VALORIZATION OF VARIOUS CONSTRUCTION AND DEMOLITION WASTE STREAMS AS PRECURSORS OR ADDITIVES OF CONSTRUCTION ELEMENTS AND MATERIALS

D. Kioupis, A. Skaropoulou, S. Tsivilis, G. Kakali*
School of Chemical Engineering, National Technical University of Athens
(**kakali@central.ntua.gr*)

Abstract
Millions of tons of Construction and Demolition Wastes (CDWs) are generated worldwide each year. In addition to the fact that these materials pose threat to the environment, landfill disposal might also be viewed as the discarding of a commodity, since they may have a high resource value. In the frame of GreenINSTRUCT project, funded by the European Union Horizon 2020, CDW materials with high technical and economic potential are identified and transformed to added value products.

Introduction
The rapid growth of the construction industry worldwide during the past decades has resulted to an enormous increase of the produced Construction and Demolition Wastes (CDWs). The composition of the CDWs varies depending on its origin (construction, renovation, repair or demolition of structures) and often contains bulky and heavy materials, including concrete, wood, asphalt, gypsum, metals, bricks, glass, plastics, etc. In European Union, the construction sector produces 850 million tons of waste per year, which represents 31% of the total waste generation [1]. According to the binding legislation set by the EU, 70% by weight of non-hazardous CDW must be re-used, recycled, or recovered by the year 2020[2].

In the frame of **"**Green integrated structural elements for retrofitting and new construction of buildings – GreenINSTRUCT**"** project, funded by the European Union Horizon 2020, CDW materials with high technical and economic potential were identified. CDW waste streams such as concrete, ceramics, plastics, textiles, glass, wood and insulating materials were selected, processed and examined as alternative precursors or additives in conventional and novel construction elements and materials. The GreenINSTRUCT (GI) project develops a prefabricated multifunctional building wall panel that stands out from the current panelised solution by virtue of its sustainability, sound insulation, thermal performance and multiple functionalities (Figure 1). This building block consists almost 90% by weight of CDWs.

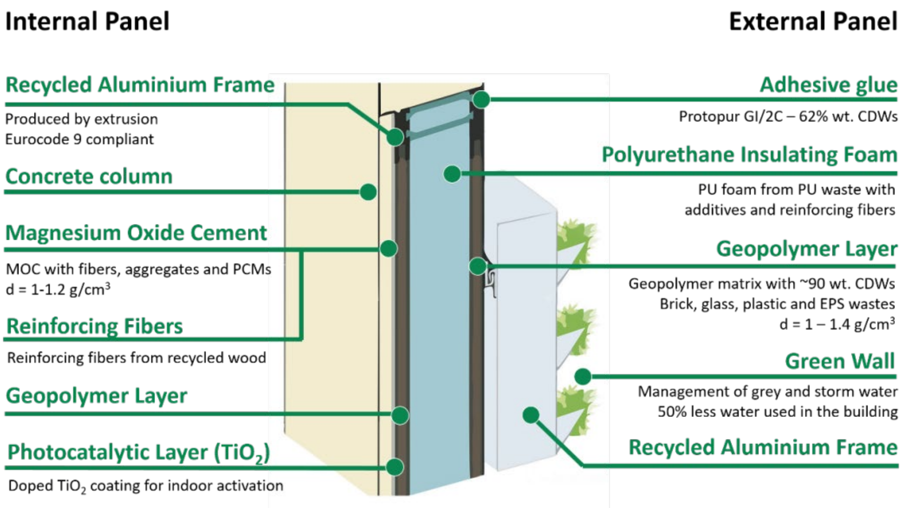

Figure 1. *Green Instruct building block comprising CDW materials.*

In the next paragraphs, the materials included in the GI building block and developed by CDWs are described.

Geopolymer layer

Geopolymer layer serves as lightweight construction element providing impact resistance and resilience to the whole building block. This green building material was developed through alkali activation[3] by valorising several CDW streams. In particular, ceramic wastes (bricks and tiles) were selected as the most promising candidates for geopolymerization since they have high amounts of SiO_2 and Al_2O_3[4]. The activation solution was prepared through the alkaline dissolution of glass waste in order to substitute the widely used commercial products and thus lowering the energy and costs needed for the geopolymer production. EPS waste was introduced into the synthesis to reduce the density of the final products while fibers produced from polyethylene wastes were added in order to improve the mechanical performance. The processing of ceramic, glass and EPS CDWs is shown in Figure 2.

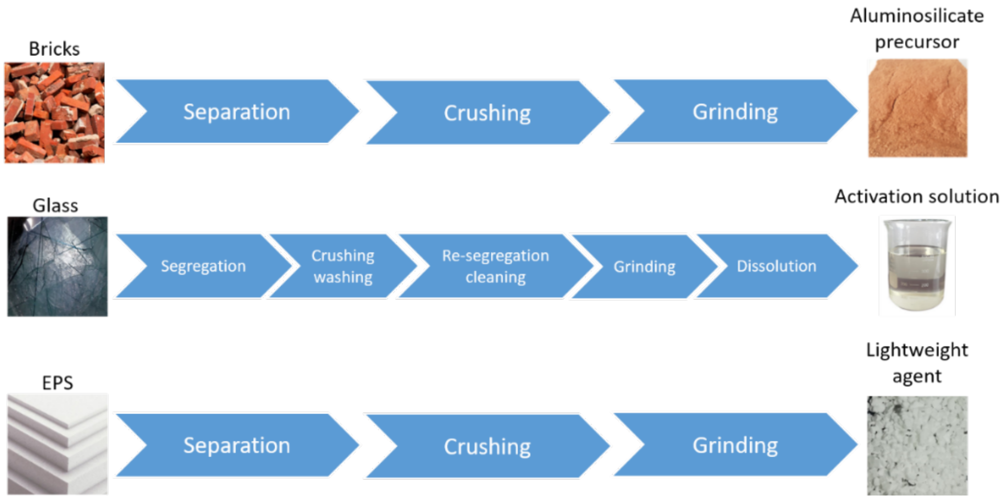

Figure 2. *CDW precursors for the development of geopolymers.*

The aluminosilicate sources (ceramic wastes) were characterized by means of XRD, XRF and FTIR in order to determine their chemical and mineral composition while alkaline dissolution tests were performed to evaluate the geopolymerization potential of the selected sources. CDW bricks were found to be more reactive in relation to CDW tiles. The fineness of the ceramic wastes was determined by laser granulometry with the mass median particle diameter (d_{50}) being close to 20 μm. The EPS granules had a particle size in the range of 1 – 4 mm.

In the frame of GI project, we achieved to produce lightweight building materials by incorporating close to 90% wt. CDW materials. Table 1 presents the properties of the developed geopolymer.

Table 1. *Properties of the geopolymeric products.*

Properties	Values	Properties	Values
Specific Heat (KJ/Kg.°C)	0.9	**Compressive Resistance (MPa)**	15.3
Thermal Conductivity (W/m·K)	0.45	**Water absorption (%)**	4.1
Density (Kg/m^3)	1300	**Sorptivity (mm/min^2)**	0.18
Poisson's Ratio	0.11	**Wet – dry cycles**	Stable
Young's modulus (GPa)	1.3	**Flammability**	inflammable
Tensile Resistance (MPa)	3.2	**CDW content (wt. %)**	88

Reinforcing fibers

Plastic and wood wastes were processed in order to produce fibers to be incorporated as reinforcement in the cementitious, insulating and adhesive materials of GI building block.

Two different families of polymer wastes were used in the GI project for the development of polymeric fibers: polyethylene (PE), polyvinyl chloride (PVC) and polyethylene terephthalate (PET). The materials were characterized attending chemical, thermal and processing criteria through FTIR, DSC, TGA, MFI and extrusion testing. The received pellets were milled for diameter reduction to ensure that the material feeding during the material extrusion runs unhindered. Then, the extrusion, spinning and cutting processes of the polymeric fibers were optimized in order to obtain the required filament diameter. Finally, PE and PET fibers were produced, while PVC showed low melt stretching which hindered the fibre production. In Figure 3 the flow sheet of the polymeric fibers development is presented.

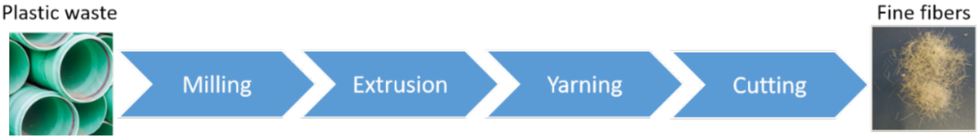

Figure 3. *Processing of the plastic fibers.*

PE fibers with different diameter range were successfully produced serving the needs of each application. PVC showed low melt stretching which hindered the fibre production. Table 2 shows the PE fibers characteristics applied in the reinforcement of geopolymer. Plastic fibers were used for the reinforcement of geopolymer, PU foam and structural adhesives.

Table 2. *PE fibers characteristics used for geopolymer reinforcement.*

Characteristics	Values
Length (mm)	6-12
Aver. Diameter (μm)	59.4
Density (g/cm^3)	0.97
Tensile Modulus (MPa)	258.60

MDF waste was used as raw material for the development of wood fibers. The wood fibers were used as reinforcing agents of the MOC layer. The processing and characteristics of these fibers are presented in Table 3 and Figure 4, respectively.

Table 3. *Wood fibers characteristics.*

Morphology	Width (μm)	Length (mm)	Degradation T (ºC)
Flat fibers with pores, "bean" shape section	20-50	0.5-5	280

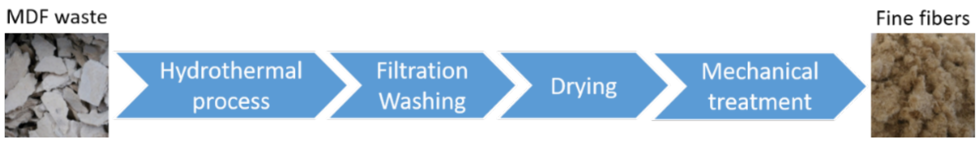

Figure 4. *Processing of the wood fibers.*

CDW in structural adhesives

The aim of this task was to develop a new structural adhesive with the highest possible content of CDWs. The introduction of CDW cement powder, PE fibers and PU foam powder in a commercial adhesive product (polyurethane 2 components – Protopur L2520/2C) was evaluated. In particular, a great amount of these fillers were premixed in a polyurethane polyol, and the formulation was finished with rheological additives. Many batches with different growing content of fillers were prepared and checked. The best result in terms of workability, stability and physical properties (viscosity, pot life, tensile strength) was obtained with a content of 62% wt. of CDW cement powder. The new formulation exhibits excellent properties in comparison with the commercial product. The bonding of the adhesive with geopolymers, aluminum and extruded PU foams (soft and rigid) was also tested. The preparation of the adhesives is presented in Figure 5.

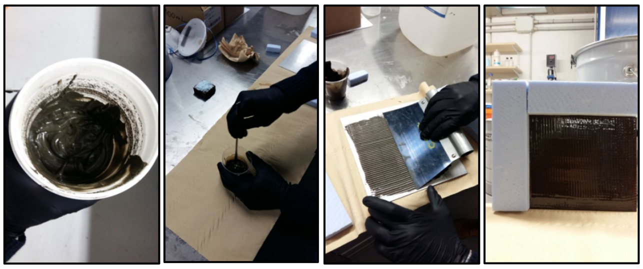

Figure 5. *Preparation – Mixing – Application – Final bonding of the adhesive (from left to right).*

The properties of the final product (GI/2C) along with those of the commercial one (Protopur L2520/2C) are presented in Table 4.

Table 4. *Properties of the developed adhesive Protopur GI/2C and the commercial product L2520/2C.*

Properties	L2520/2C	GI/2C
Viscosity	10000cps	100000cps
Mixing ratio with CTZ GI17	4 to 1	4 to 1
Pot Life of the mixture	40 minutes	30 minutes
Minimum Pressing Time	4 hours	3 hours
Tensile Strength (single lap shear test)	8.2 MPa	23.3 MPa
Shore D	50	85
Final Hardening Time (2mm thickness)	24h	24h
VOC	< 0.1	< 0.1

Processing and production of aggregates & impregnation

CDW concrete was also exploited in the development of recycled aggregates impregnated by appropriate PCMs. These materials can be used for the energy improvement of conventional and innovative building materials. Concerning the processing, waste concrete was subjected to a beneficiation process to separate the mortar from the coarse aggregate. Then, a macro-encapsulation process was developed and evaluated using a range of thermal performance tests. The vacuum impregnation unit achieved impregnation in particle sizes below 1mm; 100% absorption relative to the pore intrusion volume was achieved after 30 minutes of vacuum impregnation. A leak proof coating of aggregates was investigated and optimized using polyester resin. The PCM functionality before and after impregnation in terms of heat storage, melting and crystallization temperature (Figure 6) remained practically unchanged, indicating that the aggregates were thermally stable. Finally, incorporation of aggregates into MOC and geopolymer showed uniform distribution in both materials. Table 5 lists the main physical and thermal properties of the PCM impregnated aggregates.

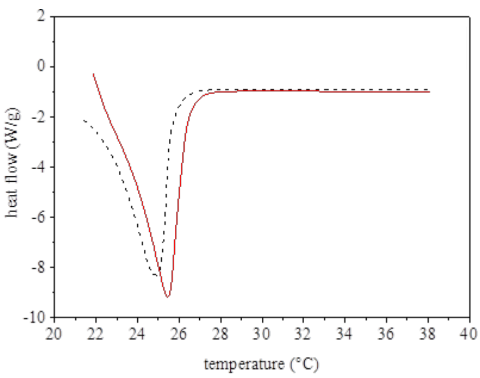

Figure 6. *Performance of PCMs.*

Table 5. *Physical and thermal properties of PCM aggregates.*

Properties	Values
Bulk density (g/cm^3)	0.8
Water absorption (% wt.)	0.05
Mass loss (% wt)	1.8
Thermal conductivity (W/m·K)	0.141
Heat storage capacity before thermal cycling (J/g)	23.7
Heat storage capacity after thermal cycling	21.2

Recycled PU layer

The application of CDW PU as raw material for the development of new insulating materials and lubricating component in the geopolymer and MOC extrusion process was explored.

Recycled PU foam was obtained from sandwich panels and it was milled to smaller size by a blade mill. Then, it was characterized by physical-chemical techniques such as microscopy, Fourier transform infrared (FTIR) spectroscopy, thermogravimetry analysis (TGA), differential scanning calorimetry (DSC) and solubility. These tests demonstrated that the foam coming from CDW is a polyurethane compound, showing the typical properties of that kind of crosslinked polymers. This material was modified through thermal degradation in order to serve as lubricant additive in the extrusion process of cementitious materials. The development of new insulating materials through the incorporation of CDWs in the form of PU foam and wood fibers was also evaluated. A rigid and a soft PU foam material was produced in order to achieve enhanced thermal and acoustic insulation properties, respectively. The incorporation content of CDW additives was kept at levels below 5% wt. in order to avoid bad mixing, bad foam evolution and deformation of produced plates. The optimized formulation for the rigid PU Foam contains 2% wt. wood fibers while that for the soft PU foam contains 1.5% wt. CDW PU foam powder. Table 6 presents the properties of the developed materials while Figure 7 shows photos of soft and rigid PU foam specimens.

Table 6. *Properties of soft and rigid PU foam developed in the GI project.*

Sample	PU foam (CDW)	Wood fibers (CDW)	Density (kg/m3)	Compression Strength (MPa)	Tensile strength (MPa)	Thermal Conductivity (W/mK)
Soft	1.5	0	22.7	0.015	0.023	0.0338
Rigid	0	2	43.4	0.113	0.239	0.0241

(a)

(b)

Figure 7. *Rigid (a) and soft (b) PU foam specimen developed by incorporation of CDWs.*

Recycling aluminium & extrusion of aluminium structural elements

The aluminium recycling process already covers 80% of aluminium products[5] placed on the market (aluminium packaging, window and door profiles, car parts, aluminium constructions, etc.). In the GI project, aluminium scrap is exploited in the production of the metallic frame of the panel which consists the main structural element of the multifunctional panel. These aluminium profile elements contains more than 90% of recyclable aluminium. The Aluminum recycling processes carried out for the purposes of the construction profile for the GI panel frame, including technological details, are shown in Figure 8. The designing efforts led to an aluminium profile solution which considers all the structural and thermal aspects. The final version of the aluminium profile is shown in Figure 9.

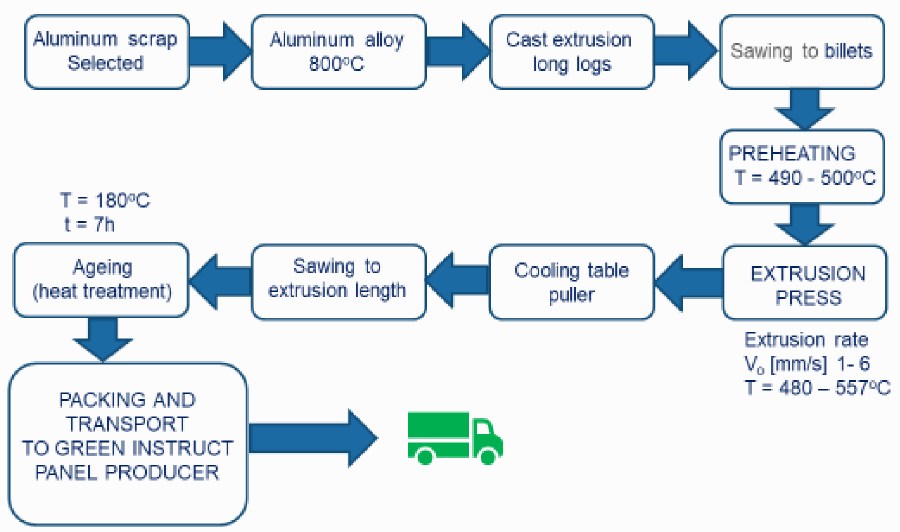

Figure 8. *Recycling process of aluminium.*

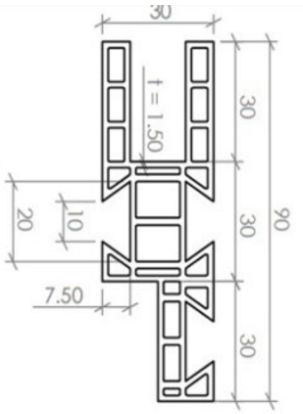

Figure 9. *Construction profile developed for GI product.*

Conclusions

In the frame of the GreenINSTRUCT project a multi-layered, integrated building block was developed containing more than 90% wt. of CDWs. Several CDW streams were valorized in the production of new, high added value products that cover the functions of structural performance, fire safety, thermal and acoustic insulation. In particular, geopolymeric building materials were produced by the exploitation of ceramic, plastic and insulation materials wastes. The final product contains more than 90% wt. CDWs. Plastic and wood wastes were successfully transformed in reinforcing agents that were incorporated in the layers of GI block. A new structural adhesive was delivered with the inclusion of 62% wt. CDW, that possesses superior performance in relation to its commercial counterpart. Recycled concrete aggregates with enhanced energy performance were developed from CDW concrete and PCMs. Furthermore, PU waste was used in the production of new insulating materials as well as in the preparation of lubricating agents for extrusion process. Finally, aluminium scrap was reprocessed in the production of the construction profile for the GI panel frame.

ACKNOLEDGEMENTS

This research work has been financed by the European Union Horizon 2020 (H2020-EEB-2016-2017, "Green Integrated Structural Elements for Retrofitting and New Construction of Buildings – GreenINSTRUCT", Grant No.: 723825).

REFERENCES

[1] European Commission (DG ENV), Final Report Task 2Service Contract on Management of Construction and Demolition Waste, 2011 (ENV.G.4/FRA/2008/0112).
[2] European Commission. COMMISSION STAFF WORKING DOCUMENT Accompanying the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the Thematic Strategy on the Prevention and Recycl 2010:72.
[3] J.L. Provis, A. Palomo, C. Shi. Cem. Concr. Res. 78A (2015) 110-125. https://doi.org/10.1016/j.cemconres.2015.04.013
[4] D. Kioupis, A. Skaropoulou, S. Tsivilis, G. Kakali, MATEC Web of Conferences 149 (2018) 01029. https://doi.org/10.1051/matecconf/201814901029
[5] Aluminum: The Element of Sustainability A North American Aluminum Industry Sustainability Report (PDF) (Report). The Aluminum Association. September 2011.