Recycling of concrete construction and demolition waste in alternative binders: Part 2 – Environmental footprint

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Abstract. The concrete demolition and construction waste (CDW) is usually recycled as aggregate. The fine fraction (crushed sand and powder) obtained from the recycling process remains less recovered – for downcycling purposes such as backfilling, if recovered at all. The feasibility study on the recycling of concrete waste as a component of a blended binder is presented in Part 1 of the study. Part 2 is dedicated to a preliminary assessment of the environmental impacts of the partial replacement of Portland cement binder by a waste concrete powder (WCP). The assessment is focused on the binder production stage as per BDS EN 15804 and does not consider any further scenarios. The environmental impacts of alternative binders with a different amount of WCP is compared to the impacts of conventional cement types CEM I, CEM II/A and CEM II/B. The results confirm that there is a significant reduction of the environmental impacts when WCP is used for cement replacement, because of the more efficient use of material resources and energy. The effect is more pronounced with the higher replacement rate. Therefore, the use of WCP in cements leads to more eco-friendly binders and can contribute to closing the concrete loop.

1. Introduction
Waste recycling and recovery is one of the main directions for achieving the sustainable goals and circular economy in EU. Construction and demolition waste (CDW) forms 25% to 30% of all generated waste in EU [1] and is estimated as the largest waste stream in the EU. CDW includes various materials that differ in type, composition, treatment needs and recovery options. The significance of CDW management is reflected in the European policies by the Waste Framework Directive [2], the EU Construction & Demolition Waste Management Protocol [3], Strategy for the Sustainability of construction sector [4], Circular Economy Action Plan [5], etc.

From environmental point of view, the recovery of demolition waste is considered a way to recapture the resources that are used originally for the manufacturing of building products. In this situation, both energy and resource efficiency can be achieved and, with advancing of technologies for reclaiming raw materials from CDW, the regulatory requirements by the EU legislation are becoming stringent and mandatory. The Waste Framework Directive [2] requires that by 2020 a minimum of 70% (by weight) of non-hazardous CDW (excluding excavated soil) must be prepared for re-use, must
be recycled or must undergo other material recovery. This requirement was transposed into Bulgarian legislation by the Waste Management Act (WMA) in 2012 [6].

When aiming at the high recovery degree, the technical and economic feasibility of treatment solutions is usually considered, but the decisions have to be taken after assessing the environmental impact of the various solutions.

The present part of the study (Part 2) is dedicated to a preliminary assessment of the environmental impacts of the partial replacement of Portland cement binder by a waste concrete powder (WCP). It is interesting to explore the recovery of concrete CDW not only in terms of reducing the waste for disposal (i.e. closing the loop for concrete), but also from the perspective of the potential positive effects on the environment from using construction materials with recycled concrete content.

2. Specifics of CDW from concrete
The demolished concrete waste is one of the main CDW streams – for Bulgaria its share is estimated to be around one quarter to one third [7] of the overall amount of CDW. According to WMA [6], at least 85% of concrete CDW shall be recovered. This percentage is calculated as quantity diverted from landfilling and treated for recovery purposes.

Preparation to reuse, recycling and backfilling are recognised by the legislation. However, due to undeveloped market for recycled construction products in Bulgaria, lack of appropriate legislation and lack of awareness, only a few options from the vast recovery possibilities are explored – recycling as crushed stone for road construction purposes (base, sub-base and drainage) and backfilling. Some additional barriers for higher recycling rate of concrete CDW are related to the availability and affordability of good quality natural aggregates and low taxes for landfilling of inert CDW (less than 2.00 EUR per ton of waste), which makes the selective demolition and at source separation of the mineral fraction of CDW not economically attractive. Many illegal or not regulated landfills still exist.

Even when recycled into aggregate, a large part from concrete CDW remains as a fine fraction (sand and filler), for which there is no market interest and this fraction is usually used for backfilling (downcycling). The purpose of our research study is to identify more valuable applications of that fraction, in accordance with the requirements of waste management hierarchy and circular economy principles. The technical feasibility study on recycling concrete waste as a component of a blended binder is presented in Part 1 of the research study. The interest in this approach arises also from the possibility to reduce the environmental footprint of concrete by using a blended binder with a smaller amount of Portland cement. So, there are opportunities for improving both energy and resource efficiency associated with the manufacturing of construction products with recycled contents. This paper explores whether and to what extents these expectations are justified by developing a preliminary theoretical assessment of some environmental indicators of alternative binders with varying content of waste concrete powder (WCP)

3. Methodology for environmental assessment
The effect of substitution of CEM I by WCP on environmental impacts is evaluated by comparing the results on predefined environmental indicators of a set of binders – CEM I, CEM II/A and CEM II/B where the amount of mineral additives is respectively up to 20 and up to 35% (very often these mineral additives are active and come from industrial waste such as fly ashes, ground granulated blast furnace slag (GGBFS) and silica fume) and 3 types of so-called alternative binder (AB), which are a blend of CEM I and various amount of WCP (5%, 15% and 30%). The substitution percentage is justified in Part 1 of the present study. Thus, the assessment includes the most used “competitors” of the WCP-blended binders – CEM II/A and CEM II/B which also have some recycled content and the amount of clinker is reduced by the same order as in the ABs.

For providing a reliable calculation of the environmental impacts of alternative binders with varying WCP content and ensuring an unbiased comparison by outlining the key environmental indicators that are influenced from the substitution of conventional cement binder by WCP, a life cycle assessment (LCA) approach in accordance with ISO 14040 [12] and ISO 14044 [13] is used to model a preliminary product system for the alternative binders. EN 15804+A1:2012 [14] serves as a basis for
development of the model and the calculations. Considering the production processes of the binders do not differ in general, the following assumptions are made:

- transport distances and the means of transport for cement raw materials, additives (limestone, GGBFS, burnt shale and WCP) are similar;
- the additives and WCP are delivered in bulk, the ready binder product is also delivered in bulk (packaging is not necessary);
- the grinding of clinker and mineral additives to the suitable fineness requires the same machinery and energy per unit mass.

3.1. Definition of the LCA goal and scope

The goal of this study is to outline some important aspects of the composition of binders that can significantly influence the environmental performance of the product. The results from this preliminary assessment are intended to be included in a more comprehensive research on the feasibility of alternative binders with recycled CDW and to justify the ecological benefits from substitution of cement binder.

The assessment is focused on the production stage (“cradle-to-gate”) and does not take into account any further scenarios that can release environmental impacts during the next stages of the life cycle according to EN 15804 (installation, use and end-of-life).

3.2. Life cycle inventory analysis

3.2.1. Functional unit

Binders for concrete are sold and used in construction by mass measurements – tons. Thus, the results are calculated for the functional unit of 1 kg binder.

3.2.2. Collection of data

Usually in practice the collection of information about the manufacturing process of a specific product is done within the context of the factory. In this case, the study is analytical and is based on referent data from the ecoinvent v.3.4 database. Certain datasets describing the production of cement type CEM I are modified in order to model the substitution of the cement with WCP. Table 1 summarises the set of the studied binders.

| Binder designation | Mineral additives, % | Type of mineral additives | Recycled content |
|--------------------|----------------------|---------------------------|------------------|
| CEM I              | < 5%                 | None                      | None             |
| CEM II/A           | < 20%                | Limestone, Burnt shale, GGBFS | 0.2% Burnt shale, 1.0% GGBFS |
| CEM II/B           | 20–35%               | Limestone, Burnt shale, GGBFS | 0.4% Burnt shale, 2.1% GGBFS |
| WCP-5              | 5%                   | WCP                       | 5%               |
| WCP-15             | 15%                  | WCP                       | 15%              |
| WCP-30             | 30%                  | WCP                       | 30%              |

Based on the referent data, the following varieties of conventional binders are considered: CEM I is a cement with more than 90% clinker by mass; CEM II/A and CEM II/B are limestone Portland cements (the mineral additive is mainly a limestone filler) with recycled content of GGBFS. The clinker content in CEM II/A is 83% by mass, the clinker content of CEM II/B is 68%. It is assumed
that the binders cover the requirements of the same strength class and can be used for the same purpose.

3.3. Life cycle impact assessment

3.3.1. Characterisation Model and Impact Categories (Indicators)
For this preliminary assessment, the EN 15804 list of indicators is reduced to the aspects that are considered most relevant for the development of alternative binders. This includes all environmental indicators, consumption of energy and water and disposed waste (table 2).

Table 2. Assessed environmental indicators.

| Indicator                                                                 | Unit               |
|---------------------------------------------------------------------------|--------------------|
| **Environmental impacts**                                                 |                    |
| Global Warming potential (GWP)                                            | kg CO$_2$-eq.      |
| Ozone depletion potential (ODP)                                           | kg CFC-11-eq.      |
| Depletion of abiotic resources-elements (ADPE)                            | kg Sb-eq.          |
| Depletion of abiotic resources-fossil fuels (ADPF)                        | MJ                 |
| Acidification potential (AP)                                              | kg SO$_2$-eq.      |
| Eutrophication potential (EP)                                             | kg PO$_4$-eq.      |
| Photochemical ozone creation potential (POCP)                             | kg ethylene-eq.    |
| **Use of resources**                                                      |                    |
| Use of non-renewable energy resources                                      | MJ-eq.             |
| Use of fresh water                                                        | m$^3$              |
| Use of secondary materials                                                | kg                 |
| **Generated waste**                                                       |                    |
| Non-hazardous waste disposed                                              | kg                 |
| Hazardous waste disposed                                                  | kg                 |

3.3.2. Calculation
The results are calculated with the openLCA software. The ecoinvent v.3.4 database is used to build the model. CML method and characterisation factors [15] are applied for calculation of the assessed indicators.

4. Results and discussion
The addition of WCP is expected to reduce the environmental impacts of ABs, compared to CEM I and result confirm this assumption. The reductions per binder type are presented in table 3.

Table 3. Summarised reductions of the environmental impacts.

| Product  | Reduction of impacts compared to CEM I, % |
|----------|-------------------------------------------|
| CEM I    | 0%                                        |
| CEM II/A | 5-10%                                     |
| CEM II/B | 15-20%                                    |
| WCP-5    | 5-15%                                     |
| WCP-15   | 15-20%                                    |
| WCP-30   | 30-35%                                    |
It shall be noted that the environmental impacts of both CEM II types are also lower. The reduction of their environmental impact logically depends on the amount of the mineral additives and is more pronounced for CEM II/B than for CEM II/A. This is mainly due to the use of limestone (10% in CEM II/A and 22% in CEM II/B) rather than to the use of recycled industrial waste – the clinker production process is very energy intensive, so bigger decrease of clinker amount in binders results in higher reduction of the environmental impacts, associated to the use of fuels – figure 1 to figure 7. However, the replacement of clinker by WCP leads to a bigger positive effect than the replacement by limestone and industrial waste – compared to CEM I, the WCP-30 has up to 35% smaller values of certain environmental indicators, while for CEM II/B the reduction does not exceed 20% (table 3).

**Figure 1.** Global warming potential (GWP) of the binders under study.

**Figure 2.** Depletion of abiotic resources-elements (ADPE) of the binders under study.

**Figure 3.** Acidification potential (AP) of the binders under study.

**Figure 4.** Ozone depletion potential (ODP) of the binders under study.

**Figure 5.** Depletion of abiotic resources-fossil fuels (ADPF) of the binders.

**Figure 6.** Eutrophication potential (EP) of the binders under study.
Figure 7. Photochemical ozone creation potential (POCP) of the binders under study.

Figure 8. Use of non-renewable energy resources.

The environmental impacts of WCP5, where the WCP is only 5%, are comparable to CEM II/A with a higher clinker replacement degree (up to 20%) and the results of WCP15 (WCP of 15%) are systematically lower than those of CEM II/A. The studied environmental impacts of WCP15 are comparable to those of CEM II/B, while the clinker replacement in WCP15 is twice smaller. WCP30 is superior to CEM II/B by having the smallest values of the environmental indicators, except for the depletion of abiotic resources-elements (ADPE).

The results for the indicators about resource use (figure 8 to figure 10) mostly reflect the same trend except for the use of secondary materials. Use of energy depends on the energy for the acquisition and processing of raw materials, so binders with less clinker content use less total energy for production. The same applies to the water use, related mainly to the processing of raw materials and the energy consumption for clinker production.

Figure 9. Use of fresh water.

Figure 10. Use of secondary materials.

The use of secondary materials makes the biggest difference of the ABs, because it depends on the recycled material content as a substitute of the primary constituents. In CEM II the amounts of GGBFS are minor and it does not differ much from CEM I, while in the blended binders the share of recycled material from WCP is considerable.

It is also interesting to pay attention to the waste generated form the production of binders although the quantities are very small. In case that concrete CDW is not recovered for backfilling purposes but landfilled, the recycling of that waste into WCP is a possible way for significant reduction in the indicator for non-hazardous waste disposed. The non-hazardous waste (figure 11) generated from the production of CEM I and CEM II is similar in magnitude, though the absolute values decrease from CEM I to CEM II/A and CEM II/B, due to the use of recycled materials from industrial waste. The values of non-hazardous waste for ABs are negative, which indicates that more waste is recovered than generated, which is positive for the environment. The higher the contents of WCP, the more waste is diverted from disposal to recovery.
The result on hazardous waste generation (figure 12) is linked mostly to the production of clinker (contribution of more than 90%). Figure 12 shows the expected result that decreasing the quantity of clinker by substitution with WCP leads to reduced hazardous waste. However, the production of clinker is a complex process regarding the waste aspects. One source of hazardous waste is the high demand for energy and fuels for acquisition, transport and processing of raw materials (lime, clay, marl). On the other hand, the cement factories in Bulgaria are permitted to implement recovery operation R1 (Use principally as a fuel or other means to generate energy) in accordance with the WMA [6], so part of the fuels used for clinker production might be RDF including hazardous waste from petrol products. Another interesting aspect is that cement binder can be used for treatment before disposal of hazardous waste by stabilization/solidification process through chemical interactions, physical absorption or encapsulation of contaminated waste [16]. In the case of WCP use, further investigations on the permeability of ABs are necessary in order to assess the possibility to use the ABs for such treatment.

5. Conclusion
The recycling of concrete CDW into powder for being used in blended binders seems to be a prominent perspective from technical and environmental point of view. The recycled concrete powder can be considered as mineral additive to cement, having intermediate properties between the hydraulic additives such as GGBFS and burnt shale and inert additives such as limestone filler. Taking into consideration that the amounts of industrial waste as GGBFS are decreasing (many metallurgical factories have been closed, including the biggest ones in Bulgaria), the alternatives for clinker replacement in cement production are also decreasing. Moreover, some other common additives such as fly ashes will also disappear when the coal thermal power plant are closed. Depending on the degree of clinker substitution by WCP, different effects can be achieved: when modest compressive strength of the binder is required (for example class 32,5 or lower) and no specific requirements related to the use of concrete based on alternative binders exist, the incorporation of up to 30% WCP can be applied and this leads to a significant decrease of the environmental footprint of the concrete. If a smaller amount (5 to 15%) of WCP is used, because of technical reasons, the replacement still has a noticeable positive environmental effect, similar to that of CEM II.

However, further research on the alternative binders has to be performed on both technical aspects and environmental footprint. The specific features of alternative binders such as concrete CDW recycling technology, way of mixing the binders constituents (clinker, WCP, gypsum), etc. are to be modelled and the environmental effects are to be evaluated. The scope of LCA might also be extended by precisely considering the source of concrete CDW, transportation activities, work of machinery used for CDW fractioning and WCP grinding. Since end-of-life aspects are important for assessing the re-use and recycling options of building materials, the multiple recycling of WCP can also be investigated.

Figure 11. Non-hazardous waste disposed.
Figure 12. Hazardous waste disposed.
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