International Conference on Sustainable Materials, Systems and Structures (SMSS 2019)
Energy Efficient Building Design and Legislation
20-22 March 2019 – Rovinj, Croatia

REUSE AND RECYCLING OF CDW MATERIALS AND STRUCTURES IN ENERGY EFFICIENT PREFABRICATED ELEMENTS FOR BUILDING REFURBISHMENT AND CONSTRUCTION - RE^4

M. Whittaker (1), K. Grigoriadis (1), M. Soutsos (1), W. Sha (1), A. Klinge (2), S. Paganoni (2), M. Casado (3), L. Brander (4), M. Scullin (5), R. Correia (6), T. Zerbi (7), G. Staiano (8), I. Merli (9), I. Ingrosso (10), A. Attanasio (10) and A. Largo (10)

(1) School of Natural and Built Environment, Queen's University, Belfast, UK

(2) ZRS Architekten Ingenieure, GmbH, Berlin, Germany

(3) ACCIONA Construction Technology Centre, Madrid, Spain; (4) RISE, Boras, Sweden

(5) CDE Global Ltd, Cookstown, UK; (6) CREAGH Concrete, Toomebridge, UK

(7) STAM S.R.L., Genoa, Italy; (8) STRESS S.C.AR.L., Naples, Italy

(9) VORTEX HYDRA S.R.L., Ferrara, Italy; (10) CETMA, Brindisi, Italy

Abstract

The EU Waste Framework Directive 2008/98/EC states that all member states should take all necessary measures in order to achieve at least 70% re-use, recycling or other recovery of non-hazardous Construction and Demolition Waste (CDW) by 2020. In response, the Horizon 2020 RE^4 project consortium (REuse and REcycling of CDW materials and structures in energy efficient pREfabricated elements for building REfurbishment and construction) consisting of 12 research and industrial partners across Europe, plus a research partner from Taiwan, was set up. For its success, the approach of the project was manifold, developing sorting technologies to first improve upon the quality of recycled aggregate. Simultaneously, CDW streams were assessed for quality and novel applications developed for timber, aggregate, and plastic waste in a variety of products including structural (e.g. beams, columns, slabs) and non-structural (e.g. building blocks, insulation panels, tiles) elements. With all products considered, innovative building concepts have been designed in a bid to improve future recycling of the products by promoting prefabricated construction methods and modular design to ease future recycling and increase value of the construction industry. The developed technologies and products will be put to the test in different test sites in building a 2 storey house containing at least 65% of CDW in the next 6 to 12 months.

Keywords: CDW-derived materials, Prefabricated structures, Recycling, Reuse

1. INTRODUCTION

Construction and Demolition Waste (CDW) constitutes the largest waste stream in the European Union (EU), accounting for more than 350 million tonnes/year excluding excavated soil and dredging spoil [1]. It consists of a heterogeneous mix of materials such as concrete, mortar, bricks, tiles, mineral aggregate, bitumen, ferrous, plastic, wood and organic lightweight particles [2]. The vast amount of CDW is deposited to landfills mainly because most existing buildings were not designed for disassembly and reuse [3]. In addition, most recovered CDW is confined to low value applications (e.g. recycled aggregate used for pipe bedding or subbase and base course in road pavement construction) despite the fact that some of its constituents have a high resource value. However, EU Waste Framework Directive 2008/98/EC [4] requires that all member states should take all necessary measures in order to achieve at least 70% re-use, recycling or other recovery of non-hazardous CDW by 2020. Consequently, the development of reliable strategies and innovative technologies is required in order to:

- Increase the percentage of CDW-derived materials in new residential construction
- Increase the technical and economic value of CDW-derived materials
- Minimise future CDW coming from the next generation of buildings
- Increase building energy efficiency

Prefabricated elements (structural and non-structural) which incorporate large amounts of CDW-derived materials can have a significant effect towards achieving the above objectives.

This paper aims to provide an outline of the efforts of the RE^4 project consortium (CETMA, ACCIONA, RISE, CDE Global Ltd, CREAGH Concrete Products Ltd, FENIX TNT, Queen's University Belfast, ZRS Architekten GmbH, STAM S.R.L., STRESS S.C.AR.L., National Taiwan University of Science & Technology, VORTEX HYDRA S.R.L. and ACR+) [5] in developing prefabricated building components which incorporate at least 65% by weight of CDW-derived materials while describing the challenges that have been faced along the way.

2. MINIMIZING FUTURE CDW FOR FUTURE GENERATIONS

2.1 Case for prefabrication

Prefabricated concrete differs from in-situ concrete as the former is first cast in the premises of precast concrete factories and then delivered to site. This has many added benefits, including better quality control, less waste, improved health and safety, increased speed of manufacturing and reduced cost [6]. Furthermore, precast concrete allows for the building of standardized products, but also bespoke elements to answer the needs of a client.

2.2 Modular design

In parallel to the development of CDW containing building elements, the prefabricated elements are designed to be reused as whole functional units. To achieve this, the designed buildings within the scope of RE^4 are to be modular, where each 'module' (beam, column, slab, façade panel, etc.) can be removed and reused later in its design life. This presents a series of challenges including:

- Ensuring all elements comply with existing building regulations
- Using available mechanical connections to facilitate assembly and disassembly
- Limiting element size for standard lorry transport, saving time and cost

- Life span, ease of repair, maintenance or replacement
- Traceability, specifying information into Building Information Modelling (BIM)

All elements were deemed suitable for modular design with the exception of foundations, as their performance relies on the soil conditions.

3. INCREASING THE % OF REUSED AND RECYCLED CDW

The reuse of CDW recycled aggregates in concrete, for example, is already permitted and standardised. Currently, EN 206:2013+A1:2016 [7] and EN 12620:2013 [8] limit the maximum amount of coarse recycled aggregates up to 50%, depending on exposure conditions. However, this limits the recycling potential of CDW. Raw CDW first needs to be treated in order to become suitable for use as recycled aggregate. This involves removing 'unwanted' fractions such as floating particles, clay and soil, ferrous metals, non-floating wood, plastic, rubber and gypsum. However, to increase the recycling rate, the amount of fractions such as ceramics (bricks & tiles) and bitumen present in treated recycled aggregate must also be reduced (Figure 1).

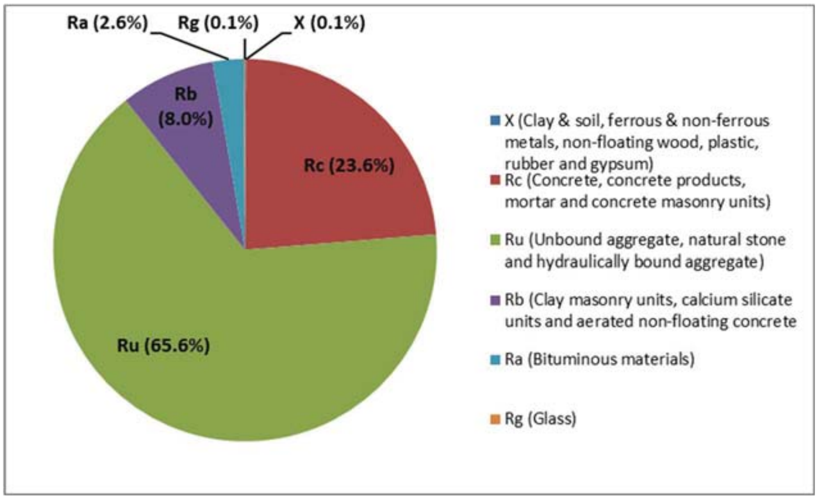


Figure 1: Typical composition of 8-16 mm processed recycled aggregate coming from a recycling plant near Marseille, France.

3.1 Improving the quality of CDW aggregates

To further improve recycling rates, attempts have been made to improve the quality of the CDW aggregates (Figure 2 a-c).

For coarse aggregates (≥ 8 mm), an automated mechanism has been devised to remove the remaining 'unwanted' particles. These particles are determined on a real time basis using advanced electronic and optical systems based on the infrared reflectance signature of different types of CDW. The sensing unit determines the reflectance of the particles in different wavelengths (1000 to 1700 nm – near infrared) to differentiate the unwanted particle which is then removed using a robotic arm. Currently, the production rate stands at 100 kg/h.

For fine aggregates removed during treatment, the particles are first scrubbed clean using an attrition cell, after which the fine aggregates are separated based on density. This is done by having the sand flow through a corkscrew shaped gravity column. In passing, the lighter particles migrate towards the outer edge and the heavier particles remain inside of the column. The particles are collected at the bottom and separated by density to the user's requirements.

a) Robotic arm and conveyor belt b) Attrition cell c) Gravity column

Figure 2 (a-c): Examples of new technologies used for improving CDW-derived mineral fractions.

3.2 What to do with the ceramic fraction?

As not to dispose of the ceramics fraction successfully removed from the CDW waste stream, two potential uses were investigated. In a first instance, the ceramic waste was ground to a fine powder to be used as a precursor. It was then activated in the presence of sodium oxide (Na_2O) and sodium silicate (Na_2SiO_3) varying their proportion to maximise strength [9], [10], [11]. The water/binder (w/b) content was fixed at 0.37. Such mixes, depending on the chemistry of the activating solution, reached strengths of up to 30 MPa, when tested on 50 mm mortar cubes.

Ceramics were also reused as floor or wall tiles. This was achieved by blending the ground ceramic fraction in resin and allowed to harden in moulds. The grading of the ceramic powder and the resin to ceramic fraction ratio were investigated to achieve the desired strength and workability properties. Optimal performance was achieved when blending 3 parts of resin to 7 parts of ground ceramic by weight.

4. RECYCLING AND USE OF CDW IN STRUCTURAL ELEMENTS

4.1 Concrete

Concrete is perhaps the focal material due to the breadth of structural and non-structural elements that can be designed within the scope of the project. The project's approach was to design various concrete types and strength grades from which various elements could be designed (beams, columns, slabs, blocks, façades, stairs, etc.). The type of concretes designed are detailed in Table 1 and include 3 types of concrete mixes – vibrated, self-compacted and semi-dry – suitable for the needs of the relevant partners within the project. After carrying out trial mixes, the designed concretes reached the target strength and workability targets set by the manufacturers within the project. Newly quarried aggregate replacement varied from 40% to 100% depending on the source of the recycled aggregate and the type of concrete produced.

Table 1: Different types of concrete incorporating high levels of CDW-derived aggregate

Product	Strength class	Consistency class	Virgin aggregate replacement level (%)
Vibrated concrete	C25/30	S2/S3	100
	C32/40	S3	83
Self-compacting concrete	C40/50	640-770 mm based on slump flow test	40 to 80
Semi-dry mix concrete	7.3 MPa	N/A	70

4.2 Reclaimed timber

A strategy for reusing timber elements from dismantled buildings for structural and non-structural elements has been developed. Different methods for the procurement and characterisation of CDW timber have been applied to generate raw materials that can be strength graded according to existing norms.

As a precondition waste wood must be free from wood preservatives, fungal or insect infestation and serious damage. The absence of wood preservatives has to be verified by an accredited laboratory and appropriate measures have to be taken e.g. cut off of affected areas.

Visual, on-site inspection is sufficient to determine fungal or insect infestation and potential damages. In addition, it enables to define the wood species, its nature and moisture content. The raw density can be estimated through literature data, in case no information about the location of growth of the CDW timber is available. Salvaged sections must then be cleaned from impurities such as metal fittings, paint etc. in order to be assessed with regards to dimensions and location of cracks, branches and slope of grain. Sections are then cut or planed to final cross section, ideally to standardized sizes in order to be classified according to DIN 4074-1:2012 [12] into the relevant sorting classes. This in turn, leads to the respective strength class according to EN 338:2016 [13]. Such procedure enables the effective reuse and recycling of waste wood with minimal loss in performance for reuse as structural elements [14].

Depending on the final strength grade, the nature of the element and its conservation, several strategies can be adopted to reuse the wood, including:

- Complete reuse of the element with minimal processing (Figure 3a)
- Reprocessing into standardized cross sections
- Reprocessing into lamellas for glulam fabrication (Figure 3b)

a) Reclaimed timber sections b) Glulam from reclaimed timber

Figure 3 (a-b): Converting reclaimed timber section into Glulam.

In the case of glulam timber beams, timber strength grade GL24 was targeted, meaning the timber beams reached a target flexural strength of 24 MPa. If the elements were deemed not to be suitable for use as structural elements, the timber could potentially still be reused to prepare non-structural elements, for example in cladding or wood fibre insulation. Because of the varied forms timber can take and the potential for a cascading use, the recycling rate of all wood and timber products remains very high.

5. RECYCLING AND USE OF CDW IN NON-STRUCTURAL ELEMENTS

5.1 Lightweight particles for the preparation of insulating elements

Typical lightweight CDW particles are small in size (≤ 4 mm) and are made of plastics and wood. RE^4 attempted to utilise these fractions in the development of insulation panels having low thermal conductivity. In addition, recycled plastics were used as lightweight aggregates in the development of low density concrete.

Table 2 below highlights the target properties for the development of lightweight Portland Cement (PC) concrete and optimised mixes meeting those targets. Depending on the source, rigid plastics or mixed wood & plastics could replace up to 70% and 50% of the natural sand fraction, respectively.

Table 2: Requirement set for lightweight concretes for panel layers

Requirements	**Target applications**	**Performance of RE^4 lightweight PC concretes**	
	Panel layers	Rigid plastics	Mixed wood & plastics
Consistency class	S4	S4/S5	S5
Density (kg/m^3) @ 28 days	800-1400	1260	1250
Compressive strength (MPa) @ 28 days	4.5-24.0	7.5	4.5
Thermal conductivity (W/mK) @ 28 days	0.16-1.00	0.31	0.29

For panels containing rigid plastics, the plastic aggregates were embedded in polyurethane foam, already a popular cavity insulation material. The ratio of aggregate to binder was varied to create panels of different density values, from 5% plastic up to 50% plastic by volume. The panels performed best at 5% plastic content, keeping the density and thermal coefficient low.

Wood scraps (≤ 4 mm in size) and plastics were also used to prepare insulating panels, moulded into shape. The production process of the panels differed depending on the material used. For wood scrap panels, the wood was first soaked in water for 72 hours. Thereafter, the wood was compacted into moulds and kept under pressure, at 15 bar and 120 °C or 160 °C from 3.5 to 30 hours. Finally, the panels were dried. To improve their fire resistance, prior to making the panels, the wood was mineralised by forcing a MgO solution into the wood under pressure (8 bar). Wood panels were found to be least dense when the curing period was the longest. Optimised wood scrap panels achieved a density of 215 kg/m^3 and thermal conductivity of 0.07 W/mK.

Some of the above types of developed insulating materials (e.g. wood-based panels) have been selected to be used in the construction of demonstration buildings in Northern Ireland and Spain or in the refurbishment of an existing building in Italy as described in Section 6.

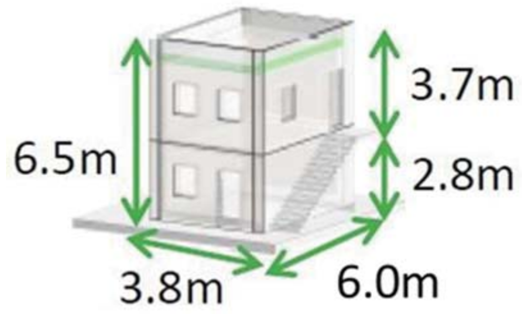
5.2 CDW aggregate in roof tiles

The substitution of virgin aggregates by CDW mineral aggregates was also investigated in extruded tiles. The extrusion process made use of only the fine mineral fraction (0 to 2 mm) and a CEM II/B-LL 32.5 R cement. By replacing 50% of the virgin aggregates with mineral CDW, a mix prepared with 1-part cement and 3-parts sand, with a w/b ratio of 0.3 complied to all relevant standards.

6. PILOT TRIALS

The ultimate test will come during the pilot trials. Several sites have been identified between the partners, including one in Northern Ireland, one in Spain and another in Italy. Table 3 details some of the elements designed to be tested in a 2-storey building with the dimensions shown. With regards to concrete products, the estimated recycling rate varies from 40% to 90%, depending on the elements.

Table 3: Types of elements (structural and non-structural) and components of a 2-storey building to be tested

Type of Element/Component	
Beams	
Columns	
Slabs	
Stairs	
Sandwich panels (structural & non-structural)	
Building blocks	
Timber façades	
Timber based inner partitions	
Wood fibre insulation panels	
Rigid plastic insulation panels	
Extruded tiles	

At this point in the project, the design of the elements (structural and non-structural) and components is in its final stages. Once industrial production of the elements/components commences, they will be used for making the demonstration buildings in Northern Ireland and Spain and performing the refurbishment of an existing building in Italy. The demonstration buildings as well as the refurbished building will be monitored in terms of energy efficiency and compared with conventional ones. Based on the above, no specific data on the performance of buildings made using the above elements and components is available at this stage of the project.

7. CONCLUSIONS

This project has tackled the concept of reusing and recycling CDW back into the built environment. Building practices were adapted to promote a modular design to facilitate the reuse of whole elements, rather than having them demolished. However, this will likely only be successful if the assembly and disassembly is facilitated, in a first attempt through design (i.e. through the use of reversible connections) and, secondly, aided with Decision Support Systems (e.g. BIM-based DSS). The disassembly adds another challenge, notably how to reuse the elements, and where (e.g. transport). Cost and environmental impact together with associated savings can also be evaluated using Life Cycle Cost (LCC) and Life Cycle Analysis (LCA) assessments. Following on, the quality of the recycled CDW was maximised, and a novel sorting method was developed to improve the quality of recycled aggregates. It is estimated that the improved aggregate will result in CDW containing concrete products with greater performance, thus increasing the amount of embedded recycled aggregates. The reuse and recycling of timber was also heavily investigated given its high potential for reuse, from structural and non-structural elements, with an effective recycling rate of approximately 80% leading up to 95% of CDW timber included in the final element. Ultimately, CDW containing elements were designed as to maximise the recycling rate in order to meet the target set in the Waste Framework Directive, e.g. a 70% recycling and reuse rate of CDW. This will ultimately be tested when building full scale elements, containing as much CDW as possible, to be used on demo buildings in Northern Ireland (CREAGH), Spain (ACCIONA) and Italy (STRESS). If successful, then existing standards and methods of practice can be challenged to facilitate the uptake of CDW in construction.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the funding provided by the European Commission Horizon 2020 Framework Programme for financing this research for RE^4 project (Grant No: 723583).

REFERENCES

[1] Resource Efficient Use of Mixed Wastes - Improving Management of Construction and Demolition Waste - Final Report. European Commission, Brussels, 2017.

[2] http://ec.europa.eu/environment/waste/construction_demolition.htm.

[3] http://www.greenspec.co.uk/building-design/design-dismantling.

[4] Directive 2008/98/EC On Waste and Repealing Certain Directives. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN.

[5] http://www.re4.eu/.

[6] Wong, R., Hao, J.L., and Ho, C.M.F., 'Prefabricated building construction systems adopted in Hong Kong', in Proceedings of the 31st International Association for Housing Science World Congress on Housing: Process and Product, Montreal, 2003.

[7] EN 206:2013+A1:2016. Concrete. Specification, performance, production and conformity. European Committee for Standardization, 2016.

[8] EN12620:2013. Aggregates for concrete. European Committee for Standardization, 2013.

[9] Reig, L., Tashima, M.M., Borrachero, M.V., Monzo, J., Cheeseman, C.R. and Paya, J., 'Properties and microstructure of alkali-activated red clay brick waste', *Con. Build. Mater*. **43** (2013) 98-106.

[10] Komnitsas, K., Zaharaki, D., Vlachou, A., Bartzas, G. and Galetakis, M., 'Effect of synthesis parameters on the quality of construction and demolition wastes (CDW) geopolymers, *Adv. Powder Technol*. **26** (2015) 368-376.

[11] Robayo-Salazar, R.A., Rivera, J.F. and Mejia de Gutierrez, R., 'Alkali-activated building materials made with recycled construction and demolition wastes', *Con. Build. Mater.* **149** (2017) 130-138.

[12] DIN 4074-1:2012. Strength grading of wood. Part 1: Coniferous sawn timber. Deutsches Institut Fur Normung. 2012.

[13] EN 338:2016. Structural timber. Strength classes. European Committee for Standardization, 2016.

[14] Cavalli, A., Cibecchini, D., Tongi, M. and Sousa, H.S., 'A review on the mechanical properties of aged wood and salvaged timber', *Con. Build. Mater.* **114** (2016) 681-687.