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EVALUATION OF ECOLOGICAL CONCRETE USING MULTI-CRITERIA ECOLOGICAL INDEX AND PERFORMANCE INDEX APPROACH

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Abstract
This paper proposes a new method of rational and quantitative assessment of ecological concrete in terms of the ecological impact and engineering performance. The concrete mix is evaluated through the multi-criteria Ecological Index (EI) and Performance Index (PI) approach. The EI accounts for the impact of the concrete on environment including the carbon emission and raw materials usage, whereas the PI accounts for the engineering performance of the concrete such as compressive strength and water sorptivity. Depending on the applications of the concrete, different criteria may be chosen for the evaluation. Concrete mixes reported in the literature comprising different types of cement, supplementary cementitious materials and aggregates are analyzed to illustrate the applicability of the proposed multi-criteria assessment method. It is shown that the proposed method is able to effectively reflect the concurrent ecological impact and engineering performance of concrete mixes, and hence facilitate rational design of ecological concrete to suit practical engineering applications.

Keywords: **Carbon emission; Ecological concrete; Ecological index; Environmental impact; Multi-criteria assessment; Performance index.**

1. INTRODUCTION

The idea of optimized usage of raw materials and reduction of greenhouse gas emissions was adopted by numerous researchers all over the world [1, 2, 3, 4]. Sustainable development is encompassed in the philosophy of modern urbanization planning [5, 6, 7]. In concrete industry, this idea is becoming increasingly well aware of. Development of energy efficient technologies in concrete production is often based on the use of suitable valorised binding materials, whose production is associated with lower energy consumption, such as fly ash, blast-furnace slag, ceramic dust, and so on [8, 9, 10, 11]. The cement industry has been using waste materials over many years for the production of CEM II and CEM III cements, whose market share has been increasing recently from year to year [12, 13, 14]. Alternative fillers such as scrap tires or sludge ash from sewage treatment plants have been introduced [15, 16, 17]. The use of cements with additives often does not cause any deterioration of the properties of concrete, instead it can improve various properties such as resistance to chemical attack and lower heat generation during hardening [13, 14, 18]. The use of recycled additives including fly ashes and other waste materials in pre-cast and ready-mix concrete is becoming increasingly common. Attempts are made to evaluate and appraise the implemented solutions and proposed environmentally friendly concretes. Rating systems for assessing the environmental performance of construction projects have been introduced. There are many formal sustainability rating systems for buildings in worldwide use today, with LEED (Leadership in Energy and Environmental Design) in the USA and BREEAM (Building Research Establishment Environmental Assessment Method) in the UK probably being the most well-known and widely adopted [19, 20]. However, in the majority of real cases, the concrete is usually assessed very roughly. Under various sustainability rating systems, users are encouraged to use cement blended with additives, or an additive in the form of waste in the concrete mix, and/or recycled coarse aggregate, in order to obtain scores or points to improve the overall positive assessment of the construction projects.

A number of researchers have proposed analytical methods for assessing the environmental performance of concrete based on one or more criteria [20, 21, 22, 23]. Some of the methods are quite simple to apply and are focused on determining the total carbon dioxide emission during the production of concrete components. Since carbon dioxide is a major greenhouse gas generated by artificial sources, the environmental friendliness of concrete is commonly represented by the CO_2 emission [12]. Another method is to determine the impact of a building on the environment throughout its lifetime [24]. This approach is more complicated because it requires detailed data on: i) Global warming (CO_2 emission); ii) Ozone depletion; iii) Acidification of soil and water; iv) Eutrophication; v) Photochemical ozone creation; and vi) Depletion of abiotic resources and fossil fuels (energy consumption) [24]. Information on how waste management is handled at the end of life of the building should also be known. The lack of such data results in the necessity of adopting less precise assumptions and reduces the reliability of the calculations and analyzes. Many different life-cycle analysis (LCA) calculation options are used and new methodologies and solutions are still being proposed recently [25, 26, 27, 28].

Most assessment methods only take into account the environmental impact, but not the engineering performance of the concrete being evaluated. The proposed method is supposed to be much simpler to apply than LCA analyzes, but at the same time it can take into account both the impact on the environment and engineering performance based on two equivalent criteria encompassed in the Ecological Index (EI) and Performance Index (PI), as explained below. The eco-friendliness of the concrete can be expressed in terms of the EI, whereas the engineering performance can be expressed in terms of the PI, where both EI and PI are calculated on the basis of selected concrete properties that are important for the given application and exposure class. This will allow to assess more comprehensively the impact of concrete on the environment and to connect it with the engineering performance of concrete. Concrete with better mechanical properties and functional parameters is usually a more durable material, and thus requires fewer repair or maintenance actions during the life cycle of the structure. This means reducing the amount of energy and materials consumption throughout the service life, which is directly related to the lowering of CO_2 emission. On the other hand, the use of low-quality waste materials and decreasing the amount of binder could potentially cause, apart from a positive environmental impact, a lowering of concrete quality or performance possibly to an unacceptable level. The proposed method will allow finding the right compromise between "traditional" high-quality concrete with comparatively large amount of CEM I cement, crushed natural aggregates, additives and appropriate dose of admixtures, and "doctrinally ecological" concrete whose quality might be at the low side or even below the acceptable level.

In the initial postulation of the method and for preliminary assessment of concrete, it is possible to use the data collected by the authors. Having cumulated more accurate data corresponding to the materials used, it is possible to refine the calculation by making use of the addition data to further enhance the accuracy of the concrete assessment.

2. DATA AND METHOD OF CALCULATION

2.1. Assumptions and values adopted for calculations

A method based on multi-criteria, three-stage assessment of the impact of a concrete mix on the environment and the engineering performance of the resulting concrete has been proposed. The proposed method is principally intended to enable the rational

Table 1.
CO_2 emission factors of concrete ingredient materials

Concrete ingredient material	Emission factor (kg CO_2/kg)	Source	Accepted value (kg CO_2/kg)	Raw materials factor (kg/kg)
Ordinary Portland cement (OPC) / CEM I	0.820 0.944 0.730 1.000	[32] [29] [22] [33]	0.850	0.80
Silica fume	0.020	[22]	0.020	0.00
Metakaolin	0.175	[33]	0.175	1.54
Ground granulated blast-furnace slag	0.1430 0.0265	[32] [29]	0.100	0.00
Fly ash	0.0270 0.0196 0.0080	[32] [29] [22]	0.008	0.00
Coarse aggregates	0.0459 0.0075 0.0050	[32] [29] [22]	0.008	1.00
Fine aggregates	0.0139 0.0026 0.0050	[32] [29] [22]	0.005	0.50
Water	1.96×10^{-4} 0.001	[29] [22]	0.001	0.10
Admixture	0.250	[29]	0.250	2.25

and balanced design of concrete mix as the optimised environmentally-friendly solution to meet the specific application requirements. Basically, the impact on the environment is represented by way of the Ecological Index (EI), and the engineering performance is represented by way of the Performance Index (PI). During the assessment process, the calculated EI would be compared to the calculated PI. In the first stage, the CO_2 emission and the amount of non-renewable raw materials used was determined for valuation of EI. To calculate CO_2 emissions, "the individual integration method" described in [29, 30] was used. This method allows the inclusion of emissions during the production and transport of concrete components and the production of a concrete mix. Taking cement manufacturing as an example, detailed data values depend on many factors and may vary among individual cement manufacturers [31]. A similar situation occurs for other concrete ingredients and their transport. This necessitates reasonable assumptions of certain values in the calculations. The values of emission factor reported in the literature and the data for use in the calculations are summarized in Table 1.

The assumed values are based on experience and latest literature data. It is noted that the exact data values from industrial production are difficult to obtain, because the exact values are dependent on a number of production parameters such as the machinery and equipment configurations, types of fuel used, manufacturing processes, and supply-chain to the production facilities. These parameters would vary from factory to factory, and would not be systematically disseminated by individual factories to third parties. Besides, there would be batch-to-batch variations of the raw materials characteristics and production parameters. Nevertheless, the purpose of the research is to develop the evaluation methodology and demonstrate its applications. When applying the proposed method, if more accurate data are available, such data can be used for evaluation of the concrete. For the calculations carried out with the proposed method, data on the compositions and properties of concretes presented in previous publications were used [11, 34, 35, 36]. The concrete mix proportions are presented in Table 2 (the unit of the concrete mix proportions is in kg/m^3).

Table 2.
Concrete mix proportions

Concrete ID	Cement	Class F fly ash	Fine aggregate		Coarse aggregate		SCM	Admixture	Water
Concrete I [35]									
REC1	300/C1	300	473/FA1	172/FA2	325/CA1	390/CA2	60/SC1	10/A1	190
REC2	300/C1	300	473/FA1	156/FA3	325/CA1	390/CA2	60/SC1	10/A1	193
REC3	300/C2	300	467/FA1	170/FA2	321/CA1	385/CA2	60/SC1	10/A1	197
REC4	300/C3	300	470/FA1	171/FA2	322/CA1	387/CA2	60/SC1	10/A1	193
REC5	300/C4	300	466/FA1	170/FA2	320/CA1	384/CA2	60/SC1	10/A1	192
REC6	300/C1	300	427/FA1	155/FA2	293/CA1	351/CA2	100/SC2	11/A1	212
HPC Concrete [36]									
HPC	480/C1	-	416/FA1	-	1247/CA5	-	72/SC1	15/A1	179
Concrete II [34]									
C I	400/C5	-	301/FA1	-	1468/CA4	-	-	4/A2	200
C II	300/C5	200	280/FA1	-	1367/CA4	-	-	4/A2	200
C III	300/C5	200	272/FA1	-	1327/CA4	-	40/SC3	4/A2	200
C IV	300/C5	200	272/FA1	-	1330/CA4	-	40/SC1	4/A2	200
C I R	400/C5	-	584/FA1	-	1073/CA3	-	-	4/A2	200
C II R	300/C5	200	543/FA1	-	999/CA3	-	-	4/A2	200
C III R	300/C5	200	527/FA1	-	970/CA3	-	40/SC3	4/A2	200
C IV R	300/C5	200	529/FA1	-	973/CA3	-	40/SC1	4/A2	200
Concrete III [11]									
REC1	300/C4	200	538/FA1	196/FA2	369/CA1	443/CA2	-	8/A1	172
REC2	300/C4	200	505/FA1	184/FA2	347/CA1	416/CA2	50/SC3	8/A1	186
REC3	300/C4	200	509/FA1	185/FA2	349/CA1	419/CA2	50/SC1	8/A1	185
REC4	300/C4	200	498/FA1	181/FA2	342/CA1	410/CA2	50/SC4	8/A1	183
REC5	300/C4	200	517/FA1	188/FA2	355/CA1	426/CA2	30/SC4	8/A1	175
REC6	300/C4	200	507/FA1	184/FA2	348/CA1	417/CA2	50/SC2	9/A1	183
REC7	300/C4	125	493/FA1	179/FA2	338/CA1	406/CA2	125/SC2	10/A1	201

Note:
The following notations for cement are used:
C1 - CEM I 42.5R;
C2 - CEM I 52.5R;
C3 - CEM II/A-M (S-LL) 52.5N;
C4 - CEM III/A 42.5N;
C5 - CEM I 32.5R
The following notations for fine aggregate are used:
FA1 - natural sand 0–2 mm;
FA2 - natural sand 2–4 mm;
FA3 - RCA 2–4 mm
The following notations for coarse aggregate are used:
CA1 - RCA 4–8 mm;
CA2 - RCA 8–16 mm;
CA3 - RCA 2–16 mm;
CA4 - NA 2–16 mm;
CA5 - crushed basalt 2-16 mm
The following notations for supplementary cementitious materials (SCM) are used:
SC1 - metakaolin;
SC2 - fluidized fly ash;
SC3 - silica fume;
SC4 - Centrilit NC
The following notations for admixtures are used:
A1 - SP FK-88 (superplasticizer);
A2 - BASF Glenium SKY 591
The unit of the concrete mix proportions is in kg/m^3.
Reference to [11, 34, 35, 36] can be made for more detailed descriptions of the concrete mixes.

Table 3.
Sample calculations of CO_2 emissions and raw materials usage

Concrete ingredients	Amount (kg/m^3)	Emission factor (kg CO_2/kg)	Distance (km)	Emission - transport (kg CO_2/kg)	Raw materials factor (kg/kg)	Total emission (kg CO_2/m^3)	Total raw materials usage (kg/m^3)
CEM I 32.5R	300	0.850	150	5.18E-05	0.80	255.0+2.3	240.0
Natural sand 0-2 mm	280	0.005	30	6.30E-05	0.50	1.4+0.5	140.0
Fly ash Class F	200	0.000	0	5.18E-05	0.00	1.6+1.0	0.00
Natural gravel 2-16 mm	1367	0.008	30	6.30E-05	1.00	10.9+2.6	1367.0
Superplasticizer (SP FK-88)	4	0.250	300	2.21E-04	2.25	1.0+0.3	9.0
Water	200	0.001	0	0	0.10	0.2+0.0	20.0
Concrete production	sum: 2351	0.008	-	-	-	18.8	-
Total value:	-	-	-	-	-	**295.7**	**1776.0**

It was assumed that CEM I Portland cement contains 100% clinker (in order to simplify calculations, the components constituting less than 5% of the cement by mass were omitted; nevertheless, if reliable data of a component material are available, the data can be incorporated in the calculation to improve the accuracy). In the case of Portland composite cement and Portland blast-furnace slag cement, the maximum possible amount of additive and the remaining amount of clinker were estimated with reference to the product specifications. For example, CEM II/B-V contains approximately 35% ash and 65% clinker by mass, and CEM III/A contains approximately 65% slag and 35% clinker by mass. The total emission was determined taking into account the percentage (mass) share and unit emissions attributed to individual cement components. Carbon emission during the transport of components was assessed according to the data given in the literature [29, 30]. When similar modes of transport are adopted, the variation of data values would be small.

The raw materials factor is a raw materials usage parameter calculated for each concrete component as the product of the consumption of natural raw materials needed to produce 1 kg of this component and an additional parameter denoted as "rarity ratio". This additional parameter expresses the availability of a given natural resource and the need to conserve it. It was assumed that the rarity ratio should take values from 0 in the case of industrial waste in surplus to 1 in the case of raw materials being depleted. With such assumptions, an arbitrary value of 0.5 was assumed for river sand due to its high availability and at the same time, the need to prevent over-dredging to preserve the fresh water habitat, whereas an arbitrary value of 1.0 was assumed for natural gravels. In the case of crushed granite or basalt aggregates, a rarity ratio of 0.75 was assumed. However, due to the fact that the production of aggregates of suitable size by crushing also results in fractions with smaller granulation, therefore it was assumed that the production of 1 kg of crushed aggregates requires 1.25 kg of rock.

Production of 1 kg of CEM I cement (100% clinker assumed) requires about 1.6 kg of raw materials [37]. The authors assumed the rarity ratio to be 0.5 because natural raw materials for cement production are available in large quantities in Poland and China (the authors' origin places). In the calculations, raw materials usage is equal 0.8 for CEM I cement, 0.52 for CEM II/B cement and 0.28 for CEM III/A cement.

Data which facilitate the valuation of rarity ratio for individual raw materials are not widely available in the literature. Depending on the availability of raw aggregate materials in the given area, values of these ratios may differ considerably. Data on aggregates are more diverse in different geographical areas of China due to the reason of significant regional variations of types and availabilities of natural aggregate sources. Therefore, the rarity ratios used in this study are based on data of natural aggregate resources available in Poland or regions with similar settings [38]. The proposed method allows the use of specific rarity ratio values of individual raw materials depending on their availability in a given country or locality. When calculating the consumption of natural (non-renewable) resources for a concrete mix, the product of the mass content of a given component and its raw materials factor was summed to give the total raw materials usage. The total CO_2 emission was taken as the sum of CO_2 emissions of the ingredient materials and their transportation. Since the transportation of materials involves burning of fossil fuel and hence carbon emission, from the ecological viewpoint, usage of locally available ingredient materials would be more preferable than materials from a long distance. The calculations for a sample concrete are shown in Table 3.

Table 4.
Calculations of CO_2 emissions and raw materials usage for reference values

Concrete ingredients	Amount (kg/m^3)	Emission factor (kg CO_2/kg)	Distance (km)	Emission - transport (kg CO_2/kg)	Raw materials factor (kg/kg)	Total emission (kg CO_2/m^3)	Total raw materials usage (kg/m^3)
CEM I 42.5R	480	0.850	150	5.18E-05	0.80	408.0+7.5	384.0
Natural sand 0-2 mm	416	0.005	30	6.30E-05	0.20	2.1+0.8	208.0
Crushed basalt 2-16 mm	1247	0.008	30	6.30E-05	0.35	10.0+23.6	1169.1
Metakaolin	72	0.175	200	5.18E-05	1.54	12.6+0.7	110.9
Superplasticizer (SP FK-88)	15	0.250	300	2.21E-04	2.25	3.8+1.0	33.8
Water	179	0.001	0	0	0.10	0.2+0.0	17.9
Concrete production	sum: 2409	0.008	-	-	-	19.3	-
Total value:	-	-	-	-	-	**489.4**	**1923.6**

In the first stage of the concrete assessment, the ecological impact of concrete is considered. Normalized CO_2 emission values and raw materials consumption are calculated. Normalization consisted of dividing the given parameters by the respective reference values, which are determined based on the high quality concrete containing 480 kg/m^3 of cement CEM I 42.5, crushed aggregate, superplasticizer and metakaolin as an additive (the concrete has approximately 490 kg CO_2 emission per cubic metre and 2000 kg/m^3 of raw materials usage) [36]. Calculations for reference values are presented in Table 4.

2.2. Calculation of Ecological Index

The value of EI is evaluated as the square root of the sum of normalized total emission and normalized total raw materials usage, multiplied by square root of 0.5 so that a concrete mix with reference values of CO_2 emission and raw materials usage will give an EI value of 1. A lower EI value means less environmental burden is associated with the concrete, i.e. the concrete is more environmentally friendly. The calculation of EI is given by Equation (1), in which EM represents the total emission in kg/m^3 and RM represents the total raw materials usage in kg/m^3. The relevant values are multiplied by the respective weighting coefficients, whose values were taken as: $w_{EM} = 0.5$ and $w_{RM} = 0.5$ in the present study.

$$EI = \sqrt{\frac{EM}{490\ kg/m^3} \times w_{EM} + \frac{RM}{2000\ kg/m^3} \times w_{RM}} \quad (1)$$

2.3. Calculation of Performance Index

In the second stage of the concrete assessment, the engineering performance of concrete is concerned. The value of PI is evaluated on the basis of the sum of normalized values of selected concrete properties. Meanwhile, the 28-day compressive strength and water sorptivity are chosen for the calculation of PI. It should be noted that the proposed method is flexible and other properties of concrete may be chosen to suit the application needs. As a reference value, the value of 28-day strength is taken as equal to 60 MPa and the sorptivity is taken as equal to 0.120 cm/h$^{0.5}$. The value of 60 MPa is often the limit of average strength of high quality concretes, and the value of 0.120 cm/h$^{0.5}$ is regarded as the limit of "good" class of impermeability when evaluating concrete according to the criteria proposed in [36]. With the assumed base values, the 28-day strength of the concrete under assessment and its sorptivity were compared respectively. The relevant quotients from normalization are multiplied by the respective weighting coefficients, whose values were taken as: $w_{fcm} = 0.6$ and $w_S = 0.4$ in the present study. The sum of weighting coefficients should be equal to unity so that a concrete mix with reference values of selected properties will give a PI value of 1. The calculation of PI is given by Equation (2).

$$PI = \frac{f_{cm}}{60\ MPa} \times w_{fcm} + \frac{0.120\ cm/h^{0.5}}{S} \times w_S \quad (2)$$

As far as the durability aspect of a reinforced concrete structure is concerned, in lieu of sorptivity, other properties related to the potential durability of concrete can be accepted. For certain applications where additional properties of the concrete are required, PI can be calculated on the basis of more than two properties and the assignment of the respective weighting coefficients depends on the preferred properties of the concrete. For example, when high resistance to chemical aggression or cyclic freezethawing is required, properties related to resistance to these impacts may be associated with larger weighting coefficients than strength or sorptivity. In this case, specific tests need to be conducted to obtain the test results of the properties for calculation. A higher PI value means better concrete properties compared to the reference values.

In the third stage of the concrete assessment, the concurrent ecological impact and engineering performance of concrete is concerned. The concurrent EI and PI achieved are appraised by a Gross Ecological and Performance Indicator (GEPI), as given by Equation (3):

$$GEPI = \sqrt{EI^2 + \frac{1}{PI^2}} \quad (3)$$

For a concrete with reference values of ecological parameters and properties, its EI and PI are both equal to 1, and the GEPI will be equal to $(2)^{0.5}$. In the expression, both EI and 1/PI have smaller values when the concrete is ecologically favourable and has desirable engineering properties, and vice versa. Therefore, when designing a concrete mix in practice, a low GEPI is aimed for concrete with favourable concurrent EI and PI, while a high GEPI should be avoided.

The following should be noted in the interpretation of EI and PI. Since the valuation of EI is dependent on the local ingredient materials and production practice in a given geographical area, the possibilities to directly compare concrete mixes produced in different countries would be limited. On the other hand, since the valuation of PI is dependent on the chosen concrete properties in connection with the application requirements, the significance to directly compare concrete mixes for fulfilling different requirements would be limited. Though it is still possible to make an approximate and qualitative comparison across concrete mixes based on different settings, highly valuable results would be yielded from comparison across concrete mixes for fulfilling any given set of requirements.

3. RESULTS AND DISCUSSIONS

In the following, concrete mixes reported in the literature [11, 34, 35, 36] as listed in Table 2 are assessed and compared using the proposed multi-criteria EI and PI approach. The concrete mixes were divided into distinct groups. Figure 1 presents the calculations of EI results for the concrete mixes. Figure 2 shows the results of EI and PI calculations. In the graph of 1/PI plotted against EI, the points characterizing the most favourable concrete mixes in terms

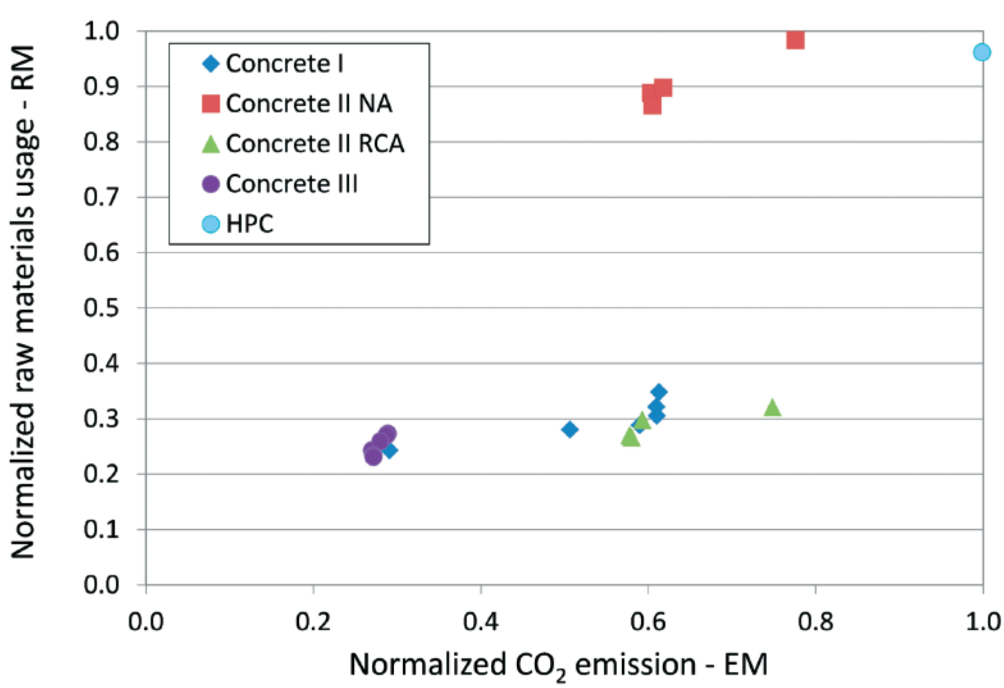

Figure 1.
Ecological Index results

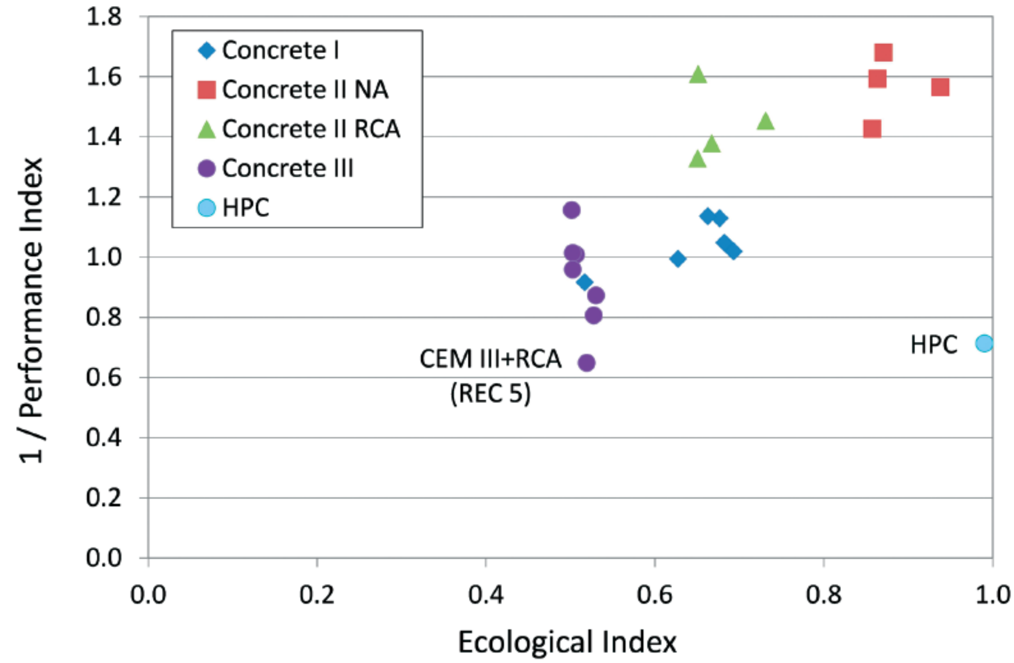

Figure 2.
Ecological Index plotted against reciprocal of Performance Index

of ecology and engineering properties are located nearest to the origin of the coordinate system. This provides a means of graphical visualisation of the concurrently achieved EI and PI with the aid of the GEPI. Numerical results of EI, PI and GEPI calculations for the groups of concrete analyzed are presented in Table 5.

The results of individual groups of concrete mixes are discussed in detail below.

Concrete I: This group of concrete contained different cement types in the amount of 300 kg/m^3, with addition of Class F fly ash from coal combustion in the Kozienice Power Plant in the amount of 300 kg/m^3 and metakaolin in the amount of 60 kg/m^3. Natural sand and recycled coarse aggregates (RCA) were employed. The EI for concrete mix REC5 with CEM III/A 42.5N cement is similar to the values for Concrete III group containing blast-furnace slag cement CEM III/A 42.5N. The use of other cements types results in higher CO_2 emissions and less favourable EI. PI values of all concrete mixes are similar and much lower than in the case of Concrete II NA and II RCA groups, with respectively natural aggregates (NA) and RCA.

Concrete II NA and II RCA: Eight concrete mixtures were included, where ordinary Portland Cement CEM I 32.5 (400 kg/m^3 and w/c = 0.5 in reference concrete; and 300 kg/m^3 of cement + 200 kg/m^3 of fly ash and water/binder ratio = 0.4 in the other concrete mixes) and supplementary cementitious materials including Class C fly ash (FA), silica fume (SF) and metakaolin (MK) were used. The contents of FA, SF and MK were respectively 50%, 10% and 10% of the cement mass in the reference concretes (mix I and I R respectively). In the concrete mix series I to IV, natural aggregate fractions of 0–2 mm (river sand) and 2–16 mm (gravel) were used. Recycled aggregate was applied in concrete mix series I R to IV R.

The change from NA to RCA would alter the consumption of raw materials in the concrete mix design. It should be noted that the water absorbed by RCA was excluded from the calculation of w/c ratio, which should reflect the quantity of free water. This resulted in the reduction of the effective w/c ratio in concrete with RCA and improvement of its properties. With the use of recycled aggregates, the EI of concrete with RCA is obviously more favourable than that of concrete with NA, whereas their PI is at a similar level. The addition of MK and SF leads to a positive impact on the PI of concrete with RCA.

Concrete III: This group of concrete contained blast-furnace slag cement CEM III/A 42.5N in the amount of 300 kg/m^3, with addition of Class F fly ash from

Table 5.
EI and PI values of concrete mixes

Concrete ID	Ecological Index (EI)	Performance Index (PI)	Gross Ecological and Performance Indicator (GEPI)
Concrete I [35]			
REC1	0.693	0.981	1.232
REC2	0.677	0.886	1.316
REC3	0.682	0.954	1.251
REC4	0.627	1.006	1.176
REC5	0.517	1.091	1.052
REC6	0.663	0.880	1.315
HPC Concrete [36]			
HPC	0.990	1.401	1.220
Concrete II [34]			
C I	0.938	0.639	1.825
C II	0.864	0.628	1.812
C III	0.858	0.701	1.664
C IV	0.871	0.595	1.892
C I R	0.731	0.688	1.627
C II R	0.651	0.622	1.735
C III R	0.650	0.753	1.478
C IV R	0.667	0.726	1.531
Concrete III [11]			
REC1	0.507	0.991	1.129
REC2	0.503	0.986	1.132
REC3	0.530	1.146	1.021
REC4	0.528	1.240	0.964
REC5	0.519	1.542	0.831
REC6	0.503	1.043	1.083
REC7	0.501	0.865	1.260

Note:
GEPI is calculated per Equation (3) and is graphically visualised as the distance from the origin of coordinate system in Figure 1 and Figure 2.
Reference to [11, 34, 35, 36] can be made for more detailed descriptions of the concrete mixes.

coal combustion in the Kozienice Power Plant in the amount of 200 kg/m^3. Individual mixtures were modified with other types of reactive supplementary cementitious additives including SF, MK, Centrilit NC (amorphous aluminosilicate), and fluidized fly ash. Natural sand and RCA were employed. Among all groups of concrete, this concrete group provides the most favourable EI results. The values of PI vary and depend on the additive used. The least favourable PI is obtained when using fluidized fly ash, whereas the most favourable PI is obtained when Centrilit NC was added in the amount of 10% by mass of cement.

The above results illustrate the favourable effects of Portland blast-furnace slag cement and higher strength cement on the concurrently achievable EI and PI, as well as the beneficial effects of using recycled coarse aggregates and supplementary cementitious materials. It should be noted that the superior rating of concrete with CEM III/A and RCA in terms of the PI values is dependent on the choice of PI criteria. In other words, a change in the PI criteria may alter the rating. For instance, if the assessment is based on the frost resistance criterion, the same concrete mixtures might show a different rating.

4. SUMMARY AND CONCLUSIONS

A method of multi-criteria assessment of concrete in terms of impact on the natural environment and engineering performance has been proposed. The method is principally intended to enable the rational and balanced design of concrete mix as the optimised environmentally-friendly solution to meet the specific application requirements. The impact on environment by the concrete is accounted for via the Ecological Index (EI), and the engineering performance of the concrete is accounted for via the Performance Index (PI). The proposed method enables a quantitative and more rational appraisal of ecological concrete. The calculation procedures for EI and PI have been explained. Dependent on the geographical area and production factors of plants, the carbon emissions of the raw materials and the concrete may vary within certain ranges. The reliability of the EI calculation would be enhanced by having more accurate production data. The compressive strength and sorptivity of concrete have been adopted in this study as the criteria for the PI calculation. Dependent on the applications of the concrete, different criteria and weighting coefficients may be assigned for composing the PI. The selection of criteria allows to cater for the exposure conditions of concrete and project-specific requirements, whereas the selection of weighting coefficients allows to cater for the relative importance of the criteria to meet the project needs. The concurrent ecological impact and engineering performance of concrete is considered via the Gross Ecological and Performance Indicator (GEPI). Examples of EI and PI evaluation comprising concrete mixtures with different types of cement, use of natural resource or recycled coarse aggregates, and addition of different supplementary cementitious materials have been presented.

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