat-based materials with regard to different waste management scenarios. Importantly, wheat-based foam materials were found to have lower abiotic depletion (use of finite resources) and global warming potentials when compared to conventional oil-based plastic foam alternatives. However, it is noteworthy that some monitored categories (e.g. eutrophication) indicated a higher environmental impact for wheat-based foam when compared to oil-based foam alternatives.

1.0 Introduction

1.1 Background

The exploitation of synthetic polymer foams for packaging applications has raised widespread environmental concerns in relation to global warming greenhouse gas (GHG) emissions, waste disposal and depletion of oil resources. As a result, consumers and governments are demanding the use of more environmentally-friendly packaging products.

To address this packaging issue a consortium was formed of both academic and industrial partners. This group, led by Greenlight Products Limited and Brunel University and assisted by government support through the EPSRC/BBSRC LINK-CIMNFC programme, aimed to develop innovative technologies for industrial production of sustainable lightweight eco-composites from wheat, natural fibres (e.g. paper, cardboards and corrugated boards) and biopolymer films.

The feasibility of a novel technology known as Regular Packing and Stacking (RPS) was demonstrated for manufacturing biodegradable Wheat-Based Foams (WBFs). In addition, the potential of two other technologies known as Compression Bonded Loosefill (CBL) and Microwave Assisted Moulding (MAM) were successfully demonstrated for manufacturing bulk WBFs. The breakthrough in processing technology of natural polymer foams and their good environmental credentials attracted interest from diverse UK industries such as packaging and construction.

The distinctive features of WBF composites are:

- The RPS foams are macro-composites consisting of foamed domains enclosed by a three-dimensional network of bonded interfaces that provide reinforcement. Manipulation of the foam cell structure and bonded interface network enables different properties to be engineered into foams (Kang and Song, 2009). High impact resistant foams can be obtained using humidity-temperature treatment to refine the cell structures. In addition, innovative processing technologies are capable of producing different structured WBFs to suit diverse applications and can be fully automated to combine with other surface materials.
- Further improvements can be achieved through design innovation, in joining the composites and applying functional coatings. The foams alone are macro-

composites with an ordered network of bonding interfaces which can be varied to control foam properties.

- When combined with skin layers, WBFs can be made into a wide range of composites to enhance their performance (e.g. water resistance, mechanical properties and printability) and thus expand their applications (e.g. in packaging, thermal/acoustic insulation or light weight structural panels). This enables a new generation of light weight eco-composites to be developed for a much broader range of applications.
- WBFs are based on annually renewable low-cost raw materials and are more sustainable than conventional oil-based plastic foams.
- Novel assembly methods and the use of water as a blowing and bonding agent enables the foam production process to be completely free of hazardous emissions. The technologies used exhibit low energy consumption and produce carbon-neutral composites.
- The materials are biodegradable and facilitate local composting to reduce landfill. Water solubility of the composites means that they can be recycled using current cardboard re-pulping systems without the need for material separation.

Research performed by the consortium paved the way for large-scale commercial exploitation of wheat starch composites and will assist the UK in fulfilling its landfill reduction targets. However, there is a lack of scientific understanding in: 1) the modification of WBF materials; 2) processing control of WBFs and eco-composites; 3) the design requirements of WBF materials and products. Thus a considerable gap exists between the preliminary research and establishment of a critical mass for widespread commercial exploitation. This combination of scientific, technological and commercial exploitation is only possible through the collaborative research efforts to bring value-for-money benefits to the UK packaging and construction industries. Without timely industrial and government assistance, the UK packaging and construction industries are likely to be left behind in competiton with our European counterparts in this strategically important area.

1.2 Overall aim:

The aim of the project was to develop novel technologies for industrial production of lighweight eco-composites applicable in packaging and construction sectors.

1.3 Specific objectives:

- To develop a portfolio of novel composites and products for cushion packaging, thermal/acoustic insulation and structural applications.
- To develop and scale-up lab-proven technologies for industrial production of WBF composites and to promote their application in packaging and construction sectors.
- To understand the processing, structure/property relationships, design requirements, eco-profile, contribution to sustainability and supply chain issues of WBF eco-composites through collaborative research between academic and industrial partners.

2.0 Materials and methods

2.1 Wheat-based foam material property characterisation

2.1.1 Characterisation of mechanical properties

Wheat-based foam samples were conditioned at 25°C and 50% RH for a week before testing in order to achieve consistent moisture content prior to mechanical tests. Tests included: 1) low-speed compression tests using a Hounsfield universal test machine to assess resistance of the foams to compression stress; 2) tensile stretch tests using a specially designed jig to grip the foams; 3) creep (deformation of the foam under constant pressure at 5.5kPa) and cushioning property tests using a standard creep tester; 4) drop weight impact tests (at 600 mm drop height with different weights to measure the effectiveness of cushion materials in absorbing impact energy); 5) bending stiffness tests using a three-point bending test method.

2.1.2 Thermal properties

Thermal conductivities of standard density foams (25kgm^{-3}) were measured with a guarded hot plate tester at the National Physics Laboratory, UK. Higher density foams were measured with a hot disc thermal conductivity tester at Cambridge University.

2.1.3 Acoustic properties

In order to determine the potential for WBFs in applications requiring acoustic attenuation, both CBL and RPS foams of different densities (see table 1.0) were tested for airborne sound absorption coefficient and airborne sound transmission loss coefficient at a frequency range of 50–6,400 Hz in comparison with two commercial polymer foams designed for sound absorption (ET21 and Basotet).

Table 1.0 Foam sound absorption and transmission

Material	Density (kgm^{-3})		
RPS (WBF)	26	-	-
High Density RPS (WBF)	68	-	-
CBL (WBF)	50	86	110
ET21*	19	-	-
Basotect ™ **	8	-	-

*ET 21/250 is a load bearing open cell polyurethane foam.

**Basotect ™ is a specialist open cell acoustic foam made from melamine.

2.1.4 Fire properties

The fire properties of the foams were measured with a cone calorimeter. Ignition time, heat and smog release of the WBFs and composites were compared with Expanded Polystyrene (EPS) and Polyethylene (PE) foams.

2.2 Wheat-based foam modification

2.2.1 Foam density

Foam density is a key factor controlling the mechanical properties of WBFs. For the RPS foams, density was varied between 25 and 500kgm^{-3} using a method developed by Wang (2008) using a combination of humidity treatment and compaction. For the CBL foams, both the wetting and compression pressure were controlled to achieve densities between 30 and 300kgm^{-3}.

2.2.2 Water and microbial sensitivity

WBFs are inherently moisture sensitive and prone to microbial attack which is a helpful feature for short-term applications that require biodegradability such as loosefill packaging. However, moisture resistance and microbial stability are essential for more durable applications such as building and construction products.

A number of proprietary polymer additives were incorporated during extrusion foaming. Water resistance of the loosefill foams was then assessed by monitoring the change in compressibility of the foams at different humidities (research performed by SCA).

In order to test the microbial sensitivity of WBFs, a fungicide (Na-PYRION 40 wt%, Janssen Pharmaceutica NV, Belgium) surface coating treatment was applied. Mould growth was monitored at BRE in an environment chamber (20 days at RH 65-70% and 20-22°C) to visually assess the effect of fungicide treatment in comparison to untreated foam samples.

2.2.3 Insect resistance

Resistance of the WBFs to insect (flour beetle) attack was studied by incorporation of a diatomaceous earth (a natural insecticide supplied by Pest Control Direct Ltd., UK), and a pesticide called XAMOX (Neo-nicotinoid supplied by Janssen Pharmaceutica NV, Belgium) during foam extrusion. The materials were then placed in incubator chambers (set at 26°C and RH 70%) each containing 20 flour beetles in a laboratory at Imperial College. Mass change in the samples was recorded by weighing the materials before and after four weeks of insect exposure (the effect of moisture absorption was subtracted). Comparisons were made with untreated foams.

2.2.4 Fire resistance

The WBFs and composite materials were spray coated with a proprietary inorganic chemical agent to enhance their fire resistance. Fire properties were then assessed as described in section 2.1.4.

2.3 Development of sandwich composites

Significant improvements in the mechanical properties of WBFs can be achieved by sandwiching foams between other bio-based materials such as paper or cardboard. Properties that can be improved include: 1) bending stiffness; 2) puncture resistance; 3) protection of the foam core from direct water attack.

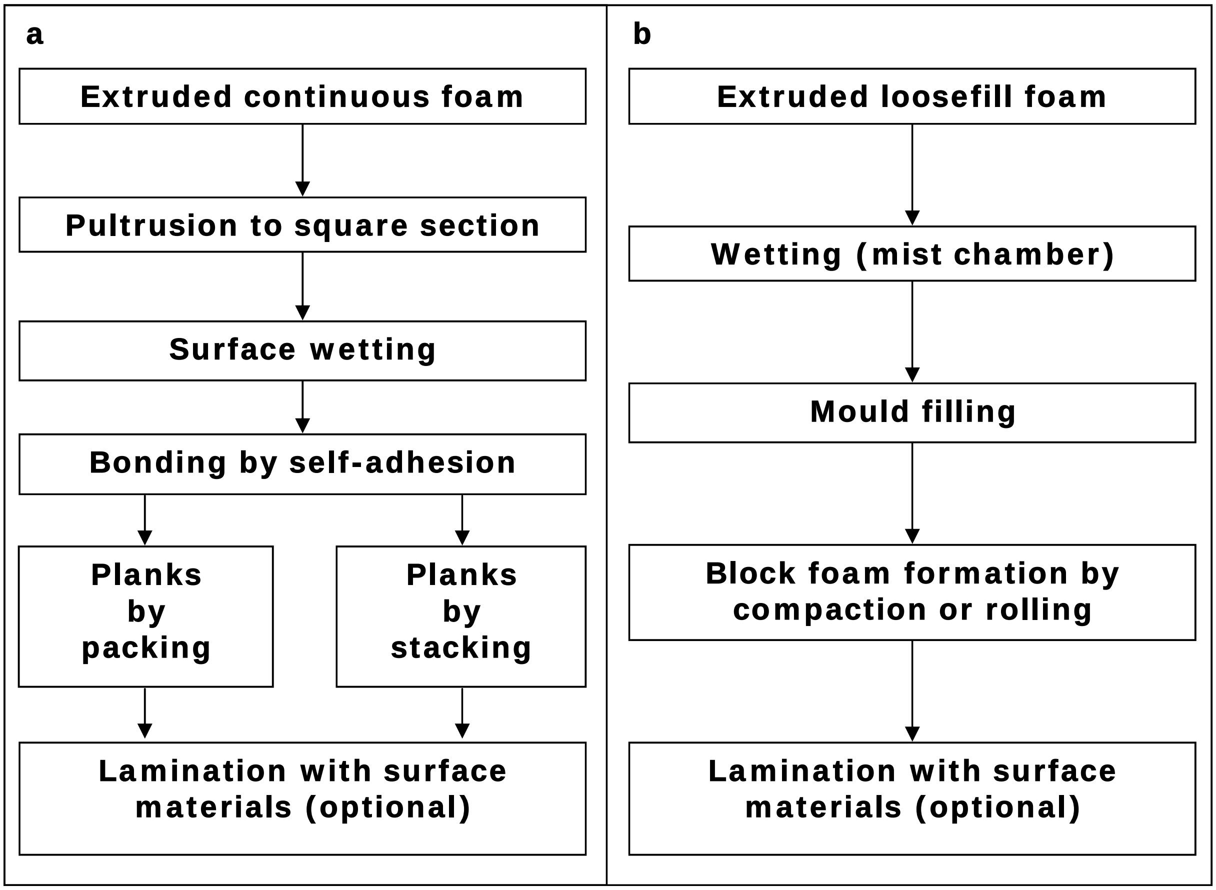
The WBFs were combined with cellulose surface materials including speciality papers, corrugated boards, paper honeycomb boards and fibre boards. The work focused on assembly and adhesion bonding of sandwich panels with different materials. These materials were then assessed for their performance with regard to mechanical properties such as bending stiffness, edge crush, puncture resistance and thermal properties (e.g. heat conductivity and fire properties such as ignition time, heat and smog release).

2.4 Development of wheat-based foam processing technologies

The development of the Regular Packing and Stacking (RPS) process, capable of making unique macro-composite foams, capitalised upon the experience learned from our earlier work (Kang and Song 2009). The main focus of the work was on matching the processing speed with that of the existing extrusion foaming production line and developing a downstream process for handling broad multi-layer planks and laminating skin materials (see figure 1.0a).

Development of the Compression Bonded Loosefill (CBL) technology (see figure 1.0b) focused on the automation process to convert wheat-based loosefills into light weight foam planks. Particular attention was given to achieving uniform and consistent foam structure by controlling wetting and bridging of loosefills to prevent large voids. Industrial expertise within the consortium assisted in liquid spray coating, handling of loosefills, rolling/compression and conveying equipment.

Figure 1.0 Wheat-based foam production



(a) RPS and (b) CBL processes.

(a)

The conversion of WBF blocks into packaging solutions (e.g. cushion packaging) was performed using die cutting, hot wire cutting and vibration wire sawing. This study was performed by FE and CD, the foam converters.

2.5 Product design and evaluation

A range of products, using the WBF and eco-composite materials, were designed, prototyped and evaluated through industrial trials. These included: thermal/cool boxes for storage and/or transport of goods; cushion packaging panels/containers and panels for structural/insulation applications. Case studies on cool boxes are given below in more detail.

To assess the thermal insulation performance of cool boxes constructed from WBF materials, a like-for-like comparison (based on identical thickness of the insulation layer) was made with EPS and PE foams. Three cool box types (A, B and C) were prepared and tested under service conditions (see below).

2.5.1 Type A cool box

The type A cool box was a simplified case without refrigerant. Two identical cool boxes were constructed with WBF and EPS panels. The outside dimensions of the boxes (as shown in Figure 2.0) were 170x170x188mm (WxDxH) designed to accommodate four 495ml cans of distilled water (to simulate beverages).

Figure 2.0 Experimental setup for type A coolbox

a b c

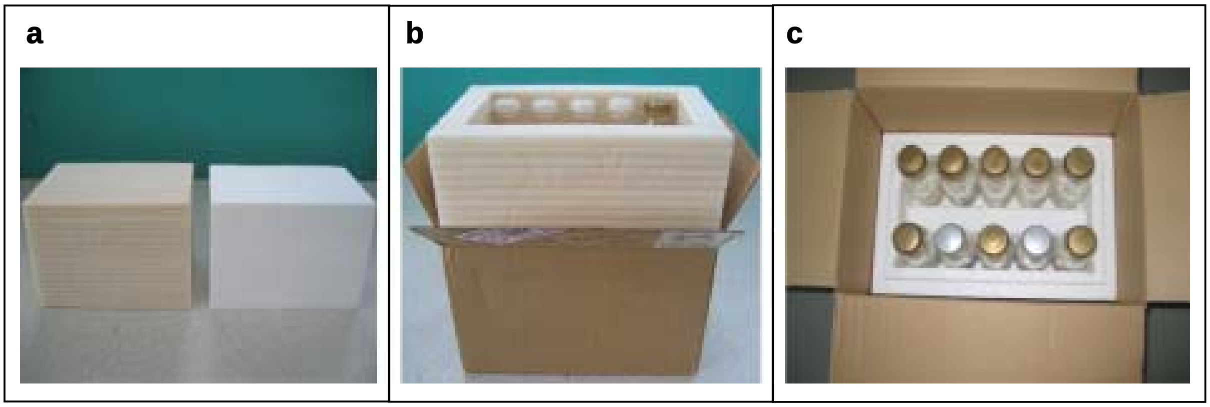
Cool box made from WBF (a); WBF cool box with water samples present (b); WBF and EPS cool boxes under temperature monitoring (c).

A 16 channel data acquisition system (model 7320 + 7020, Measurement Systems Ltd, Berkshire, UK) was used to monitor the temperature at six positions within each cool box using 'T-type' thermo-couples. Three thermo-couples were mounted with a copper/aluminium adhesive tape on the surface of the can (top, middle and bottom). The fourth was submerged in the water and the fifth was suspended in the central air pocket within the box. The sixth was placed outside the box to monitor the ambient external temperature. The water in the cans was chilled to 0.7°C using a Norpe refrigerator (Norpe, Stockport, UK) and transferred into the cool boxes. The cool boxes were then sealed and the test was carried out in a 5x3x3.5m conditioning chamber (Cryotec cold room, London, UK) set at 25°C and RH 50%. Temperature-time data was recorded over a 12 hour period.

2.5.2 Type B cool box

The type B cool box was based on an EPS cool box design packed with refrigerant currently used for mail delivery of chilled beverage samples (see figure 3.0).

Figure 3.0 Structure of type B cool box



WBF and EPS thermal insulation case (a; left and right, respectively); WBF casing in cardboard outer packaging (b); packed samples (c) without refrigerant or WBF cap.

The type B WBF cool box (see figure 3.0) replicated the current design used by Innocent Drinks Ltd. This design consists of a thermal insulation case made from EPS inserted into a corrugated cardboard box. The exterior dimensions of the cool box were 344x224x224mm (WxDxH). The wall thickness of the insulation was 36mm. The inner cavity was 272x152x152mm (WxDxH) suitable for packing five beverage bottles (250ml each) on each side of a bag of refrigerant located in the central slot. The specifications for the cool box required that chilled samples (to ~0.7ºC) should be maintained below 5ºC during a 12 hour dispatch period.

For the purposes of temperature monitoring, the beverage samples were replaced with distilled water chilled to 0.7ºC using the Norpe refrigerator. The bottles were then packed into the cool boxes together with a 475ml refrigerant pack (Innocent Drinks Ltd) pre-frozen overnight to -20ºC in a freezer (Foste, Norfolk, UK). A total of eight thermo-couples were used to monitor temperature changes at different positions in and around the cool box. The cool box was maintained at 25ºC and RH 50% as for the type A cool box (see section 2.5.1).

2.5.3 Type C cool box

The type C cool box (see figure 4.0a) was based on a current 8.5 litre capacity commercial PE foam cool box (see figure 4.0b) used by supermarkets. The WBF and PE cool boxes

Figure 4.0 Structure of type C cool box

a **b**

WBF type C cool box (a) with refrigerant packs; PE foam type C cool box (b).

were constructed with 26mm thick WBF or PE foam insulation (Hydropack Ltd; see figure 4.0a and b). Food samples (cheese) were chilled to 0°C and packed into the WBF and PE cool boxes with a frozen refrigerant pack on top of the samples. Temperature recording tags (Tini Tag , Hydropack, UK) were embedded into the food and placed in the corner air gap. The temperature was then monitored over a 25-hour road transport trial.

2.6 LCA, waste management and the supply chain

The environmental impacts of WBF material production, use and disposal were scrutinised using an auditing technique called Life Cycle Assessment [M1](LCA). This provided environmental information for each material production and use step ranging from fertiliser manufacture, crop production, WBF manufacture and conversion, end-use and end-of-life disposal. The aim of this was to establish appropriate infrastructure for management of foam material production, use and disposal as a means to ensure the use of more sustainable processes and materials.

2.7 Commercial exploitation

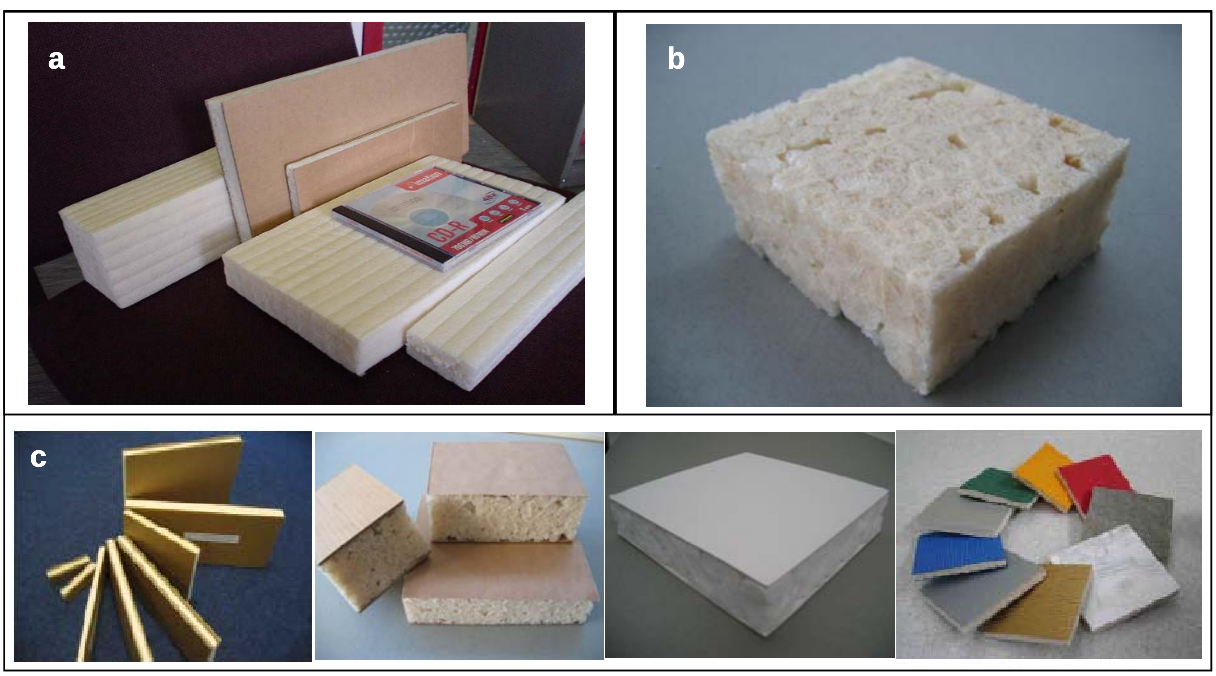
In addition to the study of WBF performance, the consortium examined the commercial exploitation potential of the WBF materials in terms of: 1) market place for WBFs in packaging and construction sectors; 2) potential product applications based on case studies in cushion and thermal packaging, ceiling/partition panels and void creation in cast concrete; 3) supply chain from raw material to manufacture and conversion of the foams including use and disposal of the materials; 4) cost analysis of materials and processing.

3.0 Results and discussion

Key technical achievements are given as an overview against the specific objectives. Only key findings are summarised from the commercially sensitive industrial R & D activities; some key findings are presented as highlights and more details can be found in the technical reports attached in the appendix (see section 6.0).

Examples of WBF and sandwich composites are shown in Figure 5.0.

Figure 5.0 Wheat-based foam and sandwich composites



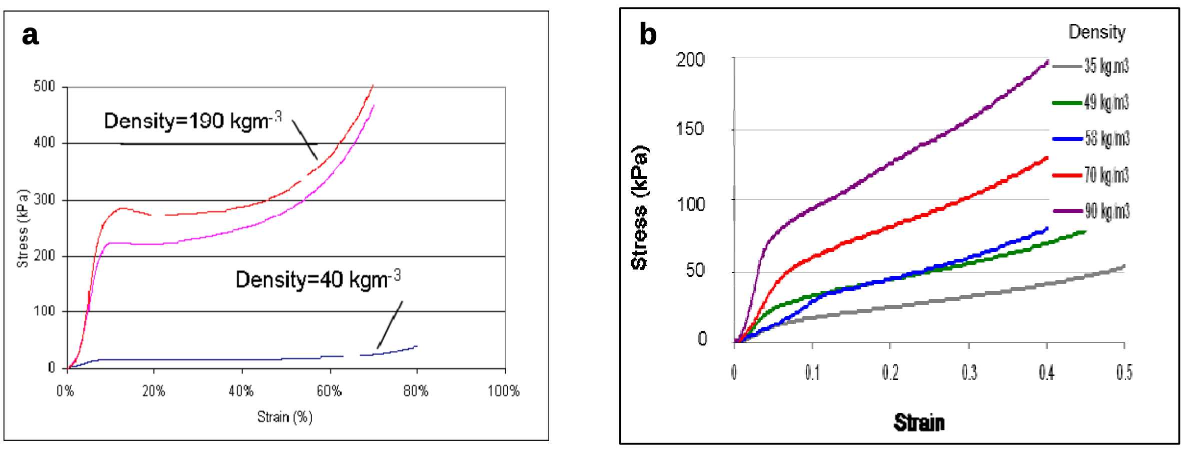
(a) RPS foam blocks; (b) CBL foam block; (c) WBF/paper sandwich composites.

3.1 Wheat-based foam material characterisation and modification

3.1.1 Compression/tensile properties

Wheat-based foams were tested for their suitability for cushion packaging by measuring their compression performance. As shown in figure 6.0, resistance to compression stress can be effectively increased by raising the foam density of both RPS and CBL foams. This means that high density WBF foams (190kgm^{-3} RPS and 90kgm^{-3} CBL) may be suitable for cushion packaging applications.

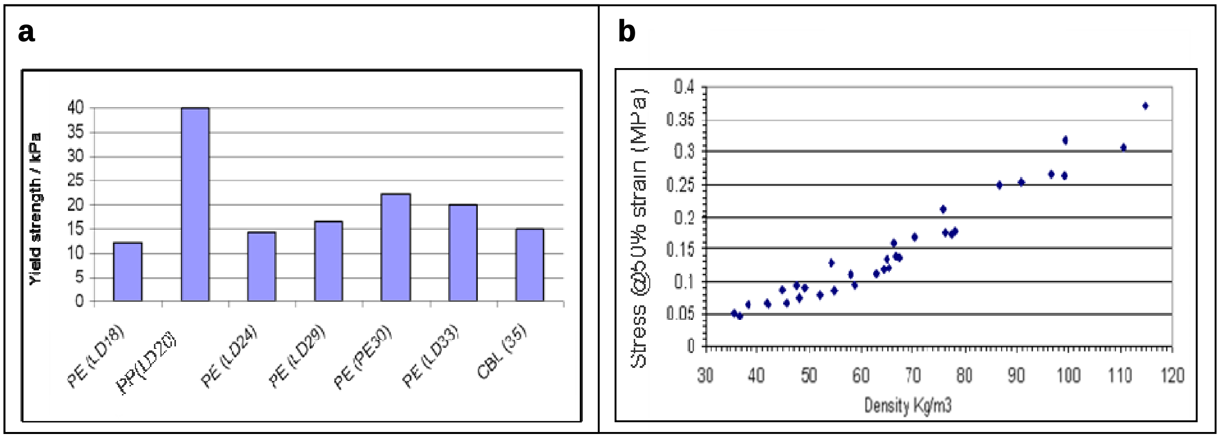
Figure 6.0 Wheat-based foam compression resistance



(a) RPS type foams; (b) CBL type foams.

Yield strength tests were performed on CBL, PE and PP foams of different densities in order to determine the pressure at which cells within the foam start to collapse. This is a standard test used to determine the viability of foams in cushion packaging applications. Figure 7.0a shows that low density CBL foam (35kgm^{-3}) has similar yield strength to PE foams of a similar density (24kgm^{-3}).

Figure 7.0 Foam yield strength and strength at compression



WBF, PE and PP foam yield strength (a), key: LD24 – low density $24 kgm^{-3}$; compression strength (at 50% compression) of CBL foam at different densities (b).

Compression strength tests were also used to determine the efficacy of WBFs in cushion packaging. Figure 7.0b shows that the strength of RPS/CBL foams increases with density. WBFs are much weaker under tensile loads when compared with most oil-based polymer foams of similar densities (data not shown). However, WBFs are intended for compressive loading in most of their targeted applications.

3.1.2 Sound damping behaviour

The acoustic properties of RPS and CBL wheat-based foams were compared with two commercial oil-based foams. Figure 8.0 shows that both RPS and CBL foams have lower sound absorption coefficients (α) when compared to conventional melamine foam.

Figure 8.0 Wheat-based foam sound absorption

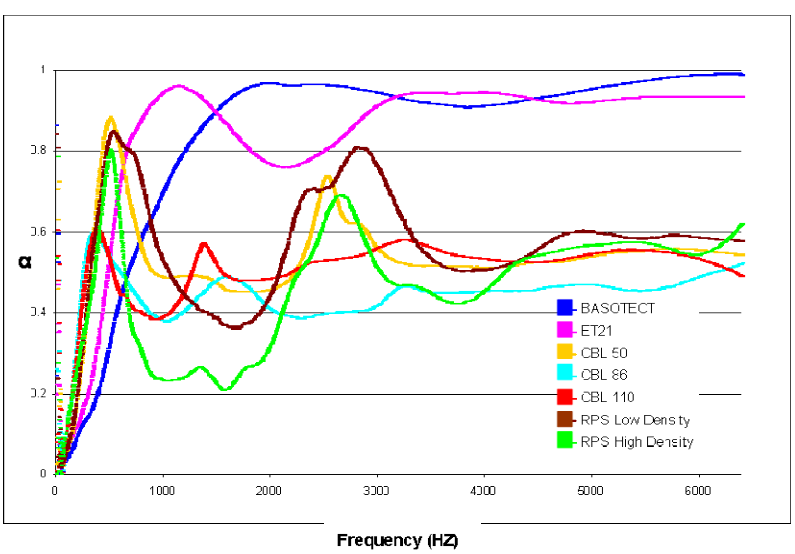


Figure 9.0 shows that the WBF materials perform well in sound barrier tests. This is exemplified by the higher sound transmission loss of both RPS and CBL foams when compared to conventional oil-based polymer foams. This suggests that WBFs may be suitable for sound barrier applications in music recording studios.

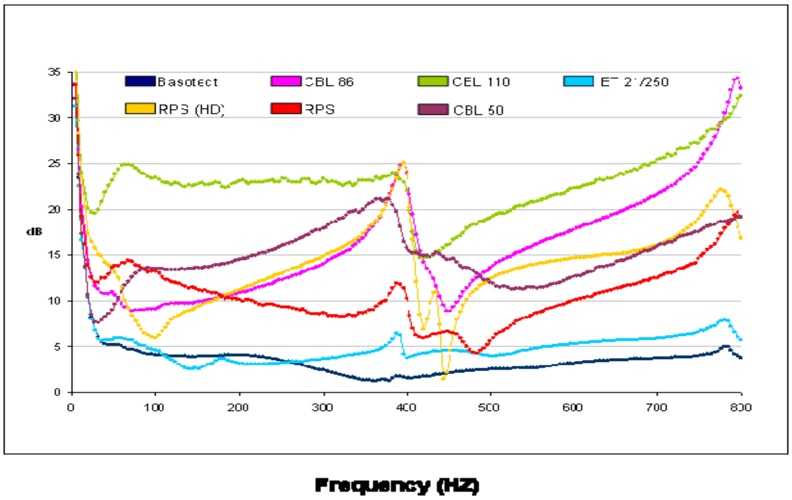
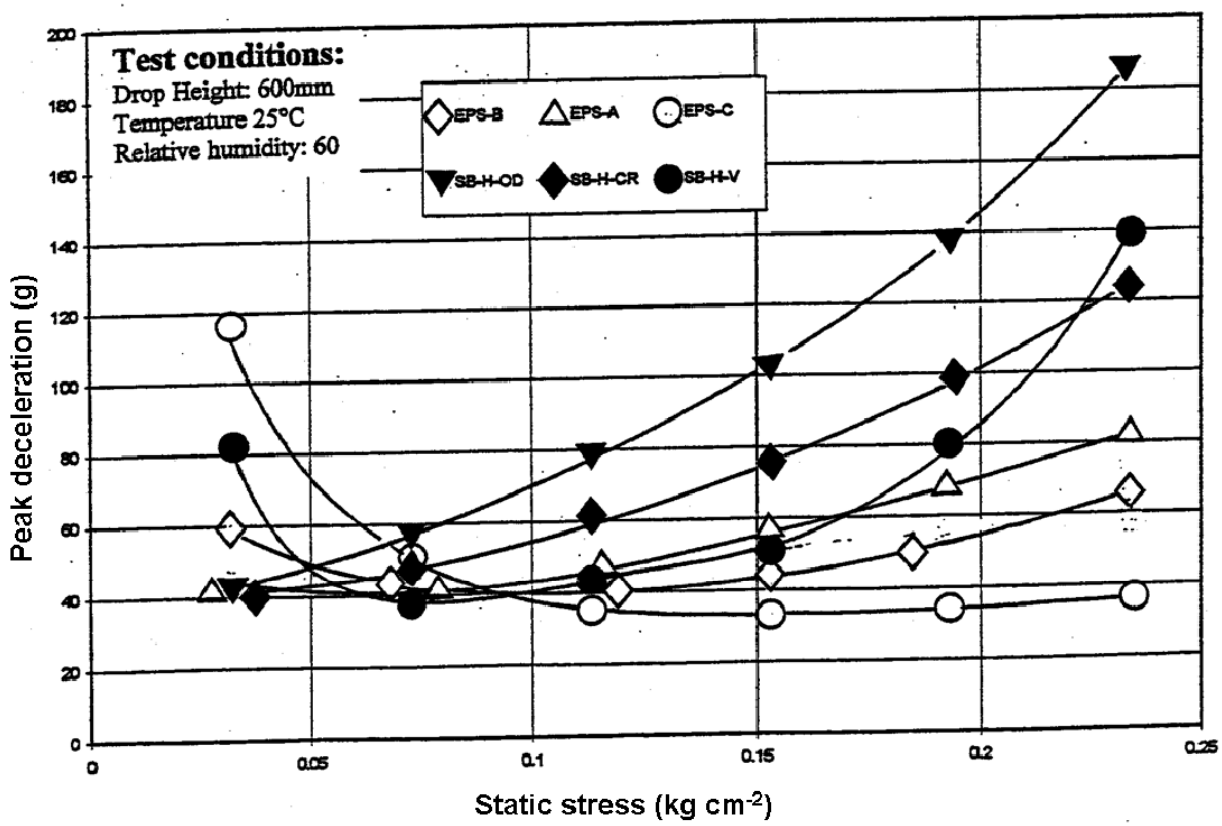


Figure 9.0 Wheat-based foam sound transmission

3.1.3 Drop weight tests

In drop weight tests RPS and CBL WBFs exhibited good energy absorption (shown by low peak deceleration upon impact) during dynamic impact tests for cushion packaging. The results in figure 10.0 show that low-density RPS foams (i.e. soft foam) can match the cushion performance of EPS foams. Clearly, there is scope for improvement of the cushioning performance of RPS by varying the foam density.

Figure 10.0 Foam cushion performance

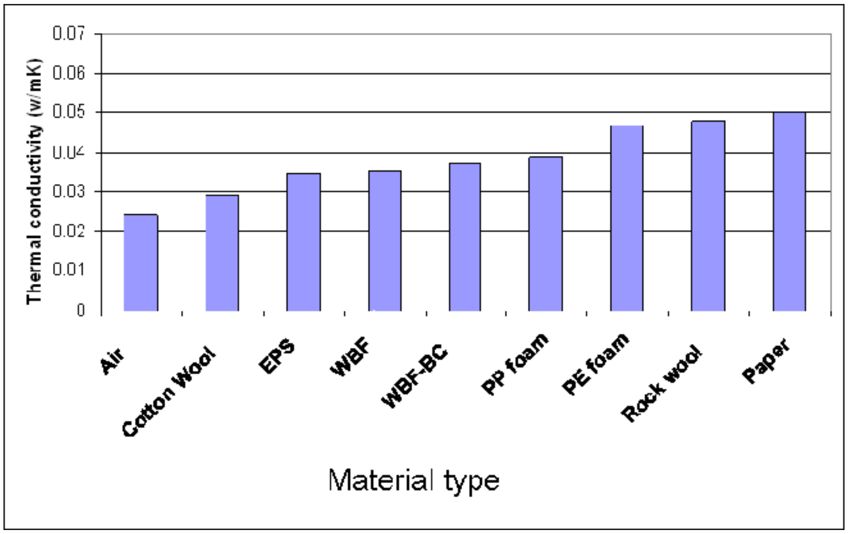


RPS foams: ▼23kgm^{-3}, ♦ 23kgm^{-3} and ● 31kgm^{-3}; EPS foams: △10.1kgm^{-3}, ◇15.4kgm^{-3} and O 25.5kgm^{-3}. The drop weight impact curves show peak deceleration of the weight on impact with the foams at different stress levels (lower peak deceleration means better energy absorption).

3.1.4 Thermal insulation performance

One of the properties required of foams used for cool box and building insulation is low thermal conductivity. To this end, RPS foams of different density were tested for their thermal conductivity. Results indicated that RPS foam thermal conductivity increases with foam density (data not shown). A comparison of RPS foam with other oil-based polymer foams (at densities of 25kgm^{-3}) indicated that WBFs have insulation properties comparable and superior to EPS and PE foams, respectively (see figure 11.0). WBFs may provide a good bio-based alternative thermal insulator to conventional oil-based plastic foams.

Figure 11.0 Foam thermal conductivity

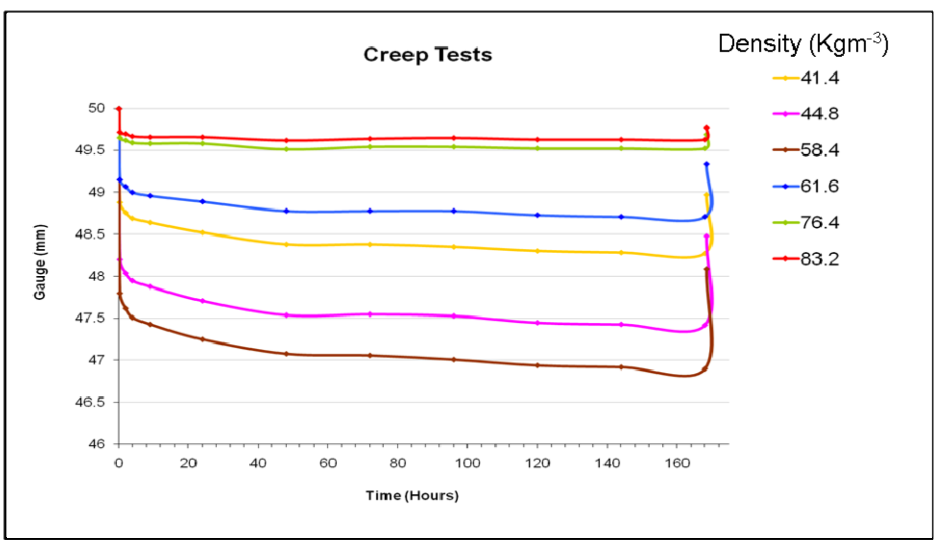


Thermal conductivity comparison of WBF and oil-based polymer foams at a density of 25kgm^{-3}. WBF-BC - sandwich board with WBF core and corrugated board skin.

3.1.5 Wheat-based foam creep behaviour

Creep at a low constant load affects the deformation of packaging foams. Excessive creep will result in loosening of packed products. CBL samples at different densities were tested under constant load at 5.5kPa, RH 50% and 23°C. Creep behaviour of the WBFs was found to be acceptable for packaging applications at moderate humidity (see figure 12.0). Higher density foams may be selected to reduce creep where it is critical to secure positioning of packed products.

Figure 12.0 Creep behaviour of CBL type wheat-based foams



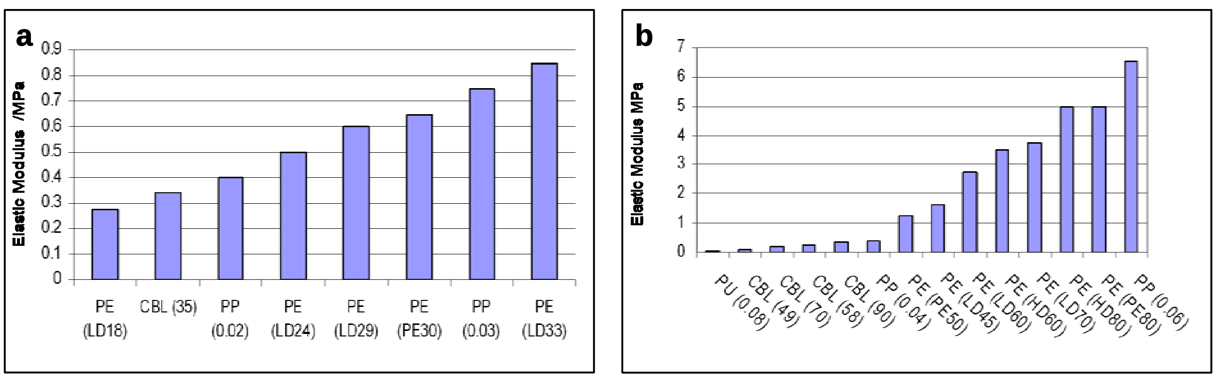
3.1.6 Antistatic characteristics of wheat-based foams

Antistatic properties are useful in packaging materials designed for shipping electronics components. Charge voltage decay tests performed on RPS foams showed that WBFs are naturally antistatic materials (decay time <1s at RH 50%) when compared to PE foams (decay time >270s at RH 50%) (data not shown). As such, WBFs may be good candidates for the packaging of electronic devices.

3.1.7 Property mapping of oil-based polymer and wheat-based foams

WBFs were compared to typical polymer foams in order to identify their potential as renewable substitutes for oil-based polymer foams. As an example, figure 13.0 shows a comparison of the elastic modulus (foam stiffness) at different WBF densities. From the results shown in figure 13.0, it is clear that CBL WBFs are more suitable for cushion packaging, but are not rigid enough for structural applications.

Figure 13.0 Foam stiffness

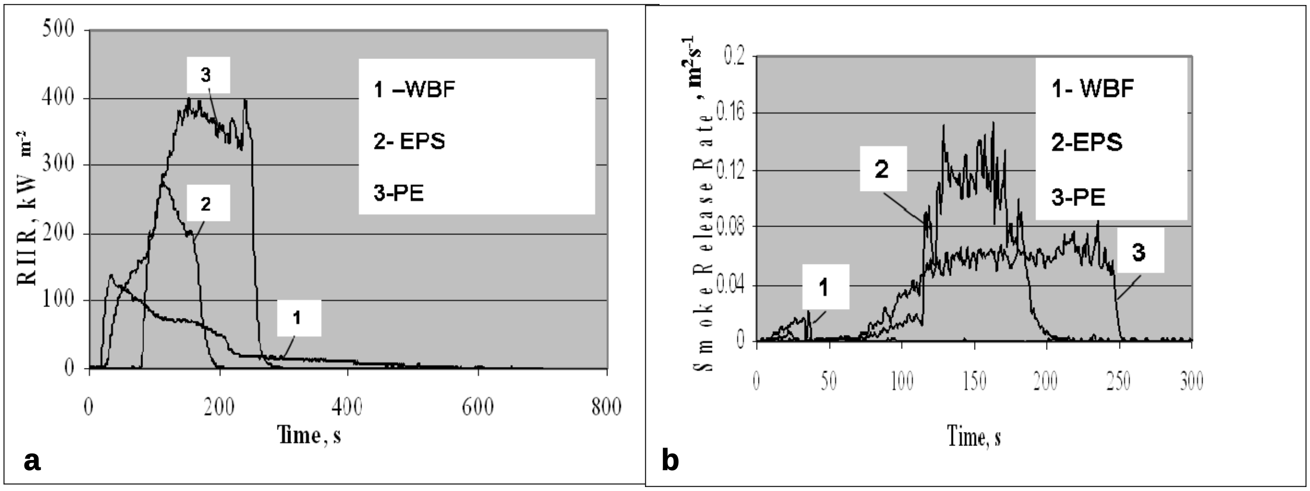


Stiffness of CBL WBFs compared to low (a) and high (b) density oil-based polypropylene (PP) and polyethylene (PE) foams. PE50 – PE density $50 kgm^{-3}$.

3.1.8 Fire properties of wheat-based foams

Fire resistance is a property required of polymer foams used in applications such as insulation and ceiling panels. Fire tests performed on the WBFs showed that standard WBFs have low heat and smog release when compared to EPS foam (see figure 14.0). The results show that WBFs have a shorter ignition time when compared to EPS foams. However, this can be extended with a fire retardant agent (Ahmadnia and Song, 2007).

Figure 14.0 Foam heat and smog release



Combustion of WBF (RPS), EPS and PE polymer foams showing heat (a) and smog (b) release rates.

3.1.9 Resistance to mould growth and insect attack

Properties such as microbial and insect attack resistance are requirements for materials used in durable applications such as building insulation and ceiling boards. Figure 15.0 shows that Na-PYRION fungicide spray coating of WBFs is effective in the prevention of mould growth over an incubation period of 20 days. The results show that fungicide treated WBFs may be suitable for durable applications such as composite ceiling boards.

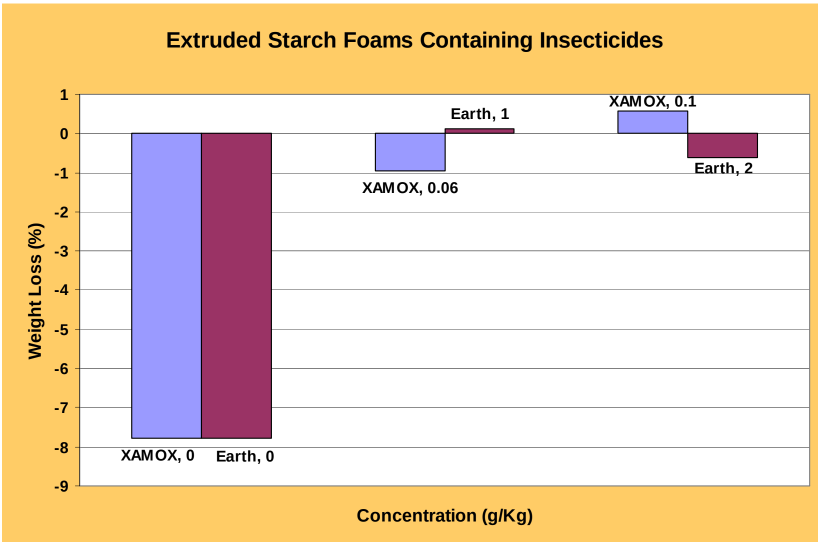
Figure 15.0 Wheat-based foam mould resistance

WBF samples treated (top) with a single coating of Na-PYRION fungicide diluted to 5g/l and untreated (bottom)

Figure 16.0 shows that both XAMOX and diatomaceous earth insecticides were effective at preventing WBF mass loss due to insect attack even at low concentrations.

The treated samples have negligible mass change in comparison to untreated samples which increased by 8% due to insect infestation. These results suggest that insecticide treated WBFs may be suitable for durable applications.

Figure 16.0 Wheat-based foam insect resistance



Insecticides XAMOX (at 0.06 and 0.1 g/kg) and diatomaceous earth (at 1 and 2 g/kg) were spray applied to WBFs. Samples were incubated with 20 flour beetles for a period of four weeks at 26°C and RH 70%. Percentage mass loss was monitored against untreated WBF samples (XAMOX 0 and Earth 0).

3.2 Block foam processing technologies

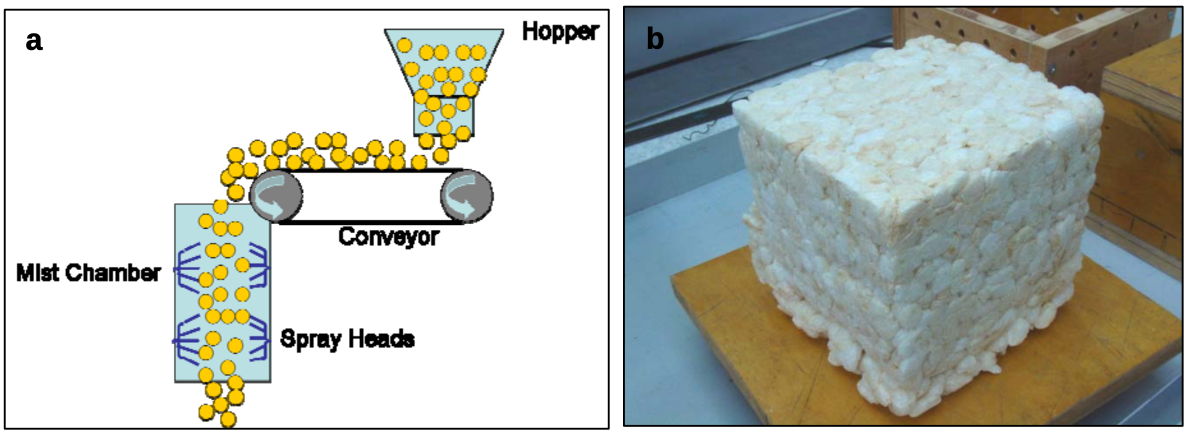
The lead partner (GLP) established initial commercial production capacity of RPS foams. The resultant thermal packaging products were used in test-of-market trials (cool box). This work was performed in collaboration with Foam Engineers and Hydrapac.

This was achieved by:

- Establishment of an Engineering Department and completion of a concept RPS machine design based on an existing demonstration RPS machine.
- Completion of an assembly design of foam handling units including a cutting unit and the interface of an extruder to the downstream equipment using a caterpillar style in-feed to the RPS machine and a caterpillar stacking unit designed to manufacture foam blocks.

The CBL process design was adjusted to lab-scale to give priority to the RPS technology. A test rig shown in Figure 17.0a was set up to study the quantity and uniformity of liquid coating in a mist chamber. Figure 17.0b shows a CBL sample prepared using the wetting system. This work provided comprehensive information for further development of the CBL process as an alternative technology to RPS (Bonin, 2009).

Figure 17.0 Compression bonded loosefill processing



(a) schematic diagram showing a CBL production test rig; (b) CBL sample prepared using the wetting system in (a).

3.3 Composite processing and conversion technology

BU and BRE worked on the development of WBF sandwich panels. The work focused on panels with different surface materials (fibre boards, honeycomb boards and speciality paper) to identify potential candidates. Extensive studies were carried out on the mechanical properties, water resistance and fire resistance of sandwich panels. The materials showed potential for applications such as disaster relief thermal shelters for the homeless, partition panels and display boards (Ahmadnia and Song, 2008). Figure 18.0 shows a ceiling board made from WBF sandwiched with fibre boards. The ceiling panel was put in the place of a conventional plaster-based ceiling tile in a 12 month trial and no deterioration was observed.

Figure 18.0 Wheat-based foam ceiling panel trial

A WBF tile was used to replace a plaster-based tile for a period of 12 months.

Foam conversion trials were carried out by BU and FE. Technologies were identified in routine sample preparation for the conversion of blocks/planks into board and packaging products.

Void creation WBFs were studied in cast concrete structures by BH in collaboration with BU, IC and an external construction company. Characteristics studied were: 1) the behaviour of the WBF materials during concrete casting; 2) the influence of bulk and surface properties on the definition of the cavities and finish. Structures were then designed for testing (see appendix B, Craig, 2009a and 2009b).

3.4 Product design and evaluation

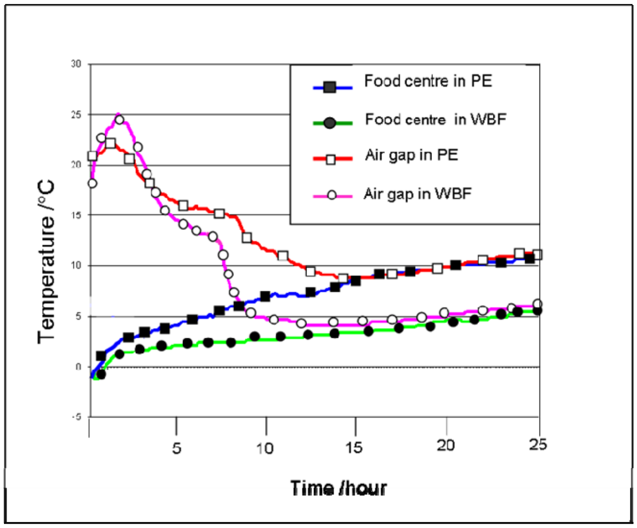
GLP supplied RPS plank materials from its Cardiff site using a prototype RPS machine. BU converted the planks to RPS foam blocks and delivered them to industrial partners: SCA, CD, KP and FE. Figure 19.0 shows examples of WBF planks made for industrial trials.

Figure 19.0 Wheat-based foam planks

3.4.1 Wheat-based foam cool box evaluation

A potential application for WBFs includes insulation in food packaging cool boxes. The performance of the type C WBF cool box described in section 2.5.3 was assessed in a road transport trial. The temperature inside the food and in the air gap between the insulation and the food was monitored over a period of 25 hours. The results in figure 20.0 show that WBF insulation is better at maintaining food at refrigeration temperatures (5°C) over 25 hours when compared to PE foam insulation. In fact, the results show that the internal food temperature of food contained in the PE foam cool box actually rose above 5°C after only 8 hours. WBF may provide a more reliable insulation material for cool boxes used in the shipping of chilled foods.

Figure 20.0 Wheat-based foam cool box performance



Food samples were placed in PE (■) and WBF (●) cool boxes containing ice packs prefrozen to -20°C. The temperature was monitored in the food (closed symbols) and in the surrounding air (open symbols) over a period of 25 hours.

FE and an external company conducted a test-of-market trial using RPS foam to replace PE foam cool box packaging in shipping mail orders of fresh foods. The trial demonstrated that WBF materials perform well and can be used as a direct replacement of PE and EPS foams in such products.

3.4.2 Wheat-based foam cushion packaging evaluation

CD carried out shipment trials of WBF cushion packed electronic devices. Results demonstrated that the WBF packaging performed well, when compared to PE foam, and offered the required protection against impact during transport, handling and accidental drops (data not shown).

3.4.3 Wheat-based foam concrete void creation evaluation

BU and BH researched the utilisation of WBF water solubility in creating novel cavities in concrete structures. The initial tests demonstrated the feasibility of using WBFs and identified areas for further improvements in water resistance which affected dimensional stability and surface finish of the cast concrete.

Water resistant surface treatment (proprietary) of the foam was found sufficient to prevent attack by the concrete mix. Concrete structures were designed for: postcasting removal of WBF; 2) strength to resist hydraulic pressure during casting (see section 6.2).

3.5 Life cycle assessment, waste management and the supply chain

LCA inventory data for fertiliser production, wheat cultivation, flour milling and wheat starch-based polymer production were collected and analysed. Inventory data was also collected from industrial partners for WBF conversion into cool boxes and for void formation in concrete.

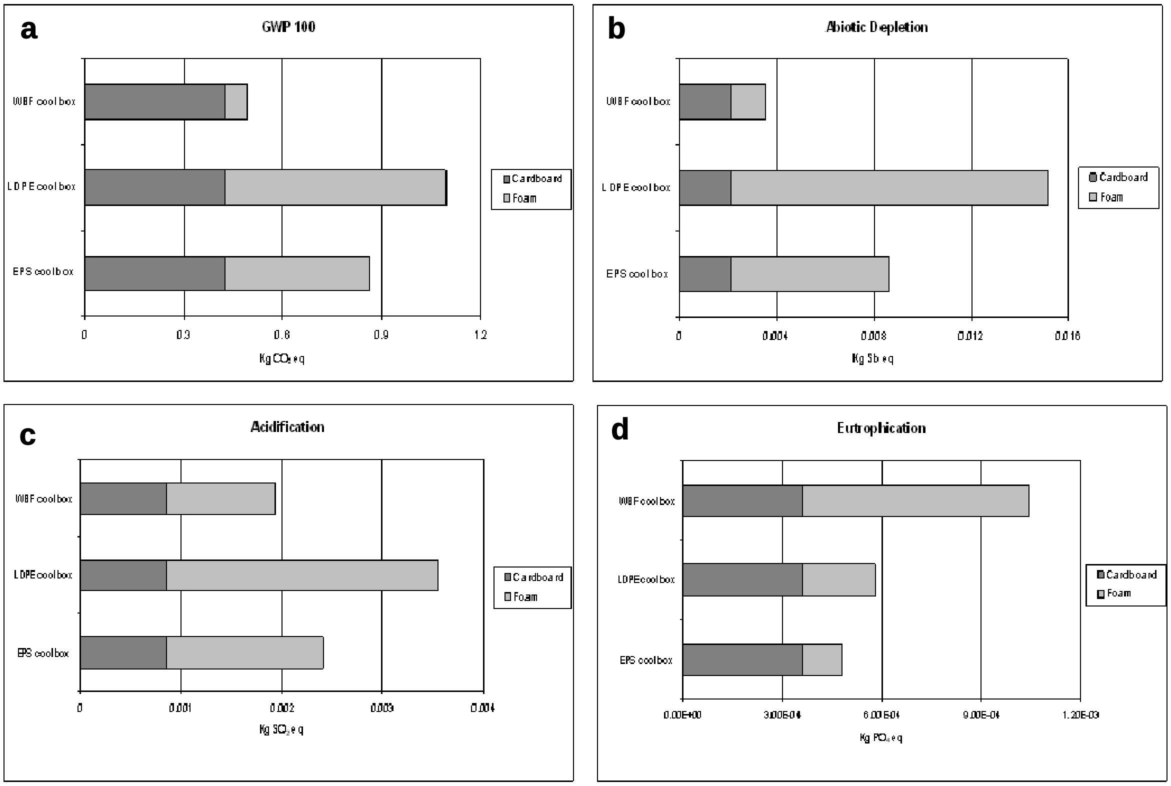
The wheat-based materials were composted to gather GHG emission and biodegradation data. In this experiment, the distribution of nitrogen (organic nitrogen, ammonia (NH_3), nitrite (NO_2^-), and nitrate (NO_3^-)), total organic carbon and oxygen (O_2) availability was measured. Emissions of carbon dioxide (CO_2), NH_3, methane (CH_4) and nitrous oxide (N_2O) were also studied to gain a complete understanding of gas emissions during composting.

LCA was completed on three prototypes made from WBF (cool box, display board and void former). The LCA results showed the environmental impacts of using WBFs (see Guo, 2009a and 2009b).

LCA was performed on the three prototypes (see above) and encompassed raw material production through to WBF product manufacture (so-called 'cradle to factory gate'). Environmental impact indicators tested included Abiotic Depletion (ADep), Global Warming Potential (GWP) and Photochemical Oxidant Creation Potential (POCP), Ozone Depletion Potential (ODP), human toxicity, ecotoxicity, acidification and eutrophication.

Results of the cool box LCA (see Figure 21.0) showed that WBF products scored better than all conventional oil-based foams tested in GWP (see figure 21.0a), ADep (see figure 21.0b) and POCP categories (data not shown). However, WBF exhibited a higher burden than conventional oil-based foams in three impact categories: 1) ODP (data not shown); 2) terrestrial ecotoxicity (data not shown); 3) eutrophication (see figure 21.0d). The fresh water/marine aquatic eco-toxicity potential tested indicated that WBF is less toxic than EPS or PE foam when applied to construction products and display boards (data not shown). However, WBF insulation has a similar score to PE insulation in this impact category (data not shown). In acidification, WBF showed better environmental performance when used in cool boxes (see figure 21.0c) and display boards (data not shown).

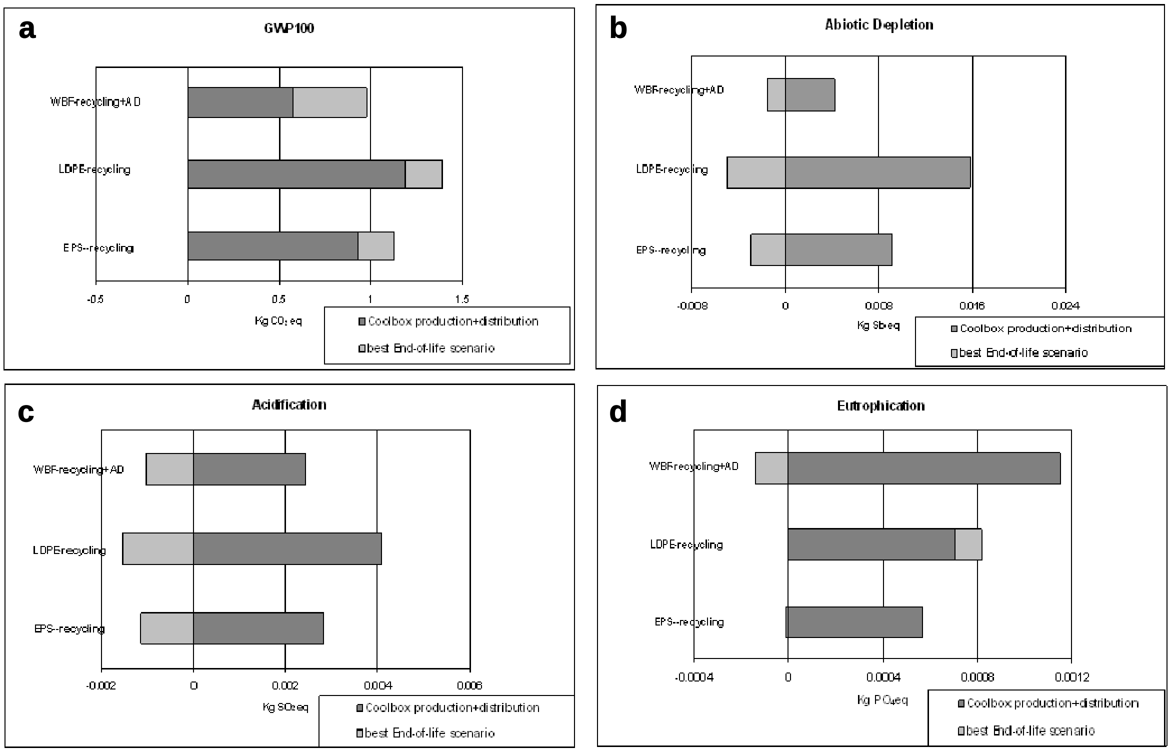
Figure 21.0 Life cycle assessment of wheat-based foams



LCA characterised scores for Global Warming Potential (GWP100) (a), Abiotic depletion (ADep) (b), acidification (c) and eutrophication (d) for the cardboard and foam components in the production phase of the cool box life cycle.

Figure 22.0 shows LCA data obtained for the best end-of-life disposal methods (recycling and recycling plus anaerobic digestion) applied to both WBF and conventional oil-based polymer foams (e.g. EPS and PE foams). The results indicated that WBF-based products have a lower environmental impact in GWP (see figure 22.0a), abiotic depletion (see figure 22.0b) POCP (data not shown) and aquatic eco-toxicity (data not shown). A comparison of both starch and oil-based foam products disposed of by recycling indicated that WBF products have a higher acidification and eutrophication impact than the oil-based foams (see figure 22.0c and d). However, it was found that LCA of oil-based products, using landfill or incineration disposal, produced similar or higher environmental impact results to WBF products disposed of in the same manner (data not shown). Comparing different end-of-life disposal options for WBF products, landfill produced less environmental impact than other disposal scenarios in ADep, ODP, human toxicity and eco-toxicity (terrestrial and aquatic) (data not shown).

Figure 22.0 Life cycle assessment of wheat-based foam cool box production, distribution and disposal



LCA characterised scores for Global Warming Potential (GWP100) (a), Abiotic depletion (ADep) (b), acidification (c) and eutrophication (d) for the whole life cycle of cool box production, distribution and best end-of-life disposal scenario.

The LCA results showed that WBF disposal by home-composting provided the least or second least impact in most impact categories except abiotic depletion and GWP (GWP is attributable to the CO_2 release during home-composting) (data not shown). Anaerobic digestion was shown to be one of the best disposal options in terms of abiotic depletion, GWP, POCP, acidification and eutrophication (data not shown). Industrial composting of WBFs produced the highest environmental impact results in abiotic depletion, POCP and all toxicity impact categories (human and eco toxicity). However, GWP from industrial composting was lower for WBFs compared with oil-based foams (data not shown).

3.6 Commercial exploitation

i) GLP has filed patents for protection of the RPS and CBL technologies in Europe, America and Australia.

ii) Facilities for achieving material commercialisation were set up.
iii) A prospective customer database was constructed.
iv) Exploratory talks and test-of-market trials were performed with end users.
v) A commercial exploitation plan was formulated.

4.0 Conclusions

- This work established an industrial process for production of WBFs and lightweight eco-composite panels. There is considerable scope for increases in productivity. WBF cool box test-of-market trials were successfully demonstrated for the mail order of thermally packaged fresh foods. Key processing parameters were investigated and proved that the CBL technology can be scaled up to produce bulk foam from loosefill WBF.
- WBFs were demonstrated to have mechanical, thermal and acoustic properties comparable to a range of low-density polymer foams (such as EPS and PE foams). This will enable starch materials to be used as an environmentally-friendly alternative to oil-based foams in a broad range of applications such as cushion and antistatic packaging, thermal and sound insulation (in packaging or construction), sandwich composite panels for partitioning, display and ceiling boards and fugitive foams for void creation in cast concrete structures.
- A portfolio of technologies was established for the modification of WBF material properties. These included: 1) additives; 2) methods for enhancement of resistance to humidity, fire, insect attack and mould growth; 3) methods for enhancement of mechanical properties by manipulation of foam densities and lamination with renewable surface materials in composite panels.
- The environmental performance of WBF materials was studied using Life Cycle Assessment (LCA) to demonstrate the environmental impacts of the materials and areas for future improvements.

5.0 References

Ahmadnia, A and Song, J. (2007). Evaluation of Fire Properties of WBF, in "Advances in Eco-materials", Brunel University Press, vol 2, pp137-142. (see section 6.3).

Ahmadnia, A and Song, J. (2008). Evaluation of mechanical properties of sandwich panels manufactured from biodegradable and renewable materials, technical report (see section 6.4).

Bonin, M. (2009). On characterisations of structure, processing and performances of wheat-based foams and composites. PhD Thesis, Brunel University (to be submitted).

Craig, S. (2009a) Eco-design in Construction, Brunel University and Buro-Happod (to be submitted).

Craig, S. (2009b) Summary of work on void creation in cast concrete structures (see section 6.2).

Guo, M, (2009a) on LCA on wheat based eco-composites, PhD thesis, Imperial College, London, (to be submitted).

Guo, M (2009b) Summary of work on LCA on wheat based eco-composites (see section 6.1).

Kang, Y. G. and Song, J (2009), Structure and compression behaviour of macro-composite WBFs, *Journal of Cellular Plastic*, vol 45, pp33-49.

Wang (2008) A Study of the structure and properties of starch foam and ecocomposites for industrial applications, PhD Thesis, July 2008, Brunel University.

6.0 Appendix

6.1 - Guo, M and Murphy. R. (2009b) Summary of work on LCA on wheat-based eco-composites.

6.2 - Craig (2009b) Summary of work on void creation in cast concrete structures.

6.3 - Ahmadnia and Song (2007) Abstract: Evaluation of Fire Properties of WBF, in “Advances in Eco-materials”, Brunel University Press, vol 2, pp137-142.

6.4 - Ahmadnia and Song (2008) Abstract: Evaluation of Mechanical Properties of Sandwich Panels Manufactured from Biodegradable and Renewable Materials, Technical Report.

6.1 Summary of LCA work on wheat-based eco-composites

M. Guo and. R. Murphy, Imperial College London.

Life Cycle Assessment (LCA) research was carried out by Imperial College London to evaluate the environmental impacts of WBFs. The LCA profiles of WBFs were evaluated over their whole life cycle in a 'cradle-to-grave' approach using primary data collected from industry partners supplemented with secondary data from publicly available sources. Various 'end-of-life' scenarios were modelled for the waste treatment of WBFs including landfill, home-composting, industrial-composting, and anaerobic digestion. Case studies were used to compare the LCA performance of WBFs with conventional, oil-based polymer foams (HDPE/LDPE/EPS) in: 1) thermal insulation packaging (cool box); 2) external geometry (trough mould); 3) internal structure forming (former) in the construction sector; 4) display boards. Further comparison was also undertaken between WBF and two additional starch-based foams derived from potato and maize starches.

The key findings from the LCA work were:

- **Production stage -** WBF-based products scored better than or equal to conventional petroleum-based foams (the 'standard' polymers EPS/LDPE/HDPE) in six environmental impact categories - Abiotic depletion, GWP, POCP and acidification. WBF scored poorer than conventional petroleum-based foams in three impact categories: Ozone Layer Depletion (ODP), terrestrial eco-toxicity and eutrophication.

Table 2.0 Life cycle assessment of wheat-based foam products

Impact category	**Production stage only**			
	Cool box	***Trough mould***	***Former***	***Display board***
Abiotic depletion				
GWP100				
ODP				
Human toxicity				
Ecotoxicity (*Fresh water)*				
Ecotoxicity (*Marine)*				
Ecotoxicity (*Terrestrial)*				
POCP				
Acidification				
Eutrophication				

= WBF ***lower impact*** than oil-based polymer
= WBF ***higher impact*** than oil-based polymer
= WBF ***similar impact*** to oil-based polymer

- When the product distribution and the end-of-life waste treatment stages (e.g. composting, landfill, anaerobic digestion, energy-from-waste and recycling) were brought into the analysis, the WBF-based products generally retained better environmental impact scores than oil-based polymers in abiotic depletion, GWP, POCP, eco-toxicity fresh water and eco-toxicity marine. Oil-based products with recycling as the end-of-life scenario had better environmental impact scores in acidification and eutrophication but, oil-based products disposed of via landfill or incineration produced similar or higher environmental impact scores, when compared to WBF products, in these categories.

- Comparing the different waste treatment scenarios for WBF products, Home-composting represented the best or second best disposal choice in most impact categories, except abiotic depletion and GWP (GWP was due to the release of CO_2 during the home-composting phase). Anaerobic digestion was one of the best options in terms of abiotic depletion, GWP, POCP, acidification and eutrophication impact categories in part due to biogas recovery and use in combined heat and power (CHP) generation substituting for fossil fuel. Industrial-composting of WBFs was the least environmentally-friendly scenario in abiotic depletion, ODP, human toxicity and eco-toxicity categories and also scored poorly in GWP due to release of CO_2 during composting. The landfill scenario produced a lower impact than the other waste management scenarios in five impact categories: Abiotic depletion; ODP; human toxicity and eco-toxicity (terrestrial and aquatic). This is explained by the 'best practice' assumed in the landfill model which includes bio-gas recovery for electricity production (substitution for impacts of grid electricity) and leachate minimisation. However, even with this, landfill delivered much higher burdens in the GWP, POCP, Acidification and Eutrophication impact categories due to fugitive emissions and some leachates modelled during the landfill period.

- A preliminary exploration of alternative starch-based feedstocks for foam production (maize and potato starch) indicated that these tended to have higher impacts in most categories than the WBFs. This finding is tentative due to a reliance on database sources for the potato and maize starch manufacturing rather than the primary, manufacturer-supplied data used for the WBFs. The starch manufacture phase of the life cycle was indicated to be the main cause of increased impact scores between potato/maize foams and WBFs. In comparison with the oil-based foams, the production of potato and maize starch-based foams showed better environmental impact scores in abiotic depletion, GWP and POCP. However, potato/maize and WBFs generally had a higher burden in other impact categories compared to oil-based alternatives.

As part of the work, new research data was generated from laboratory studies on the biodegradability/digestibility of WBF and WBF-insulated cool boxes under aerobic and anaerobic conditions. The lab-scale simulation of home-composting showed approximately 90% mass loss of WBF in aerobic composting within 20 days at 25ºC. After 70 days incubated at 37ºC under anaerobic conditions, WBF gave an ultimate methane yield value of 362.7mlCH_4/g VS in the BMP test corresponding to 68% (±2%) of the theoretical methane production based on COD results. Higher ultimate methane yields from anaerobic digestion of WBFs can be expected in commercial practice (due to more vigorous microbial inocula than that used in the lab-scale BMP test). These results addressed a shortage of published information on disposal options for biodegradable foam materials. They were used in the LCA work to support the end-of-life modelling and gave good indications that anaerobic digestion and home or industrial composting are promising technical options for the disposal of WBF products.

Taken as a whole, the LCA work identified WBF (and other starch-based foam materials) as having favourable environmental profiles when compared to oil-based foams. However, some impact categories (e.g. eutrophication, which is affected by crop agriculture) showed higher impacts for WBFs over petrochemical alternatives. Importantly, WBF scored much lower than oil-based foams in GWP and abiotic depletion (use of finite resources).

6.2 Summary of cast concrete void creation work

S. Craig, Buro Happold.

6.2.1 Search for potential applications in construction industry

A patent search was conducted and talks with various Buro Happold engineers were held to find possible applications for extruded WBF (ESF) in the construction industry. These applications take advantage of the properties of WBF: 1) biodegradable; 2) water-soluble; 3) low thermal transmittance; 4) acoustic transmittance.

The following applications were found:

1. Partition panel systems for interiors and exhibition spaces.
2. Panelling systems for outdoor temporary structures, such as disaster relief shelters.
3. Sacrificial concrete formwork (from simple blocks to complex shapes for architectural projects).
4. Simple void-forming for concrete elements (prefabricated concrete slabs, large civil engineering structures, foundation protection, floating floors).
5. Complex void-forming for concrete elements (acoustic absorption panels, service integrated structures).

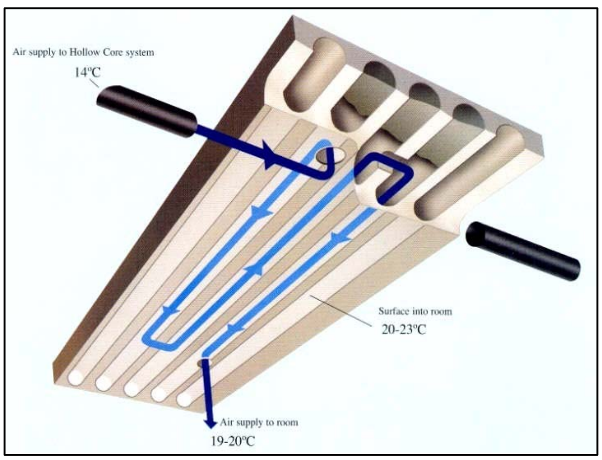
It was noted that expanded polystyrene foam (EPS) is already widely used for small and large scale concrete formwork, particularly in civil engineering projects. The two largest companies in this market are Cordek and Vencel Resil.

6.2.2 Initial testing and concept design

Concrete formwork was seen by the project partners as particularly interesting. There are many different techniques for forming concrete using different materials; the choice of which to use depends on many factors, including the function of the concrete form and cost. EPS is used for a wide variety of jobs in building and civil engineering, including complex geometries, and sacrificial formwork for creating internal voids, where wet concrete is poured over the foam, and, depending on the function of the void, it is either left in or flushed out with solvents. Other materials used for void-formers include cardboard, thin sheet metal and plastic. Our idea was that ESF might provide an alternative to these and EPS.

Voids in concrete can fulfil multiple functions. One type of pre-cast concrete slab has an internal void-network which plays a structural and thermal role (see figure 23.0). The voids reduce dead-weight, and create a passage way for cool night air to pass through and discharge the slab of heat accumulated during the day, thereby 'unlocking' the thermal mass in a building. The pre-cast concrete slabs are formed by pultrusion, which places firm limits on the complexity of geometry achievable (only smooth circular channels). It has been suggested in the literature that measures such as roughening the internal surface and changing the internal geometry might improve performance. Internal geometries such as a 'corkscrew' or louvered fins might give better heat transfer for the same pressure drop. Our idea was to develop an ESF product to form such internal geometries. To perform this function successfully, it must not dissolve on contact with wet concrete (it is very water-soluble), it must hold its shape under buoyant load and it must be easy to flush out with water after the concrete has set.

Figure 23.0 A Termodeck slab



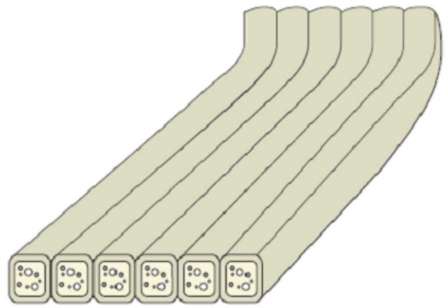
Cool night air can be fed through the concrete slabs to discharge them of heat accumulated during the day. This makes the concrete structure function more effectively as a thermal mass and reduces the energy demand for cooling. However, the slab manufacturing process puts limits on the internal geometry. Spiral shaped voids may exchange heat better than smooth channels without a debilitating increase in air fan power.

Supplementary sheets show a range of ESF void-former concepts (see figure 24.0). Initial tests examined load deflection characteristics of alternatives against EPS and cardboard tubes (see figure 24.0, 25.0 and 26.0). The ESF tubes must hold their shape under buoyancy forces for less material than a bulk material equivalent. ESFs are required to use less water at lower pressures to flush-out the material afterwards. The foam can be encapsulated in a film, membrane or 'skin' to isolate it from water and water vapour in order to stop it from dissolving prematurely and decreasing in size when submerged in wet concrete. This membrane would ideally be starch-based, attached or formed as part of the extrusion and pultrusion process. Alternatively, it could simply be placed in a suitable biodegradable refuse bag and sealed.

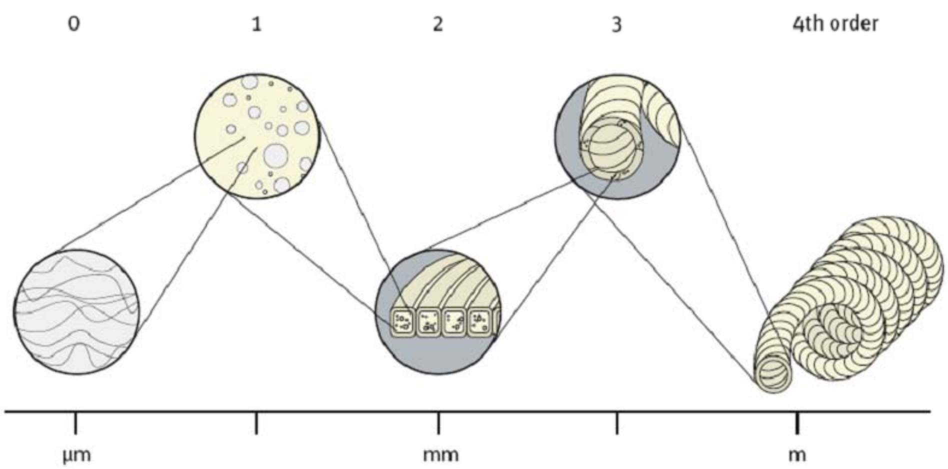
Another alternative ESF structure is a double-hollow spiral (see figure 24.0) designed for easy manufacture and adaptability for different applications. The 'corkscrew' void left behind in the concrete may increase the rate of heat transfer without a detrimental increase in fan power. The idea is that this may help buildings reduce their cooling energy demand by making better use of diurnal swings in external temperature.

The process of manufacture is designed to be a continuation of the extrusion and pultrusion process already in place to make ESF planks. The sides of the planks are made sticky by wetting them before forming the planks into helical tubes of the required diameter. The tubes are then wetted so that they can be spiralled once more. This manufacturing method should, in principle, result in very little waste material. Importantly, the resultant product may have many possible applications where temporary structural protection or support is required temporarily.

Figure 24 *Starch void-former concept based on biomimetic principles suggested by BioTRIZ*



The starch foam comes in planks, five rods wide. The rods are extruded then pultruded to make them square and stick together. The heat, pressure and water make the edges denser.



The planks already have at least two structural levels of hierarchy. Twisting a plank twice round – going from plank to tube to spiral – adds two more. Adding structure means it may resist known buoyancy forces for less material than a bulk equivalent. Bagging it makes it waterproof. A length is restrained and concrete poured over it to form a building slab. When the concrete has cured, the foam is flushed out to reveal an empty cork- screw. With several slabs installed in a building, cool night air can be passed though the empty corkscrew channels to discharge the building of heat during the summer. This helps reduce demand for air-conditioning.

Figure 25 *Buoyancy force on different sized cylinders submerged and restrained in wet concrete 250mm deep*

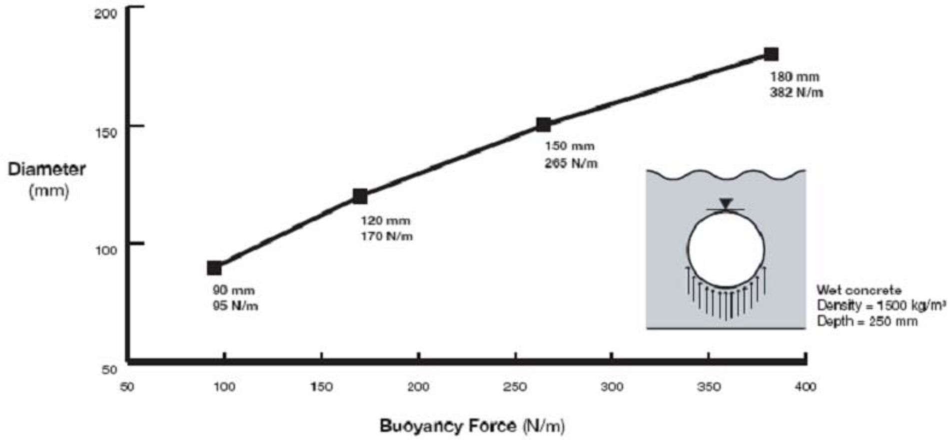
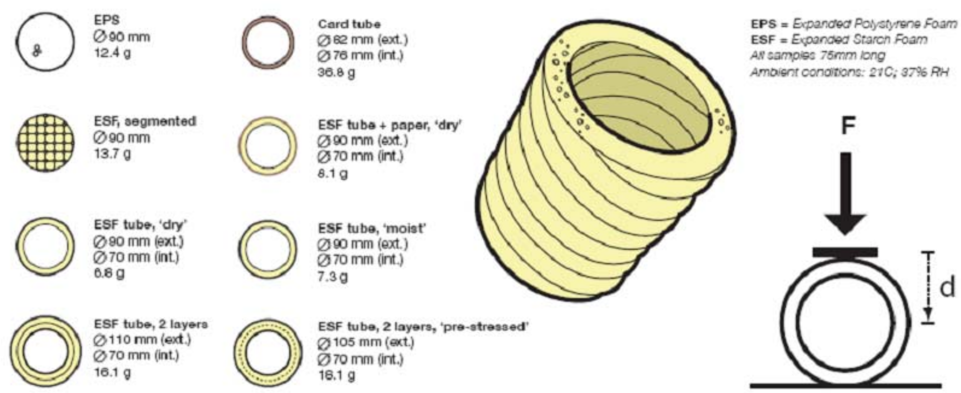
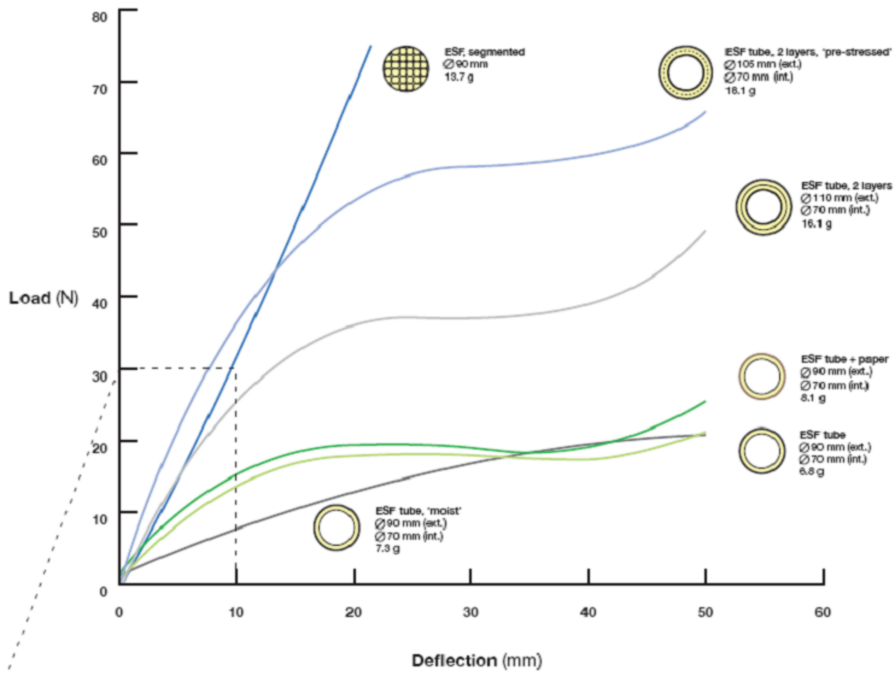


Figure 26 *Samples and set-up of load-deflection test*





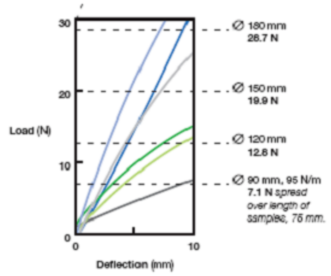
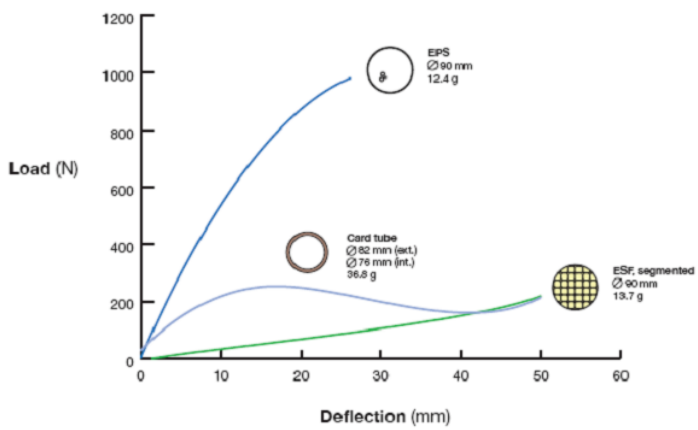


Figure 27 *Load-deflection of tubular concept ESF void-formers (above). Two established void-formers vs. ESF segemented cylinder (below). ESF tubes and spirals (see figure 20) have yet to be tested under hydrostatic pressure. But these results suggest an ESF tube or spiral could be designed to bear hydrostatic pressures when submerged under wet concrete (see insert, left, and figure 22). EPS and cardboard void-formers may be 'overdesigned'.*



6.3 Abstract: Evaluation of fire properties of starch foam

Ahmadnia and Song, Brunel University (2007).

Proceedings of the 8th International Conference of Eco-Materials - ICEM8
Brunel University, UK, 9-11th July 2007

EVALUATION OF FIRE PROPERTIES OF STARCH FOAM

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Abstract

In order to understand behaviour of starch based foams in applications where fire properties of the materials are important, wheat-based starch foam were characterised using a cone calorimeter. Properties assessed include heat release rate, time to ignition, smoke emission and release of toxic gases. The results were compared with two petroleum-based foams: an expanded polystyrene and a non-cross linked polyethylene. The effect of a fire redundant coating agent on fire properties of the starch foam was also assessed. The results showed that foams based on starch have desirable characteristics such as lower rate of heat release and smoke production and surface coating with a fire retardant solution is shown to be effective to delay the time to ignition and significantly reduce the rate of heat release.

Keywords: Starch foam, Cone calorimeter, fire retardancy, coating

6.4 Abstract: Evaluation of mechanical properties of sandwich panels manufactured from biodegradable and renewable materials

Ahmadnia and Song, Brunel University (2008).

EVALUATION OF MECHANICAL PROPERTIES OF SANDWICH PANELS MANUFACTURED FROM BIODEGRADABLE AND RENEWABLE MATERIALS

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Abstract

Two composite sandwich panels were fabricated from fibreboard and Beeboard (a honeycomb structure made from recycled paper and a wheat-based foam, WBF). Tensile, flexural, and impact tests were performed to evaluate the mechanical properties of WBF. Three point bend and drop weight impact tests were carried out on the sandwich panels. The density of the foam was 26 kg/m^3 which was prepared at Brunel University with a proprietary technology known as regular packing and stacking (RPS) technology using a wheat flour-based material which enables production of WBFs in plank or block forms. The stacking sequence and direction of strands affect the tensile properties of WBFs. Using this type of composite in building construction introduces many advantages such as superior sound and thermal deflection and insulation, respectively. The use of WBFs also provides an important environmental advantage because they are renewable as opposed to petroleum-based materials that are not.