Acta Polytechnica CTU Proceedings **33**:226–231, 2022
https://doi.org/10.14311/APP.2022.33.0226

UTILIZATION OF RECYCLED AND SECONDARY MATERIALS IN CONCRETE PRODUCTION - LCA

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Abstract.

The paper describes an assessment of concrete in terms of environmental impacts in relation to the utilization of recycled materials. The article includes a short summary of the literature search on evaluation methods for environmental impacts and on recycled and secondary materials. The environmental impacts of several concrete mixtures were calculated. The reference concrete mixture containing only cement as a binder and only natural aggregate was compared with other mixtures containing recycled and secondary materials as a binder or aggregates. Some of these concrete mixtures were then compared within the whole structure. Variant design of a simple structure was performed, whereas the variants differed in the concrete mixture. These variants were then evaluated in terms of environmental impacts.

Keywords: Concrete, environmental impacts, life cycle assessment, recycled and secondary materials, variant design.

1. Introduction

In past years, the issue of sustainable development and the impact of construction activities on the environment are gaining importance. It is desirable to minimize negative environmental impact by suitable design, optimal manufacturing process and material selection. The environmental aspects of sustainable development in the construction industry consist also in the utilization of secondary raw materials in the design and construction of new structures.

1.1. State of the art

Most often, studies deal with comparison conventional concrete and concrete containing waste or recycled materials such as fly ash, slag or recycled aggregate. The comparison of unit volumes of different concrete mixtures almost always shows, that lower cement dosages make the concrete more environmentally friendly. Cement production is responsible for a significant amount of released harmful emissions and its energy consumption is very high. Hence, it plays a crucial role in the overall environmental impact of a concrete structure and the cement content in the concrete mixture is a key factor for its environmental assessment. For example, a study [1] reported that a 30% reduction of the cement content leads to a 26.6% reduction in CO_2 emissions. Similar results observed study [2]. The decrease of cement dosage leads also to an energy and raw materials savings. A study [2] reported a 21 % decrease in energy consumption and a 4,3% decrease in raw materials consumption for a 35% reduction of cement content in concrete.

The fact, that the environmental impacts of the concrete structure are largely dependent on the cement consumption, led to many research projects dealing with a utilization of latent hydraulic materials as a partial replacement of cement. These supplementary cementitious materials (SCM) are capable of hydrating when used together with cement. Typical examples are fly ash, blast furnace slag and silica fume. The use of these materials as a partial cement replacement reduces the environmental impacts of concrete production. Moreover, the SCM are usually waste products, which are generated during the production of other materials or during the energy production. For example, fly ash is a by-product of thermal power plant electricity production and blast furnace slag is a by-product of steel production. Thus, there is another environmental advantage, which lies in a utilization of waste products. It should be mentioned that the replacement of cement by SCM generally does not leads to a decrease in strength of the concrete. The strength of the concrete containing these materials can be comparable or even higher. Cement production harms the environment especially in terms of global warming and climate change and in terms of energy consumption. Hence, most studies deal with these environmental impacts and the environmental benefits of using cement replacement materials. The study [3] compares several concrete mixtures with different fly ash replacement levels (25%, 30% and 40%). With the increasing cement replacing level, carbon dioxide emissions decrease. For replacing level of 25%, 30% and 40%, the study reported a decrease in CO_2 emissions by 6%, 11% and 23%. Deterioration of mechanical properties occurred until the replacement level reached 40 %. On the contrary, these mechanical properties improved for lower

		REF	FA	BFS	WPA	WTR	RCA	PC
Cement	[kg/m^3]	380	280	324	380	410	380	0
Water	[kg/m^3]	190	236	180	200	200	190	0
Fine aggregate	[kg/m^3]	705	1142	681	572	840	705	1580
Coarse aggregate	[kg/m^3]	1100	493	1160	1020	960	0	0
Fly ash	[kg/m^3]	0	95	0	0	0	0	0
Blast furnace slag	[kg/m^3]	0	0	36	0	0	0	0
Waste plastic aggregate	[kg/m^3]	0	0	0	143	0	0	0
Waste tyre rubber	[kg/m^3]	0	0	0	0	40	0	0
Recycled concrete aggregate	[kg/m^3]	0	0	0	0	0	1100	0
Waste PET (as a binder)	[kg/m^3]	0	0	0	0	0	0	472
Superplasticizer	[kg/m^3]	2	1.8	0	0	0.8	2	0

TABLE 1. The composition of the concrete mixtures.

cement replacement levels. For example, at 30 % replacement level, the compressive strength increased by 10 %. If the study was carried out for a real structure, the difference in environmental impact would be more significant than when comparing unit quantities of concrete. This is due to possible reduction of the dimensions of supporting structural elements. Nevertheless, it should be mentioned, that the difference would not be significant in case of this study, because there is not a significant increase in strength. Some studies deal with the utilization of blast furnace slag as a partial replacement of cement. These studies reported, a reduction of environmental burden, when cement is partially replaced. For example, study [4] reported, that for 50 % replacement level, CO_2 emissions reduced by 39 %. The study [2] reported similar results. The reduction of CO_2 emissions, and thus the influence on global warming is the most significant environmental benefit. On the other hand, replacing cement by blast furnace slag has only little effect on raw material consumption.

Many studies deal with comparison conventional concrete and concrete containing recycled aggregate, which is produced by crushing waste concrete or bricks. According to most of these studies, use of this recycled aggregate leads to reduction of released harmful emissions and consumed raw materials and energy. Furthermore, utilization of these waste materials is another benefit. For example, the study [5] compares the environmental impacts of the production of conventional concrete containing only natural aggregate and concrete containing recycled aggregate. The natural aggregate was partially or fully replaced by crushed waste concrete. According to this study, the use of recycled aggregate was advantageous for most environmental impact categories. This was the most significant for the consumption of raw materials, which decreased by 47 % when natural aggregate was fully replaced by recycled aggregate. The reduction of energy consumption was less significant, about 30 % for fully replaced natural aggregate. Study [6] reported, that the benefit of using recycled aggregate strongly depend on the transport distance of recycled aggregate. If recycled aggregate is transported over a long distance, the environmental burden caused by the transport may outweigh the environmental benefits of using waste material.

2. Methods

This paper deals with the utilization of recycled and waste materials in concrete production and its advantages in terms of environmental impacts. At first, the assessment in terms of environmental impacts was performed for concrete, which contains only cement as a binder and only natural aggregate (REF) [7]. Then, the assessment was performed for other concrete mixtures, which contain secondary or waste materials as a binder or aggregate. In two of these material variants, there was cement partially replaced by fly ash (FA) [8] or by blast furnace slag (BFS) [9]. In some other variants, there was natural aggregate partially or fully replaced by waste plastics aggregate (WPA) [10], crushed waste tyre rubber (WTR) [11] or recycled concrete aggregate, obtained from demolished buildings (RCA) [7]. One more material variant was included in this evaluation - innovative material called polymerconcrete, which is composed of aggregate and plastic waste, which replaces cement as a binder (PC) [12]. This material is made from fine aggregate (aggregate size $0 - 4$ mm) and waste PET, which is cut into small pieces. The production consists in homogenizing the mixture of plastic waste and small aggregate at high temperature. According to the experiments performed in [13], average compressive strength of this material is 22,7 MPa and average flexural strength is 7,91 MPa. All these mixtures were compared with each other. In the next step, a simple reinforced concrete structure - reinforced concrete frame - was designed from selected concrete mixtures. Then, these structures were compared in terms of environmental impacts. The composition of the concrete mixtures evaluated in this paper is shown in the Table 1.

Environmental impact	Explanation
Global Warming	Global warming is a long-term increase in global average temperature caused by excessive production of greenhouse gases.
Acidification	Acidification is the ongoing decrease in the pH of the environment. This phenomenon is caused by the presence of acid-forming substances in the atmosphere, which react with water to form acids.
Eutrophication	Eutrophication of the environment leads to ecosystem disturbance due to excessive nutrients in water and soil due to excessive fertilization.
Photochemical Oxidant Creation	Photochemical oxidants are air pollutants that are formed under the influence of sunlight by complex photochemical reactions in air that contain nitrogen oxides and reactive hydrocarbons and cause damage to organisms.
Abiotic Depletion	Abiotic depletion refers to the depletion of abiotic resources such as fossil fuels, minerals, and clay.

Table 2. Environmental impacts.

2.1. Life cycle analysis

The assessment of materials and structures in terms of environmental impacts was performed using Life-cycle assessment (LCA) according to relevant standards [14]. The LCA approach is usually based on the whole life-cycle of the investigated product or at least its significant part. So, the assessment includes obtaining raw materials, their transport to the place of processing, manufacturing of the final product, use of the product and further maintenance or repairs if necessary, and final disposal of the product. However, the prediction of the course of the phase of use is sometimes not possible. In these cases, the evaluation includes only a part of the life cycle, it includes for example only obtaining raw materials, their transport to the place of processing and manufacturing of the final product ("cradle to site" evaluation). In this paper, the assessment was performed for concrete as a material for further use, and for a concrete structure too. The evaluation of a unit quantity of different concrete types included the phase of obtaining of raw materials, their transport and processing and manufacturing of the final product. The evaluation of a concrete structure included these phases too, and it includes in addition the phases of transport of concrete and steel and manufacturing of final structure.

At first, the consumption of raw materials and emissions released into the environment were defined for each interproduct such as cement, aggregate, water, fly ash, blast furnace slag and other materials. Within the assessment, the most significant environmental impacts were considered: consumption of raw materials, global warming and climate change, acidification and eutrophication of the environment and photooxidant formation. In LCA, these environmental impacts are called impact categories. Principles of these environmental impacts are explained in Table 2.

The environmental impacts of each interproduct were calculated. Impacts on the environment were quantified by so-called impact category indicators - measurable variables that can be used to observe changes in the environment. The values indicate the extent of environmental damage caused by human activities. Usually, the impact category is influenced by various of substances where some substances are very harmful, and some less. Thus, all the substances are converted to an equivalent amount of the reference substance (for example carbon dioxide for global warming and climate change or sulfur dioxide for acidification of the environment).

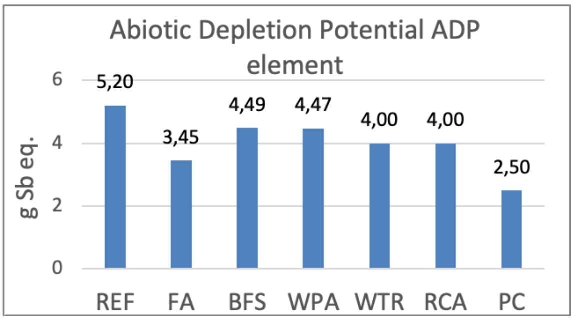
The effect of a specific substance to each impact category was determined by so-called characterization models. A characterization model for a specific impact category is a set of values that reflect the ability of various substances damage the environment within the impact category. All of the issued substances are converted to the equivalent amount of a reference substance by using these values (characterization factors - CF). This paper used a characterization model which is recommended in Product category rules (PCR) for concrete products [1]. The resultant impact category indicator was calculated according to the following relationship:

$$VXY = CF1, XY \cdot \sum m1i + CF2, XY \cdot \sum m2i + ... + CFn, XY \cdot \sum mni \tag{1}$$

where VXY is a result of the impact category indicator (XY indicates the impact category), CF is a characterization factor and m is an amount of a released substance.

When evaluating the impact categories, emissions of following substances were considered: carbon dioxide CO_2, sulfur dioxide SO_2, nitrogen oxides NOx, carbon monoxide CO, methane CH_4, Non-methane volatile organic compound NMVOC, nitrous oxide N_2O, hydrochloric acid HCl, hydrofluoric acid HF, hydrogen sulfide H_2S, ammonia NH_3.

In this paper, seven material variants in the amount of 1 m^3 were compared (Table 1). In addition, several of the above-mentioned material vari-



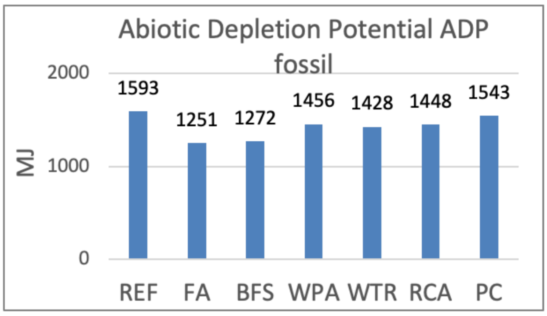


Figure 1. Comparison of 1 m^3 of concrete mixtures regarding sustainability.

ants were compared in designed structure: conventional concrete, concrete with fly ash, concrete with blast furnace slag, concrete with plastic aggregate, concrete with waste tyre rubber and concrete with recycled concrete rubber - the structure design was performed for all material variants except polymerconcrete. Because of the lack of experience in reinforcing of this material, the load-bearing structure designed from this material was not included in the assessment. A simple reinforced concrete frame was designed from different types of concrete. Because of different strength of the concrete types, the volume of concrete needed for the construction depends on the material variant. The amount of steel is the same for all variants. The assessment of the material variants in terms of environmental impacts depends strongly on the volume of concrete, which is used for the structure. Therefore, the frame was designed with utilization of the highest load-bearing capacity of the structural elements to make this assessment relevant. The compressive strength of the mixtures and volume of concrete for the variants are shown in Table 3.

Variant	The compressive strength [MPa]	The volume [m^3]
REF	32.3	740.00
FA	36.2	728.40
BFS	36.2	728.40
WPA	29.5	749.86
WTR	33.8	735.36
RCA	29.2	751.60

Table 3. The compressive strength of the concrete and volume ofăconcrete for designed variants.

3. Results

3.1. Results for 1m^3 of concrete

The results of the sustainability assessment are related to the specific environmental impact. The following figure shows the comparison of the concrete mixtures for considered impact categories.

Polymerconcrete was evaluated for all most impact categories as the best material variant. This is probably because this material does not contain any cement, whose production is very burdening for the environment. On the other hand, the energy consumption (the impact category Abiotic Depletion Potential ADP fossil) is relatively high, higher consumption was calculated only for conventional concrete. The obvious reason is the high heat consumption for melting the waste polymer. Moreover, the use of this material for structures is limited and there is a lack of previous experience with its production. Very favourable results have also been obtained for concrete with fly ash. The obvious reason is the reduction of cement consumption due to its partial replacement by fly ash. In the case of concrete with blast furnace slag, cement is also partially replaced, but the replacement level is lower. Hence, the results are less favourable for this material variant. Material variants, in which recycled materials replaced aggregates, were evaluated as less favourable in terms of environmental impacts. This is because the production of aggregates does not cause such a high environmental burden as the production of cement. Another reason is that the waste material (concrete, plastic, tyre rubber) for production of aggregates replacement must be mechanically processed (crushed). This process is energy intensive and reduces the environmental benefits of using waste material. Therefore, for reducing the environmental impacts it is preferable to replace cement.

3.2. Results for concrete structures

For comparison of the whole structures, a simple reinforced concrete frame was designed from different types of concrete. Regarding the environmental impacts of concrete frames designed from different material variants, the results did not differ significantly from the previous comparative study (comparison of unit quantities of concrete mixtures). All investigated concrete mixtures have the similar compressive strength. Therefore, the dimensions of the supporting elements of the frame do not differ significantly and consumption of concrete is very similar for all designed variants. It is obvious, that a partial replacement of cement by SCM is the most advantageous in terms of environmental impacts. The Figure 3 shows the comparison of the designed variants for considered impact categories and Figure 2 shows the sketch of the designed frame.

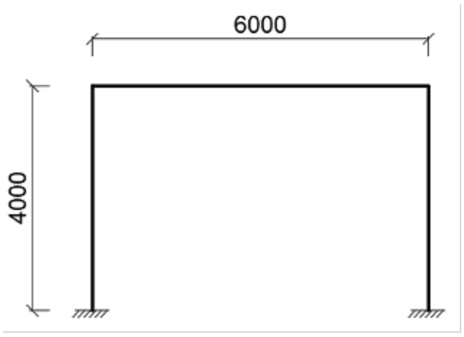


FIGURE 2. Designed concrete frame.

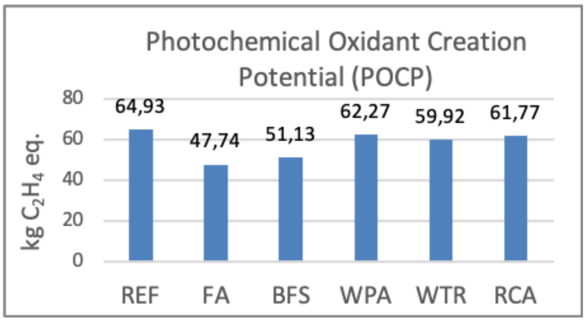


FIGURE 3. Comparison of the concrete frames regarding sustainability.

4. Conclusion

According to this study, in terms of environmental impacts, it is most advantageous to replace a part of cement by supplementary cementitious materials (SCM), such as fly ash or blast furnace slag. Cement production causes a large environmental burden and many environmental impacts are significantly dependent on cement consumption. It could be reduced by partial replacement of cement by SCM. Furthermore, supplementary cementitious materials are often waste or secondary materials and their utilization is another environmental benefit.

Polymerconcrete is also very favourable from the environmental point of view, especially in terms of consumption of raw materials. However, the production of this material is energy intensive, due to the melting of waste plastic. Moreover, so far there is no experience with its use in structures. Therefore, it is desirable to find a suitable use for this material, for example non-bearing part of structures, such as floors or pavements.

When choosing a material for a specific structure, it is necessary to investigate the influence of the transport of recycled materials to the structure site. The transport distance of recycled materials, especially recycled concrete aggregate or waste plastics aggregate, is probably greater than the transport distance of natural aggregates.

The utilization of recycled material in concrete usually brings benefits in terms of environmental impacts. On the other hand, the influence of the use of recycled materials on the mechanical properties of concrete must be considered. The use of some waste materials may increase uncertainties in the mechanical behaviour of concrete due to the variability of the properties of these materials. This is typically related to materials that are not commonly used in concrete production, such as recycled concrete aggregate, waste plastics aggregate or waste tyre rubber. Hence, it is more appropriate for load-bearing structures to reduce the environmental impacts by using SCM.

Acknowledgements

This outcome has been achieved with the financial support of the Ministry of Education, Youth and Sports, project: Durability of concrete structure and assessment of its life cycle, SGS19/149/OHK1/3T/11.

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