Economic and Environmental Assessment of New Generation Concretes

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Abstract. The identification of an anthropogenic environmental degradation has led to a transformation of social and economic trends in the world, which has resulted in the idea of sustainable development, which, in recent years, has become a key point of scientific consideration and a challenge for economic operators. Previously, the dominant aspects of the design of buildings and constructions were functional and structural issues. Nevertheless, based on sustainable development, a new approach to design has emerged, taking into account all the requirements for sustainable construction in one design process, called ILCD – integrated life-cycle design. The new concept combines the design of a building at the level of material, structural element and the whole structure, while, at the same time, assessing design solutions in terms of meeting technical requirements and, among others, economic and environmental efficiency. The development of concrete technology involving a new generation concrete with significantly improved properties, not only in terms of strength and durability but also in terms of rheology, has made it necessary to evaluate these materials from an economic and environmental point of view. The article presents such an assessment of new generation concretes. In this way, the idea of integrated design was presented in practice. The paper also indicates the sources of data and the tools that can be used for the inventory of the indicators for individual processes. The conducted analyses were also an attempt to estimate selected issues of the integrated design of new generation concrete technology against the background of normal concrete technology.

1. Introduction
Ongoing climate change observed worldwide should force the necessity to include in the construction process the assessment of the environmental impact of the assumed project. European Commission [1] stated that the execution of constructions and their use accounts for about half of all raw materials extraction and energy consumption and about one-third of water consumption in the EU. The sector also generates almost one-third of all waste and makes a significant contribution to global GHG (greenhouse gas) emissions. These statistics underline the major responsibility of the construction industry for the implementation of sustainable production patterns in the sense of construction products, thus considering all its stages. It should be stressed that the negative environmental impact of construction works is manifested at every stage of a building's life cycle. Therefore, on the basis of sustainable development, a new design approach has emerged, taking into account all the requirements for sustainable construction in one design process, called ILCD – integrated life-cycle design. The new approach combines the design of a facility at the level of material, structural element and the entire structure while assessing design approaches to meet technical requirements as well as economic,
environmental and social efficiency. Including the above-mentioned requirements in the construction, design makes the design process complex and interdisciplinary. The concept assumes the division of a building's life cycle into phases, within which design solutions are evaluated at three successive recognition levels (Figure 1). Thus, design takes a complex, three-dimensional form [2].

![Figure 1. Graph of integrated design](image)

Given the necessity to adapt construction and material solutions to sustainable development standards, it seems crucial to analyse and evaluate both existing technologies and those newly implemented and developed. This is of particular importance in the case of concrete structures, which, due to material and cost factors, represent a significant share in all recently constructed facilities. It should be noted that in the European Union alone, annual concrete production amounts to nearly 224 million m$^3$ [3]. Due to the increasing loads acting on the concrete element, with a simultaneous tendency to reduce the cross-sections of these elements, the modern technology of conventional concrete proves to be insufficient. Therefore, over the past decades, continuous progress in concrete technology has resulted in the development of new generation concretes with significantly improved properties not only in terms of strength and durability but also in terms of rheology [4]. Such concretes include high-performance concrete (HPC), also known as high strength as well as self-compacting high-performance concrete (HPSCC), which is based on the self-compacting concrete (SCC) and high-performance concrete (HPC) concepts. According to the statistical data kept and published by the European Ready Mixed Concrete Organization, only 11% of ready-mixed concrete is HPC [5]. The analysis of HPC production statistics carried out by Pacheco-Torgal [6] indicates that these trends do not change. The reduced usage of this material may result from hasty conclusions about the lower economic and environmental efficiency of this technology, which is often the result of analyses limited to individual indicators, determined only in the production process of this type of concrete [7,8]. A slightly different evaluation of these concretes may be obtained by taking into account all aspects of ILCD in the design process.

The paper presents an economic and environmental assessment of new generation concretes in the context of a wide possibility of their composition modification and reduction of production costs and its negative impact on the environment.
2. Tools and methods
The analysis of selected concrete mixtures was based, among others, on EPD (Environmental Product Declarations) of concrete mix semi-products [9] by calculating their share in the mixture. In addition, the energy consumption and emission performance of the mixtures under consideration were determined in the context of their transport and construction on the building site. The analyses are of a systematic nature and cover the stage of material production, transport as well as placement and compaction of the mixture on the construction site. [10]. The BRE (Building Research Establishment) guidelines [11,12] were used to standardise and rank the environmental impacts of selected environmental effects and on this basis, the hierarchy of the analysed mixtures was made considering the combined economic and environmental aspects.

2.1. Composition of concretes mixtures
The analysis was conducted for 10 concrete mixtures differing in the proportion of individual components and the final compressive strength. The calculations were carried out for normal concrete mix (NSC), self-compacting concrete mixes (SCC 1÷3), high-performance concrete mixes (HPC 1÷2) and high-performance self-compacting concrete mixes (HPSCC 1÷4). The compositions of each mixture were determined using the literature data [13–17] regarding, among other things, the possibility of reducing the cement content in individual mixtures by increasing the proportion of silica fume or fly ash (Table 1).

| Ingredients          | NSC | SCC 1 | SCC 2 | SCC 3 | HPC 1 | HPC 2 | HPS CC1 | HPS CC2 | HPS CC3 | HPS CC4 |
|----------------------|-----|-------|-------|-------|-------|-------|---------|---------|---------|---------|
| Cement CEM I 32.5    | -   | -     | -     | -     | -     | -     | -       | -       | -       | -       |
| Cement CEM I 42.5    | 380 | -     | -     | -     | -     | -     | -       | -       | -       | -       |
| Cement CEM II/B-V    | -   | 310   | -     | -     | -     | -     | -       | -       | -       | -       |
| 32.5R                | -   | 350   | -     | -     | -     | -     | -       | -       | -       | -       |
| Cement CEM III/A 32.5| 370 | -     | -     | -     | -     | -     | -       | -       | -       | -       |
| Sand 0/2 mm           | 190 | 170   | 161   | 200   | 160   | 160   | 160     | 160     | 160     | 160     |
| Sand 8/16             | 580 | 700   | 713   | 700   | 668   | 668   | 840     | 840     | 840     | 840     |
| Gravel 2/8            | 400 | 468   | 477   | 375   | -     | -     | -       | -       | -       | -       |
| Gravel 8/16           | 860 | 468   | 477   | 375   | -     | -     | -       | -       | -       | -       |
| Basalt aggregate 2/8 | -   | -     | -     | -     | -     | -     | -       | -       | -       | -       |
| Silica fume           | 1240| -     | -     | -     | -     | -     | -       | -       | -       | -       |
| Fly ash              | 990 | 990   | 990   | 990   | -     | -     | -       | -       | -       | -       |
| Superplasticizer      | 3.2 | 2.59  | 2.45  | 6.5   | 3.25  | 4.05  | 5.55    | 5.85    | 6.15    | 7       |
| Average compressive  | 41.2| 42.0  | 47.0  | 37.0  | 89.2  | 91.1  | 90.5    | 95.7    | 94.3    | 91.4    |

2.2. Environmental impact indicators
Using the Abbe and Hamilton studies [18] 11 environmental indicators were adopted for assessment: Global warming potential (GWP), Net use of fresh water (FW), Depletion potential of the stratospheric ozone layer (ODP), Acidification potential of soil and water (AP), Eutrophication potential (EP), Radioactive waste disposed (RWD), Abiotic depletion potential for non-fossil resources (ADPE), Formation potential of tropospheric ozone (POCP), Hazardous waste disposed (HWD), Abiotic depletion potential for fossil resources (ADPF) and Non-hazardous waste disposed (NHWD). Their selection considered the possibility to credibly determine the value of the factors on the basis of available databases and to analyse multiple effects simultaneously. According to the author, other aspects indicated in EN 15643-2 [19] are significantly correlated with the above-mentioned set, therefore it is justified to narrow down to the set of eleven indicators indicated.
Concrete is a material formed from the mixing of particular ingredients, gaining its properties in the result of cement hydration. At the same time, its environmental profile is determined by the features of individual ingredients of a concrete mixture and the processes allowing its production, transport, laying and compacting. Table 2 presents the unit values of the environmental indicators of semi-products of concrete mixtures – the data comes from Environmental Product Declarations (EPD) [20–24]. Since the silica fume and fly ash is a by-product of industrial processes, its impact ought to be indicated by allocation procedure. However, the difference between the GWP indicator, in terms of economic allocation and non-allocation, is not significant [25]. Thus, only environmental impacts related to loading at a power plant, depot and transport were assigned to silica fume.

### Table 2. Unit values of environmental indicators of ingredients of the analysed concrete mixtures

| Ingredient | GWP [kg Co$_2$-eq.] | FW [m$^3$-eq.] | ODP [kg SO$_2$-eq.] | AP [kg (PO$_4$)$_3$-eq.] | RWD [kg] | ADPE [kg Sb eq.] | POCF [kg Ethene eq.] | HWD [kg] | ADPF [MJ] | NHWD [kg] |
|------------|---------------------|---------------|---------------------|--------------------------|----------|------------------|----------------------|----------|-----------|-----------|
| Cement     | 8.98E+02            | 5.70E+02      | 3.10E+00            | 3.92E+00                 | 2.62E+00 | 3.10E+00         | 5.70E+02            | 1.84E+00 | 7.24E+04  | 7.78E+03  |
| Water      | 3.10E+00            | 5.70E-04      | 3.10E+00            | 3.92E+00                 | 2.62E+00 | 3.10E+00         | 5.70E+02            | 1.84E+00 | 7.24E+04  | 7.78E+03  |
| Sand 0/2   | 3.92E+00            | 8.98E+02      | 2.62E+00            | 3.10E+00                 | 7.26E+03 | 1.17E+00         | 4.38E+00            | 2.38E+03 | 9.81E+04  | 9.81E+04  |
| Silica fume/Fly ash | 2.62E+00 | 3.10E+00      | 2.62E+00            | 3.10E+00                 | 2.62E+00 | 3.10E+00         | 5.70E+02            | 1.84E+00 | 7.24E+04  | 7.78E+03  |
| Gravel 2/8 | 3.10E+00            | 3.10E+00      | 3.10E+00            | 3.10E+00                 | 3.10E+00 | 3.10E+00         | 5.70E+02            | 1.84E+00 | 7.24E+04  | 7.78E+03  |
| Crushed stone | 3.10E+00 | 3.10E+00      | 3.10E+00            | 3.10E+00                 | 3.10E+00 | 3.10E+00         | 5.70E+02            | 1.84E+00 | 7.24E+04  | 7.78E+03  |
| 8/16 natural gravel | 3.10E+00 | 3.10E+00      | 3.10E+00            | 3.10E+00                 | 3.10E+00 | 3.10E+00         | 5.70E+02            | 1.84E+00 | 7.24E+04  | 7.78E+03  |
| Superplasticizer | 1.84E+00 | 1.84E+00      | 1.84E+00            | 1.84E+00                 | 1.84E+00 | 1.84E+00         | 5.70E+02            | 1.84E+00 | 7.24E+04  | 7.78E+03  |

The environmental indicators for the concrete placement and compaction processes were calculated based on the energy consumption of the indicated processes [26] (Table 3), using the PL: Electricity grid mix ts model. It should be noted that self-compacting concrete mixtures do not require vibrating.

### Table 3. Energy consumption of the processes of laying and compacting of concrete [26]

| Process            | Type               | Process energy consumption |
|--------------------|--------------------|----------------------------|
| Concrete pump      | electricity        | 0.49 kWh/m$^3$            |
| Flexible stick-type vibrator | electricity | 0.29 kWh/m$^3$            |

Environmental indicators for transport processes were determined in the GaBi programme, using the models EU-28: Transport, truck-trailer (40 t total cap., 24.7t payload) ts and EU-28: Transport, small truck (up to 14 t total cap., 9.3t payload) ts., assuming a transport distance of 100 km, a load factor of 85%, and fuel consumption of 1.7 l/100 t·km. The assumed distance for the transport of the mixture is based on the assumption that up to such distance it is economically advantageous.

### 2.3. Eco-indicator

For the assessment of environmental impacts, the Ecopoint [12] unit was used, for which the standardization process takes the form [11] of equation (1).

$$N_i = \frac{S_i}{R_i}$$  \hspace{1cm} (1)

where:
- \(i\) - categories of impact,
$N_i$ - standardised result,
$S_i$ - the characteristic value of environmental impact,
$R_i$ - reference value (annually per resident of EU-28).

Reference values for GWP, FW, ODP, AP, EP, ADPE, POCP, ADPF and NHWD, were adopted on the basis of [11,12,27]. For HWD, the reference value was determined based on statistics published by [28], and for RWD, according to [29] (Table 4).

| GWP* ODP AP EP POCP ADPE ADPF FW HWD NHWD RWD |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 12,300 | 0.22 | 71.20 | 32.50 | 21.50 | 39.10 | 273,000 | 377 | 187.43 | 3,750 | 3.91 |

* units according to characteristic values of indicators

The weights of environmental indicators are derived from surveys and expert interviews conducted in 2015 by Abbe and Hamilton [18]. The indicators and their weights used to assess and compare the variants are presented in Table 5.

| Criterion weight* [%] |
|---|---|---|---|---|---|---|---|---|---|
| GWP ODP AP EP POCP ADPE ADPF FW HWD NHWD RWD |
| 24.1 | 13.5 | 8.4 | 8.2 | 5.8 | 6.6 | 4.0 | 15.2 | 5.0 | 2.1 | 7.0 |

* According to [18]

Once the values of the selected environmental indicators were standardised and weighted, the Ecopoint value ($E_p$) was calculated according to the equation (2).

$$E_p = \sum_{i=1}^{n} N_i \cdot w_i$$

where:
$N_i$ - standardised result of environmental impact for the $i^{th}$ category,
$w_i$ - weight of $i^{th}$ category.

2.4. Cost analysis

For each mixture production costs were estimated. The costs were determined based on information collected directly from the manufacturers and do not include the costs of transporting the mixture to the construction site. The adopted price level for individual components of the mixtures is presented in Table 6.

| Cement CEM 32,5 [PLN/t] | Cement CEM 42,5 [PLN/t] | Water [PLN/m³] | Sand 0/2 [PLN/t] | Silica fume/Fly ash [PLN/t] | Gravel 2/8 crushed stone [PLN/t] | Gravel 2/8 and 8/16 natural [PLN/t] | Superplastizer [PLN/kg] |
|---|---|---|---|---|---|---|---|
| 550 | 600 | 5 | 40 | 100 | 100 | 70 | 5 |

Similarly to the Eco-indicator, for the production costs thus determined, standardisation was applied by reference to the lowest price obtained as in equation (3).
where:

\( i \) – considered concrete mixture,

\( K_i \) - the standardized cost outcome of the mixture,

\( C_i \) - the total production cost of the mixture,

\( C_{\text{min}} \) - the minimum production cost of the mixture.

3. Results and discussion

The analyses provided the basis for determining the level of the negative environmental impact of particular mixtures defined by the value of eco-indicator taking into account both the process of mixture production and technological processes related to their transport and construction. The obtained values of eco-indicator broken down into unit values of environmental indicators of analysed concrete mixtures are presented in Figure 2. The results obtained in the calculations were referred to 1 m³ of the concrete mixture.

The studies revealed that with the assumed parameters of the model, the process of construction of concrete structures contributes most to the deterioration of the ecosystem through global warming, freshwater consumption and acidification. A large contribution to the total impact is also made by radioactive waste from the group of naturally occurring radioactive materials (NORM), mainly from the combustion of solid fuels in the energy generation process.

When referred to a basic volume unit, the SCC3 mixture indicated the lowest environmental impact \((E_p = 0.992)\) of all analysed mixtures. Such a result is caused by the lowest cement content, the production of which is characterised by high emission level, energy consumption and water
consumption. The results obtained for HPC and HPSCC mixtures confirmed this, in which, together with the reduction of cement towards a higher content of silica fume or fly ash, a decrease in $E_p$ value was noted. In the HPSCC4 mixture, the amount of cement was reduced by 15%, which reduced the eco-indicator by approximately 11% (compared to HPSCC1). A similar level of reduction was observed in the remaining mixtures.

Given the above observations, Figure 3 presents the proportions of the processes and semi-finished products of concrete mixes of particular types, in which the greatest reductions in the amount of cement have been made.

![Figure 3](image-url)

**Figure 3.** Contribution of processes and semi-finished products of selected concrete mixtures to the environmental impact a) NSC, b) SCC3, c) HPC2, d) HPSCC4

In all the studied mixtures, the cement content (its production) represents over 85% of the negative environmental impact. Therefore, it seems appropriate to seek further possibilities of reducing the amount of cement in concrete mixes with the use of e.g. by-products of combustion, etc.

Estimated production costs of the analysed mixtures are presented in Table 7. In turn, in Figure 4, standardised values of individual mixtures are presented.

**Table 7.** Estimated production costs of the analysed concrete mixes

| Mixture | NSC  | SCC1 | SCC2 | SCC3 | HPC1 | HPC2 | HPSCC1 | HPSCC2 | HPSCC3 | HPSCC4 |
|---------|------|------|------|------|------|------|--------|--------|--------|--------|
| Cost [PLN/t] | 340.35 | 328.82 | 320.85 | 303.5 | 442.77 | 426.52 | 436.15 | 426.85 | 418.9 | 414.15 |

The analysis of the obtained production costs of concrete mixes indicated the commonly known correlation of their values with the cement content. Therefore, it can be assumed that concrete mixes with the lowest unit price simultaneously exhibit the lowest $E_p$ value, as shown in Figure 5. Thus, it
should be noted that in the case of using concretes with reduced cement content, a double beneficial effect is obtained both in terms of cost calculation and less negative environmental impact.

![Figure 4. Standardised production costs of the analysed concrete mixes](image1)

![Figure 5. The results of a summary analysis of estimated production costs and environmental impact of the analysed concrete mixes](image2)

4. Conclusions

The research covers the environmental and economic assessment of material solutions in the technology of normal, self-compacting and high-performance concretes, with simultaneous consideration of transport and construction processes. The generalised results allow determining the directions of reduction in the negative impact of concrete structures on the environment through the conscious use of technical parameters of new generation concretes and formulation of concrete fresh mixtures. Substituting cement with alternative binders, e.g. micro-silica or fly ashes, helps to reduce the negative impact of concrete on the environment, reduce its production costs and, at the same time, improve the technical parameters of concrete.

Further possibilities to reduce the environmental indicator of concrete related to the technology of cement production and sources of energy generation (coal, nuclear and hydroelectric power plants). However, one should be aware that the main component (50%) of carbon dioxide emissions during cement production is generated by a chemical process called calcination, in which calcium carbonate is
decomposed into calcium oxide and carbon dioxide. Therefore, cement substitution is a promising direction to reduce the environmental indicators of new generation concrete.

The findings prove that it is necessary to analyse materials in the construction industry in the context of their direct use in construction. The indicators values of the total effect of new generation concretes, calculated per unit of concrete mix volume, may often lead to misleading conclusions about their negative impact on the environment. For example, the application of high strength concrete reduces the overall environmental impact of the structure by reducing the geometric dimensions of the structural elements, which are particularly noticeable in compressed elements. Consequently, analysing the different structural and material variants and calculating the total environmental impact of the element as well as their costs, including the performance characteristics of the structure, should become an appropriate approach to the design of civil engineering structures. Given the set of parameters influencing the outcome of the assessment, the analyses should be carried out individually within a given project.

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