Chapter 14
Efficient Recovery of Valuable Resources from Construction and Demolition Waste Towards Circular Economy in Construction Industry—Sustainability Assessment and a Case Study

Emircan Ozcelikci, Alper Aldemir, and Mustafa Sahmaran

Abstract Considerably high amounts of CO_2 release to the atmosphere trigger global warming. Although there are several methods to reduce the level of CO_2 release, the extent is still very limited and recently-growing awareness of sustainability/global warming have been pushing the entire construction industry to seek alternative methods for rigorously lowering/eliminating the level of CO_2. The key strategic objective of the study is to develop eco-friendly/innovative, 100% CDW-based construction materials and demountable structural systems. This study aims to achieve higher levels of circularity in civil engineering materials/structures, contributing to the reduction/elimination of CO_2 emissions much more rigorously through the following key objectives: (i) Upgrading CDW recycling/reuse efficiency by capturing CO_2 from the atmosphere to improve properties of CDW-based constituents via accelerated mineralization/carbonation, (ii) Development of holistically-designed advanced material property improvement technologies to even enhance the greenness of 100% CDW-based materials/structures through efficient CO_2 binding/elimination capability, (iii) Validation of the ultimate products (materials/structures) with additional green perspective through a detailed large-scale field demonstration. Despite the abundance of studies in this area, there is currently very little work on demonstration activities on the real-time applicability of geopolymers development using industrial by-products and CDWs. Successful outputs of this study and their real-time demonstration will offer a fully sustainable construction system, including speed of construction/design flexibility/air purification/cost reduction/energy and material saving/avoidance of unwanted pollution-heavy demolition processes and make much larger audience to be influenced by the study's results.

Keywords Circular economy · Construction and demolition waste · Case study

E. Ozcelikci · A. Aldemir · M. Sahmaran (✉)
Civil Engineering Department, Hacettepe University, 06800 Ankara, Turkey
e-mail: sahmaran@hacettepe.edu.tr

L. Bragança et al. (eds.), *Creating a Roadmap Towards Circularity in the Built Environment*, Springer Tracts in Civil Engineering,
https://doi.org/10.1007/978-3-031-45980-1_14

14.1 Introduction

Portland cement (PC)-based traditional concrete is the second mostly used material globally, following water and cement industry alone is responsible for ~9% of total anthropogenic CO_2 emission [1]. Furthermore, current construction practice of materials' overproduction, insufficient longevity of concrete structures and accumulation of construction and demolition waste (CDW) are becoming increasingly. CDW industry is one of the largest global solid waste producers, accounting for 25–30% of total urban waste in Europe [2]. Such CDW production requires relatively high demand for proper handling not only to lower CDW going to clean landfills endangering health of people/environment, but to reduce concrete production that will be, otherwise, used to construct/renovate /repair/maintain new/existing infrastructure. It has been shown that, constituents from CDW, widely available and troublesome, can effectively be used singly/in combination to produce geopolymer binders, achieving major progress compared with most work utilizing common aluminosilicates as precursors (e.g. fly ash/slag/metakaolin) that are highly demanded by PC industry, expensive or even unavailable for certain regions for geopolymer production [3–5]. Additionally, aggregates conventionally constitute more than 70% of the volume of concrete mixtures and those diverted from recycling applications are mostly used in low-tech applications and/or are deposited to landfills, risking the health of individuals/poll ting environment. The properties of aggregates can be significantly improved by chemically binding CO_2 into their composition, achieving double benefits of better performance of CDW-based aggregates and deceleration of global warming [6].

With the successful production of CDW-based "green" concretes, the reliance and negative environmental impacts of PC, clean aggregates and traditional concrete whose mass production are major contributors of CO_2 emissions/global warming will believe to be significantly reduced. Moreover, incorporation of these "green" concretes into demountable structural components further reduces energy/material/ workmanship needs and additional waste creation anticipated with conventional construction methods. Lowering these negative effects will have clear impacts on the quality of lives of people (environment-/health-/society-wise) worldwide considering the current issues of PC production/CDW generation.

To tackle the drawbacks of concrete production, achieve truly effective/easily appl cable/uncommon solutions for CDW problem and advance beyond the current state-of the-art, the main focus of this study is to the production of CDW-based PC-free "green" concretes to be incorporated in the development of lego-like/demountable structural elements that do not create additional waste, do maximize reductions in energy needs (>50%) and CDW upcycling and promote circularity in novel civil engineering materials/structures. Also, demonstration of study outcomes is crucial for wide-spread visibility/applicability and impact because almost never demonstration activity has been conducted in the current literature on geopolymer development according to the author's best knowledge. Therefore, final part of the study will be devoted to the design/construction of a real-time 1-storey residential building incorporated entirely with the study outcomes (i.e. fully demountable structural elements with 100% CDW-based green concretes having enhanced CO_2 capturing capability). The study will show easy-to-apply/effective/sustainable approach for a cleaner environment/energy efficiency/CDW upcycling/significantly cheaper/affordable housing targeting in-need people all around the world.

14.2 Laboratory Scale Experiments

The development of CDW-based green concretes, accelerated carbonation process of recycled aggregates, and design of fully-demountable structural elements such as column, beam and slab and their connection details were presented in this section.

14.2.1 Development of CDW-Based Geopolymer Concretes

In the development of CDW-based geopolymer concretes, unknown-origin CDW-based materials such as brick, tile, concrete and glass wastes were first collected separately from a demolition site. Thereafter, in order to achieve the suitable fineness for geopolymerization, these materials were put through a two-step crushing and grinding process. To enhance the mechanical and durability properties of CDW-based geopolymer concretes, 20% slag by weight was replaced with CDWs in the binder design. Three different alkali activators such as sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3) and calcium hydroxide ($Ca[OH]_2$) were used to activate CDW-based materials. Fine recycled concrete aggregate (FRCA) and coarse recycled concrete aggregate (CRCA) obtained by crushing of concrete waste into different sizes were first subjected to an accelerated CO_2 capture process and then used as the aggregate phase of the mixtures. Figure 14.1 shows the visual images of materials used in the development of CDW-based geopolymer concrete.

In the development of CDW-based geopolymer concrete, several mixture designs were made in which various parameters such as precursor combinations, alkali activator concentrations, aggregate/binder and water/binder were investigated. According to the findings, the mixture contains 80% mixed CDW, 20% slag, 1:1 precursor/RCA ratio, 8 M NaOH, 1:2 wt% NaOH/Na_2SiO_3 ratio, $Ca(OH)_2$ at 5 wt% of the precursor and 0.33 water/precursor ratio were selected and used for the development of structural elements. In their unprocessed state, CDW-based materials are often inert and, when combined to produce geopolymers, they frequently form N-A-S-H type gel structures after geopolymerization reactions. In this study, CDW-based materials were supplemented with calcium sources such as slag and $Ca(OH)_2$ in order to reach structural strength. Thus, C-A-S-H type gel structures were also formed in the final matrix, which contributed to the strength along with the N-A-S-H gel structures. In addition, a certain amount of Na_2SiO_3 was added as an extra alkaline

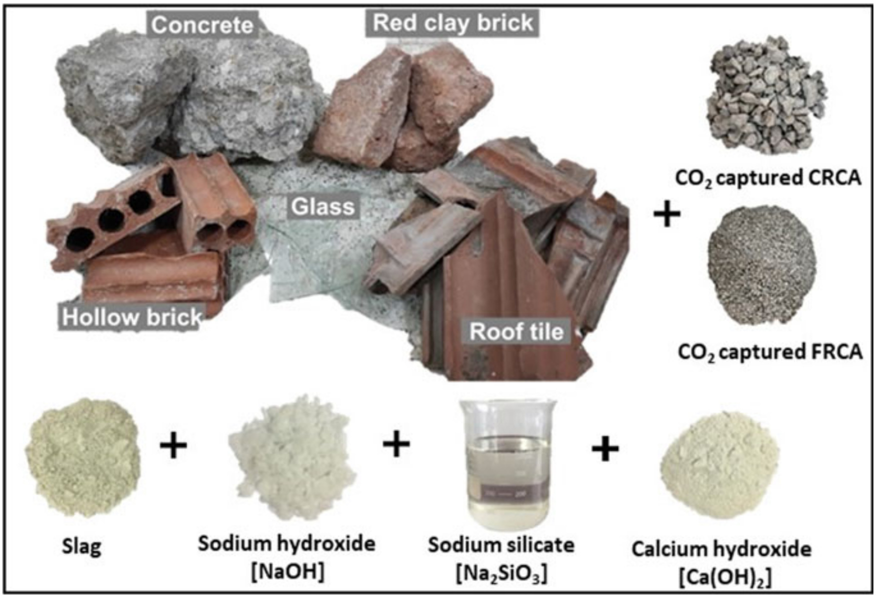

Fig. 14.1 Visual images of the materials using in geopolymer concrete production

activator to provide reactive Si ions to the system and to maintain the Si/Al balance of the matrix. To ensure worldwide reproducibility, the amount/concentrations of these inclusions used to boost geopolymer strength should be tailored based on CDW composition. For the CO_2 capture process of RCAs, a pilot-scale carbonation reactor with a rotational chamber (Fig. 14.2), which can provide to implement different ranges of operational parameters [e.g., temperature (25–100 °C), humidity (50–95%), CO_2 concentration (0–20%) and pressure (0–5 bar)] was developed. After carbonation, the water absorption value of RCAs decreased by 32.7%, while the flow value and compressive strength of the mortars containing carbonated RCA increased by 9.6 and 28%, respectively, compared to the reference mortars.

As a result of the experimental study, CDW-based geopolymer concretes reached a maximum compressive strength of 39.7 MPa and splitting-tensile strength of 2.93 MPa at the end of 28 days of ambient curing. Additionally, the durability performance of CDW-based geopolymer concretes were examined by conducting many tests such as drying shrinkage, water absorption, efflorescence, resistance against freeze-thawing cycles and sulfate solution. According to the results, the durability performance of CDW-based geopolymer concretes was found to be similar or better than that of PC-based structural concretes.

Fig. 14.2 Accelerated CO_2 capture process of RCAs

14.2.2 Design of Fully-Demountable Structural Elements

The structural design procedure of fully demountable buildings is composed of reinforcement design and the connection design (Fig. 14.3). For the case study, a 1-story residential building with a plan area of approximately 250 m^2 is designed. The structural design included both vertical load demands (i.e., dead load of structural elements, design snow load and live loads) and lateral load demands (i.e., earthquake loads and wind loads). The internal force demands under the effect of predefined loading patterns were obtained using a commercial structural analysis program (i.e., SAP2000 v21).

The computer model was formed using frame elements for beams and columns whereas the slab elements were modelled by utilizing shell elements. All the connections for structural elements (i.e., beams, columns and slabs) were assumed to be pin connection as all the proposed dry-joint connections developed in the scope of study permits rotations at the connections. After these demand calculations, the reinforcement design was performed using the fundamental rules in conventional concrete with a different material model for geopolymer concrete [7]. In addition, the design of connection was thoroughly based on scaled tests of each connections and their validated unscaled numerical models. The detailed design, material selection, testing and performance criteria of the structural elements developed within the scope of the demonstration activity were previously presented to the literature [8, 9].

Fig. 14.3 Details of connections of demountable structural elements

14.2.3 Sustainability Assessment for Circular Built Environment

In order to reveal the environmental advantages of CDW-based geopolymer concretes and demountable structural elements, life cycle assessment (LCA) was carried out. The LCA was applied followed by (ISO) 14,040 and 14,044 standards with the use of GaBi software [10]. In this analysis, cradle-to-gate approach with a functional unit of 1 m^3 CDW-based geopolymer concrete structural elements was determined (Fig. 14.4). According to the findings, demountable structural elements produced

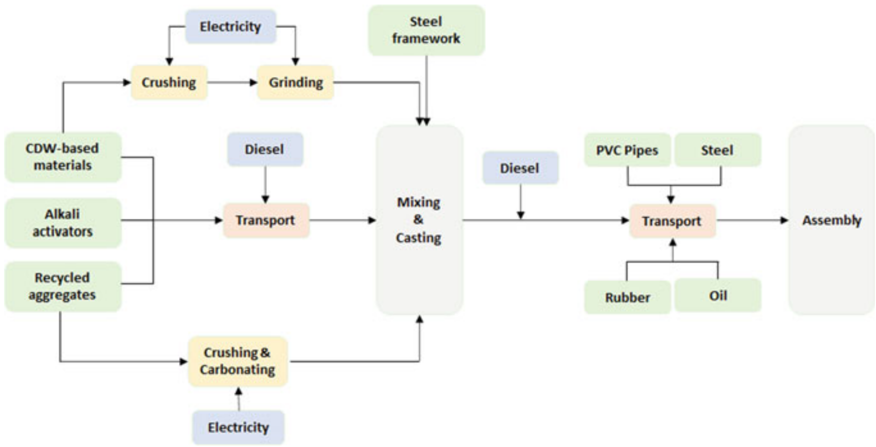

Fig. 14.4 Plan and system boundry of LCA study

with CDW-based geopolymer concrete exhibited 12.6% lesser global warming potential (GWP), 4.5% lesser eutrophication potential (EP), 11.8% lesser smog formation potential (SFP) and 2.4% lesser fossil fuel depletion (FFD) compared to demountable structural elements produced with conventional PC concrete. Additionally, considering to possible cyclic use of demountable structural elements several times in their whole lifecycle, it can be stated that demountable types of structural elements will be better in terms of environmental impacts overall.

14.3 Real-Time Field Demonstration

The construction of the first-ever real-time demonstration of a fully demountable 1-story building is one of the study's main goals in order to increase the credibility and trust of different stakeholders in dry/demountable reinforced concrete connections and CDW-based geopolymer concrete. At the initial stage of the field demonstration activity, the foundation of the building was built in the demonstration field. Firstly, a thin layer of gravel was laid on top of the soil in order to obtain a flat and workable environment (Fig. 14.5a). Accordingly, a mat foundation was constructed (Fig. 14.5b). The base plates that are used to anchor the demountable columns were installed inside the mat foundation before the concrete was cast.

The materials used for the production of prefabricated elements (CDW-based materials, slag, alkaline activators, chemicals, CO_2 captured recycled aggregates, steel profiles, reinforcement) were supplied and transferred to the prefabricated concrete manufacturer. Structural elements (columns, beams and slabs) were prefabricated to demonstrate the validity of the demountability of such elements when

Fig. 14.5 Construction of the mat foundation, **a** laying of gravel; **b** building of the foundation

dry connections are used (Fig. 14.6). At the end of the 28-day ambient curing, all structural elements were transferred to the demonstration field.

The construction of real-time 1-story building was started with the installation of vertical structural elements. All the columns were labeled and placed near the mat foundation with the help of a mobile crane. Afterward, the columns were lifted to their vertical position placed on base plants and bolted to maintain their aligned positions (Fig. 14.7). All demountable column elements were installed in less than three hours.

Fig. 14.6 Preparation of prefabricated geopolymer structural elements

Fig. 14.7 Installation of columns

Fig. 14.8 Installation of beams

Fig. 14.9 Installation of slabs

After the installation of column members, the beams were transferred to the field and placed between every two columns by simply sliding them through the beam-to-column connections (Fig. 14.8). All beam installation operations also took less than three hours. It should also be noted that the columns and beams were produced with relatively large sizes so it allows future uses in multi-story buildings.

The structural system of the prototype building was continued by placing the slab elements on top of the beams (Fig. 14.9). A membrane was placed between the slab and the beam to fill any manufacturing spaces. This operation was also easy to apply and the whole construction operation of the structural system was finished in the course of two days.

Besides the structural elements, the walls of the building were also made of precast panels, thus the building can be fully demountable. The panels were also mounted with the help of a mobile crane and each panel took a time around 15 min on average to be installed (Fig. 14.10). Additionally, other non-structural members such as windows, doors, etc. were installed on the prefabricated construction.

Finally, the first-ever real-time demonstration of a fully demountable 1-story building constructed with CDW-based geopolymer concrete has been completed as shown in Fig. 14.11. After the successful construction of the green building, installation of other work items such as electrical, plumbing and heating systems were carried out.

Fig. 14.10 Installation of non-structural elements

Fig. 14.11 1-story building field demonstration

14.4 Conclusion

In this study, it was aimed to develop fully-demountable structural elements produced with construction and demolition waste (CDW)-based green geopolymer concrete. With the achieving successful results from these elements, a demonstration of a real-time 1-story residential building was carried out as the next step. According to the findings, the following conclusions were drawn:

- CDW-based materials such as brick, tile, concrete and glass waste can be successfully utilized in geopolymer concrete production up to 40 MPa compressive strength after 28 d ambient curing.
- After the carbon capturing process on the CDW-based recycled concrete aggregates (RCA), the water absorption of RCAs decreased by 32.7% and the compressive strength of the mortars containing carbonated RCA increased by 28%.
- It was demonstrated that the modular demountable system design provides a fast, reliable and practical construction approach compared to the traditional construction system.
- Life cycle assessment revealed that CDW-based geopolymer concrete showed 12.6% lesser global warming potential, 4.5% lesser eutrophication potential, 11.8% lesser smog formation potential and 2.4% lesser fossil fuel depletion compared conventional PC concrete.

It is believed that real-time demonstration of the study's outcomes will help the impact of this study to last for years to come and will be used as a viable tool and advertisement element for anybody who is interested in making collaborations/ learning more about CO_2 capture/storage, innovative CDW recycling and design-for-demountability for future reuse. Owing to holistic solutions, highly-pure recycled building materials/higher traceability/market acceptance and thereby, higher levels of circularity will ensure widespread utilization of recycled materials in construction industry. The study will also contribute to higher circularity of the new building products, leading to even lower impacts in the subsequent lifecycles. Successful outcomes of the study can be reproduced through rigorous classification and characterization of country-specific CDWs, which is considered the main challenge in successful material development, selection of alkaline activators suitable for CDW composition, and integration of modular system design into the developed products.

Acknowledgements The authors gratefully acknowledge the financial assistance of the Scientific and Technical Research Council (TUBITAK) of Turkey and the British Council provided under projects: 218M102 and European Union's Horizon 2020 research and innovation programme under grant agreement No: 869336. This work was also supported by Newton Prize 2020.

References

1. Makul N (2020) Advanced smart concrete—a review of current progress, benefits and challenges. J Clean Prod 274:122899
2. Tan J, Cai J, Li X, Pan J, Li J (2020) Development of eco-friendly geopolymers with ground mixed recycled aggregates and slag. J Clean Prod 256:120369
3. Yıldırım G, Kul A, Özçelikci E, Şahmaran M, Aldemir A, Figueira D, Ashour A (2021) Development of alkali-activated binders from recycled mixed masonry-originated waste. J Build Eng 33:101690
4. Ilcan H, Sahin O, Kul A, Ozcelikci E, Sahmaran M (2023) Rheological property and extrudability performance assessment of construction and demolition waste-based geopolymer mortars with varied testing protocols. Cement Concr Compos 136:104891
5. Ozcelikci E, Kul A, Gunal MF, Ozel BF, Yildirim G, Ashour A, Sahmaran M (2023) A comprehensive study on the compressive strength, durability-related parameters and microstructure of geopolymer mortars based on mixed construction and demolition waste. J Clean Product 136522
6. Ruviaro AS, Silvestro L, Pelisser F, de Azevedo ARG, de Matos PR, Gastaldini ALG (2022) Long-term effect of recycled aggregate on microstructure, mechanical properties, and CO_2 sequestration of rendering mortars. Constr Build Mater 321:126357
7. Kocaer O, Aldemir A (2022) Compressive stress–strain model for the estimation of the flexural capacity of reinforced geopolymer concrete members. Struct Concr 1–20
8. Akduman Ş, Kocaer O, Aldemir A, Şahmaran M, Yıldırım G, Almahmood H, Ashour A (2021) Experimental investigations on the structural behaviour of reinforced geopolymer beams produced from recycled construction materials. J Build Eng 41:102776

9. Aldemir A, Akduman S, Kocaer O, Aktepe R, Sahmaran M, Yildirim G, Ashour A (2022) Shear behaviour of reinforced construction and demolition waste-based geopolymer concrete beams. J Build Eng 47 103861
10. Mir N, Khan SA, Kul A, Sahin O, Ozcelikci E, Sahmaran M, Koc M (2023) Construction and demolition waste-based self-healing geopolymer composites for the built environment: an environmental profile assessment and optimization. Constr Build Mater 369:130520