FINAL REPORT

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1. Executive Summary

A review of the embodied energy values of the various building materials shows that the embodied energy of the most widely used insulation materials in construction applications is characterized by very high values. This mainly results either from the energy intensive conditions applied for the manufacturing of the mineral based insulation materials or from the high embodied energies of the oil- based raw materials used for the production of the organic based ones. Moreover, conventional insulating materials can suffer from various disadvantages including not stable thermal and acoustic performance overtime, combustibility, shrinkage and setting, and pollution of the indoor building environment.

In this frame the objective of the project was the development novel inorganic insulation materials and building insulation masonry components, that will have at least 50% lower embodied energy and 15% lower cost than their commercial counterparts and at the same time they will not present technical, health and/or environmental drawbacks.

This objective has been achieved through the development of innovative technological routes for the production of the 3I materials, combining the use of appropriate mineral and other industrial wastes and by-products with novel low energy consuming synthesis processes based on inorganic polymerization and thermal expansion. The new formulations and products are called “3I” materials, since they will be Inorganic, Insulating and Incombustible.

Within the 4 years of its duration, LEEMA achieved to successfully develop: a) various formulations of inorganic precursor polymers based on inert, natural alumino-silicate raw materials, originating from “zero-embodied energy” wastes of industrial mineral exploitation and other industrial wastes and by-products as well as novel low energy processing technologies that take advantage of the unique and favorable chemical and mineralogical composition of the above wastes; b) 3I loose-filling materials to be used to fill cavity walls, or as replacement of lightweight aggregates in various products (boards, bricks, mortars, plasters, etc.); c) 3I formed products (foam blocks, EPBs, fibre boards) to be used in new or retrofitted buildings and d) 3I bricks.

The LEEMA products are characterized by a high degree of innovation, competitive thermal performance, low environmental impacts and high added value for the end-users. Some of the products are ready to be introduced in the market, while others require some further improvements. The new 3I products have been evaluated against the relevant EN standards, and a roadmap to their certification has been established. The assessment of their environmental sustainability has been performed with life cycle assessment studies.

The new products and technologies will have significant economic and technological impact on the Construction and mainly the insulation sector Construction (granular insulation, insulating blocks, boards and bricks). Moreover, the successful completion of the project can result in additional environmental, political, economic and social impacts (mineral wastes reduction, low embodied energy insulation materials and masonry components, etc.).

2. Project Context and Objectives

2.1 Introduction

Although, the European citizens are becoming increasingly familiar with the concept of energy in use – that is the energy required by the occupants of an existing building, primarily for space heating, water heating and lighting – and of the need to reduce it, they have not realized yet that energy is needed not only to run a building but it also takes considerable amount of energy to create the building products and the building itself.

The embodied energy of a building, defined as the total energy required to produce the building components, transport them in place and construct the building, is a significant component of its lifecycle impact and can be the equivalent of many years of operational energy. An average household contains about 1,000 GJ of energy embodied in the materials used in its construction, which is equivalent to about 15 years of operational energy consumption. Moreover, it is important to point out that when increasing the level of energy performance of buildings in operation, which is the current trend in the construction of new buildings dictated by many EC (EPBD 2010/31/EU) and member state directives, the embodied energy of the building materials represents a much higher percentage of the energy spent in the whole life cycle of the building.

Therefore, the development and use in construction works of building materials of low embodied energy will directly reduce the overall environmental impact and improve the sustainability of the building sector.

2.2 Project Objectives

A review of the embodied energy values of the various building materials shows that the embodied energy of the most widely used insulation materials in construction applications is characterized by very high values. This mainly results either from the energy intensive conditions applied for the manufacturing of the mineral based insulation materials or from the high embodied energies of the oil- based raw materials used for the production of the organic based ones. Moreover, conventional insulating materials can suffer from various disadvantages including not stable thermal and acoustic performance overtime, combustibility, shrinkage and setting, and pollution of the indoor building environment.

In this frame the objective of the project was the development novel inorganic insulation materials and building insulation masonry components, that will have at least 50% lower embodied energy and 15% lower cost than their commercial counterparts and at the same time they will not present technical, health and/or environmental drawbacks.

This objective has been achieved through the development of innovative technological routes for the production of the 3I materials, combining:

a) use of appropriate inert, natural alumino-silicate raw materials, originating from "zero-embodied energy" wastes of industrial mineral exploitation and other industrial wastes and by-products;

b) application of novel low energy consuming synthesis processes based on inorganic polymerization and thermal expansion that take advantage of the unique and favorable chemical and mineralogical composition of the above wastes;

The new formulations and products are called "3I" materials, as they are Inorganic, Insulating and Incombustible.

The new 3I products have been evaluated against the relevant EN standards, and a roadmap to their certification has been established. The assessment of their environmental sustainability has been performed with life cycle assessment studies.

Within this overall framework, the main research areas covered within the project are the following:

1. Definition and quantification of the technical specifications of the new insulation components (3I loose-filling material, 3I formed products - foam blocks, EPBs, fibre and non-fibre boards - and 3I polymer bricks) proposed to be developed in order to meet the market requirements and comply with the EPBD and the technical, safety, health and environmental performance standards. The properties that have to be measured and the relevant methodology for the characterisation of the wastes to be used as raw materials for the development of the new components and also the evaluation of the new insulation components performance will be studied (WP1);
2. Development of various formulations of inorganic precursor polymers, which upon suitable processing will lead either to the direct synthesis of formed insulation products (in the frame of WP4) and insulating polymer bricks (WP5) or to an easily expandable precursor material that will be used for the production of bulk insulating materials (WP3)
3. Development of 3I loose-filling materials with superior performance, reduced embodied energy and lower cost compared to the currently applied bulk insulation products (expanded perlite, stone and glass wool, polyurethane bubbles) to be used to fill cavity walls, to cover the space between soil and concrete floors and under flat green roofs in retrofitting works, but also in new buildings to provide thermal insulation and protection from water drainage, as filler for plasters, mortars, paints and joint compounds and for wrapping ducts to provide thermal insulation and fire resistance. The solid inorganic precursor polymer developed in WP2 will be used as primary material for the synthesis of the new 3I loose-filling materials. The development of the 3I loose-filling material will include two stages: a. expansion of the precursor inorganic polymer and b. surface coating of the expanded particles to render them completely hydrophobic (WP3);
4. Development of new 3I formed products (foam bls, EPBs, fibre and non-fibre boards) with similar thermal performance to the currently available products for similar applications,

but also with good acoustic insulation and mechanical properties, chemically inert, stable over time and fire resistant to be used as insulating boards in new or retrofitted buildings, to cover roofs and walls (external and internal); additionally, the insulating boards will be also used to cover ventilation pipes, wire networks, steel constructed buildings, etc. For the synthesis of the new 3I formed products, the inorganic polymer paste developed in WP2 will be used as primary material, while different low embody energy and cost processing routes will be applied for its further processing, depending on the type of the final board to be developed (WP4);

5. Development of new bricks, with improved thermal and acoustic insulation properties, reduced embodied energy and mechanical properties similar to those of special insulating clay bricks currently available in the market, by using: a. the solid polymer material, developed in the frame of WP2, for binding perlite in order to create a composite brick body; b. the 3I loose-filling or foamy material, developed in WP3 and WP4 respectively, to fill the brick cavities (WP5);
6. Evaluation and assessment of the technical performance of the new 3I products under real weather conditions in order to be used in the building sector and testing of the new 3I products with all the relevant EN standards in order to prove their compliance with technical, safety, health and environmental standards and the targets set by EPBD (WP6);
7. Assessment of the environmental impact related to the production and application of the new 3I products through a detailed Life-Cycle Analysis, and comparison to that of the most widely applied insulation materials, aiming to demonstrate the energy benefits and the environmental sustainability of the proposed insulation products (WP7);
8. Technical and environmental evaluation of the new processes and 3I products developed in the frame of the project (WP8);
9. Evaluation of the economic feasibility (pre-feasibility study) of the new processes and products developed in the frame of the project and development of a realistic preliminary business plan for the industrial application of the new production processes and a market penetration strategy for the exploitation of the new 3I products (WP9).

3. Project Results

Based on DoW, the work of the project was structured in 11 WPs, namely: WP1 (Materials specifications and characterisation), WP2 (Development of inorganic precursor polymeric materials), WP3 (Development of 3I loose-filling materials), WP4 (Development of 3I formed products), WP5 (Development of 3I polymer bricks), WP6 (Field tests of the new 3I components – Certification), WP7 (Life Cycle Analysis), WP8 (Technical evaluation of new products), WP9 (Business plan), WP10 (Project management) and WP11 (Project scientific coordination).

Within this respect the activities carried out and the beneficiaries involved in them are the following:

3.1 WP1: Materials specifications and characterisation

The work of WP1 was completed on M11. The main characteristics of the currently used insulating materials and masonry components in the targeted building applications were reviewed and evaluated. Based on these data, the specifications and technical requirements for the characterisation and performance assessment of the new 3I products for each application were identified. At the end of the project the specifications of the final products and raw materials were updated based on the research results.

Moreover the properties and the characteristics of the various types of wastes to be used as raw materials for the synthesis of the new insulation products were defined. Finally, for each material and new insulation component a list of properties and the relevant measurements procedures were determined. This list has been properly modified and finalised at the end of the project, taking into account the results of the research performed.

All beneficiaries were involved in these activities, while NTUA collected all the data and prepared D1.1 (Specifications of waste materials and new products) which was submitted on M7 and D1.2 (Properties of waste materials and new products) which was submitted on M21. NTUA reviewed the two documents at the end of the project, taking into account the project's results. The revised versions of D1.1 and D1.2 are included in the 3rd periodic report as Annexes.

3.2 WP2: Development of inorganic precursor polymeric materials

The proper types of silicate/alumino-silicate waste materials have been identified and fully characterized by NTUA. Moreover, a study of the compatibility between the silicate/alumino-silicate wastes available across EU and the market expectations – technical requirements has been performed.

NTUA performed a detailed study of the chemistry of the inorganic polymerisation reactions and identified the optimum process conditions aiming to the formation of precursor inorganic polymers with optimum composition and properties for the development of the new 3I products. The research focused on the development of proper inorganic polymer formulations for the two main pillars used to develop the various LEEMA products, as seen in Figure 1: 3I Loose Fill materials, and 3I inorganic polymeric binders

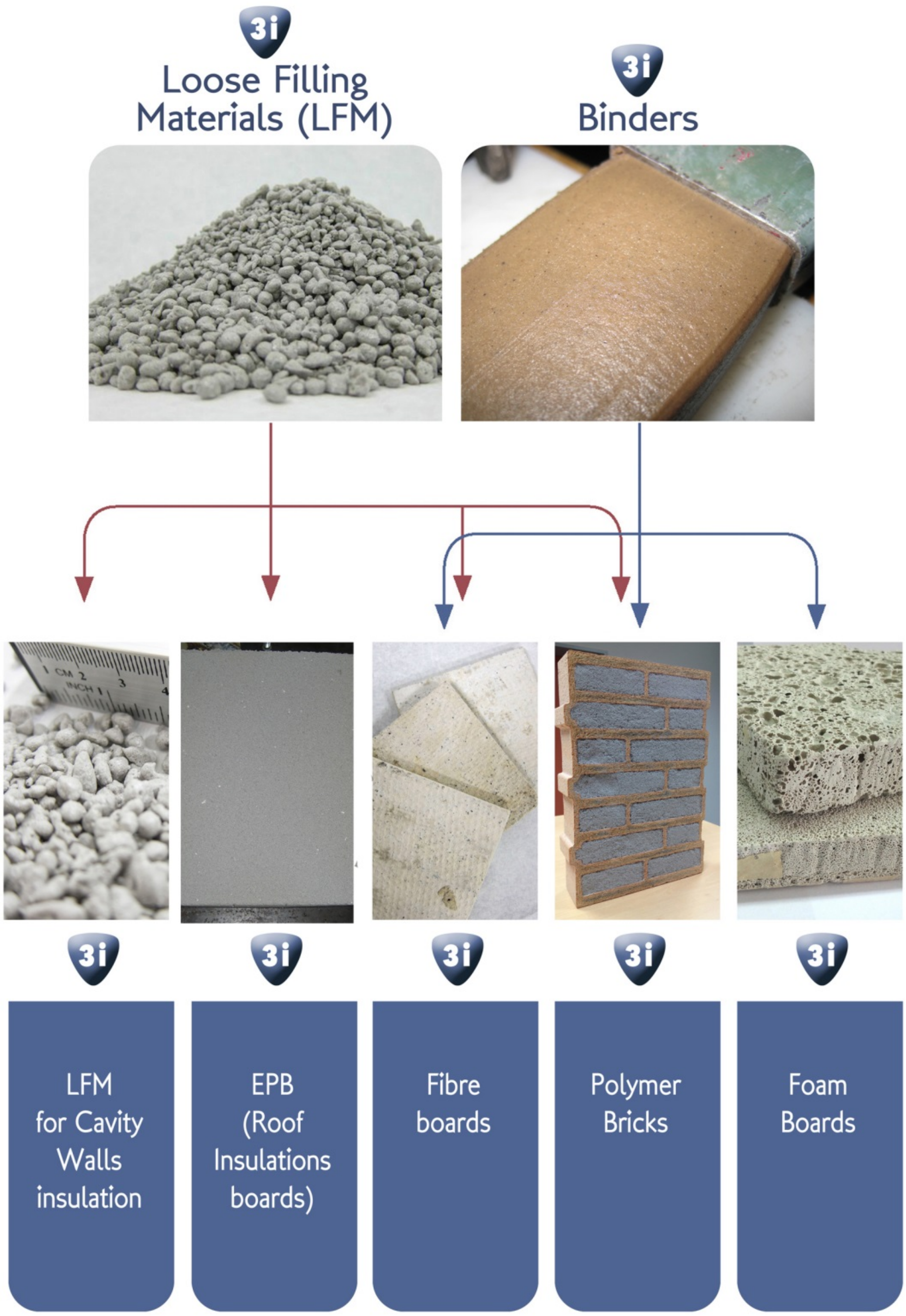

Figure 1. The LEEMA products

The key parameters have been identified in each case, and the lab scale synthesis of the different 3I products has been optimised.

- 3I Loose fill materials (3I LFM):

Various formulations for 3I Loose Fill Materials (3I LFM) have been developed yielding granulate samples with LBD ranging from 14 up to > 100 kg/m^3. The key parameters that affect the properties of the final products have been identified, and the lab scale synthesis process has been optimised. Appropriate formulations have been selected and fine-tuned according to the specifications set for each different application (cavity walls, 3I EPBs, 3I fibre boards, 3I bricks and facades).

- Inorganic polymer binders (3I Binders) for 3I compact boards and polymer bricks

Various formulations for inorganic polymer binders have been developed. The key parameters have been identified, and the lab scale process has been optimised. Optimum formulations based on perlite tailings yield specimens with compressive strength above 20MPa. The first extrusion trials showed that geopolymer pastes based on perlite tailings can be successfully extruded by extruders similar to the ones used in the clay industry, specially equipped. The rheological properties of the geopolymer pastes are crucial for the successful extrusion, and were further studied.

- Inorganic polymer binders (3I Binders) for 3I foamed blocks

The rheological properties of the 3I binders had to be carefully designed to obtain foamed geopolymer pastes. The research has been performed on three stages: synthesis of geopolymeric paste, foaming of the paste and curing of foamed paste. For each stage, the key parameters were defined, and the process was optimised. Optimum formulations yield foamed products with density as low as 350 kg/m^3 and thermal conductivity of 0.065W/mK.

WP2 was successfully completed on month 24, providing selected formulations for the lab and pilot scale development of the various LEEMA products in WPs 3, 4 and 5. Nevertheless, the knowledge obtained within WP2 was used to properly adapt the formulations when requested, especially during the up-scale of the products development and production.

3.3 WP3: Development of 3I loose-filling materials

A lab scale expansion furnace was developed and used for the expansion of small scale 3I loose-fill material precursors for the evaluation of the various formulations developed in WP2. The IR lamps temperature was set at 600 °C, while the actual expansion temperature was estimated to be ~300-350 °C, significantly lower than the expansion temperature for natural perlite.

The pilot scale production of the 3I LFM was designed based on the lab scale process. The pilot production consists of a mixing unit (typical cement mixer), a crushing/ sieving system and an Infrared expansion furnace with higher capacity compared to the lab scale furnace.

A hydrophobation process was developed by S&B, based on solid siloxane vapours. A lab scale method has been used for the hydrophobation of small scale samples. Moreover, a pilot scale vertical cylinder-like reactor was installed in Ritsona. However, as the new 3I Loose Filling materials have good water repellency and in most cases further improvement was not necessary, it was decided to skip the hydrophobatrion step so as to reduce the production cost.

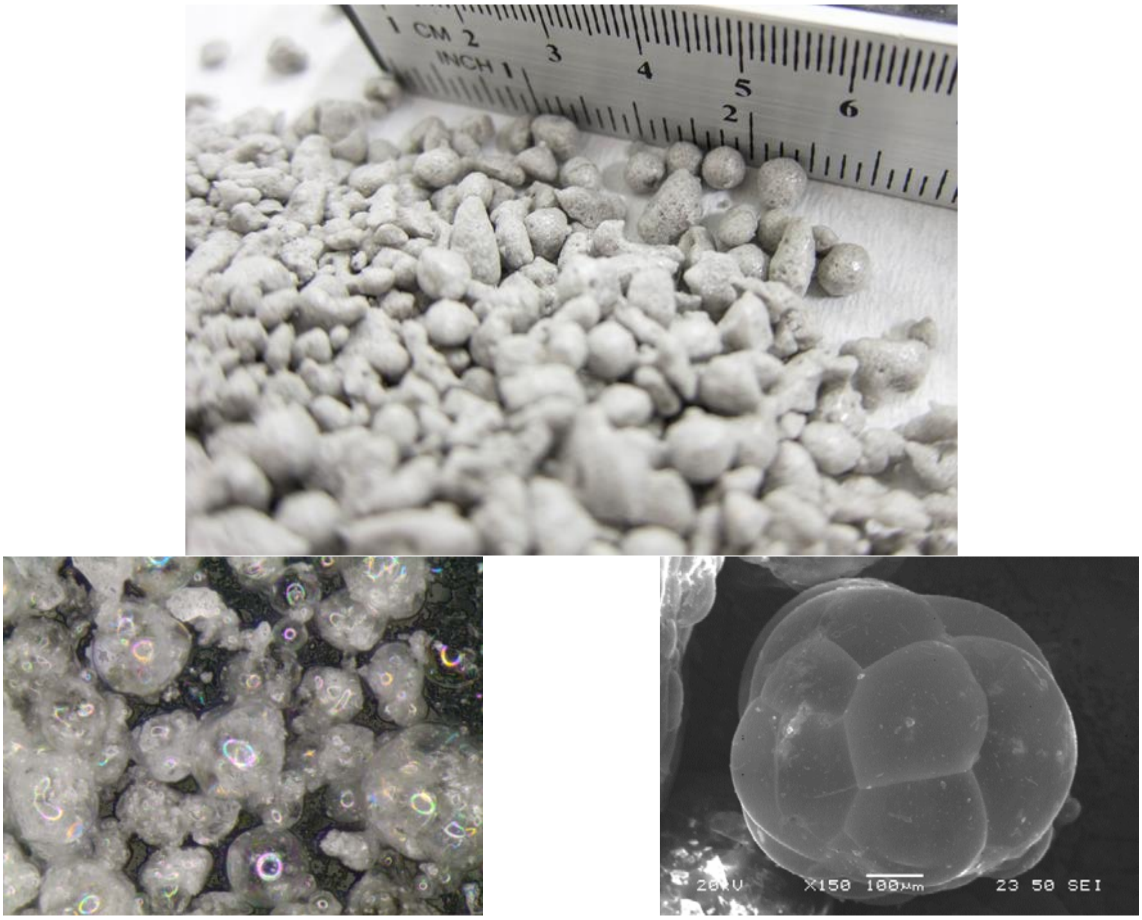

Figure 2. 3I Loose Filling materials

Initially, small scale samples of 3I Loose filling materials were produced by NTUA at lab scale, hydrophobised by SandB when necessary, and delivered to the industrial partners, for the different applications. After the selection of the most suitable materials, pilot scale samples were produced by SandB and NTUA and delivered to the industrial partners, to be used in the pilot scale production of the LEEMA products. The final 3I Loose Filling materials are presented below:

1. Loose fill material for cavity walls.

1.2 m^3 of 3I Loose Filling material for cavity walls was delivered to WP6 partners for field tests and the final evaluation. The sample has 35% lower LBD and 17% lower thermal conductivity, compared to the commercial hydrophobic expanded perlite for cavity walls. The water absorption is similar even without hydrophobation and it was decided to eliminate this step to reduce the production cost. The crushing resistance is lower, due to the lower LBD, but is considered adequate. A small amount of the sample was hydrophobized by SandB to be evaluated for its water repellency by WP6 partners.

2. Loose fill material for 3I Fibre Boards.

Several small and large scale samples were prepared and delivered to ETEX for lab and pilot scale experiments. The first large scale sample ($1m^3$) was produced and delivered in June 2013 for the first pilot scale production trials of fibre cement boards. The final – optimized sample (1 m^3 delivered to ETEX in October 2014) had similar LBD and lower thermal conductivity compared to the expanded perlite currently used by ETEX. The crushing resistance was significantly improved so as the material withstands the production process of the fibre boards. Moreover, the water repellency was significantly higher compared to expanded perlite, even without hydrophobation.

3. Loose fill material for 3I Bricks and EPBs.

The work under WP3 continued in order to identify the most suitable 3I Loose Filling material for 3I EPBs, despite the withdrawal of TCERAM. Several small scale samples were prepared and delivered to SCHLAG for lab scale experiments.

The final grade of 3I LFM, selected to be used both for 3I Bricks and Facades as well as 3I EPBs, was produced at pilot scale by SandB and NTUA (~0.85m^3). Compared to the expanded perlite TCERAM uses in their production, the 3I LFM has 41% lower LBD and 20% lower thermal conductivity. The crushing resistance is lower, as expected, but still considered adequate in order for the material to be used for the production of 3I EPBs. Compared to a commercial expanded perlite product, which is the best available commercial benchmark as provided by SCHLAG, the 3I LFM has similar density and 13% lower thermal conductivity.

During the 3rd reporting period, NTUA performed additional experiments in order to further optimize the expansion of the 3I LFM grade for 3I Bricks and facades and 3I Bricks. The productivity of the IR expansion for this specific grade was rather low, due to the fine granulometry of the precursor, resulting in high energy consumption per kg of product. Expansion trials on a vertical electrical oven, used for expansion of special grades of natural perlite, showed that the 3I LFM can be successfully expanded at significantly lower temperature (530-580 °C) compared to perlite (1100-1200 °C), achieving also a higher productivity. The energy consumption per kg of 3I LFM expanded in the vertical electrical oven was 83% lower compared to perlite, and 77% lower compared to IR expansion of this specific 3I LFM grade.

3.4 WP4: Development of 3I formed products

3.4.1 Task 4.1 Development of 3I foam blocks

An optimized lab scale foaming process was developed based on the formulations developed in WP2, using inorganic or organic foaming agents. A range of lab scale prototypes with densities ranging between 450-650 Kg/m^3, thermal conductivity 0.06-0.10 W/mK and compressive strength 0.8-2.7 MPa were produced.

The up-scaling was focused on the use of organic foaming agents. It was decided that efforts on up-scaling would focus on the organic foaming agents. The optimization on pilot scale took a lot of effort, as the inorganic polymerization and the foaming process are both strongly dependent on the volume as well as the geometry of the samples. Extrusion was also considered as a shaping method. Although the extrusion trials performed by Morando, in cooperation with NTUA, were successful, it was decided that the most suitable shaping method was casting.

Pilot scale prototypes have been produced with densities ~600 kg/m^3 and λ below 0.11 W/mK. The samples can be successfully cut, retaining their shape and mechanical properties. The required amount of samples were produced by FIBRAN and NTUA and delivered to WP6 for characterization.

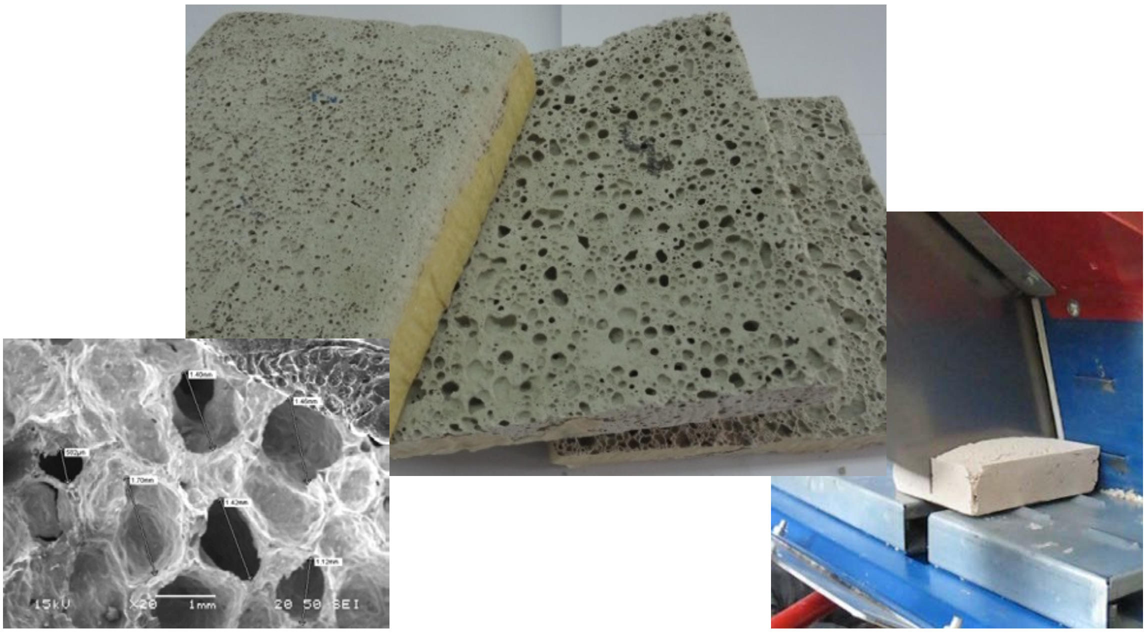

Figure 3. 3I Foamed Blocks

The first results indicated that the 3I Foam Blocks had relatively low compressive strength. Therefore, the inorganic polymer formulation of the block was re-optimised by NTUA at pilot scale in order to improve the mechanical strength of the blocks. The new samples exhibited improved compressive strength values while the density and thermal conductivity were similar to the first batch.

3.4.2 Task 4.2 Development of 3I EPBs

Different samples of 3I LFM have been delivered to TCERAM for lab scale production of 3I EPBs. Lab scale products were successfully produced, replacing partially or fully the expanded perlite by the 3I LFM. The first lab scale 3I EPBs exhibited similar performance to the reference samples.

After TCERAM's withdrawal, the development of the 3I EPBs was undertaken by NTUA and Morando. NTUA focused on the lab scale development of a suitable formulation, based on a totally inorganic binding system and the selected grade of 3I LFM, using different shaping methods and curing conditions. The optimum lab scale samples had a thermal conductivity of 0.051 W/mK, similar to that of commercial Fesco boards, even though the density was slightly higher (192 kg/m^3).

The most promising formulations were selected for the pilot scale development of a suitable shaping method and curing protocol, performed by Morando in cooperation with NTUA.

Based on the results of the pilot scale development, 20 boards of 3I EPBs were produced by Morando and delivered to WP6 for characterization.

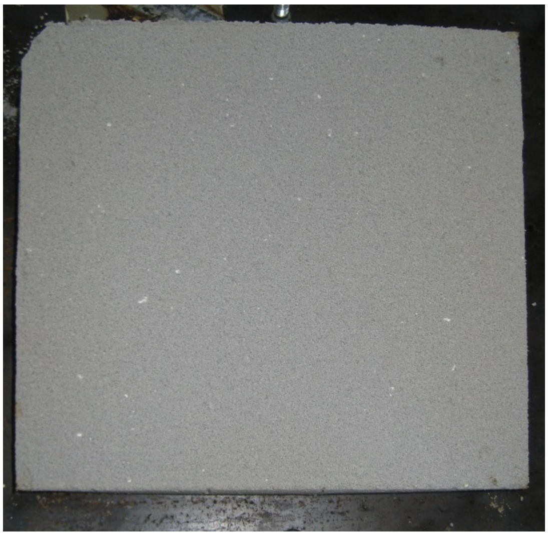
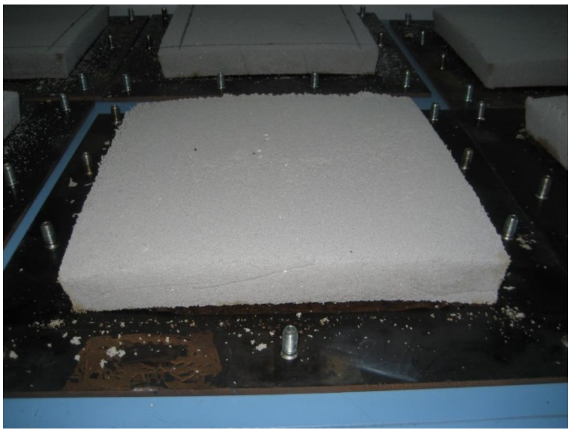

Figure 4. 3I EPBs

3.4.3 Task 4.3 Development of 3I fibre and non-fibre boards

The development of 3I Fibre boards by ETEX followed two different routes:

A. 3I Fibre cement boards (3I FC Boards), where the standard lightweight filler is substituted by 3I LFM;

B. 3I Fibre boards, where a 3I based (geopolymeric) binder is used, replacing the cementitious matrix.

Different lab and pilot scale samples of 3I LFM have been delivered to ETEX for evaluation as replacement of expanded perlite in the Hatschek production of FC boards.

Several pilot scale trails were performed by ETEX for the production of different FC boards on mini-Hatschek (MiH) line. The LFM material was evaluated as substitution for the standardly used expanded perlite in Promatect H and Eterspan boards, and the standardly used exfoliated vermiculite in the Supalux boards. After the first trials, the efforts focused on fibre boards based on the Promatect-H product, replacing expanded perlite with the 3I Loose Filling material.

Figure 5. 3I Fibre Cement Boards

Several pilot scale trials tool place from July 2013 to September 2015. No major production problems were experienced when using the 3I LFM. Some accumulation issues were resolved by proper pre-handling of the 3I LFM. The 3I boards seem to have similar (or slightly higher density) but significantly higher flexural strength. The final sheet samples will be characterised and evaluated under WP6.

The development of 3I Fibre boards with inorganic polymer binder is an extremely ambitious goal as, except for the development of a suitable binder formulation, a suitable board shaping-production process needs to be developed, as confirmed also by the first extrusion experiments. Lab scale experiments on inorganic polymer binders, based on the formulations developed under WP2, were performed, showing promising results. Extruded sheet samples, produced during the various extrusion trials by Morando and NTUA have been evaluated, giving promising flexural strength from 4-12 MPa, depending on the inorganic polymer formulation.

3.5 WP5: Development of 3I polymer bricks

One of the objectives of LEEMA project is the substitution of expanded natural perlite with the new geopolymeric based LFM as insulating material for insulant-filled bricks. The most important property of an insulant lay in the thermal conductivity of the bound granules, forming a rectangular thermal insulation board with dimensions 20 cm to 20 cm, as this bound sample board represents the insulant conditions in the construction material, the brick, and can be measured using the standard procedure for thermal conductivity.

Several 3I LFM samples were delivered to SCHLAG. The first prototype bricks and façade panels were produced by SCHLAG in July 2013 thus proving in principle the substitution of natural perlite with 3ILFM.

Figure 6. 3I brick for new buildings: "POROTON T7"

Figure 7. 3I Façade panel for refurbishment: "WDF"

The final 3I LFM sample (non hydrophobised as well as hydrophobised) was successfully bound to form the insulant boards. The board of the non-hydrophobised sample showed a very good thermal conductivity of 35.5mW/m.K with apparent density of 64 g/L in dry conditions at mean temperature of 10 °C. The hydrophobised plate showed higher values (40.2 mW/m.K for thermal conductivity and 115 g/L for the apparent density), due to agglomeration issues. After the optimum process parameters were defined, 3I Bricks and facades were produced, filled with 3I LFM as well as perlite as reference, and evaluated by SCHLAG and MFPA.

For the ambitious goal of substitution of the heavy clay based brick body with geopolymeric material, several extrusion trails took place by Morando and NTUA. Efforts were made by NTUA to adapt the formulations so as to enhance the extrudability of the pastes. Morando designed and constructed a dedicated pilot scale extruder for "soft-clay" extrusion. During the final trials, the extrusion process was optimized and several samples were produced in order to be evaluated for use in 3I fibre boards (ETEX) or 3I Bricks (SCHLAG).

Figure 8. Successful extrusion of 3I Binders

SCHLAG evaluated the samples, which offered an apparent density of 1300 kg/m^3 and thermal conductivity values were determined to 280 to 295 mW/m K in dry conditions and about 330 mW/m K in wet conditions (23 °C and 80 % RH). The bending strength measured was relatively low, probably due to cracks in the tested specimens.

SCHLAG is developing new generations of bricks for single or multi-family buildings. The geometry of the new brick is mostly given by a former brick generation of perlite filled brick. The performance of thermal conductivity was simulated by MFPA. Different hole patterns of the brick body have been modelled by finite element method (FEM) in order to determine the equivalent thermal conductivity of the brick. The equivalent thermal conductivity - as a measure of the thermal resistance of the whole brick for a given thickness - is a function of the thermal conductivity of the components. These components are the brick material (burnt clay or 3I-material) and the holes in the structural material with or without insulating filling. These results can be used both for the burnt brick products and for the 3I-polymer bricks.

3.6 WP6: Field tests of new components – Certification

WP6 partners provided input in order to create a detailed inventory of the potential applications of the 3I products in buildings, and the relevant characteristics to be tested. The test programs, based on EN and/or national standards, for all the 3I products (intermediate as well as final) have been agreed among the relevant partners and are reported in WP6 deliverables.

The amounts required, according to the agreed test program, of each 3I product final samples were produced by the relevant partners.

Based on the results of the products' characterization and evaluation performed in WP6, BBRI prepared a very useful Roadmap to Certification for each of the products developed in the LEEMA project, which is included in the Exploitation Plan.

3.6.1 3I Loose Filling materials

3I Loose Filling materials for Cavity Walls

The final large scale sample (1.2 m^3) of 3I Loose Filling material for cavity walls was produced by SandB and NTUA and delivered to WP6 for a complete evaluation. The main properties of the 3I Loose Filling material for cavity walls are summarized in the relevant technical datasheet.

The new 3I Loose Filling material exhibits significantly lower bulk density than the reference material, by approximately 40%. Thermal conductivity of the 3I Loose Filling material is around 20% lower than that of reference expanded perlite. Consequently, the reference material exhibits almost twice higher particle strength as compared to the 3I filling material. Nevertheless, the new 3I loose filling material performed better than the reference material in the settlement by vibration test, with less than 13% settlement ratio, whereas the reference material results in more than 15% settlement.

The water repellency of both the 3I loose filling material as well as reference material lies within the limits given by the corresponding normative. Hydrophobized 3I material performs slightly better than the reference material.

In general, it can be stated that the new 3I material is at least as good as or better than the reference material in terms of the material performance. Considering the lower production cost, significantly lower embodied energy and the advantages in terms of the sustainable resource management, the new 3I loose filling material offers clear advantages in comparison to the commercially available products.

Blowing of 3I loose filling material

A test campaign was performed by BBRI to test the application of 3I LFM for cavity walls and compare it to commercial products. The outcome of the test campaign was the detailed technical guidelines for the application of 3I LFM as cavity insulation.

The settlement in cavity walls due to hygrothermal cycling was tested according to EN 1501-1, on timber-frame structures filled with 3I LFM during the test campaign. Since the expanded perlite product turned into powder during blowing, no comparison of its settlement could be made with the 3I LFM. Therefore, a comparison was made with blown cellulose (blown in the simulation of the timber-frame walling structure with the same blowing equipment).

The results indicate the settlement of 3I LFM with a membrane vapour barrier is only 0.08%, well below the acceptable levels (<1%) and significantly lower (68-77% lower) compared to that of cellulose insulation.

Figure 9. Application of 3I LFM for settlement testing

3I Loose Filling materials for 3I Fibre Boards

The final pilot scale sample of the 3I Loose Filling materials for 3I Fibre Boards was produced by SandB and NTUA. ~1m^3 of this sample was delivered to ETEX to be used for the pilot scale development of the 3I Fibre Boards and ~ 120L to WP6 for characterization. The properties of the

3I Loose Filling material and reference expanded perlite are summarized in the technical datasheet of 3I Fibre Boards.

The results indicate that the 3I Loose filling material for 3I Fibre boards has 19% lower density, 8.2% lower thermal conductivity and significantly increased compaction resistance and water repellency compared to the currently used expanded perlite.

3I Loose Filling materials for 3I Bricks and Facades and 3I EPBs

The final pilot scale sample of the 3I Loose Filling materials for 3I Bricks and 3I EPBs (~0.75m^3) was produced by SandB and NTUA. ~0.55 m^3 of this sample were delivered to SCHLAG in two batches and another 200L were used for the development and pilot scale production of the 3I EPBs. The main properties of the reference and 3I Loose Fill material for 3I Bricks and EPBs are summarized in the relevant technical datasheets.

In case of the 3I Loose Filling material for 3I Bricks and Facades and 3I EPBs, the performance was compared to a commercial reference expanded perlite for the 3I Bricks and the reference expanded perlite used by TCERAM. The results indicate that the 3I Loose Filling material has slightly higher density but lower thermal conductivity compared to the best available commercial expanded perlite suitable for filling bricks. Compare to TCERAM's expanded perlite, the 3I Loose Filling material has significantly reduced density (-46%) and 16% lower thermal conductivity.

3.6.2 3I Foamed blocks

The pilot scale samples of the 3I Foam blocks were produced by NTUA and FIBRAN and delivered to WP6 for evaluation. The summarized properties of the 3I foam blocks are presented in the relevant technical datasheet. The new 3I foam blocks exhibit relatively high density and lower compressive strength compared to commercial AAC products. However, it is interesting to observe that even for almost twice higher density the new 3I material has similar thermal conductivity. Even though a direct comparison of materials from different density classes is not straightforward, it can be stated that the new material offers significant improvement of the thermal properties. The 3I Foam blocks shows high water absorption, probably related to the increased porosity and amount of large pores.

After receiving the first results, the inorganic polymer formulation of the block was re-optimised by NTUA at pilot scale in order to improve the mechanical strength of the blocks. A new batch has been produced and characterised by NTUA. The new samples, based on the re-optimized formulation after the pilot scale production of the samples for WP6, exhibited improved compressive strength values but similar density and thermal conductivity to the first batch.

3.6.3 3I EPBs

The production of the pilot scale 3I EPBs samples was performed by Morando, with the assistance of NTUA. The required specimens were produced by Morando in four batches and delivered to WP6. Commercially available Fesco boards were chosen as the reference materials. The main properties of the 3I EPBs are summarized in the relevant technical datasheet.

In general, the performance of the new 3I EPBs is comparable to that of the commercially available reference material. Thermal conductivity is approximately 30% higher than in case of the reference material, however the density of the 3I material is also significantly higher. One of the particularly important aspects is the fire resistance. Due to extremely low organic content (ca. 5%), the new 3I EPBs are classified as A1 material, which is a great improvement in comparison with the reference material (class C).

3.6.4 3I Fibre boards

The main properties of the reference and 3I Fibre Boards are summarized in the relevant technical datasheet.

The 3I Fibre Boards exhibit slightly higher density (+4%), increased bending strength (up to 20%) combined with lower thermal conductivity (-12.6%). The hygral expansion is higher compared to the reference boards, but the value is acceptable.

Durability and resistance to environmental influences was investigated in heat-rain test and EOTA wall test. Both materials exhibited excellent behaviour. The 3I Fibre Boards exhibited excellent durability, similar to the reference boards; Even after the extreme temperature and humidity conditions in the heat-rain test as well as freeze-heat-rain cycles in the EOTA wall test, no cracking or deformation whatsoever was visible on the specimens of the 3I or the reference Fibre Boards.

One of the most important properties of the Fibre boards is their bending behaviour. According to EN 12467, one of the classifications of the boards is based on the bending strength under ambient conditions. 3I boards exhibited slightly higher bending strength (without pre-conditioning), but also the difference between the two loading directions (parallel and perpendicular to the manufacturing direction) was higher in case of the 3I material. Both materials (3I and reference boards) can be classified as class 1 (bending strength of 4 MPa). After conditioning (25 or 50 wet-dry cycles, exposure to warm water) the 3I Fibre boards fulfil the requirement of EN 12467, maintaining at least 75% of the bending strength after exposure, with the exception of Batch-2 after 50 cycles with falls slightly below the required limit. Nevertheless, the behaviour is always similar or better compared to the reference boards.

It can be concluded that the new 3I Fibre Boards exhibit similar or somewhat better behaviour than the reference boards in terms of material properties.

The durability of the 3I Fibre Boards and reference materials was tested by the heat-rain cyclic test (EN 12467) and EOTA wall test (ETAG 004:2013 Guideline for European technical approval of external thermal insulation composite systems (ETICS) with rendering). Both materials, 3I fibre boards and reference materials, exhibited no signs of damage after completing the heat-rain cycles as well as after completing the EOTA-wall climate test.

3.6.5 3I Bricks and Facades

The key properties of the 3I Bricks and facades are summarized in the relevant technical datasheet. The thermal conductivity of the 3I products is comparable to the reference products with expanded perlite.

The moisture storage function and hygrothermal behaviour or perlite- and 3I LFM- filled Bricks was studied. The investigated non-hydrophobic 3I LFM had the highest moisture storage capacity (compared with natural perlites), creating a moisture-buffer that results in considerable lower values of humidity in the contact zone of internal insulation to the existing building construction. In this way, 3I LFM are able to protect an existing building construction from getting to wet under investigated normal indoor climate conditions. It was concluded that:

- - A non-hydrophobic 3I LFM- filling of a POROTON® WDF facade-bricks, applied as internal insulation of lime-stone wall shows the best hygrothermal behaviour of the construction, compared with perlite fillings: There is non-internal condensate and the values of humidity are comparable low.
- - Fillings with hydrophobic Perlites, (= state of technology for SCHLAG) show a better hygrothermal behavior than non-hydrophobic perlites.

3.7 WP7: LCA

3.7.1 Life cycle analysis of the new processes and products

The objective foreseen for this WP is to apply the LCA methodology in order to define the energy and environmental burdens of the new processes and 3I products developed within the project and to assess the environmental impacts related to the manufacturing phase including also insulating performances.

Starting from results obtained in the first 36 months, DAPPO has applied the LCA methodology to several product categories, each one with an industrial referent:

- Loose Fill Materials for several applications (SandB),
- Fiber Cement Boards (ETEX),
- Foamed Blocks (FIBRAN),
- Expanded Perlite Boards (NTUA and Morando),
- Insulating bricks/facades (SCHLAG).

The analysis is focused on manufacturing steps, excluding Use phase and End of Life phases. LCA study – 2nd iteration (D7.2) has been delivered to consortium at December 2015 and uploaded on ECAS.

The analysis is based on a comparison between “State of art products” (SoA) and “Innovative products” (INNO) developed during LEEMA project, which perform the same insulation service.

In order to provide an effective comparison between SoA and INNO products, the functional unit has been chosen based on mass and thermal values of different products (when they were available). Therefore, two different FU have been selected depending on the case (Table 1):

1. Same thermal insulation with the R value = 1 m^2K/W,

2. Same weight with the Mass = 1 kg of product.

Each SoA product is going to be transformed into the respective Inno product by replacing the current raw material/s with the 3I products, updating, if needed, also the manufacturing process.

At the end of the project the second iteration LCA study has been completed. The study includes the evaluation of real manufacturing processes, with effective products comparisons based on same service provided: as main results it has been possible to really understand the benefits coming from LEEMA projects, in the development of a new generation of greener building products.

This LCA study has been performed in accordance with internationally recognized guidelines (see e.g. ILCD Handbook: General guide for Life Cycle Assessment - Detailed guidance") and standard (ISO 14044:2006) main requirements.

The results of the analysis have been achieved following main requirements of the Recommendations 2013/179/EU "Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations". The Life Cycle Inventory model has been implemented through dedicated software, GaBi 6.

The description of the Reference and 3I products are presented in Table 1, together with the FU and the difference achieved in two key impacts:-Primary Energy Demand (measured in MJ) and Global Warming Potential (measured in kg of CO2 eq.);

Table 1: Functional Unit Selection and key impacts reduction for 3I and reference products

3I Product	Reference	Selected FU	Equivalent weights per FU		Difference		
			3I	Ref.	Prim. Energy Demand	Global Warming Potential	Aggregated impact
3I LFM for cavity walls	Expanded perlite (SandB)	1 m^2 for R-value of 1 m^2 K/W	2.315	5.659	**-60%**	**-65%**	**-60%**
3I LFM for 3I Fibre Boards	Exp perlite ETEX		3.928	4.872	**-63%**	**-65%**	**-30%**
3I LFM for 3I Bricks and 3I EPBs (VEF expansion)	Exp perlite SCHLAG		1.528	2.05	**-56%**	**-63%**	**-35%**
3I Fibre Boards with 3I LFM	ETEX's Promatect-H boards	1 m^2 for R-value of 1 m^2 K/W	147	164	**-20%**	**-17%**	**-25%**
3I Fibre Boards with 3I LFM and 3I Binders		1 kg of product	1	1	**-43%**	**-51%**	**-47%**
3I EPBs	Fesco Boards (TCERAM)	1 m^2 for R-value of 1 m^2 K/W	19.61	8.46	**-15% (per kg)**	**+12% (per kg)**	**+12%**
3I Foam Blocks	AAC Blocks (Ecoinvent)	1 kg of product	1 kg	1 kg	**-5%**	**-58%**	**-51%**
3I Bricks with 3I LFM	Poroton T7 Bricks with expanded perlite	1 m^2 for R-value of 1 m^2 K/W	38	40	**-13%**	**-23%**	**-30%**
3I Bricks with 3I LFM and 3I Binders		1 kg of product	1 kg	1 kg	**-55%**	**-24%**	**-39%**
3I Facades with 3I LFM	Poroton WDF Facades with expanded perlite	1 m^2 for R-value of 1 m^2 K/W	23	25	**-19%**	**-31%**	**-31%**
3I Facades with 3I LFM and 3I Binders		1 kg of product	1	1	**-51%**	**-30%**	**-35%**

In order to provide a more comprehensible outlook of results a Results Aggregation Procedure (empiric) has been proposed in order to give a unique indication for each new product developed (compared to respective benchmark according specific Functional Unit).

Several impact categories have been considered for each comparison and the most important ones have been focused in order to provide a more comprehensible outlook of the results, presented in Table 1.

The indicators which have been deeper investigated are the following ones:

- Primary Energy Demand (measured in MJ) - PED
- Global Warming Potential (measured in kg of CO2 eq.); - GWP
- Eutrophication Potential (measured in kg of N eq.);
- Ozone Depletion (measured in kg of CFC-11 eq.);
- Resource Depletion (measured in kg of Sb eq.);
- Water Demand (measured in kg).

3.7.2 Energy Savings

An energy performance simulation was conducted by NTUA for a typical multi-family, low-rise residential building in Genoa (Italy). The software used was eQUEST, a sophisticated building energy use analysis tool which provides professional-level results with an acceptable level of effort.

The simulated building consists of two floors hosting apartments with a total surface area of $1860 m^2$ and an average floor to floor height of 2.8 meters. The building uses a natural gas burner in order to cover its heating with a ventilation rate of 14.3 L/s. The heating temperature is set at 20 °C.

3 cases were considered: The reference building with an empty 60 mm cavity (Case 1), cavity retrofitted using expanded perlite (Case 2) and 3I LFM for cavity walls (Case 3).

The **U-value of the 3I LFM retrofitted wall is 72% lower** compared to the empty cavity wall. Compared to the perlite filled wall, the 3I LFM filled wall has **23% lower U value**. The simulation results indicate a reduction of the yearly energy consumption by **20%** when retrofitting the empty cavity with 3I LFM compared to expanded perlite. Compared to the old, poor performing construction, the energy reduction upon retrofitting with 3I LFM is **71%**.

3.8 WP8: Technical evaluation of the new products

3.8.1 Technical evaluation of 3I Loose Filling materials (SandB)

Within the LEEMA project three different grades of 3I LFM were developed to be used in the different application in the project. The three grades, even though very similar in their production process, recipes and specifications were evaluated independently in this deliverable due to significant changes in their production process yield and the specifications set for the different applications. In the business plan described in D9.12 all three grades will be produced in the same facility sharing parts of the production line, in a production plant based in South Germany in order to facilitate deliveries of the expanded material to the other partners (SCHLAG and ETEX). All the technical evaluation study below is based on the above assumption.

3I LFM for Cavity Walls insulation

Based on preliminary market studies it was decided to focus on the South Germany market of cavity filling for new residential and non-residential housing where the market size is estimated to be **350,000m^3/year**. The production process parameters and mainly the energy consumption of the whole process with focus on the low energy expansion as well as the low CO_2 gas emissions conclude to a very efficient production process that SandB finds attractive and believes will enhance the business model. The low energy process could particularly be a selling point to potential customers that wish to take advantage of the low embodied energy products in their buildings.

The specifications of the final product meet and exceed the specifications of current products used in this application. In particular, the low λ value (0.038 W/mK in comparison to existing state of the art 0.048 W/mK), the low LBD and the improved behavior in wall settlement may be excellent selling points making this product unique and competitive in the market. Overall, SandB finds this product superior to other similar products (expanded perlite) in the market and will seriously consider marketing it.

3I LFM for 3I Fibre Boards

This LFM grade was developed within the project to serve ETEX and be incorporated in their production process for making fibre cement boards. Similarly to the production process of the previous grade of 3I LFM, the production process parameters in terms of energy consumption and CO_2 gas emissions are considered attractive and conclude to a product that meets the specifications of the client, in this case ETEX. In particular the specifications of the final product are exceeding the properties of the currently used expanded perlite by ETEX in terms of lower λ value (0.041 W/mK in comparison to existing state of the art 0.045 W/mK), and lower LBD and this improved behavior as well as the lower embodied energy parameter are excellent selling points making this product unique and competitive in the market. Overall, SandB finds this product superior to other similar products (expanded perlite) in the market and will seriously consider marketing it.

3I LFM for 3I Bricks & Facades and 3I EPBs

This grade of 3I LFM was designed to be used as a filling material in the production of bricks by SCHLAG and also was decided to be used as the main material for the production of EPBs whose business plan within the LEEMA project was taken over by SandB. Both in terms of production yield and energy consumption, SandB finds the whole production process of this specific grade of 3I LFMs very efficient, also in terms of emissions. The specifications of the produced grade are of significant economic advantage since this particular market (insulation bricks and roof insulation) is strongly dependent on the lower λ (34.4 mW/mK instead of 35.8 mW/mK). This particular fine grade might be the most promising in terms of marketing and SandB might be very interested in marketing it.

3.8.2 Technical evaluation of 3I Fibre Boards (ETEX)

The development of 3I Fibre Boards followed two different routes, which are commented hereafter separately:

- 3I Fibre cement (FC) boards, where the standard lightweight filler is substituted by 3I LFM;
- 3I Fibre boards, where a 3I based (geopolymeric) binder is used to substitute the cementitious matrix, and combined with 3I LFM.

Technical evaluation of 3I FC boards with 3I LFM replacing expanded perlite

ETEX considers the new 3I FC boards to show promising results in terms of mechanical and thermal propriety. The better performances (highest flexural strength and lower λ_{10}) were achieved with recipes incorporating silica fume which gave a dark (anthracite) color to the final boards. Slightly higher bending strength and lower thermal conductivity was observed for the 3I FC boards, for all the different pre-conditioning or ageing cycles. The obtained performance of 3I FC boards was in most cases slightly higher than the reference FC board. In all properties tested the technical data remained within the tolerances of the specification.

LCA results have shown that by replacing the currently used expanded perlite, with the new 3I LFM the board has better performance in terms of environmental impact, and would be a good addition in the product category “ETEX compact boards”.

3I Fibre Boards with 3I Binder and 3I LFM (All-3I-Fibre Boards)

The final development and marketing of a product like all-3I-FC board is an extremely ambitious development route. In fact, next to the development of a suitable binder formulation, one has to find/develop a suitable board shaping process. Lacking this appropriate equipment, at the moment there is no capability for ETEX to produce in their facilities such a geopolymeric product. ETEX is always interested to improve the know-how and acquire new knowledge especially on geopolymeric materials. Within the LEEMA project, NTUA and Morando made a lot of effort to get an extrudable geopolymer product and also optimize the extrusion. In the future, with proper research and development activities ETEX would be interested in marketing this product.

3.8.3 Technical evaluation of 3I EPBs (SandB)

At the moment this product does not meet the desirable specifications for this application (roof insulation). Several stages of R&D activities are still required and there is a lot of potential and room for improvement. Still this is a product based on a low embodied energy raw material and it could have very promising result and marketing selling point having the additional advantage of being totally inorganic, therefore incombustible. Another application could be suitable for this formulation targeting insulation materials for high temperature processes (e.g. foundry).

3.8.4 Technical evaluation of 3I Foam blocks (Fibran)

The technical analysis for the 3I Foam Blocks is presented below:

Strengths

- Inorganic - incombustible
- Sustainable, as they are based on the exploitation of aluminosilicate/ silicate wastes , recycled materials, by-products
- Low thermal conductivity coefficient combined with good mechanical properties
- Energy efficient synthesis process
- Compatibility with current manufacturing processes

Weaknesses

- The compressive strength is accepted for common infrastructures but not for AAC referred specific applications. (This is not bad for the entrance in the main market of the product)
- For exterior insulation the foamed blocks have to be sealed with a non-foamed geopolymer binder, also developed in the frame of LEEMA project.
- Further optimization is needed in order for the blocks to be fully adopted in lightweight blocks market needs

Opportunities

The 3I foam blocks are adapted to be applied as:

- load bearing protected cavity walls (limited to 1 floor)
- non-load bearing separation walls or fill-in walls
- exterior insulation layer for post-insulation built against existing walls (provided with an adequate protection (water barrier).

Threats

- Market share could be lower than 10% at maturity stage (4-10 years) after the 3rd year due to economic crisis and instability at Middle East. (It is estimated that even for lower market share the investment is profitable)

Further research is necessary in order for the blocks to fully meet the specifications set by the targeted lightweight concrete blocks market, mainly in terms of optimization of the thermal conductivity/mechanical strength and water absorption.

3.8.5 Technical evaluation of 3I Bricks and Facades (SCHLAG)

3I Bricks and Facades with 3I LFM replacing expanded perlite

For better binding affinity to 3I-granules further activities took place in order to find even more efficient binders. The binder search was extended to a broader variety of organic and inorganic binding agents. Moreover, different binders were tested together with foaming agents to produce binding foams instead of the pure binders. Therefore, first steps could be done to use less binding material without losing binding affinity. Probably, several successful experiments indicate to be on the right way for more efficiency. Further R&D activities will be spent in the future on binding foams. Together with binding agents the “in-situ” water repellency agent adding was tested as well, but with no sufficient breakthrough, so far. Due to the anti-foaming property of the water repellency agents like silanes the formation of binding foams were not possible.

SCHLAG sees high potential in sales for 3I LFM filled bricks and facades, if the end-users appreciate the lower embodied energy advantage of the product in spite of equal or nearly equal designed thermal conductivity values. Moreover, the technical advantage of the better moisture behaviour of 3I LFM leads to a remarkable point for better sales.

3I Bricks and facades with 3I Binder and 3I LFM (All-3I-Bricks and Facades)

After the first extrusion trials with the 3I binders, for the honorable goal of brick body substitution, it was obvious that this task is complicated and the effort in R&D high. Morando, using their expertise in extrusion and suitable equipment, took over the extrusion experiments in cooperation with NTUA. SCHLAG evaluated the prepared samples received from Morando.

Overall, SCHLAG sees a lot of potential in the new 3I binders, but even more need for R&D activities. Several open issues could be addressed, like the avoiding of cracks and lamination, especially under moistening conditions or the optimization of thermal insulation and compression strength.

3.9 WP9: Business plan

3.9.1 Task 9.1: Exploitation of products and knowledge

Exploitation plan

The exploitation plan has been revised at the end of the project. The following aspects have been addressed:

- The list of Exploitable Results has been refined in agreement with the project consortium, underlining also each ER TRL
- The provided identification of the potential exploitation routes (product, project and service based exploitation routes) through the BFMULO analysis has prepared the ground for an the appropriate set up of agreements among the Partners on the use of the foreground after the project
- The expectations of each partner regarding the results that they are involved in.
- The way of obtaining CE marking for each of the developed products. Based on the results of the products’ characterization and evaluation performed in WP6, BBRI prepared a very useful Roadmap to Certification for each of the products developed in the LEEMA project.

The key exploitable results have been identified and characterized and are in agreement with the project consortium

Market Analysis

During the project, several market surveys and analysis were performed providing valuable input for the Preliminary Business Plan.

A web- survey was conducted in November 2013 by ACE to collect data on the requirements of architects for insulation materials.

During the last year of the project, AMS and FENIX distributed questionnaires to identify the end-users requirements. The questionnaire of AMS was distributed to their link of end users among Greece and Europe. FENIX distributed a questioner to the visitors at IBF Brno 2015.

Prefeasibility study

3I Loose Filling materials (3I LFM)

The prefeasibility study of the 3I LFM is based on the assumption that a production plant will be set up in South Germany and will produce all three grades designed in the LEEMA project; i) for cavity wall insulation, ii) for lightweight aggregates in fibre cement boards and iii) a grade designed for two applications: infill in insulation bricks and facades and as a major component in the production of roof insulation EPB boards. Three separate profitability studies were done, in the form of 10-year business plans, one for each grade and they all gave positive results in terms of NPV, IRR and a return of investment within or right after these ten years.

3I Fibre boards

The prefeasibility study of 3I Fibre boards was done for both productversions: 3I FC boards where 3I LFM is replacing expanded perlite and the ambitious approach of all-3I-FC boards (3I binder and 3I LFM). In the business plan of the first product ETEX uses their existing production line with minor adaptations in order to produce the new 3I FC boards while for the second futuristic product, ETEX would need to set up a new extrusion line. The 10-year profitability studies of all products have shown positive NPV and IRR and a return on invested capital within the 10 years.

3I Bricks and Facades

The 3I bricks and facades studied in the business plan were only the products were the infill of the insulation bricks and facades is incorporating 3I LFM instead of expanded perlite. Schlagmann sees high potential in sales for 3I LFM filled bricks, if the end-users appreciate the lower embodied energy advantage of the product in spite of equal or nearly equal designed thermal conductivity values. Moreover, the technical advantage of the better moisture behaviour of 3I LFM leads to a remarkable point for better sales. Schlagmann calculates the return of invest after 2 years.

3I EPBs

The business plan of 3I EPBs is based on the assumption that further optimised 3I EPBs will be marketed and includes a production line connected to the one of the production of 3I LFM in south Germany. The results of the 10-year profitability study conclude to a high NPV and IRR and a return on invested capital right after 10 years.

3I Foamed Blocks

The business plan of 3I Foamed blocks is based on the design of a new production line based in Greece that will be dedicated to the production of these 3I Foamed Blocks and will serve the Greek and Balkans market. The 10-year profitability study leads to very healthy business results with a high NPV, IRR and quick ROIC within the 10 years. FIBRAN has also a designed sales effort & sales promotional plan which is based on the low embodied energy advantage and low cost of ownership strategy.

3.9.2 Task 9.2: Dissemination and training activities

The aim of dissemination activities is to reach the widest audience, to gain the public awareness of the project potentials and to demonstrate to the potential end-users the advantages of the new insulation products over the conventional ones. This includes presentations of the new processes and products in exhibitions, relevant fairs of the construction sector worldwide and in other related events, presentations in conferences and seminars of the project technological and scientific results, project website to host all the information concerning LEEMA as well as accounts in popular social media.

The Project's web site has been created, successfully launched and is continuously updated by NTUA (D9.1: Web-site, submitted on M9). The Project website address is: www.leema.eu. Additionally, accounts in the most popular Social media were created (Facebook, Twitter, LinkedIn, Google+ and Youtube) and are constantly updated, to increase the project's visibility.

The project partners have been engaged in several dissemination activities such as; organization/participation in workshops, fairs and exhibitions, presentations and papers in conferences and scientific journals, participation in clustering activities with other projects, preparation of dissemination material (brochures, posters etc, and dissemination videos).

Data sheets of the different LEEMA products were prepared by BBRI with the assistance of NTUA and the industrial partners. The data sheets include the properties of the pilot scale samples, as determined in WP6, as well as their potential applications.

BBRI performed real scale application tests for the 3I Loose Filling material for cavity walls. The outcome was the detailed Technical Application Guidelines for the application of 3I Loose Filling material as insulation in cavity walls.

4. Potential Impact

The LEEMA project aimed to develop a new generation of insulation materials and building masonry components namely 3I loose-filling materials, 3I boards, 3I polymer bricks and façades that are characterised by considerably lower embodied energy than the currently available ones. Besides low energy footprint, the new insulation products have competitive technical, health and environmental properties as far as, long term insulation performance, incombustibility, resistance to moisture absorption and water attack, stability, safety in handling and installation, non-polluting indoor environment and cost, are concerned.

Table 2 summarized the key properties of the LEEMA products, compared to commercially available materials for similar applications. In order to compare the embodied energy of insulation products, their thermal performance should also be taken into account. Therefore, the embodied energy of the various products is calculated per functional unit (FU); 1m^2 of insulation with appropriate thickness to provide an R-value of 1m^{2}K/W. The same approach was applied for the cost.

Table 2. Key properties of LEEMA 3I and commercial products for similar applications

Application	Product	Density	λ	Embodied Energy		Embodied CO_2		Cost	Euroclass
		(Kg/m^3)	(mW/mK)	(MJ/Kg)	(MJ/FU)	(CO_2/Kg)	(CO_2/FU)	(€/FU)	
Insulation	**3I LFM**	**60**	**36-38**	**9.1**	**21**	**0.46**	**1.07**	2.3	A
	Expanded Perlite	60-160	40-60	10	50	0.52	2.6	10	A
	EPS beads	25-30	33	109.2	100.9	3.29	3.04	3.6	F
	EPS boards	15-30	30-40	109.2	90.1	3.29	2.71	2.5	E
	XPS boards	20-50	30-40	95	91.2	4.39	4.21	3.8	E
	Glass Wool	16-25	31-43	28	19	1.28	0.92	2.5	A1
	Stone Wool	20-40	31-43	20	23	1.12	1.36	3.4	A1
	Aerogel blankets	180	15	53	19.6			90	C
Fibre Cement sheets	**3I FC Boards**	**1007**	**146.8**	**8.05**	**1190**	**0.64**	**94.5**	**91.8**	**A1**
	Refer. FC Boards	968	168	9.03	1469	0.68	111.2	105	A1
	Commercial FC panels	1300-2000	150-600	10.4-15.3	2028-18360	1.09-1.28	213-1536	94-375	A2, s1, d0
Roof and high temperature insulation	**3I EPBs**	**288**	**68**	**24.6**	**482**	**1.53**	**30**	**48.6**	**A1**
	Fesco Boards	150-200	50-55	29	245	1.37	11.6	38	C, s1. d0
	Perlite boards	110-150	50-55					42-47	A1
	Perlite/silicate insulation	190-225	63-68					80	A1
Building Blocks	**3I Foam Blocks**	**700**	**110**	**3.26**	**250**	**0.17**	**13.3**	**11**	**A1**
	AAC	400-750	100-200	3.45	155-525	0.41	18.5-61.7	11-22	A1
	Lightweight aggregate blocks	650-1600	250-600	0.9-2.3	390-900			36-84	
Insulating Bricks & Facades	**3I Bricks**	**527**	**64.3**	**5.8**	**196.5**	**0.17**	**5.8**	**17.7**	**A2, s1, d0**
	Perlite Bricks	571	67.4	6.3	242.5	0.21	8.2	18.5	A2, s1, d0
	3I Facades	549	65.9	6.5	235.2	0.21	7.6	19.8	A2, s1, d0
	Perlite Facades	547	63.3	7.4	256.2	0.28	9.8	19.0	A2, s1, d0

The new products and technologies will have significant economic and technological impact on EU building sector mainly in the Construction and insulation sectors (granular insulation, insulating blocks, boards and bricks). Moreover, the successful completion of the project can result in additional environmental, political, economic and social impacts (mineral wastes reduction, low embodied energy insulation materials and masonry components, etc.).

More specifically, the impacts include:

1) Reduction by at least 50% of the embodied energy at component level; 2) Reduction by at least 15% of the total costs compared to existing solutions; 3) Improved durability of the new components resulting in less frequent replacement; 4) European impact on energy efficiency at building level; 5) contribution to achieving EU policies; 6) Improvement of the quality of the building indoor environment.

4.1 Reduction by at least 50% of the embodied energy, at component level

The 3I LFM for cavity wall insulation has significantly reduced embodied energy per functional unit compared to commercial insulation products; more than 58% compared to expanded perlite, more than 75% compared to organic insulation products. Moreover, the embodied energy of 3I LFM is comparable to inorganic fibrous insulation products and even the high performing innovative aerogel blankets.

3I Fibre Boards have 19% lower embodied energy compared to the reference boards produced by ETEX. Compared to commercially available fibre cement panels, the embodied energy can be up to more than 10 times lower. For the highly ambitious 3I Fibre boards where the cementitious matrix is replaced with the 3I binders, the embodied energy can be 43% lower, considering the same performance with ETEX boards.

The 3I Foam blocks can have up to 52% lower embodied energy compared to commercial AAC blocks, and more than 70% compared to lightweight aggregate concrete blocks.

The 3I EPBs, due to the higher density and thermal conductivity of the pilot scale prototypes, have higher embodied energy compared to commercial Fesco boards. However, their embodied energy per kg is 15% lower, which will lead to a product with lower embodied energy per FU, once the optimization is completed.

The 3I Bricks and facades with 3I LFM show 8-12% lower embodied energy compared to their counterparts filled with expanded perlite. For the ambitious 3I Bricks and Facades with 3I binder replacing the clay brick body, the embodied energy can be reduced up to 55%.

The results indicate that the reduction of embodied energy by at least 50% has been achieved by most of the LEEMA products.

4.2 Reduction by at least 15% of the total costs compared to existing solutions;

The cost of the LEEMA products is also compared to their commercial counterpart, taking into account their performance, so it is presented per functional unit.

The 3I LFM has 77% lower cost compared to expanded perlite, up to 40% compared to organic insulation, 8-32% compared to inorganic insulation and more than 97% compared to innovative aerogel blankets.

The 3I Fibre boards have 13% lower cost compared to the reference ETEX boards, and can be more than 75% lower compared to other commercial fibre cement panels.

The 3I EPBs, as they still required further research to be optimized, still exhibit higher cost compared to the commercial Fesco boards. However, the cost per m^3 is lower, so once the performance is optimized the overall cost per functional unit is expected to be lower. Moreover, 3I EPBs with their current properties have comparable cost to other commercially available perlite boards, and 39% lower cost compared to perlite /silicate high temperature insulation products.
The 3I Foam Blocks can have up to 50% lower cost compared to AAC commercial products, and more than 86% compared to lightweight aggregate concrete blocks.

The 3I Bricks and Facades with 3I LFM show comparable cost compared to the reference perlite filled products. Considering the highly innovative and ambitious 3I Bricks and Facades where the clay brick body will be replaced with the inorganic polymer 3I binders, the cost is expected to be more than 15% lower.

4.3 Improved durability of the new components

Improved durability of the new components will result in less frequent replacement. The currently available insulation materials have a non-stable thermal performance overtime due to ageing and humidity absorption.

The 3I LFM for cavity walls show significantly lower settlement, both by vibration and hygrothermal ageing, compared to commercial bulk insulation products. 3I LFM grades for the other LEEMA products exhibit excellent water repellency, even without hrdrophobation.

The 3I Fiber boards successfully passed the strict ageing protocols of the EN standards, proving their excellent durability.

If required, the hydrophobisation treatment can be applied to further enhance the products' resistance to moisture absorption and water attack.

4.4 European impact on energy efficiency at building level.

In several combinations for the different applications of the 3I insulating materials, the U-values and, therefore, the energy efficiency achieved at building level are expected to be better than that of the conventional construction components;

The **U-value of the 3I LFM retrofitted wall is 72% lower** compared to the empty cavity wall. Compared to the perlite filled wall, the 3I LFM filled wall has **23% lower U value**. The simulation results indicate a reduction of the yearly energy consumption by **20%** when retrofitting the empty cavity with 3I LFM compared to expanded perlite. Compared to the old, poor performing construction, the energy reduction upon retrofitting with 3I LFM is **71%**.

4.5 Contribution to achieving EU policies.

The EU policies on energy efficiency, as stated in the recast of the Energy Performance of Building Directive (2010/31/EU) and the 2012/27/EU Energy Efficiency Directive have set new standards for the building sector, targeting near-zero energy buildings by 2020. The EU building sector can significantly contribute to the achievement of these objectives, as it is the largest energy consumer, consuming about 40% of total energy used in EU and responsible for 36% of the EU CO_2 emissions. Space heating in buildings accounts for more than 50% of the total energy consumption in buildings and directly depends on building insulation.

The 3I LFMs, developed within the LEEMA project, can be successfully used as bulk insulation or as lightweight aggregates in various insulation and masonry components such as roof and high temperature insulation boards (3I EPBs), fibre cement sheets (3I Fibre Boards) and 3I insulating bricks and facades, providing competitive thermal performance to currently available products. The 3I LFMs are lightweight, totally inorganic and incombustible, and, due to their synthetic nature, their properties (density, thermal conductivity and grain size) can be fine-tuned depending on the application. They have very low environmental impact, due to the use of mineral wastes and industrial by-products and the low expansion temperature. Due to their high affinity with cementitious binders, the 3I LFMs can replace traditional lightweight aggregates such as expanded perlite or EPS beads in various other products such as lightweight concrete, mortars, plasters etc. reducing resource depletion and use of energy intensive oil-based raw materials. Moreover, the 3I LFMs can be recycled, further reducing their environmental impact.

The 3I binders are also based on mineral tailings (wastes), limiting the exploitation of natural resources (clay, cement). The use of waste as raw materials and the low temperature processing (their mechanical properties are obtained after curing at temperatures up to 70 °C for a few days) render the 3I binders competitive in terms of embodied energy and cost. Moreover, they are compatible with traditional aggregates and conventional shaping methods (moulding or extrusion) and therefore suitable for the production of pre-fabricated non-structural construction elements. The 3I Binders have been evaluated with promising results for use as a replacement of the cementitious matric of Fibre cement sheets or the clay brick body. Moreover, 3I Foamed blocks, based on 3I binders, could replace commercial lightweight masonry components such as AAC or lightweight aggregate concrete blocks.

Therefore the project's results can significantly contribute to the EU energy and environmental policies, contributing to the easier and much more efficient implementation of the EU measures and directives concerning energy efficiency in the building sector, and respecting the strict sustainability rules.

4.6 Improvement of the quality of the building indoor environment

The moisture storage function and hygrothermal behaviour or perlite- and 3I LFM- filled Bricks was studied. The investigated non-hydrophobic 3I LFM had the highest moisture storage capacity (compared with natural perlites), creating a moisture-buffer that results in considerable lower values of humidity in the contact zone of internal insulation to the existing building construction. In this way, 3I LFM are able to protect an existing building construction from getting to wet under investigated normal indoor climate conditions. It was concluded that:

- - A non-hydrophobic 3I LFM- filling of a POROTON® WDF facade-bricks, applied as internal insulation of lime-stone wall shows the best hygrothermal behaviour of the construction, compared with perlite fillings: There is non-internal condensate and the values of humidity are comparable low.
- - Fillings with hydrophobic Perlites, (= state of technology for SCHLAG) show a better hygrothermal behavior than non-hydrophobic perlites.

This aspect of the 3I LFMS will definitely contribute to the improvement of the indoor air quality, maintain the humidity at low levels.

5. Contact information

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