Publishable Summary

Introduction

Our modern life would be impossible without the availability of versatile plastics – bottles, packaging, electrical items, cars, construction – the list is almost endless. However, increasing prices of raw material, environmental concerns and cost implications of disposal are growing every year!

One of the biggest challenges facing the recycling industry is what to do with mixed plastic waste – whilst there have been many advances in recycling technology, this type of waste remains an area for development. In order to develop sustainable pathways to recycle mixed plastic waste, innovative technologies that can use it as a raw material and create something productive and beneficial are vital, and the recognition that increasing the re-use of mixed post-consumer plastics waste is an excellent opportunity to reduce the impact of high raw material prices. It will also significantly reduce the cost burden of EU WEEE and Waste Directives and help reduce Europe's growing plastics waste problem.

The reuse of mixed waste plastics is appropriate for low to medium value products such as building materials, flood barriers, temporary structures, flooring and marine products. This is also the main market segment that is losing out to non-EU competition. Enabling this segment to reduce materials costs will lower demand for virgin polymers (and potentially other materials such as plywood and metals), which will have a downward effect on raw material prices. Simultaneously, the increased demand for recyclates will help the polymer recycling industry.

PRIME seeks to create a 'cradle to cradle' approach for this waste, to eliminate it from landfills and turn it into a valuable resource that can be used in high value products. It was proposed to develop a cost-effective flexible moulding technology using a combination of established and innovative techniques, and use mixed polymer waste to manufacture high value, complex, recycled polymer products (80-98% mixed waste polymers) with good surface quality that have similar properties to timber or aluminium. The materials will have with a mixed recyclates core and a reinforced skin, balancing stiffness, surface quality and strength, and designed to be suitable for a wide range of complex products such as flood barriers, temporary walkways, emergency structures and buildings, and marine products

Basic Research

A series of panels were made consisting of different skin and core compositions. These were made on the test rig at Brunel and then were tested at MatRI and Brunel for flexural test (3 point bend), impact test (Charpy and Drop), density and water absorption measurements to complete the testing an additional thermal test i.e. thermal expansion, were performed on the PRIME samples to determine its mechanical properties. During the process it became apparent that we had pay particular attention to the size of specimens as the foam is highly heterogeneous and can have porosity i.e., if the size of a specimen is small scale, the disparity of mechanical test results (which are highly dependent of the average porosity) will be very important. The results of all the different tests v skin core combinations were analysed and materials chosen for further trials.

Two reinforcement strategies were examined a) reinforcement of the skin layer and b) design (by modelling). A range of polymeric materials with the inclusion of glass fibre were moulded and tested for potential skin applications. The results presented give the consortium a good choice of composites for selecting appropriate skin materials for the final Flood Barrier and other applications.

Environmental testing

An extensive literature survey with regards to the process of environmental degradation and review of the proposed materials was undertaken. In the PRIME project, two types of polymer material have been suggested for further trials and these 2 polymers are to be used only in the skin which is most exposed to sunlight and therefore most susceptible to UV ageing and UV additives can be added to impart the stability of the polymers from 12 to 20 years. Fire resistance of the materials used for the manufacture of the skin and core has also been researched. Full environmental and fire resistance testing will be carried out on the prototype samples.

PRIME boards were immersed in water. Water up-take was measured by weight increase of the board sample after drain the excess water. The actual water uptake was approx. 6.5% in the open foamed structure hence water could be taken up by the foamed fused core boards, therefore the edge of the board should be sealed if necessary to avoid water uptake when being used outdoors.

Fire retardant tests and mechanical tests on the new PRIME samples were carried out as a collaboration between EMA and Brunel. Complete document on the Prime website.

The reuse of mixed waste plastics is appropriate for low to medium value products such as building materials, flood barriers, temporary structures, flooring and marine products. Hence, uses of sandwich panels in the field of building and housings need to meet fire regulations. To improve the fire reactions of the panels, the strategies can correspond to the incorporation of fire retardants in the reinforced skin, or to the use of recycled flakes from fire retarded waste electric and electronic products, or also to combine both solutions. Glass reinforced polypropylene and polyamide blends were used as skin composition. Fire behaviour of all the samples for the various compositions prepared was tested using cone calorimeter. Finally, in order to investigate the loss of mechanical behaviour, due to the introduction of fire retardants, the impact resistance of panels was also tested.

The following observations were made:

- ✓ Both core and skin compositions influence the fire behaviour of the panels
- ✓ The main pHRR is only influenced by the presence of FR in the skin
- ✓ Compositions with 20wt% of APP lead to the better reduction in the following fire retardant parameters: 2°peak of HRR and THR (50KW/m²)
- ✓ At 35KW/m² , compositions with FR in the skin and ABS FR can extinguish

It can be suggested that panels can auto-extinguish in contact with an heat source

- ✓ No synergistic effects between APP in nanoclays in the skin (thickness is not enough? Interference with glass fibres?)

- ✓ Cohesion of residue is governed by the presence of FR in the core

In conclusion despite the peak of heat release, which is an important parameter for the fire risks, is governed by the presence of fire retardants in the skin, the presence of flame retardants in the core influences strongly the total heat released during the combustion, as well as the ability to auto-extinguish for moderate irradiances. The use of an intumescent flame retardant system composed of ammonium polyphosphate acting as charring agent lead to a high level of performance for the skin and since there is no interfacial de-cohesion, it shows that this intumescent system is compatible with the brominated compound/antimony oxide flame retardant system present in the core.

This combination seems interesting since it can bring solutions for the waste management of WEEE plastics containing bromine compounds. Nowadays, more and more regulations, such as RoHS (Restriction of Use of Hazardous Substances) European directive, forbid the use of such components in new equipments. Moreover, it has been shown that the incorporation of FRs in the skin was not detrimental to the impact resistance, while the presence of FRs in the core had a minor influence on its property.

UV testing was carried out on compounds made from ETU and SRM102 according to EOTA (European Organisation for Technical Approvals) Technical Report which specifies exposure procedures for artificial weathering using EN ISO 4892.

The radiant exposure range in Northern Europe is typically 128MJ/m² per year. The simulation exposure conditions were for a moderate climate in Europe.

The test sample was thermoformed Twintex. Tensile testing before and after exposure was used to determine the effects of UV exposure and the results show that there is negligible degradation due to UV radiation.

LCA (Life Cycle Analysis) is a standardized method used to evaluate the environmental impacts of a product or a service (ISO 14040). It's a global method, all the life cycle is studied from the extraction of raw materials to the waste treatment. It is also a multi-criteria approach, as several categories of impact on the environment are evaluated, contrary to the carbon footprint or water footprint for instance, which only focuses on one category of impact. The multi-criteria aspect enables to identity any transfer of pollution between different environments. The ISO 14040 series defines the 4 main steps to follow to perform a LCA: Goal definition and Scoping, Inventory analysis (LCI), Impact assessment and Interpretation (Figure 1).

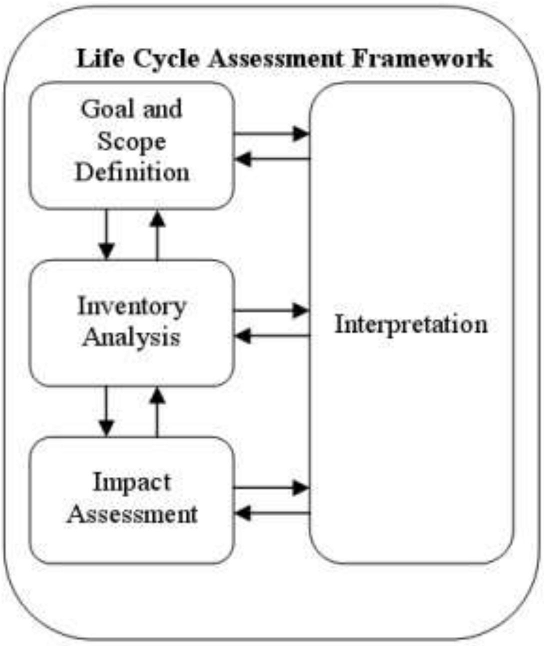


Figure 1: LCA's methodology framework

The first phase enables to define the goals and scope of the study. The question the LCA is answering must clearly be formulated. The different choices in terms of systems boundaries, geography, assumptions and allocation must be defined. The functional unit is also defined: this is a reference value that is appropriate for the function served by the product being assessed, and to which all the flows and results (environmental impacts) can be related. Thus, when different systems are compared, it is possible to guarantee that the various alternatives under consideration do indeed perform the same service. An inventory of all the inputs and outputs for the system is then carried out. This involves quantifying all of the elementary flows which enter or exit the system under consideration, meaning:

- resources (materials and energy) taken from the environment without anthropogenic transformation beforehand;
- pollutant emissions and final waste discharged into the environment (air, water, ground) without subsequent anthropogenic transformation.

The third phase involves assessing the potential impacts that the previously inventoried inputs and outputs have on the environment. All the environmental flows are then converted into a limited number of indicators (or impacts) using characterization models.

This study aims to inform the debate on which material offers the most environmentally friendly solution to produce a flood barrier: aluminium or a sandwich structure, made with a core of recycled polymer and skins of composite. The process to produce the PRIME panel was developed during the project. The core is made of various recycled polymer, to simplify the study it has been assumed that the core was only made of recycled Acrylonitrile-Butadiene-Styrene (ABS) from electronic wastes (WEEE).

It has also been assumed for the purpose of comparison that the two flood barriers have the same average life time of 10 years.

The study complied with the ISO 14040 series of standards governing the use of LCA.

The functional unit is a measure of the service provided by the product systems. It is used to normalize the environmental effects, allowing comparisons with other periods, systems or scenarios which might provide an identical service. In this study, the functional unit is the following:

'Provide a protection of 2m² against flood during 10 years, with the same mechanical performances'

Two scenarios were compared: an aluminium flood barrier and a prime panel flood barrier.

The aluminium panel is made of 60%wt of recycled aluminium. The PRIME panel is made of a sandwich structure: a core with recycled polymer, here ABS, and skins made of Twintex, a commercial Polypropylene/Glass fibers composite.

For the aluminium flood barrier, the following life cycle stages were considered:

- Production of aluminium
- Production of recycled aluminium
- Extrusion
- Cutting
- Installation on site
- Transport between each steps
- Generation and supply of electricity

For the Prime panel, the following life cycle stage were included

- Collection of WEEE
- Shredding of plastic wastes
- NIR sorting
- Polypropylene production
- Glass fibers production
- Twintex production
- Assembly of the skins and the core (PRIME process)
- Installation on site
- Transport between each steps
- Generation and supply of electricity

The systems for the two products are provided graphically in figures 2 and 3.

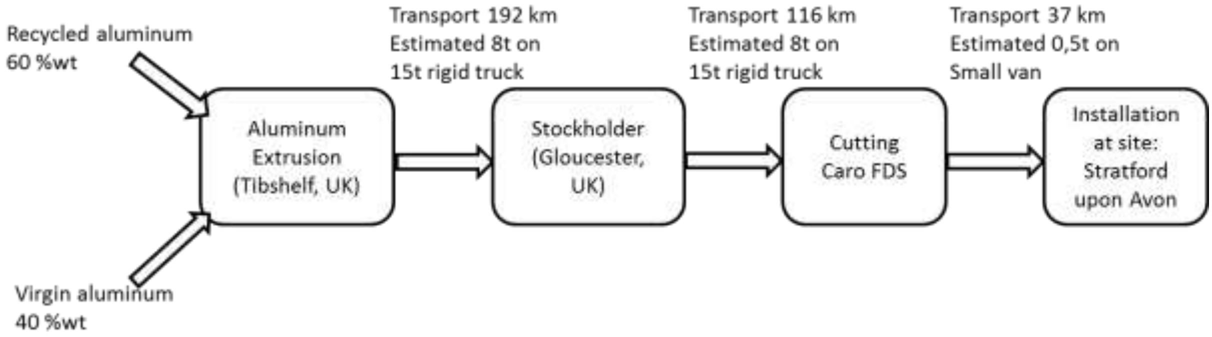


Figure 2: Aluminium barrier system

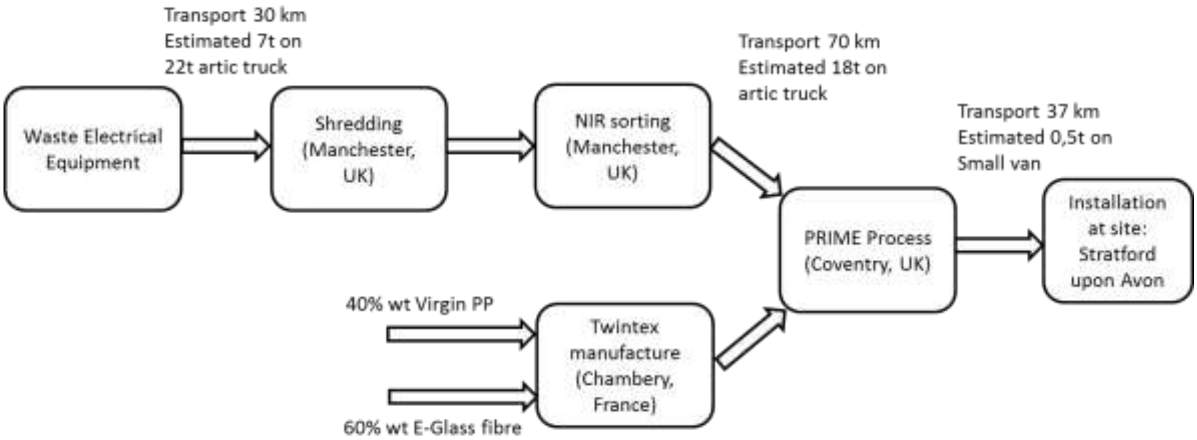


Figure 3: PRIME Panel System

The different processes used and the data for the transport phases were given by the partners of the PRIME project. Then, for each process, a model process was taken into the GABI or ecoinvent database.

A common problem in LCA studies is the allocation, i.e. how to distribute the impacts of a process which produces several products or use several inputs. In this study, the allocation was made in mass.

The energy consumption and the following environmental impacts were studied:

- Global Warming potential
- Eutrophication potential
- Human toxicity potential
- Photochemical ozone creation potential
- Acidification potential

On the base of their relative contributions, data from the inventory were aggregated to evaluate each of these impacts.

The **Global warming potential** (GWP) is characterized by the effect of substances contributing to the warming of the Earth's atmosphere. Related substances are, for instance, carbon dioxide, methane and nitrous oxide.

The **Eutrophication Potential** (EP) refers to emission of substances into the environment resulting in over-fertilisation. Eutrophicating substances are for example nitrates, phosphates and ammonium salts.

The **human toxicity potential** represents the degree to which a chemical substance elicits a deleterious or adverse effect upon the biological system of human exposed to the substance over a designated time period.

The **photochemical Ozone creation Potential** (POCP) describes the formation of photo oxidants (ground level ozone, etc.) originating from hydrocarbons and nitrogen oxides being affected by sunlight.

The **acidification Potential** (AP) is defined by the emission of substances into the environment leading to a decrease of pH-value, e.g. nitrogen oxides and sulphur oxides.

The use of a sandwich structure made with a recycled plastic core reduces the environmental impacts of the production of a flood barrier. Hence from this study the production of the PRIME panel is more environmentally friendly than the production of aluminium flood barrier.

The complete document can be found on the Prime website

Development of PRIME process

A study was carried out to determine the feasibility of employing electrostatic methods to apply a polymer skin to a mould tool prior to fusing the outer skins with the core material in the PRIME process. It was found that electrostatic deposition can improve the transfer efficiency of coatings because the electrostatic forces help overcome other forces, such as momentum and air flow that can cause the atomised materials to miss the intended target. The improved efficiency can save coating material, time, and labour. Despite these potential benefits to the PRIME process, it was discovered that there remain a number of hurdles and shortcomings to all available techniques. While electrostatic methods are very good at achieving uniform and controlled coatings, the thicknesses achievable are fairly limited. Most coating techniques only achieve thicknesses of around 150um on cold substrates and about twice that number of pre-heated substrates. Even 'thick' film techniques such as electrostatic fluidised bed powder coating are only usable to thicknesses of 500µm per coating. Since electrostatic deposition methods typically involve high voltages, high pressures and small particle sizes (liquid or power), a number of potential safety hazards were identified. This study highlighted a number of issues encountered in using electrostatic methods within the PRIME process, e.g. achievable thickness, safety etc. These limitations imply that electrostatic techniques are unfeasible in view of the objectives of this project and alternative approaches are going to be evaluated.

For the core the majority of the raw materials were received as flakes or pellets, and these were size reduced. Different combinations of recycled Polyolefin (PO) and Polystyrene (PS) were trialled and a mixture was chosen as the core material. A number of sample sandwich boards were manufactured using the chosen core material and different skin formulations. The skins were manufactured using different forming. The boards were then made by laying a bottom skin in the mould, filling it with the pre blended core and then laying a top skin on the core. For simplicity these were manufactured using compression moulding.

Both skin sheets and PRIME boards were tested by using a drop weight impact tester followed by optical examination and were carried out in accordance with ISO 6603.The fractured surfaces and section from the impact tests were examined optically. Chip wood board samples and a plywood board samples with similar thickness of PRIME boards were also tested for comparison purposes. The overall conclusion is that the choice of skin materials plays a major role on the PRIME products. It is also encouraging to report that our work and tests are demonstrating that the developed PRIME products display similar if not superior level of properties when compared with plywood.

Mould heating system design

A simplified mould / polymer heat transfer model has been carried out and concluded that the energy required increases linearly with panel area and core thickness. Also that the time required is essentially constant with panel area but increases exponentially with core thickness. The simple model considered allowed us to make a few important observations: Energy required increases linearly with panel area and core thickness and time required is essentially constant with panel area but increases (approximately) quadratically with core thickness.

IR heating system generates a series of infrared “pulse cycles” which starts with short wave infrared to heat the air between the emitter and stabilise initial operating conditions. The next cycle is medium wave infrared that penetrates the upper layer of the sample. Finally, a long wave infrared penetrates the middle and lower section of the sample. Benefits of the IR heating system are highly efficient conversion from stored chemical energy (e.g. propane) into IR heat energy, lowering NOx, CO and unburned hydrocarbons emissions, achieving temperatures of up to 600°C in 30 seconds on the IR heater surface, rapid cooling of IR heater surface within minutes and the flexibility of energy sources e.g. LPG, natural gas, etc. Based on these benefits, the Consortium has decided to purchase two IR heating systems which will be evaluated as a heating methodology for manufacture of PRIME samples

An IR heating system was designed to be flexible in allowing assessment of the effect of distance between the IR heating and mould surface, effect of cooling of the different distances between the IR heater and mould surface and effect of time on the heating profile in the mould tool also the spectral power density of the gas catalytic burner was also be configured by altering the gas/air ratio. This allow the burner to operate in either the red flame (620–750 nm wavelength) which give efficient heating to the part or blue flame mode (450–475 nm wavelength).

Small moulds both metal and ceramic were coated with sprayable conductive ceramic materials using an automated process and were trialled; however it is was considered that at this time in the project the gas catalytic heater was the best option.

In order to obtain the optimum mould heating methodology, calibration trials were carried out and more than 32 different products were manufactured. These were made from different combinations of skin and core materials. This allowed the consortium to choose the best skin core combinations for the boards. This information was used in the modelling trials.

Finite element based PRIME design tool.

Modelling of the PRIME beam, using standard beam theory and corresponding analytical formulas was carried out and this work led to the development of a design tool able to quickly provide quantitative data on the performance of the PRIME composite panels submitted to simple loading conditions. The software uses a "traffic signal" style indicator. Green, yellow and red colours mean respectively that both, one or none of the mechanical conditions have been satisfied.

At the conclusion of numerous design trials and corresponding FE analyses, the design tool (Figure 4) has been developed and refined and is based on FEA results and has been proven to be give proven results in the design scenario.

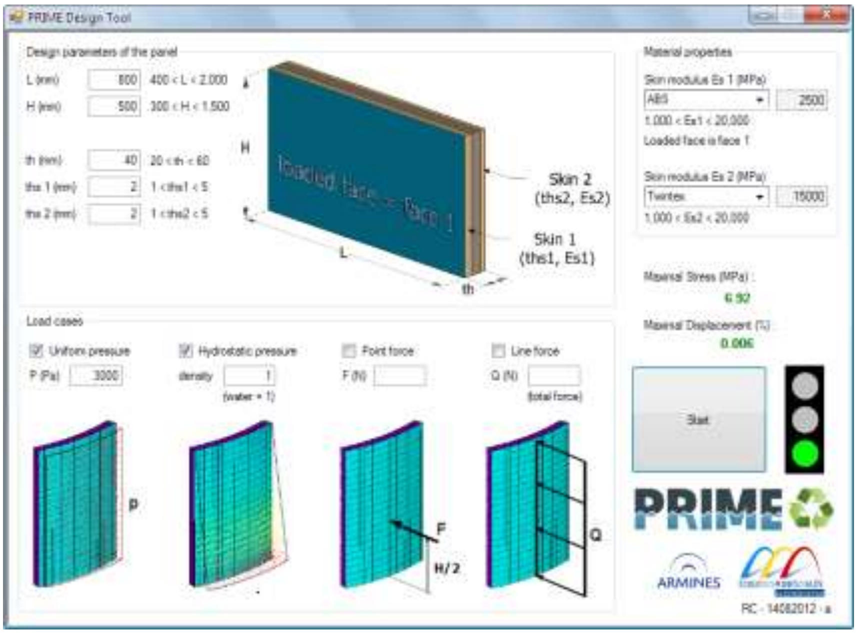


Figure 4 Design tool

PRIME pilot facility

The consortium between them designed an integrated unit Figure 5.

Figure 5: Integrated Unit

The prime facility was commissioned and a protocol was devised Figure 6.

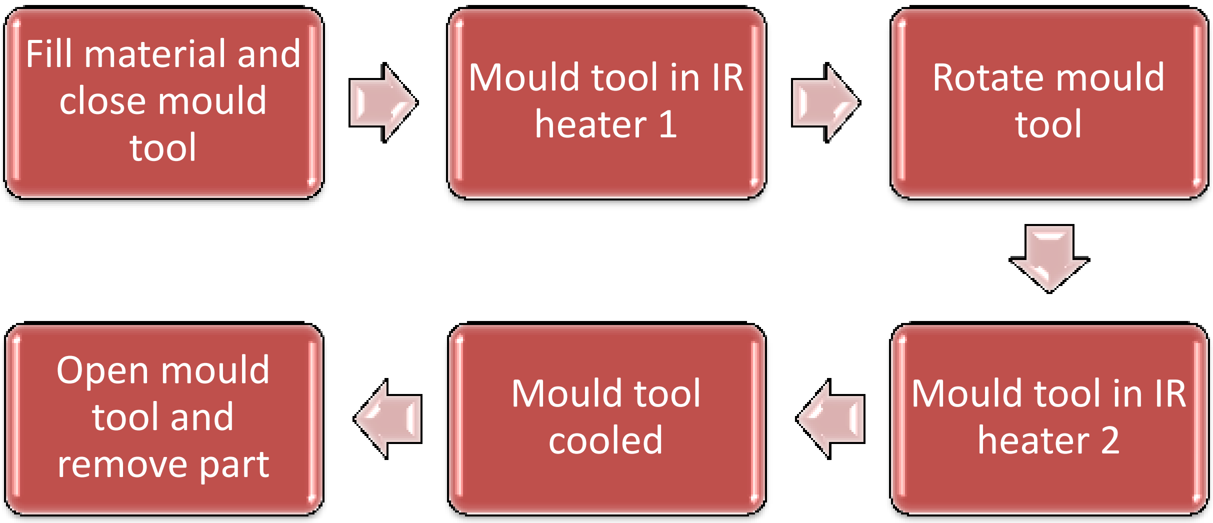


Figure 6 Protocol for producing parts.

A validation regime was agreed and proved and a standard operating procedure was written and given to the partners during the training session. A number of different skin and core combinations have been validated for different scenarios.

Flood barrier product design & test

Using the Finite Element based PRIME design tool (Figure 4) a theoretical calculation was carried out for the hydrodynamic and hydrostatic loads on a flood barrier spanning 2m between supports and 1200mm high will be calculated to determine the bending moments and shear force on both the supports and panels.

The theoretical design - combination of static and dynamic loads was given as Max stress = 26Mpa and deflection = 11.5%

A number of small flood barriers were produced for testing purposes.

The consortium agreed that after reviewing the many alternative options curved, external ribbed and internal ribbed a flat flood barrier would be produced as the design tool predicted that it would meet the required stress and deflection parameters.

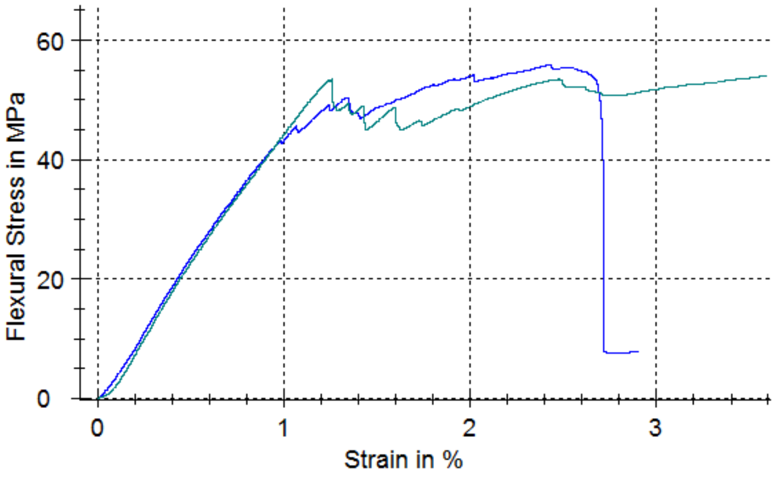
At this stage alternative deployment techniques were also investigated however Caro decided that they may implement some of suggestions post project.

The PRIME panels manufactured using the rig based at CARO according to the design calculations from EMA, and were mechanically tested using Instron/Zwick flexural tests set at Brunel University. These tests were performed to determine the mechanical properties of the panels, and the performance of the PRIME panels demonstrated better than average mechanical performance as shown in the tables below.

In the theoretical design Task 6.1, combination of static and dynamic loads are given as: Max stress= 26Mpa, deflection = 11.5% however the actual test results that the CARO PRIME board demonstrated very good mechanical properties (Figure 7), i.e. much higher maximum stress (54.95 MPa) and lower deflection (If taken at 26MPa. it will be 0.5% deflection and at 45.95MPa. it will be only 1% deflection)

Project : FP7-PRIME

Batch : Boards manufactured using Rig at Caro



Statistics:

Boards manufactured using Rig at Caro	Flex Mod	Strength	Str Break	Stn Fmax	Stn Break
n = 2	GPa	MPa	MPa	%	%
x	4.48	54.95	-	3.02	-

Figure 7 flexural test result and stress-strain plot of board made at CARO

Hydrostatic tests were also carried out on the flood barrier. The objective of this test was to ensure the sealing and deployment system operates efficiently when used in a realistic flood scenario.

The barrier, manufactured using PRIME rig at CARO according to the design calculations from EMA, was tested in CARO's standard stainless steel rig that could be filled with water. No leakage was noticed and the tests validate the design calculations from EMA. Bonding of (0.5 x 0.25 m) panels to make (1.0 x0.5 m) were carried out following which the panels were subjected to the prototype flood barrier test Figure 8.

Figure 8. Tank filled with water with the PRIME barrier in place to determine leakages or materials failure

In conclusion the barrier hydrostatic testing procedure was successfully carried and the results obtained were very encouraging since no mechanical failure or leakages from the panels were noticed.

The panels demonstrated that they could withstand the pressures and mechanical forces exerted by the water in the tank on to the PRIME panels.

The procedure of the operation also demonstrates that the results conform to the theoretical design generated from EMA's work.

A detailed training manual has been produced to train key members of the Associations in all aspects of the PRIME technology.

Dissemination

To aid dissemination of the PRIME project a website (Figure 9) has been created which gives the public information on the Project Goal, Partners, Project Objective and Dissemination. The website is located at www.fp7prime.eu

Figure 9: Screenshot of project website

The knowledge base wiki was updated from the version produced in P2 with information about the Life Cycle Assessment of the recycled plastic flood barrier and also the fire reaction of recycled plastics. The latest version can be found at http://www.prime.wikispaces.net and people can register to use it. A word version is also available on the Prime project website.

A sixteen page commercial review document has been uploaded to Prime project website covering: Introduction, PRIME Process, Energy Efficiency, Mechanical Modelling Tool, Future Applications, Environmental Analysis, Fire Reaction, UV Resistance, Life Cycle Analysis and PRIME Panel Cost Estimator.

A detailed training manual has been produced to train key members of the Associations in all aspects of the PRIME technology.

IP

The partners have all agreed that the IP will be protected by Trade Secret and a Trade Mark (Prime techniques) associated with 'Building materials of plastics material' has been applied for.

Conclusion

PRIME clearly demonstrates the increasing potential of using recycled mixed plastics to create high end products that can be used in many industries.

Resource recovery, Life Cycle Analysis and carbon efficiency are now becoming significant purchasing considerations to product specifiers and buyers, especially for the public sector and construction. There is also a considerable amount of goodwill from end users, corporate and individual, to choose the recycled product option, if it matches their expectations in regards of quality and cost.

In order to meet such quality and cost expectations with products manufactured with high percentages of recycled polymers, it is important to consider both the product specification and the properties of the recycled polymers.

For example, building products are a specific product group where the combination of mechanical properties, competitive through life cycle costs and reduced carbon footprint offered by thermoplastic composites, can offer real advantages over materials such as concrete, timber and glass fibre. The inherent waterproof nature of thermoplastic materials can also offer significant advantages over established construction materials in the outdoor environment, and the focus has been on the manufacture of lightweight deployable flood defence products.

Increasing the re-use of mixed post-consumer plastics waste provides an excellent opportunity. These waste streams are generated within our own economies, and instead of paying to dispose of materials, by designing products to efficiently reuse materials already within the waste stream can add value, create demand and provide employment, whilst reducing the overall domestic carbon footprint. A recycled thermoplastic product made from the PRIME process can also have a carbon footprint 60% better than a similar product made from virgin materials, and at similar quality and price.

In addition to this, the technical and manufacturing developments of PRIME have also been complemented by Life Cycle Analysis, comparing panels manufactured using mixed plastics waste and aluminium panels currently used in flood defence barriers, and it has been demonstrated that the recycled plastic panels are more environmental friendly than the aluminium equivalent. Also, a significant benefit for PRIME is that panels can be produced using recycled materials and be formulated to give a degree of flame retardancy and UV stability furthering its potential use.

Apart from the environmental concerns and disposal costs, the other business benefits are clear. The use of recycled plastics as a raw material can add to companies' environmental credentials, such as carbon footprint reductions, lifecycle analysis benefits or in developing its corporate social responsibility agenda. PRIME provides an impressive example of the versatility of recycled plastics packaging in new products and applications.

Project Consortium

The project consortium is made up of the following pan European partners:

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