Circular Economic Modelling—Barriers and Challenges Throughout the Value Circle

Birgitte Holt Andersen, Giovanni Salvetti, and Anastasija Komkova

Abstract The transition from a linear to a circular economy is a process that has already started throughout our societies as one important strategy to reduce CO_2 emissions and by decoupling the use of natural resources, materials and fossil fuels from economic activity. Using examples from the Construction Industry, this paper argues that key premises must be present for circularity to happen. The business case at each level of the value circle must be viable. New building standards backed up by adequate policy measures, e.g. green public procurement, CO_2 and virgin materials taxation is likely to be required. Finally, securing future supply of secondary raw materials (SRM) must be demonstrated and adequate supply chains of SRM to emerge.

Keywords Circular economic modelling · Transition to circular economy · Barriers and opportunities · Secondary raw material (SRM) · Geopolymer cement · Construction materials

1 Background

1.1 Construction Sector

The construction sector as a whole account for 36% of global energy use and 39% of energy related CO_2 emissions [1]. Around a third of the emission derives from the production of concrete, amounting to 5–8% of CO_2 global emissions [2, 3]. Additionally, the sector is the most material resource consuming sector with an

B. H. Andersen (✉) · G. Salvetti
Institute for Applied Economics and Health Research (ApHER), Ewaldsgade 3, 2200 Copenhagen, Denmark
e-mail: bgha@appliedeconomics.dk

A. Komkova
ETH Zurich, Chair of Sustainable Construction, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland

V. M. C. F. Cunha et al. (eds.), *Proceedings of the 3rd RILEM Spring Convention and Conference (RSCC 2020)*, RILEM Bookseries 35,
https://doi.org/10.1007/978-3-030-76543-9_12

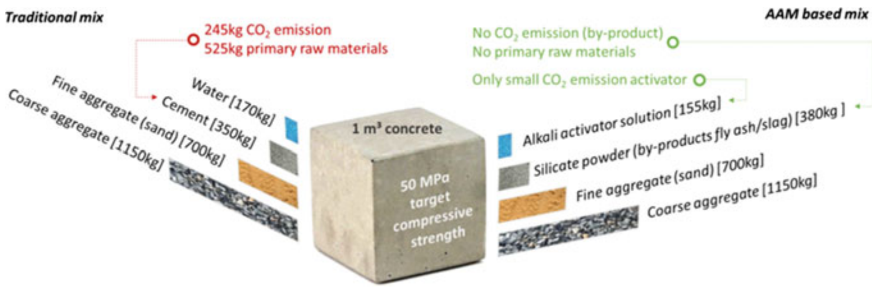

Fig. 1 Content of OPC concrete compared with Geo-polymer concrete. *Source* DurSaam

annual average of about 5.4 billion tonnes of raw materials, almost 4 times higher than the second most resource consuming sector; agriculture and fishing [4].

The most common cement is Ordinary Portland Cement (OPC), which is produced by calcination of limestone, which then is heating up to 1400 °C to produce the clinker [5]. To produce one tonne of OPC results in the emission of 0.82 tonnes CO_2 [6].

On the positive side, the construction sector represents a huge potential for circularity, in particular since many of the virgin materials currently used in building materials can be replaced by a wide range of secondary raw materials (SRMs), ranging from by-products or waste streams of industrial production to the use of recycled end-of-life materials from construction and demolition waste (CDW). Figure 1 shows the ingredients required to produce 1 m^3 of traditional concrete compared with 1 m^3 of a green type of concrete, the so-called geopolymer concrete.

1.2 On-going Research in Circularity Related to Developing Green Cements

The present research will take advantage of three on-going research projects: URBCON,[1] DuRSAAM[2] and WOOL2LOOP[3] as the basis to develop a circular economic model. All three projects aim at developing an alternative to OPC. From an ecological point of view, the geopolymer cement has two distinct advantages to Portland cement: (a) lower energy requirements, (b) it can be produced almost entirely using SRMs, such as mineral wool, mining slags, fly ash, etc. It has been assumed that geopolymer cement has the potential to replace at least 20% of current cement applications, mainly for precast applications, e.g. façade panels, floorings, ceiling elements and other more specialized applications where geo-polymer cement

[1] Interreg NWE project: 'By-products for sustainable concrete in the urban environment', www.nweurope.eu/urbcon.

[2] Marie Curie PhD training network, http://www.dursaam.ugent.be.

[3] Horizon2020 project: Geopolymer technology for the development of mineral wool waste value chains. https://www.wool2loop.eu/en/.

has absolute technical performance advantages compared to OPC. Furthermore, comparing geopolymer cement with OPC the potential reduction of CO_2 emissions range between 26 and 80% [6].

While the focus of the Wool2Loop project is to collect and reuse mineral wool waste (MWW) to produce specific geo-polymer products, the focus of URBCON is to use local waste to produce 'urban concrete', a circularity concept closely associated with relevant policies of the cities involved. Finally, DuRSSAM is a collaborative PhD framework aiming at delivering world-leading training in this multidisciplinary field through 13 PhDs in interrelated aspects of Geopolymer concrete, fibre reinforced high-performance concrete, and textile-reinforced mortar, as well as sustainability assessment.

1.3 The Aim of This Paper

The aim of this paper is to report on progress in developing a circular economic model is to (1) understand the premises for which a transition to a more circular economy within the building material sector can take place by analysing the business case at each step of the value chain from sourcing of SRM; to production of geopolymer cement; design and manufacturing of the building materials; use phase and end of life, (2) identify the main hindrances facing such transition, including technical, legislative, standardisation, market type barriers and user acceptance (3) assess security of future supply of suitable SRMs as competing demands for critical SRMs can be expected in the future, combined with scarcity of some SRMs such as fly ash (due to fewer coal power plants in the future) and blast furnace slags (due to reduced steel production in Europe). The first aim and the third aim will be the primary focus of this paper.

1.4 Approach

The current research includes literature review, data collection including statistics, model developing, interviews with industry and other stakeholders. As the research projects are still on-going, the results presented in this paper are preliminary. The technical work related to the development of the geo-polymer cement is not yet finalised, wherefore the results of LCA and LCCA are also not yet available.

2 Results Related to Circular Economic Modelling

In the following we will present the preliminary findings regarding the premises for which this specific area of the construction industry can turn circular by substituting virgin materials with industrial waste streams resulting also in a considerable reduction in CO_2 emissions. Likewise, the paper presents a first estimation of availability of key secondary raw materials (SRM) critical to secure future supply for production of geopolymer cement.

2.1 The Business Case at Each Step of the Value Circle

The current research has taken a pragmatic approach in assessing and describing the business cases along the value chain in order to understand the premises for which a transition to a circular economy can take place.

Sourcing SRM

The first step of the value circle is sourcing of suitable Secondary Raw Materials (SRMs) for the production of geopolymer cement. Examples of suitable SRMs are depicted in Fig. 2. Each SRM representing a distinct sourcing value chain.

Construction and Demolition Waste (CDW) accounts for more than one third of all waste in Europe, in the order of 850 million tons a year. That means on average each of us produce more than 1½ tons of CDW on a yearly basis [7]. The CDW is usually made up by Minerals (concrete, natural stones, plaster/gypsum, foamed clay bricks, glass, mineral wool); Organic materials (wood, asphalt, various plastics and PVC); and Metals: (iron, steel copper). According to the Waste Framework Directive (2008/98/EC), article 11.2 demands Member States to achieve a minimum of 70% recycling of non-hazardous CDW by weight in 2020. Currently, the recycling of CDW stands at around 50%, with huge variations across the different member states. CDW management protocols has been introduced by the EC as non- binding guidelines to facilitate higher recycling rates. *Pre-demolition audit (PDA) is an activity organized*

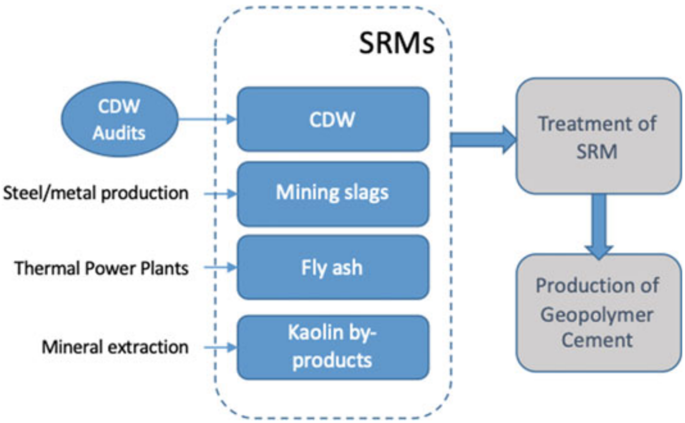

Fig. 2 Examples of waste streams feeding geopolymer cement

by the owner of the building or infrastructure resulting in the inventory of materials and components arising from the future demolition, deconstruction or refurbishment projects, and their management and recovery options. It was originally initiated in order to identify hazardous materials, such as lead, PCB and asbestos, prior to demolition. PDAs are already compulsory in some Member States, such as Belgium, The Netherlands, France, Sweden, Finland, Austria, Bulgaria, and Czech Republic [8].

So, who owns the waste or the CDW? Traditionally, a waste has been seen as a liability and associated with a certain deposit or landfill cost, which typically lies in the range of 100EUR-200EUR per ton. As waste is gradually becoming an asset representing a given value, it is interesting to understand who owns the waste or the SRM. In case of CDW, the building itself is obviously owned by the property owner, but at the moment a contract is signed for demolition it is the demolition company that owns the CDW. Hence, the business case is viable, if you can turn a negative cost (a landfill fee) for a given waste into an income generating material.

Treatment of SRM

The recycling market has emerged over the past decades as a results of increased regulated waste management. Recycled steel, iron, glass, paper, asphalt, aggregates markets are well established. According to EuRIC,[4] the recycling industry consisting of some 5500 companies, generate a turnover of 95BEUR. In the case of 'new' waste streams, such as mineral wool waste or certain type of mining slags, new SRM value chains and new recycling companies are likely to emerge.

In case of mineral wool waste (MWW), certain investments are needed in order to make the waste useful. The main source of MWW is from demolition. At the demolition site, the MWW has to be separated from other types of demolition waste. Due to the low density of the wool, some kind of processing at the demolition site is needed to reduce the volume of the MWW prior to transporting. Before the MWW can be used for geopolymer cement production is has to be grinded into very fine particles. The milling process could be done either by the demolition company as an intermediate supplier or by the final user of the material, e.g. the cement company. The cost of an industrial milling machine with a capacity of 15 tons/hour is 50 K EUR.[5]

The costs of the MWW powder can be added up as follows:

$$\begin{aligned} &\text{Cost price of MWW powder} = \left[\text{Labour Cost of separation}/T\right] \\ &\quad + \left[\text{Transport cost of MWW powder}/T\right] + \left[\text{Milling machine CAPEX}/T\right] \\ &\quad + \left[\text{Milling machine OPEX}/T\right] \end{aligned}$$

If the market price of the MWW is higher than the cost price, or the deposit costs cost of MWW is higher than the Cost price of MWW, the business case is valid.

[4] The European Recycling Industries Confederation.

[5] According to the Wool2Loop project.

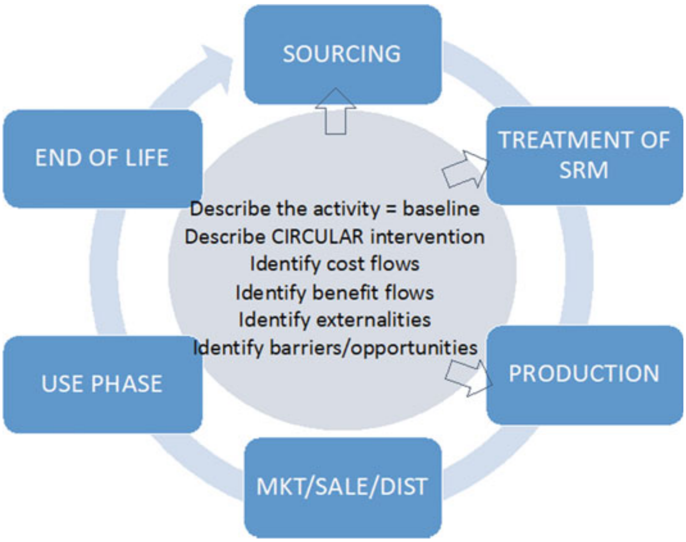

Fig. 3 Conceptual framework to assess the potential for economic circularity

Production of Geopolymer cement

At the level of production of geopolymer cement, at least two scenarios can be considered. The production can either take place at existing production facilities of cement or construction materials. Alternatively, new players can establish themselves to specialise in the production of geopolymer cement. For existing production facilities, only marginal investments will be required to accommodate the use of CRM for the production of geopolymer cement. Additional cost flows for established players concerning the production of geopolymer cement and products based on geopolymer cement, can be grouped as follows: CAPEX and OPEX of production facilities, training of staff for handling and additional health and safety procedures to handle the activator while preparing the geopolymer cement mix. However, the total investment due to using geopolymer cements is not expected to vary considerable compared to other normal alterations in the production flow.[6] This aspect will be further investigated through the pilot phase of both Wool2Loop and URBCON project.

The market perspectives, the use phase and end of life considerations is still ongoing research.

Based on the conceptual circularity model and excel model is under development to capture and analyse all the data and narratives being collected from the various stakeholders in the value circle in order the access the economic viability (Fig. 3).

[6] According to industrial partners in Wool2Loop and URBCON.

2.2 Main Hindrances for Turning Circular

Globally, concrete is the most widely used construction material [9] and demand for sustainable concrete is gradually increasing. However, there are several barriers preventing the transition towards circular economy in the construction sector.

While the technology associated with geopolymer production is evolving and are promising, certain technological barriers remains, but currently examined within the ongoing research projects, (Wool2Loop, URBCON and DuRSAAM). The developing geoploymer technology is associated with lack of long-term data on concrete durability in real world settings [10]. Another barrier for adapting geopolymers at the industrial scale is the absence of relevant regulatory standards for geopolymer concrete.

The main market hindrances are associated with lack of incentives fostering the concrete industry to adapt to sustainable technologies. As the prices of the virgin materials remain relatively low, the concrete producers tend to use conventional materials to remain competitive in the market. On the other hand, the application of the industrial by-products and waste materials in the concrete production can minimise the use of the finite natural resources and create new business opportunities as pressures from various stakeholders increase as public opinion demands actions to reduce CO_2 footprint and deliver against the UN sustainability goals.

However, the perception and reaction to the geopolymer cement representing a green solution to the construction industry remains uncertain and does potentially constitute a main barrier. Key stakeholders include construction companies, architects, construction engineers, certification agencies, but also Public procurement policies are seen as potential driver for public construction investments. Costs, performance, durability, LCA and LCCA will form part of the value proposition.

2.3 Availability of Secondary Raw Materials (SRM)

In order to secure supply of the alternative raw materials it is important to investigate stocks and flows of those materials that can partially or completely substitute virgin raw materials in concrete production. In the context of producing geopolymer cement we have made a preliminary mapping and assessment of order of magnitude availability of key SRMs. These includes Mineral Wool Waste (MWW), Bio Fly Ash (BFA), Ground granulated blast furnace slags, and Kaolin by-products (Fig. 4).

As there is no publicly available data on the volume of mineral wool produced in Europe, the previously developed models suggest that MWW amounts to approximately 2.5 mt in year 2020, based on assumption that MWW constitute 0.2% of the total CDW generated in Europe [11]. Due to the increase in the use of insulation over the last decades, the availability of MWW is expected to reach 4mt in year 2040 and assuming shorter building refurbishment trends, it can rise up to 10 mt.[7]

[7] Based on internal communication within Wool2Loop project.

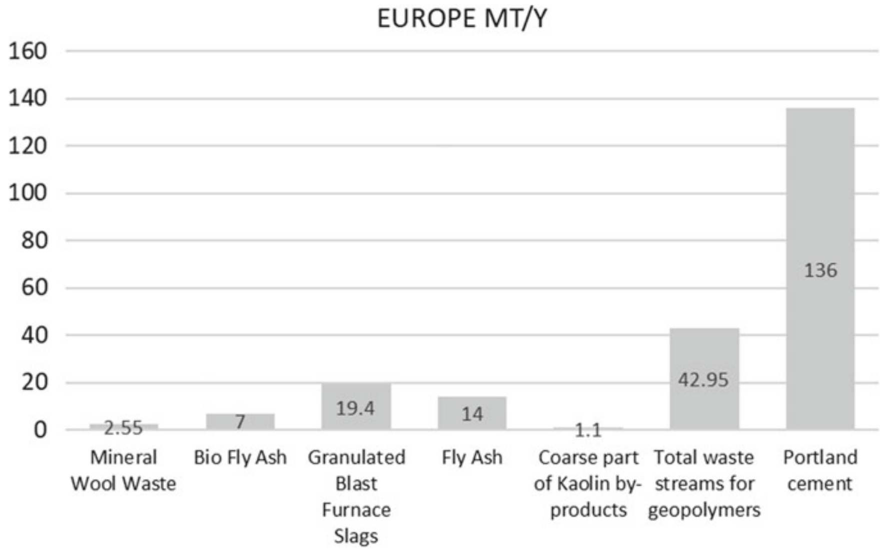

Fig. 4 Waste streams available for geopolymer binders

Fly ash is produced during coal combustion at thermal plants, and the European production of fly ash was approximately 35 mt in 2008, with 13.6 mt was used in concrete production [12]. It has been estimated that 1 ton of fly ash can produce approximately 3 m^3 geopolymer concrete [13]. In the future, however, fly ash from coal fired power plants will decrease as coal will be out phased as EU are shifting towards greener energy sources. Instead fly ash from bio-based thermal power plants will increase. The stockpiled fly ash can be used as alternative reserves, where stock size should be estimated.

The calcined natural clays such as metakaolin are often used in geopolymer concrete production as a precursor, however the coarse kaolin by-products available at a rate of 1.1 mt can be used as an alternative precursor.[8]

Blast furnace slag is a by-product of steel industry. In Europe, the total production of blast furnace slag was 24.6 mt in year 2016, with granulated blast furnace slag was approximately 78.9% or 19.4 mt [14]. Approximately 60% of blast furnace slag has been applied in cement production/concrete addition and about 24% for road construction [15].

Within the concrete production process, the above-mentioned industrial by-products and waste materials are activated with alkaline solutions. Activators, such as sodium silicate, potassium silicate, sodium hydroxide and potassium hydroxide, typically used in geopolymer concrete production have a high carbon footprint as manufacturing processes of these chemicals are energy demanding. Activators therefore account for the major part of environmental impact of geopolymer concrete [16]. In geopolymer mixtures, the inorganic activators can be partially substituted

[8] According to industrial partners in Urbcon project.

with waste materials. For example, rice husk ash, which is a by-product from the rice industry, can be used to minimize sodium silicate content in the geopolymer concrete [17]. The alternative materials include urban and industrial glass waste that can be used as an alkaline activator for blast furnace slag [18].

The main learnings from this preliminary exercise is that in the order of 43 tons of suitable SRM are available to produce geopolymer cement on a yearly basis, more than enough to replace up to 20% of the current OPC applications.

3 Conclusions

According to the statistics there is still a long way to a full circularity circle within the construction industry. Ideally, full material circularity is reached when only recycled materials are used. In principle all LCAs will be zero in a perfect circular economy.

The good news is that there exist technological and economic potential in using the SRMs in geopolymer cement production and that the future supply of relevant SRMs are plentiful. There exist opportunities to create a business case for geopolymer cement and we have identified potential stakeholders that can benefit from the emerging markets.

3.1 Future Research

- Complete data collection and assessment of costs flows and benefit flows to document the business case at each stage of the value circle
- Further stakeholder interactions to understand willingness to change and acceptance of new building standards
- Further literature reviews into the subject of pricing of SRMs
- The economic aspects of the activators

Acknowledgements Thanks to the projects Wool2Loop and URBCON and all partners in contributing with knowledge, insights as well as hard and soft data.

References

1. UN: Global Status Report, 2017. https://www.worldgbc.org/news-media/global-status-report-2017. Last accessed 2019/12/20
2. Lehne J, Preston F (2018) Making Concrete Change. Innovation in Low-Carbon Cement and Concrete. The Royal Institute of International Affairs (UK), Chatham House
3. Habert, G., Ouellet-Plamondon, G.: Recent update on the environmental impact of geopolymers. RILEM Techn. Lett. **1** (2016)

4. BIO Intelligence Service: Sectoral resource maps. European Commission, Prepared in response to an Information Hub request (2013)
5. Gartner, E.: Industrially interesting approaches to “low-CO_2” cements. Cem. Concr. Res. **34**(9), 1489–1498 (2004)
6. Turner, L.K., Collins, F.G.: Carbon dioxide equivalent (CO_2-e) emissions: a comparison between geopolymer and OPC cement concrete. Constr. Build. Mater. **43**, 125–130 (2013)
7. Eurostat: Waste Generation (2016). https://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics. Last accessed 2019/12/19
8. European Commission: EU Construction and Demolition Waste Protocol and Guidelines. https://ec.europa.eu/growth/content/eu-construction-and-demolition-waste-protocol-0_en. Last accessed 2019/12/20
9. Meyer, C.: The greening of the concrete industry. Cement Concr. Compos. **31**(8), 601–605 (2009)
10. Duxson, P., Van Deventer, J.S.J.: 17—Commercialization of geopolymers for construction—opportunities and obstacles. In: Provis, J.L., van Deventer, J.S.J. (eds.) Geopolymers. Woodhead Publishing, pp 379–400 (2009)
11. Väntsi, O., Kärki, T.: Mineral wool waste in Europe: a review of mineral wool waste quantity, quality, and current recycling methods. J. Mater. Cycles Waste Manage. **16**(1), 62–72 (2014)
12. Feuerborn, H.-J.: Coal combustion products in Europe–an update on production and utilization, standardisation and regulation. In: World Coal Ash Conference (2011)
13. Lloyd, N., Rangan, V.: Geopolymer concrete with fly ash. In: Proceedings of the Second International Conference on Sustainable Construction Materials and Technologies, UWM Center for By-Products Utilization (2010)
14. EUROSLAG: Statistics 2016—Euroslag. https://www.euroslag.com/products/statistics/statistics-2016/. Last accessed 2019/12/06
15. Coppola, L., Buoso, A., Coffetti, D., Kara, P., Lorenzi, S.: Electric arc furnace granulated slag for sustainable concrete. Constr. Build. Mater. **123**, 115–119 (2016)
16. Habert, G., De. Lacaillerie, J.D.E., Roussel, N.: An environmental evaluation of geopolymer based concrete production: reviewing current research trends. J. Clean. Prod. **19**(11), 1229–1238 (2011)
17. Kamseu, E., Moungam, L.M., Cannio, M., Bilong, N., Chaysuwan, D., Melo, U.C., Leonelli, C.: Substitution of sodium silicate with rice husk ash-NaOH solution in metakaolin based geopolymer cement concerning reduction in global warming. J. Clean. Prod. **142**, 3050–3060 (2017)
18. Puertas, F.,Torres-Carrasco, M.: Use of glass waste as an activator in the preparation of alkali-activated slag. Mechanical strength and paste characterisation. Cem. Concr. Res. 57:95–104 (2014)