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Beneficial use of recycled aggregates from concrete sludge using a new dry washing technology

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Abstract. Demands for a more sustainable concrete production with reduced waste streams and lower carbon footprint has introduced new solutions that transform waste streams into recyclable raw materials and bring them back into the value chain. Here, recycled aggregates with carbonation potential from a dry-washing technology for concrete trucks are considered to reduce concrete waste. Accordingly, the environmental impacts of a dry-washing method in ready-mix concrete production were investigated through a scenario-based attributional life cycle assessment (LCA) approach. The environmental impacts are calculated by a cradle-to-gate LCA modelling in SimaPro® based on onsite interviews in Norway, existing environmental product declarations (EPD), and geography-specific life cycle inventory data. Also, the properties of the reclaimed aggregates have been tested to ensure their mechanical strength for use in fresh concrete. LCA showed that the dry-washing method reduces environmental impact compared to the conventional handling of concrete sludge. The technology reduces the concrete sludge by > 80% thereby reducing the treatment of washing water. Using recycled aggregates decreases the extraction of virgin aggregates. The study contributes to circularity in the production design of concrete by controlling the material and waste flow in the life cycle of concrete.

1. Introduction

Concrete is the second most used material in the world, after water. It is also a known fact that cement production stands for 6-8% of the global CO_2 emission [1]. In the strive for a more sustainable way to produce concrete with reduced waste streams and lower carbon footprint per unit of concrete, new solutions and methods have been introduced in recent years with the aim to transform waste streams into reclaimed and recyclable raw materials and promote the re-introduction of those materials back into the value chain [2]. A constant focus has been put on recycling of concrete and masonry in construction and demolition waste (C&D waste) over the past 25 years [3, 4]. This is also emphasized at European level in the revised EU Waste Framework Directive, for which a 70 % target for recovery of C&D waste was included in 2011 [5].

In comparison, insignificant efforts have been made for recycling of the returned concrete and in particular for concrete sludge from concrete production. Returned concrete and equipment washout slurry (concrete sludge) can be handled by several different solutions. They vary in complexity and practicality as compiled in Adomako et al. (2023) [6]. The waste by nature appears in fresh condition with a significant amount of cement mortar [7, 8]. In 2015 it is estimated that over 125-250 million tonnes of these wastes are generated each year globally (0.5-1.0% of annual production) depending on quality control during production and use in construction [9]. A summary of management strategies to process the waste has been outlined as (a) Recycling in new downgraded products by a process of delivering fresh concrete for pre-cast concrete products or use in backfilling. (b) Reuse in new batches of concrete mixture with or without chemical admixtures or additives. (c) Recycling after hardening of fresh concrete waste by crushing into recycled concrete aggregates (RCA). (d) Reclaiming by a wash-out process using mechanical aggregate reclaiming system to reclaim aggregates and grey water [10]. The outlined management strategies for treatment vary in different countries and are also linked to economic, environmental and logistics issues [10-12].

The United States Environmental Protection Agency published a best management practice report on the subject [13]. Common for these methods are the significant amounts of water use. Since concrete is alkaline (pH approximately 12-13) due to the presence of $Ca(OH)_2$ and alkali hydroxides, water used for washing of concrete truck mixers and other equipment will be high in pH. Any wash water must therefore be processed before being emitted back into nature or public waterways. One of the most used methods today is the type described by Maksimychev et al. [14] where returned concrete is discharged into the feed hopper of the screw reclaimer. The coarse aggregates and sand are separated from cement paste by washing with water. Although the aggregates are reclaimed 100 %, the fine solids end up as concrete sludge and need to be handled and further treated. Very often it is dewatered and landfilled.

In this study, recycled aggregates have been made from returned concrete and concrete sludge using a newly developed dry-washing technology for concrete trucks. It reduces concrete waste and creates aggregates that have the ability to bind CO_2 by carbonation which is environmentally beneficial. Furthermore, it reduces the water needed for equipment washing up to 80% which is of significant importance because of environmental requirements for the water discharged from concrete plant to the recipient. In Norway a new pollution regulation came into force January 2023 [15] with specific concentration limits for a number of chemical substances and pH in the discharged water. The dry-washing technology is beneficial to complying with these criteria as it reduces the process water consumption significantly.

Furthermore, the quantity of CO_2 absorbed by carbonation was determined in laboratory for the recycled aggregates in the current study. The laboratory experiments were based on the CO_2 absorption method explained in earlier studies [1, 5, 16]. The CO_2 amount was further used in the LCA calculations that form the basis for the development of the EPD for commercial concrete grades.

2. Materials and Methods

2.1. The Re-Con zero EVO process used in production of dry washing aggregates (DWA)

In 2014 Ferrari et al., [8], presented a new method for reclaiming fresh returned concrete. The main innovation was to not use any water at all in the transformation process. Instead, a powder system consisting of water absorbing and setting accelerating chemical compounds were mixed into fresh returned concrete with the aim to transform it into a gravel-like material. The system (Re-Con Zero EVO) consists of 2 components: Part A and B, both in powder form. Part A is a superabsorbent polyacrylamide that can absorb about 500 times its own weight in water. When adding Re-Con Zero EVO to returned concrete, cement and ultrafine particles are flocculated by the polyacrylamide. As a result, the paste increases rapidly in viscosity and the concrete loses its workability. By maintaining a mixing motion either by rotation in the concrete mixer truck or by stirring the concrete with a wheel loader or excavator shovel, agglomerates are formed, see Figure 1. These agglomerates can either be made up by just fines particles or a mix of core stone particles from the different size fractions in the original mix. When the returned concrete has a high water/cement ratio, low cement content or when the temperature is low, the process can be helped by adding the part B powder product. This component is an aluminate-based setting accelerator that promotes ettringite formation and thus increases the water consumption of the solids part forming agglomerates. Hence, Re-Con Zero EVO contribute to easily convert retuned concrete into agglomerating aggregates that can be used in the dry washing cycles (see next section). Used in this application, it can be called Dry Washing Aggregates (DWA).

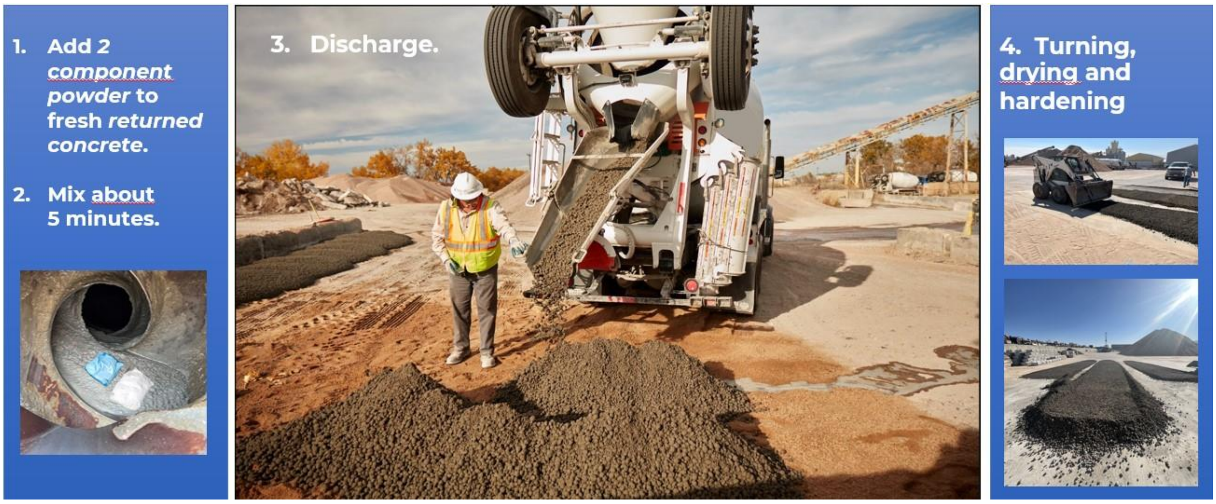

Figure 1. Preparation of DWA by adding Re-Con Zero EVO powder in the concrete mixer drum with returned concrete.

2.2. *Dry-washing procedure*

DWA was used to clean concrete trucks without returned concrete but with the inside of the drum covered with cementitious paste. Normally, these trucks are washed out with water at the end of a working day and the waste as material goes to either sedimentation in pools or to thickening and filter press treatment into cakes that are sent to landfill as waste. Instead of being washed out as waste, the cementitious fines were absorbed by and bonded onto the DWA that were fed into the concrete truck mixer drum, see Figure 2. By feeding 2-3 tonnes of the DWA into the empty dirty trucks, the initial tests showed a 70-80% absorption of the finer particles (< 200 µm). Each additional dry washing cycle leads to accumulation of cementitious paste in the DWA. This also increases the potential for CO_2 absorption by carbonation. In the present study, the CO_2 absorption potential was determined in laboratory after 8 dry wash cycles. The number of cycles the DWA can be used to dry wash at concrete plants depends on local conditions but are generally between 10-20.

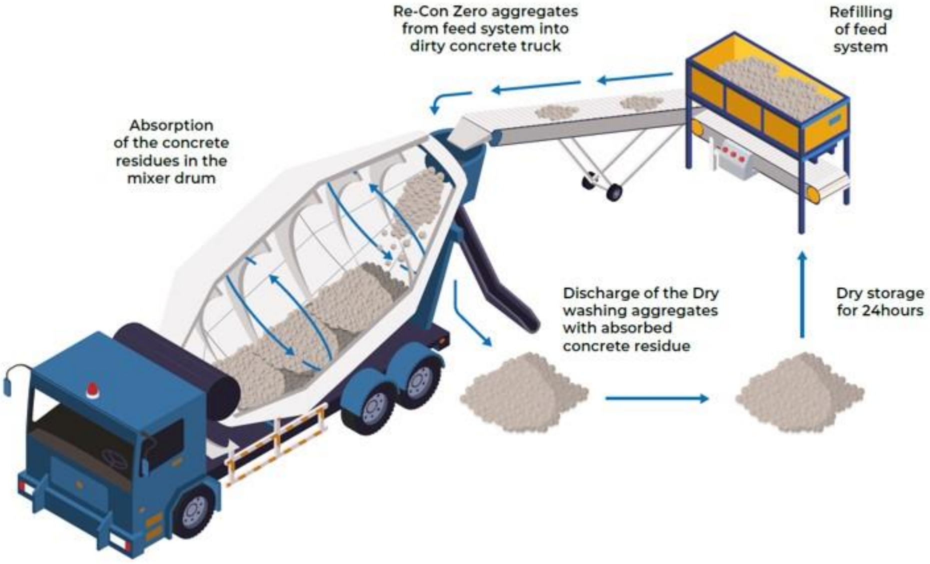

Figure 2. Illustration of the dry washing process with DWA.

2.3. *Carbon-uptake by carbonation*

Carbonation of concrete is a well-known aging process in concrete, as thermodynamic stable $CaCO_3$ is formed when air or water-borne CO_2 dissolves in the concrete pore water, it can be regarded as a natural process in time [17]. Furthermore, when the carbonation layer is formed during service life, the carbonate species need to penetrate through the denser carbonated layer and thus deeper and deeper into the concrete and the carbonation rate slows down with the square root of time (roughly described). The overall reaction can simply be described by:

$$Ca(OH)_{2\ (aq)} + CO_{2\ (aq)} \Rightarrow CaCO_{3\ (s)} + 2\ H_2O_{\ (l)}$$

In the current study DWA for CO_2 absorption measurements were produced in a laboratory concrete mixer according to a procedure described in [18]. The concrete sludge was prepared in laboratory by mixing water, cement and sand. After 8 dry wash cycles, the CO_2 absorption was determined for the recycled aggregates. The recycled aggregates were placed in special designed chambers that were determining the consumption of CO_2 due to carbonation. The temperature, moisture and CO_2 concentration were controlled throughout the exposure. In this method, the exact amount of CO_2 bound by carbonation was determined. Accelerated conditions around 5000 ppm CO_2 were used in the current study.

The CO_2 exposure tests with Re-Con Zero aggregates and recycled aggregates showed an increase in CO_2-uptake after 8 dry washing cycles. After 50 days of exposure the measured CO_2-uptake was 30 kg/tonne for Re-Con Zero aggregates (after the first transformation from returned concrete) and 37 kg/tonne for DWA (Re-Con Zero aggregates being submitted to eight dry washing cycles). This CO_2-uptake potential has been used as a basis for further calculations.

2.4. *Environmental assessment*

LCA has been developed as a tool for assessing environmental aspects of different construction works and construction products during their lifetime. The concept of LCA can be understood as stated by Baumann and Tillman [19]; *"It means that a product is followed from its 'cradle' where raw materials* *are extracted from natural resources through production and use to its 'grave', the disposal".* LCA addresses the environmental aspects and potential impacts in this context and the general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences [20]. At both International and European levels, standards have set a framework for the assessment of environmental, economic, and social aspects, the three sustainability pillars, for both buildings and civil engineering works, and for construction products using Environmental Product Declarations (EPD), which provide standardised environmental information about the impact of making, using, and disposing of products. For making whole life carbon assessment (WLCA) for buildings, EPDs are used to serve the environmental data about construction products. EPD is videly used for assessing the environmental footprint of concrete products [21]. The European EN 15804 standard [22] and the Internatinal ISO 21930 [23] give the requirement to be followed for EPD development. Using the rules of EN 15804 or ISO 21930, European and International Standards are developed to provide complementary PCR (product category rules) for specific product types, for example EN 16757:2022 [24] for concrete and concrete elements. This standard allows for including CO_2 uptake by carbonation.

Reviewing more than 200 EPDs (from epd-norge.no, and ibu-epd.com) for RMC products indicated that no EPD has included washing water for trucks (and landfilling of sludge and transport to landfill) in the concrete production process. Almost all EPDs have considered the life cycle stages A1-A4 (production stages and transport to construction site), and only the water usage in the concrete production process is directly mentioned. It is not clear if washing water is considered in the water usage or not. It means that in EPD results the indicator of "use of fresh water" is underestimated.

The EPD review also indicated that carbonation has not been included, even though the EN 16757:2022 allows for and gives calculation rules for including CO_2 uptake. It means that among more than 200 EPDs, only two reports (e.g., NEPD-3694-2639-SE) have included carbonation. In addition, reviewing LCA study [25-41] indicated that carbonation potential is still rarely included in various LCA stages (building life cycle and beyond life cycle). In the LCA studies carbonation is mostly calculated based on Fick's 1st Law of Diffusion [27], or other mathematical [33, 42] and numerical approximation [37]. Failure to consider carbonation in EPD and LCA studies of RMC despite the existence of the required equation and calculation methods could be that carbonation is depending on use conditions (e.g. exposure type and degree) and RMC manufacturers often do not know the intended use.

To indicate the influence of the dry washing process and carbonation on the environmental impact of concrete production, an EPD was conducted following the guidelines outlined in EN 15804 and its cPCR for concrete and concrete elements [EN 16757:2022]. Accordingly, the global warming potential of the concrete production process after 100 years in the normal process (reference mixture from EPD, C35/C45) was compared with that in concrete manufactured by replacing fine and coarse aggregates in the reference mixture with recycled aggregates from the dry washing process. It is worth noting that the binding potential of concrete after 100 years is also considered in calculations. This comparative analysis was carried out through a case study conducted at a production unit within the Velde company in Norway.

Regarding the concrete information in the reference case, EPD for C35/45 ready mixed concrete (RMC) from Velde company, as published by the EPD program operator EPD Norge (NEPD-2508-1250), was utilized. The level of Global Warming Potential (GWP) in this EPD is at the average level compared to other EPDs for C35/45 concrete produced by other companies, see Figure 3.

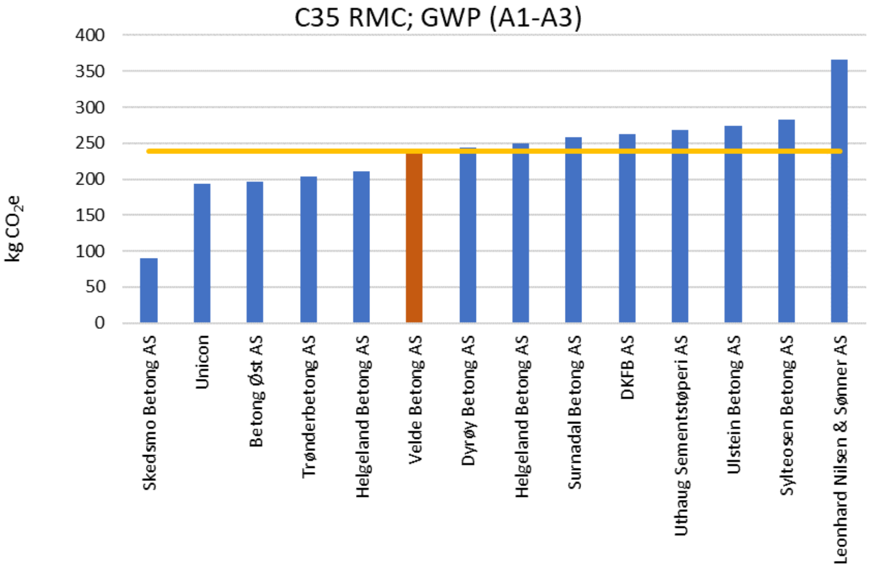

Figure 3. Greenhouse gas emissions given as CO_2e/m^3 for A1-A3 for different RMC manufacturers EPD.

In accordance with this EPD, the system boundaries for the production of 1 m^3 of concrete, considering the specified mixtures (cement 15.82%, aggregates 76.89%, water 7.12%, chemicals 0.17%), encompass the A1-A4 life cycle stages. The functional unit was established as 1 m^3 of concrete, with the exclusion of the use, maintenance, and final disposal stages to focus solely on the production process. Allocation is carried out in compliance with provisions in EN 15804. Input energy, water, and the production of waste in the proprietary production are uniformly allocated among all products through mass allocation.

On the other hand, the implementation of the dry washing method in a ready-mix concrete plant yields recycled aggregate. Two new concrete mixtures were considered to draw a comparison with the conventional concrete production process for C35/45. In the first one, 40% of the natural aggregates in the reference mixture are replaced with recycled aggregates, and in the second one, the entire 100% of aggregates are substituted. The environmental impact of natural aggregate production contributes with 16.56 kg CO_2e/m^3 concrete. This replacement introduces alterations to certain factors in the LCA study. Primarily, the recycled aggregates are manufactured using Re-Con-Zero Evo. The environmental impact of Re-Con-Zero Evo is taken into account based on the EPD in EPD Norge (S-P-01105) in accordance with EN 15804.

The utilization of recycled aggregates in concrete production serves to diminish the extraction of natural aggregates for new mixtures. Replacement of natural aggregate and the associated effect of carbonation is based on measurements, specifically focusing on the CO_2 uptake capacity achieved by substituting 40% or 100% of natural aggregates in concrete mixtures.

Furthermore, the implementation of the dry washing method contributes to a reduction in concrete waste generated in ready-mix plants. This, in turn, lessens the volume of concrete waste directed to landfills and relieves the associated burden of landfill transportation. The environmental implications of this decrease in landfilling and the corresponding transportation processes are evaluated using the generic process integrated into SimaPro® software.

It is worth noting that the dry washing process slightly increases internal transportation within the plant, a factor that should be taken into consideration in calculations. The internal transportation was also considered through the generic process in SimaPro® software.

The life cycle impact assessment (LCIA) was performed using the Global Warming Potential (kg CO_2e/m^3 concrete GWP) as the main environmental indicator impact.

3. Results and Discussion

Based on the results of EPD for RMC from Velde betong, see Figure 3, the GWP calculated for concrete production (A1-A3) is 237.22 kg CO_2e/m^3 concrete; the reference mix. This conventional production process with use of 100% virgin aggregates is used as baseline and compared with data for use of dry process with two different replacement scenarios for recycled aggregates.

When reclaiming 1 m^3 of returned concrete into reclaimed aggregates, it is assumed that 2 kg of Re-Con-Zero Evo is used in the dry washing process. Referring to the EPD of Re-Con-Zero Evo (S-P-01105), production of this material causes 5.88 kg CO_2e/2 kg Recon Zero. This value is added to the GWP of the reference mix in both replacement scenarios. Natural aggregates are replaced with recycled aggregates with 40% and 100% in the two scenarios. The GWP for production and transport of natural aggregates is 25.80 kg CO_2e/m^3 concrete, NEPD-4200-3429-NO. This value is subtracted from the GWP of the reference mix for the 40% and 100% replaced aggregates scenarios, respectively.

Considering the 5 km distance between the concrete plant and landfill, with a truck size of >32 metric tonnes and emission class of EURO6, the GWP of the transport resulting from the generic process (see table 1) in SimaPro is 0.1 kg CO_2e/t.km transport. Regarding landfilling and concrete waste reduction in the dry washing process, it is assumed that 1% of the sludge in each m^3 of concrete (0.01*2400 kg) is wasted during the production process. Applying the generic process (see table 1) for landfilling of inert waste in SimaPro, the GWP of the landfilling is 0.006 kg CO_2e/kg mass. The dry washing method reduces the concrete waste by 80%. Hence, 80% of concrete waste landfilling (0.01*2400*0.006*0.8 kg CO_2e/kg mass landfilling) and waste transport (0.01*2.4*0.1*5*0.8 kg CO_2e/t.km transport) to landfill is subtracted from GWP of the reference mix, for both replacement scenarios. However, the internal transportation during the dry washing process, which is assumed to be 50 m, is added to the GWP of the reference mix (0.01*2.4*0.05*0.1 kg CO_2e/t.km transport).

Table 1 Life cycle inventory of transportation and landfilling processes from SimaPro®

Name	Amount	Unit	Comment
Transport, freight, lorry >32 metric tonne, EURO6 {RER}| transport, freight, lorry >32 metric tonne, EURO6 | Cut-off, S	5*0.024	t.km	Amount and distance of concrete waste transport; Process from ecoinvent
Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Cut-off, U	24*0.8	kg	Amount of concrete waste landfilling; Process from ecoinvent

The binding potential after 100 years for concrete in reference mix is measured to 97 kg CO_2e/m^3 concrete. CO_2 uptake for 40% and 100 % of replacement scenarios is 29 and 72 kg CO_2e/m^3, respectively. By adding the binding potential of recycled aggregate after 100 years to the binding potential of concrete in reference mix (C35/45), CO_2 uptake potential for concrete mix with 40% and 100% replacement is derived.

The global warming potential after 100 years in the reference mixture of concrete and replacement scenarios is calculated by subtracting the values of binding potential after 100 years from the CO_2 production value. The calculated values for GWP in year zero and after 100 years, as well as the binding potential for concrete in different types, are provided in table 2.

Table 2 Global warming potential (GWP) of concrete in reference mix and in dry process

Concrete type	GWP in year zero*	Binding potential after 100 years*	GWP after 100 years*
Reference mix (C35/45); natural aggregate	237.38	97	140.38
C35/45; 40% replacement of natural aggregate with recycled dry washing aggregates	227.67	126	107.23
C35/45; 100% replacement of natural aggregate with recycled dry washing aggregates	217.35	169	48.35

* kg CO_2e/m^3 concrete

The GWP of the concrete in reference mix and mix with 40, and 100% replacement of fine and coarse aggregates is shown in Figure 2. In this figure, the highest GWP (237.38 kg CO_2e/m^3 concrete) in the year zero is for the reference mixture which uses wet wash process and natural aggregate. Applying dry washing process in both replacement scenarios decreases the GWP in the year zero. It is because of less fresh concrete waste and consequently, less transport to landfill and landfilling of fresh concrete waste. Additionally, in the replacement scenarios, the CO_2 production related to extraction of natural aggregates is also subtracted from GWP in the reference mixture. As expected, the highest variation in GWP (4.53%) is for the concrete mix in the dry washing process with 100% replacement of natural aggregates. The change in GWP from year 0 and year 100 is equal to CO_2 uptake over 100 year. Based on Figure 4, CO_2 uptake has lessened GWP over time by 77.8% in concrete mixture including dry washing and 100% of aggregate replacement. For the concrete mixture including dry washing and 40% of aggregate replacement, the variation is 55.3%, and for the reference mixture it is 40.9%. It should be noted that replacing 100% of virgin aggregates with recycled aggregates is not yet a common practice. However, in a suitable strength class and exposure class, and with the use of specialized admixtures that mitigate the absorption of the recycled aggregates, it is possible to create such a mix without increased need for water and cement to achieve workability over long time.

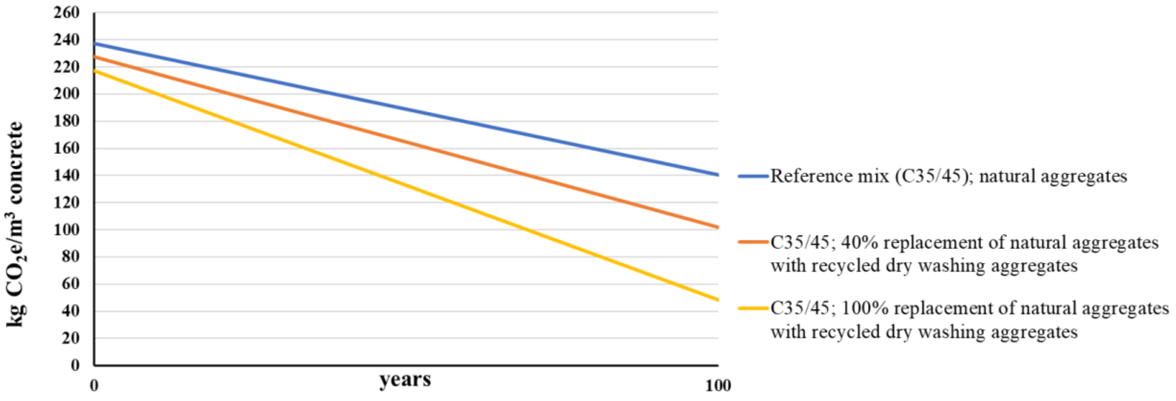

Figure 4. Reduction of kg CO_2e/m^3 RMC by CO_2 uptake during 100 years life time for a reference product with natural aggregates, a scenario with 40% replacement with recycled dry washing aggregates and a scenario with 100% replacement with recycled dry washing aggregates.

In addition to the environmental benefits of dry washing process in ready-mix plants, the economic advantages are of great importance. Based on the results in the study of the dry washing process, the environmental and economical benefits in ready mix production could considerable and fully scalable in a global context. The production and delivery of concrete is very similar all over the world. According to Global Concrete and Cement Association [43] the production volume of concrete in 2020 was 14.0 billion m^3, or approximately 32 billion tonnes. Estimations from interviews with major concrete producers indicate that on average, the waste stream of washout slurry is around 1% of the produced concrete volume. The global waste stream would then amount to 320 million tonnes. The costs of handling this waste stream vary, but in general the cost elements are a) transport to a landfill site and b) gate fee at the landfill.

Using some average costs reported by producers we can assume a transport cost of 0.15 EUR per tonne per km. Landfill cost can be assumed to be 30 EUR per tonne. The total cost for the concrete industry for washout slurry in this example with a distance from the ready mix production site to landfill of 30 km would be:

a) Transport cost: 320.000.000 tonnes x 0.15 EUR/tonne/km x 30 km = 1.44 billion EUR
b) Landfill Gate fee cost: 320.000.000 tonnes x 30 EUR/tonne = 9.6 billion EUR

These costs could be reduced by 70-80% if Dry washing is used, as the cementitious washout is transformed into aggregates, instead of waste.

Water consumption in concrete production is considerable. Ready-mix concrete is delivered by trucks with a capacity of approximately 7 m^3 per load. On average, one can assume that one truck needs to be washed out for every third load to avoid build-up of the cementitious waste inside the drum mixer, using 1000 litres for each wash. This means a total water consumption of 14 billion m^3/7 m^3/3x1000 litres = 667 million m^3 of water. In full scale testing, a 50% reduction of water consumption has been reported. This would have a major impact in areas where access to water is restricted.

4. Conclusion

The solutions in Mapei Re-Con line transform waste streams of returned concrete and truck washout slurry into recyclable aggregates. This means considerable cost savings from reduced purchase of natural aggregates, transport in and out of the concrete plant, high operational costs for washing and reclaiming and finally reduced landfill costs for residual waste.

During the 100-year use phase (B1 in LCA / EPD terminology), the C35/45 concrete containing natural aggregates has a carbonation potential of 100 kg of CO_2. The actual amount would be reduced by the conditions of exposure etc. as described earlier in this text. Simulations of using 40% or 100% replacement of aggregates with Re-Con Dry Washing aggregates show an increased theoretical potential of recarbonation after 100 years. Other positive effects to climate mitigation are less excavation and production of natural aggregates, less transport of natural aggregates and transport to landfill. In addition, this technology contributes to reduction of water use significantly and improves working environment as it minimises energy use, dust and noise compared to conventional methods of handling returned concrete and truck washout slurry.

It was mentioned that dry washing process reduced the GWP of the concrete production in both mixtures (40% and 100% replacement of natural aggregate). However, the level of GWP in reference mix (C35/45) for wet process could be different in various companies. In this regard, Figure 3, indicates that GWP-value for EPD from Velde company is at the average level compared to other companies. The variation in GWP of C35/45 concrete among producers is primarily driven by: cement content and type. Companies using lower cement content (e.g., Skedsmo Betong AS, 13.72%) and lower GWP cements (e.g., Skedsmo Betong AS, CEM III/B with 253 kg CO_2e/tonne) achieve significantly lower overall GWP compared to those using higher cement content (e.g., Leonhard Nilsen og Sønner AS, 20.51%) and higher GWP cements (e.g., Leonhard Nilsen og Sønner AS, CEM II with 694 kg CO_2e/tonne).

The findings showed that further emphaises on the recycling of concrete sludge are needed to utilize the full environmental benefits. However, each individual or combined recycling solution must be adapted to the local factory conditions (available space, distance to recipients, production volume etc.). The dry-washing technology is versatile and can also be installed in combination with other concrete sludge reduction measures.

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