Green Integrated Structural Elements for Retrofitting and New Construction of Buildings

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Green Integrated Structural Elements for Retrofitting and New Construction of Buildings

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Abstract. Governments across Europe have ambitious visions for the construction sector sector. For example, in the UK, as part of the Clean Growth Grand Challenge within the Governments Industrial Strategy, we are aiming to halve the energy use of new buildings by 2030; delivering new construction assets at a third of the cost and significantly quicker; provide assets that are cheaper to run, smarter, safer with lower emissions; and ultimately create cleaner air. As part of this deal and the wider The 'Construction Sector Deal' sets out an ambitious partnership between the industry and Government that aims to transform the sector's productivity through innovative technologies and a more highly skilled workforce aims to transform the efficiency of construction techniques through digital technologies like Business Information Modelling; reduce running costs through energy generation and storage technologies; and conduct research and development and demonstration programmes supporting innovations. The core aim of the project is to seamlessly combine four integrated layers with high structural performance, which would provide high levels of insulation, a healthy indoor environment, high aesthetic value, along with CO_2 capture, and greywater management. The competitive advantage of the Green INSTRUCT panel is (1) sustainable and cost effective - using more than 70% wt. C&DW including concrete, bricks, plastic, metals; (2) safety and energy efficiency - meeting Eurocode standards for fire safety, thermal insulation with U-value of 0.14 $W/m^2.K$ and acoustic insulation coefficient under 60dB and (3) Customisation potential -multi-layered, modular & prefabricated building block for new and old building. This paper will discuss key project achievements in terms of material development and innovation and challenges faced so far during the project.

1. Introduction

With the development of urbanization in Europe and particularly in the developing countries, building construction, renovation and demolition have produced an enormously huge amount of construction and demolition waste (C&DW). For example, in 2017, disposal of C&DW in China exceeded three billion tons and accounted for 30% to 40% of the total amount of waste [1]. C&DW is not only dauntingly huge, but is often unsorted with different and complex components. Therefore, effective disposal and recycling has become a demanding task for every country. At the same time, we are facing an increasing shortage of natural materials such as sandstone [2], which is another impetus to reduce our dependence on fresh resources and allow for the use of waste, which would otherwise be deposited to landfill. The 'circular economy' (CE) concept is fast becoming a new model for resilient growth. Creating and optimizing resource 'loops' along value chains in the construction industry will help meet the needs of growing and urbanizing populations while mitigating against a continued rise in primary resource use, associated emissions and environmental pollution. The CE is now a core component of the EU's 2050 Long-Term Strategy to achieve a climate-neutral Europe [3], with the aim to 'implement a plan for guiding circular development, encourage the circular use of resources between production and society, and accelerate efforts to recycle resources from refuse'. Our project 'Green Integrated Structural Elements for Retrofitting and New Construction of Buildings' (Green INSTRUCT) is part of the EU research and innovation initiative to work on 'New technologies and strategies for the development of pre-fabricated elements through the reuse and recycling of construction materials and structures' [4]. The core aim of the project is to seamlessly combine four integrated layers with high structural performance, which would provide high levels of insulation, a healthy indoor environment, high aesthetic value, along with CO_2 capture, and greywater management. The competitive advantage of the Green INSTRUCT panel is (1) sustainable and cost effective including concrete, bricks, plastic, metals; (2) safety and energy efficiency - meeting Eurocode standards for fire safety, thermal insulation and acoustic insulation coefficient and (3) Customisation potential -multi-layered, modular & prefabricated building block for new and old building. This paper will discuss the most recent project achievements in terms of material development, demonstration activities and future work.

2. Key Project Achievements

2.1. Overall Green INSTRUCT Scheme

In the Green INSTRUCT project, prefabrication for refurbishment is approached from a modular perspective, through the development and deployment of a universal building block, with customization potential. To achieve this objective, the Green INSTRUCT consortium combines unique skills in material development from CDW, green technologies, manufacturing and construction in both new buildings and refurbishment, with the experience and presence of experts in their respective fields. During the Green INSTUCT project, a multi-layered integrated building block (summarised in figure 1) has been developed containing more than 70% per weight of CDW. The block has been designed to be incomparably faster to install than conventional envelope walls of the same size. The developed prototype adheres to Eurocode standards and provides thermal insulation with a U-value of 0.13 W/m^2.K and acoustic insulation of 57dB. It also contributes to on-site grey and storm water management, through the integration of a vertical Green Wall, providing additional functionalities.

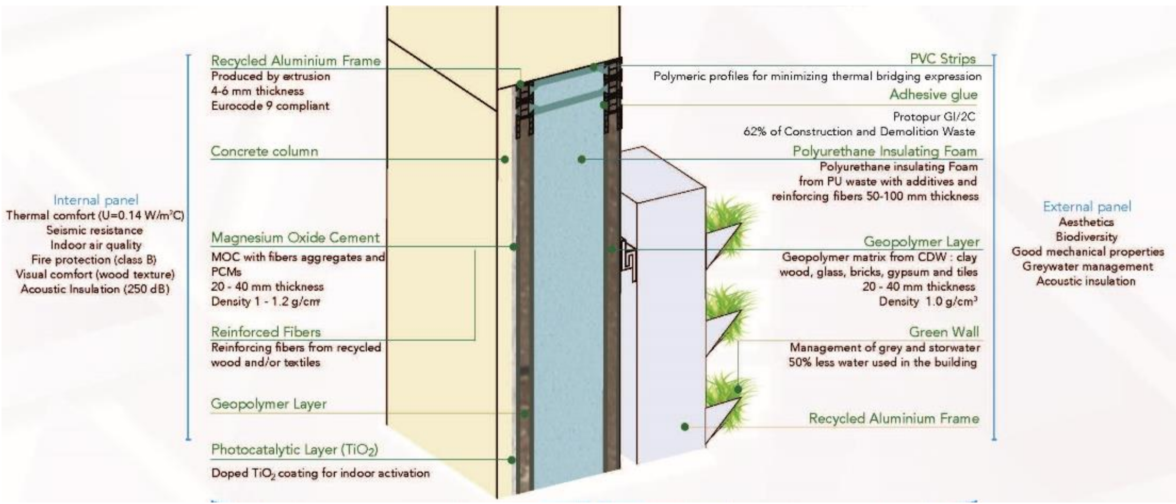

Figure 1. Overall scheme of the Green INSTRUCT panel.

2.2. Geopolymer layer and extrusion manufacturing

Brick waste powder was characterized and appropriately developed as a raw material for the geopolymer synthesis. Waste expanded polystyrene (EPS) and waste polyethylene (PE) fibres were used to reduce the geopolymer density and ductility, respectively. Lightweight geopolymer with a density of 1.3 g/cm^3 and compressive strength and flexural strength of 15.3 and 3.2 MPa were prepared, respectively (Table

1). Also, a hydrothermal processing for the conversion of glass into water glass that can be used as the activation solution was developed and optimized (Figure 2); a conversion rate of glass to water glass was found to be close to 81% wt. Successful extrusion of 150 mm-wide panels was performed using a laboratory scale extruder. Hydroxypropyl Methylcellulose (HPMC) thickener was added as a water retention aid with the added benefit of lubricity. The addition of PE fibres provided further binding and allowed the geopolymer to have 'green strength,' i.e., retain its shape upon exiting the die. The mixing and extrusion process of the geopolymer is shown in figures 3-5.

Table 1. Geopolymer properties.

Properties	
Specific Heat (KJ·Kg-1·°C-1)	0.9
Thermal Conductivity (W.m-1·°C-1)	0.45
Density (Kg·m-3)	1300
Poisson's Ratio	0.11
Young's modulus (GPa)	1.3
Tensile Resistance (MPa)	3.2
Compressive Resistance (MPa)	15.3

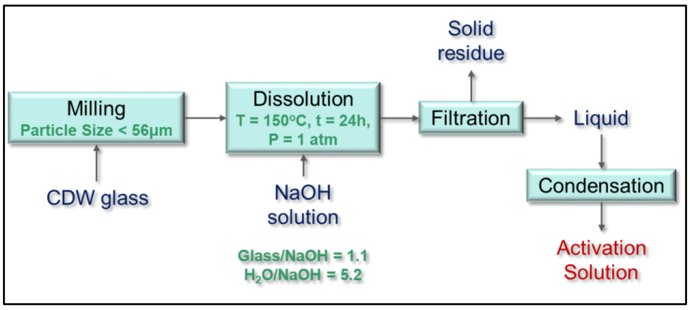

Figure 2. Geopolymer activator manufacturing process.

Figure 3. Initial geopolymer mixing.

Figure 4. Geopolymer dough-like consistency.

Figure 5. Extruded geopolymer panel.

2.3. PU Foam insulation layer

PU foam powder and wood fibres, both from CDW, were incorporated into pristine PU resin to produce rigid and flexible PU foam for thermal and acoustic insulation purposes, respectively (figures 6 and 7). Optimised combinations of CDW wood fibre and waste PU foam led to both the compressive and tensile

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strength of the new PU foam to be maintained while reducing thermal conductivity by 15% in the hard PU foam and 10 % in the soft PU foam.

Figure 6. Hard PU foam plate.

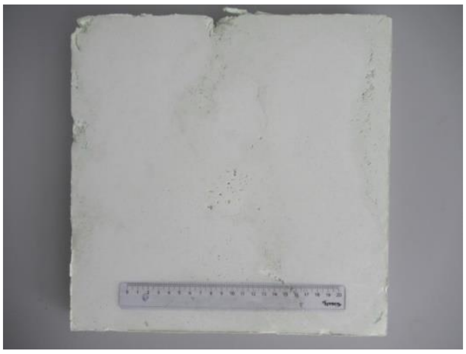

Figure 7. Soft PU foam plate.

2.4. Photocatalytic surface coating

An efficient photocatalytic surface coating was developed as a passive indoor air cleaning technology without posing any harm to human health. TiO_2 powders doped with organic and inorganic elements optimized for coating formulation and indoor activation with optimized loading and low agglomeration was achieved. Best results concerning the air pollutant (NOx, Acetaldehyde) as well as the liquid pollutant (Methyl Orange-MO) degradation were achieved for doped and co-doped TiO_2 or mixed oxides (TiO_2/SiO_2), as shown in figure 8. A paint formulation using an optimised blend of dispersing agent, rheological modifier, defoamer, pH stabiliser and coalescing agent was devised and up-scaled (figure 9).

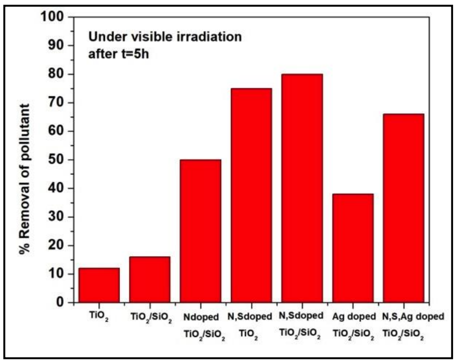

Figure 8. % MO Removal of different doped TiO2 or TiO2/SiO2 samples.

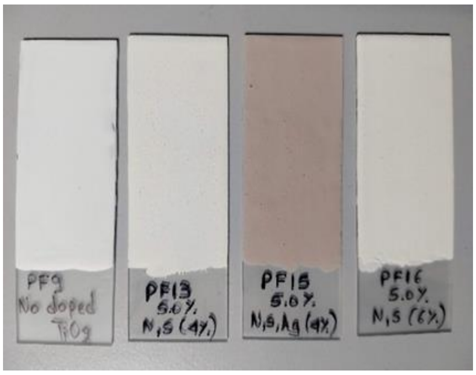

Figure 9. Paints applied onto glass slides.

2.5. Recycled aluminium structural elements

A construction frame for the GI Panel was designed and manufactured using 65% scrap aluminium. A novel die tool (figure 10 was designed and manufactured for the production of the frame (figure 11). The profiles were cut and folded into the construction frame, then joined using novel polymeric connectors, which avoided the introduction of thermal bridges (figure 12).

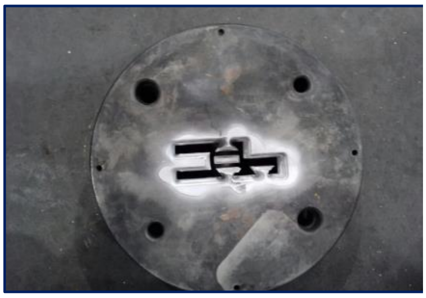

Figure 10. Aluminium extrusion die tool.

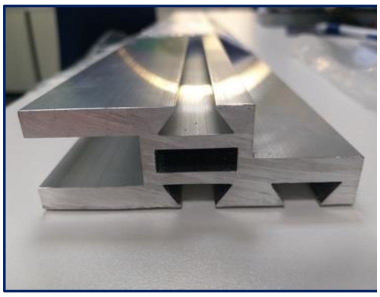

Figure 11. Extruded aluminium profile.

Figure 12. Aluminium profiles with polymer connectors.

2.6. Development & extrusion of MOC layer

Effects of varying calcination conditions on the chemical and physical properties of magnesium oxide (MgO) were investigated using the more sustainable precursor material of magnesium hydroxide ($Mg(OH)_2$). Extremely pure and thus more reactive MgO was obtained using a 17.6% less energy intensive calcination regime compared to industrial grade MgO obtained from the calcination of dolomitic lime. As a result, the magnesium oxychloride cement (MOC) that was produced from the sustainably sourced MgO obtained a 50% increase in flexural strength and a 22% increase in compressive strength. This was mostly due to its homogenous microstructure consisting predominantly of the phase-5 hydration product. The final optimised MOC formulation contained wood fibre recycled from MDF, waste wood-saw dust and PCM-impregnated aggregates is shown in figure 13.

Figure 13. MOC including sawdust, wood fibre and PCM-impregnated aggregates.

2.7. PCM-impregnated aggregates

Recycled porous concrete aggregates impregnated with a paraffin phase change material (PCM) were produced using a macro-encapsulation process (figure 14) for inclusion in the GI block for the purpose of passive temperature control. The vacuum impregnation unit (figure 15) achieved impregnation in particle sizes below 1mm; 100% absorption relative to the pore intrusion volume was achieved after 30 minutes of vacuum impregnation. Also, the PCM functionality before and after impregnation in terms of heat storage, melting and crystallization temperature remained practically unchanged, indicating that the aggregates were thermally stable. The latter results also revealed that the heat storage capacity of the aggregates was ≈21 J/g.

Figure 14. PCM-impregnated aggregates.

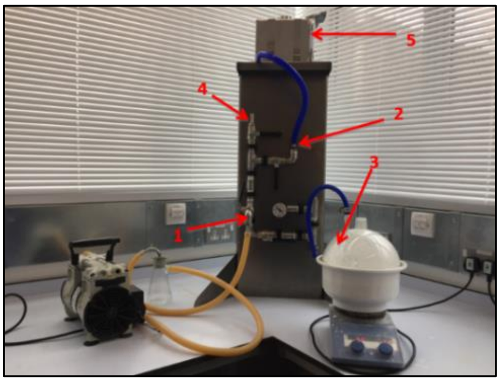

Figure 15. Vacuum impregnation unit.

2.8. Performance design & optimization through CFD

The design of the GI Panel was established after an iterative process between sound and thermal insulation numerical analyses. Figure 16 presents a horizontal cross-section of the final design with the material to be assembled and respective thicknesses. Temperature and heat flux distribution It was concluded, through numerical thermal analyses, that the GI Panel could achieve a very ambitious thermal performance level of 0.13 W/m².K U-value, as shown in temperature and heat flux distribution in figure 17. Sound insulation performance computational analyses allowed to verify that the final GI Panel design would achieve sound insulation performance requirement of 57 dB (figure 18).

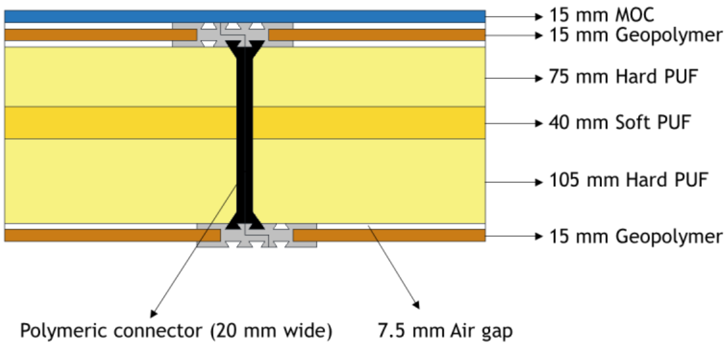

Figure 16. Horizontal cross-section of the final GI Panel design.

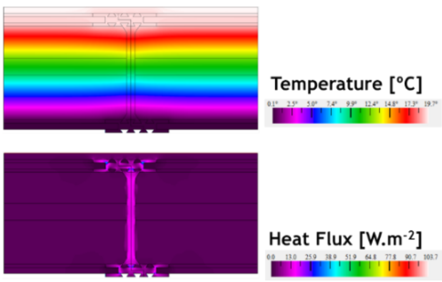

Figure 17. Thermal performance.

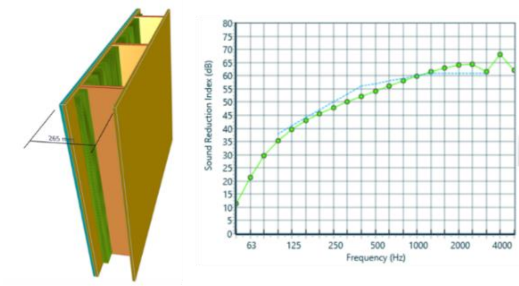

Figure 18. Sound insulation performance.

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2.9. Building and Information Modelling

2D and 3D architectural designs of the GI panel, by using software and processes such as AutoCAD and REVIT were completed (figure 19). It was ensured that the developed models were interoperable with other tools and could be accessed by the relevant stakeholders. The modelling completed all aspects of the design and detailed architectural models. In addition, a clear strategy for end-of-life was defined. The identification and compilation of the dismantling, re-use and recycling procedures were initiated (figure 20).

Figure 19. GI panel render on two storey model.

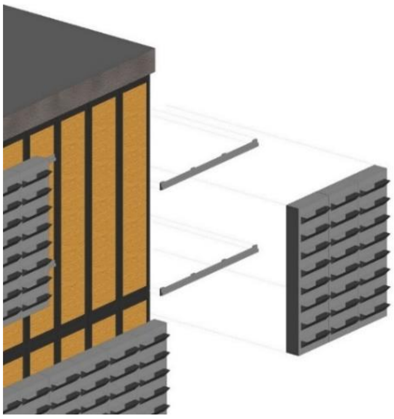

Figure 20. Panel composition and railing fixing.

2.10. Vertical Green Wall panel

A functional green wall layer with an integrated grey-water and stormwater management function based on a constructed wetland approach was developed (figure 21). 1.6 m^2 of panel is necessary to treat up to 60 litres of greywater per day, which corresponds to the average greywater production of one person per day. The green wall was also recorded, per year, to produce 3 kg/m^2 biomass and sequester 500 g/m^2 CO_2. Water cleaning performance of the green wall panel was extensively tested during the development phase. In order to achieve water of sufficient quality for a number of re-use scenarios (toilet flushing, garden irrigation, laundry washing, groundwater recharge, etc. as per EU guidelines 91/271/EC), it was determined that 25 m^2 of green façade area would be needed to clean 1 m^3 of greywater per day. A representation of the water purification performance of the green wall is presented in figure 22.

Figure 21. Green wall facade panels.

Figure 22. Water purification performance of the green wall.

2.11. Challenges

- PVC elements cannot be easily extruded as each profile requires an adequate tailor-made cooling system for each shape and the required profile's cross section is not a commercial one. Issues related to the material and manufacturer procurement need to be addressed. If the parts that integrate the design cannot be produced at a reasonable cost, the design will need to be adapted by assessing the appropriate manufacturing technologies for the production of the PVC parts.
- To overcome various issues (e.g. structural deformations of the cassette due to thermal stresses of the aluminium due to welding, panel thickness, etc.), the cassettes of the green wall were also tested using stainless steel in addition to aluminium. Also, green wall panels for cold winter climates need to be planted very differently than panels for mild winter regions, requiring solutions like the use of a heating coil and/or enclosure.
- The yield of the fibre extrusion scale-up process was around 15% of the total amount of fed material. Clogging of the extruder filters by the presence of inorganic species and/or cross-linked parts in polyethylene was the main hindrance. In spite of that situation, 4.3 kg of fibre were extruded. Also, the extrusion-filament of the recycled HDPE for fibre production resulted in a very low strain ability that hindered the possibility to spin the material.

3. Conclusions

The largest and the most important impact that the outcomes of the Green INSTRUCT project can make is the realisation of the introduction of a building block with higher resource and production efficiency that will ultimately contribute to a climate change resilient construction economy. Currently, there doesn't exist a building block that is made from a comprehensive and streamlined supply chain of construction and demolition waste materials and can be used for both new constructions and building retrofitting. The Green INSTRUCT project aims to utilise the continuous manufacturing technology of extrusion to produce the individual panels of the building block and the structural frame. The building block will also capture CO_2 from the management of grey and storm water using an integrated vertical green wall. Introducing such a building block would significantly contribute to the resilience and sustainability of the construction sector in the UK and worldwide, as it would allow the industry to address the intrinsic CO_2 emission.

Acknowledgments

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