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ECO_2 framework assessment of limestone powder concrete slabs and columns

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ABSTRACT

Producing limestone powder requires comparably far less energy than the production of ordinary Portland cement (OPC), making it a promising sustainable solution for partial replacement of OPC in concrete. Lower production energy could be translated into lower environmental impact and lower cost, which are two pillars of the sustainability of the resulting concrete. However, the question remains if replacing OPC with larger percentages of limestone powder would compromise the performance of the resulting concrete to a level that surpasses the environmental and economic gains. In order to assess the collective impact of these concretes, a performance-based multi-criteria decision analysis framework, ECO_2, is used. For that purpose, 26 experimentally verified, concrete mixtures with and without limestone powder were evaluated through potential application in two types of reinforced concrete (RC) structural elements (slabs and columns) under identical environmental condition. The main results of the research showed a clear environmental advantage of concrete with a reduced OPC content, but the relatively higher superplasticizer amount in some cases could affect the final sustainability performance of the resulting mix. In the case of RC slabs, the best ECO_2 score was obtained for concrete containing limestone powder. Mixtures with 200–250 kg of cement per unit volume of concrete had the highest ECO_2 score for all the considered criteria. In the second case, due to the nature of the structural performance requirements in columns, the crucial influence of the concrete compressive strength is clear. The obtained results have shown approximately equal sustainability potential of OPC and limestone concretes in vertical elements such as columns. However, it seems that a certain improvement in the design of concrete mixtures with a high limestone powder content could make these competitive in all fields.

1. Introduction

Accelerated progress of science, technology, and industry has led to improved quality of human life, but also to increased negative consequences on the environment. Of all human activities, the construction industry is recognized as one of the largest consumers of

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natural resources and energy, and also one of the largest generators of waste and pollutants in the environment [1]. The concrete sector causes a significant part of these impacts during its materials (primarily cement) production, the usage phase, and demolition. This is due to the fact that concrete is the most widely used human product with an annual production of about 35 billion tons [2]. To meet the growing needs of humanity, it is estimated that concrete production will increase by as much as 50% by 2050 [2]. The production of ordinary Portland cement, one of the main components of concrete, is responsible for 8–10% of total anthropogenic CO_2 emissions [3, 4], which makes it the most environmentally problematic phase in concrete production. With this in mind, the application of supplementary cementitious materials (SCMs) to partially replace OPC can make a significant global contribution to improving the sustainability of the entire sector.

As opposed to established pozzolanic SCMs such as fly ash and ground granulated blast furnace slag which are soon to be less abundant globally [5–9], numerous tests of mechanical properties of concrete have been recently successfully conducted in which up to 65% of cement has been replaced by inert or weakly reactive SCMs, i.e. fillers [10–14]. Of all the fillers, limestone (LS) powder has the greatest potential, primarily due to its exceptional performance, wide availability, and low price [1]. Accordingly, in the regulations of many countries, it is allowed to replace as much as 35% of cement clinker with LS powder [15]. However, currently, the average LS powder content in cement is only 6–7% globally [16], far below the maximum prescribed value.

In order to enable a large reduction of OPC and the wider use of LS concrete, it is very important to properly perform its mix design and achieve adequate mechanical and durability properties. The existing literature shows that this is possible, especially by applying some of the numerous particle packing methods [17–19]. These methods, despite the significantly reduced amount of cement by using LS powder as an SCM, enable the improvement of certain properties of concrete necessary for their structural application, where 60% of cement in Europe is estimated to be used [20].

The high replacement percentages of OPC with LS powder are reported to potentially decrease the concrete workability [21,22]. However, some studies show solutions to this problem, such as applying suitable water reducing admixtures, increasing the content of LS powder, or limiting the minimum content of the powder component [11,23]. In terms of mechanical properties such as compressive and tensile strengths, modulus of elasticity, etc., the addition of LS powder at the expense of cement reduction, followed by a reduction in water and increased superplasticizer content, may achieve similar or even higher values [10,11,24]. At the same time, if mixtures of the same composition are designed, the strength of concrete containing LS will be lower due to the dilution effect [25–27].

A reduced amount of cement paste through the addition of LS powder mainly results in lower durability properties of these concretes compared with conventional ones [28,29]. Because of significantly impaired carbonation resistance, it was recommended that LS powder in concrete as OPC replacement not exceed 15% [30]. These properties of LS concrete mostly depend on OPC and LS powder content, porosity (air void content and pore size distribution), as well as water-to-cement ratio [27,31]. Besides that, the OPC replacement with LS reduces the alkalinity of the pore solution in concrete due to the pozzolanic chemical reaction between LS and aluminate phases which consumes the portlandite phase causing, together with dilution effects, a deterioration in carbonation resistance [24,27]. It is then necessary to prevent the steel corrosion for the required service life by designing an adequate concrete cover depth.

Given the established incentive to produce more sustainable concrete, there is a shortage of literature studying the environmental and economic impact of the subject matter. In this regard, no studies discussing the economic merit of producing concrete with a high percentage replacement of LS powder were found; this mainly being attributable to the lower production energy. In this sense, the literature trend shows that replacing OPC with LS powder lowers, with varying degrees, the global warming potential (GWP) for the binder [32,33]. A detailed study including the transport of the raw local materials showed that the reduction in GWP (15% and 25%) was equal to the percentage replacement of cement [29]. Nevertheless [34], advised that, using compressive strength normalized GWP as an indicator, the LS powder addition is limited to low-strength concrete applications. However, up to 15% utilization of LS powder as a filler is proven to reduce, along with 30% of calcined clays, the carbon footprint of the resulting concrete up to 40% [35,36]. Similarly, analyzing concretes of similar target strengths in which about 40% of cement has been replaced by LS powder [10], a GWP reduction of up to 50% is found. Comparing concretes of different strengths but comparable durability performance, proved that mixtures with 50% less cement content achieve 35% lower GWP [32]. Evidently, a detailed study of different environmental impacts of concrete with varying percentage replacements of OPC with LS powder is still missing.

The above-presented results prove that LS concrete has a clear potential of achieving properties comparable to OPC concrete, this making it an attractive and potentially more sustainable alternative. Therefore, the sustainability assessment of structural concrete with a high LS powder content implies a combination of the environmental, economic, and technical indicators. In order to determine the optimal choice of concrete, a multi-criteria decision analysis (MCDA) methodology is required to evaluate alternatives. Such methods have been shown to be successful in identifying optimal alternatives in the face of conflicting criteria and have been applied to different cases such as flat slabs [37], continuous flight auger piles [38] and concrete columns and on different types of materials such as recycled aggregate concrete [39] and fibre reinforced concrete.

The main objective of this research is to fill the knowledge gap in terms of sustainability of structural concrete with a high LS powder content. In that sense, the first extensive and comprehensive sustainability assessment of this type of concrete, based on own experimental research and a meta-analysis of results published in the literature, was conducted. It was done by using the multi-criteria decision analysis framework ECO_2 method (ECOlogical and ECOnomic assessment) developed by Hafez et al. [40,41]. Therefore, this paper provides a holistic assessment of the suitability of structural application of concrete with a high LS powder content, by combining the environmental, economic, and structural performances, which could be a significant contribution to the research community as well as the construction sector.

2. Materials and methods

2.1. Data collection from previous studies

The first step was to examine published experimental studies on concrete including LS powder. Data on the composition of concrete mixtures containing LS powder tested for workability of fresh concrete (slump or flow test), mechanical properties, i.e. compressive strength at the age of 28 days, as well as carbonation (accelerated or natural tests) was collected. The search was conducted in relevant databases such as Science Direct and Scopus, using the following keywords: limestone powder/filler, limestone cements, eco-friendly concrete, low cement concrete, compressive strength, durability, carbonation, and a combination thereof. Only concretes with partial replacement of cement by LS powder ($\geq$15%) were considered, excluding those in which powder was used as an admixture of cement to improve certain performance, as is the case with self-compacting concrete. Mixtures with LS powder without including a control OPC mix for comparison were also discarded. After applying the previous criteria, 10 relevant studies were selected with over 150 tested concrete mixtures, of which 82 potentially contained all required data [30,32,42–49]. The small number of mixes is indicative of the research gap, yet considered satisfactory for the current study. All studies were conducted in the period 2004–2021 in five countries across Europe: Germany (4), Italy (2), United Kingdom (2), Switzerland (1) and Portugal (1).

As the main goal of this paper is the sustainability assessment of structural concrete with a high LS powder content, all mixtures must meet the conditions necessary for being suitable to be used in structural applications. Therefore, the workability must meet the set criteria, which is a minimum slump/flow class of S2 ($\geq$50 mm) and F2 ($\geq$350 mm) according to Refs. [50,51] respectively. The mean compressive (cube) strength at 28 days in the range 35–65 MPa was targeted, to obtain compressive strength classes C20/25 to C45/55 [52]. In order to ensure the required service life of 50 years, all structural elements must fulfill carbonation resistance requirements for exposure class XC3 [52].

More than half of the 82 mixtures were uncompliant with the previously criteria (Fig. 1). A total of 30 mixtures were rejected due to their strength being below 35 MPa; 22 more were excluded due to unsatisfactory durability, and 8 mixtures were excluded because of not having comparable mixtures. Finally, 22 concrete mixtures were found to satisfy all the prescribed criteria. Eight mixes were control (OPC only) and 14 mixes included different ranges of partial replacement by LS powder, as follows: nine mixtures were with 15% LS, four mixtures with a 25–30% replacement range and only one mixture in which 50% of cement is replaced by LS powder. The database was provided as Supplementary material to this article. As the quantities of cement in the reference mixture differ for each study, it is not convenient to group those according to the percentage of cement replacement. Alternatively, mixes were grouped according to the total amount of cement (per m^3), as follows: >300 kg (G1); 250–300 kg (G2); 200–250 kg (G3); <200 kg (G4) as seen in Fig. 1 (b).

2.2. Experimental program

2.2.1. Materials

In the second step, in order to investigate the feasibility of replacing OPC with LS filler in Serbian conditions, four concrete mixtures were designed, with similar target strength and workability, but different compositions. The proportioning of the concrete mixture was done based on the absolute volume method. In addition to the traditional mixture using 330 kg of cement, three other mixtures were tested in which 30%, 45% and 55% of the cement, respectively, were replaced by LS powder.

Ordinary Portland cement CEM I 52.5R (max 5% additional constituents) was used for own tested mixtures. Commercially available high purity LS powder with the chemical composition in accordance with EN 197–1 [15] is applied: $CaCO_3$ content is 98%, $MgCO_3$ is 1.4%, Fe_2CO_3 is 0.1% and HCl insoluble content is 0.5%. The mean particle size of LS powder was $d_{50} = 5.36$ μm, which shows that LS has finer particles than OPC ($d_{50} = 11.1$ μm). A three-fraction (Danube) river aggregate with a nominal maximum aggregate size of 16 mm was used, as well as water from the city water supply. To ensure the desired workability of mixtures, besides adding a dosage of second-generation superplasticizer (based on polycarboxylate), it was necessary to increase the content of fine particles, so that the amount of LS added was larger than the amount of cement replaced.

The composition of the designed concrete mixtures, together with those selected from literature, is shown in Table 1. The values of all constituents are shown as mass per unit volume of concrete. The concrete mix code can be deciphered as XX-Y%-Z, where X is the symbol for the country of origin of the study, Y is the % of cement replacement and Z is the mass per unit volume of the CEM I component in the concrete mix. As seen in Table 1, all the concrete mix compositions were listed for the sake of later quantifying the attributable environmental and economic impact to each mix. The environmental impact was evaluated using an LCA methodology

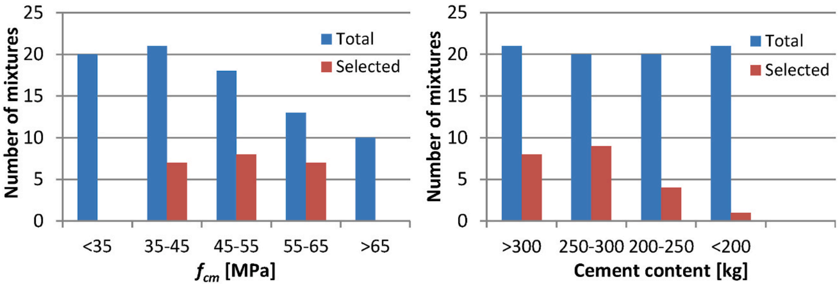

Fig. 1. Total number of concrete mixtures considered/selected in terms of compressive strength (a) and cement content (b).

Table 1
Composition of the selected concrete mixtures (alternatives).

Reference	Concrete Mix	CEM I [kg/m^3]	LS [kg/m^3]	Water [kg/m^3]	*w/c*	Plast. [kg/m^3]	Fine aggregate [kg/m^3]	Coarse aggregate [kg/m^3]
Radović et al., 2021	RS[a]-0%-330	330	0	169	0.51	3.3	963	887
	RS-30%-230	230	200	143	0.62	6.45	963	887
	RS-45%-180	180	250	126	0.70	8.6	963	887
	RS-55%-150	150	280	112	0.75	8.6	963	887
Palm et al., 2016/Neufert et al., 2014	DE[b]-0%-320	320	0	160	0.50	1.0	717	1157
	DE-35%-244	244	131	136	0.56	2.4	717	1157
	DE-50%-190	190	190	136	0.72	11.9	717	1157
Lollini et al., 2014	IT[c]-0%-300	300	0	183	0.61	2.5	1226	631
	IT-15%-212	212	38	152	0.72	4.0	1309	674
	IT-15%-255	255	45	183	0.72	2.5	1226	631
	IT-30%-210	210	90	138	0.66	7.0	1306	673
	IT-30%-245	245	105	161	0.66	5.0	1233	635
Collepardi et al., 2004	IT2-0%-400	400	0	160	0.40	2.0	874	1026
	IT2-0%-350	350	0	175	0.50	0.53	883	1037
	IT2-0%-300	300	0	180	0.60	0	904	1061
	IT2-15%-340	340	60	160	0.47	1.8	865	1015
	IT2-15%-297	297	53	175	0.59	0.35	879	1031
	IT2-15%-255	255	45	180	0.71	0.0	899	1056
	IT2-25%-300	300	100	160	0.53	1.8	867	1018
Leemann et al., 2015	CH[d]-0%-335	335	0	150	0.45	1.35	675	1252
	CH-0%-315	315	0	157	0.50	0.6	675	1252
	CH-15%-270	280	50	148	0.53	0.7	677	1253
	CH-15%-264	264	46	155	0.59	0.3	677	1254
Dhir et al., 2007/Meddah et al., 2014	GB[e]-0-355	355	0	185	0.52	0.4	670	1200
	GB-15%-302	302	53	185	0.61	0.4	670	1200
	GB-25%-266	266	89	185	0.7	0.4	670	1200

[a]RS – Serbia; [b]DE – Germany; [c]IT – Italy; [d]CH – Switzerland; [e]GB – United Kingdom.

involving six mid-point indicators: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Abiotic Depletion Potential (ADPE), Photochemical ozone creation potential (POCP), and Cumulative Energy Demand (CED). The economic impact evaluation covered the market price of every constituent and transportation costs.

2.2.2. *Testing of specimens*

After mixing, the standard slump/flow methods [50,51] were used for the quantitative assessment of concrete workability. Concrete was poured into molds and compacted using a vibrating table. For the compressive strength testing, 150 mm cube samples were prepared, while carbonation resistance was tested on 120 × 120 × 360 mm concrete prisms. After 24 h, the samples were removed from the mold and cured in water at a temperature of 20 ± 2 °C until the age of 28 days, at which point three cubic samples of each mixture were tested to obtain the compressive strength. However, for carbonation testing only two prismatic samples were conditioned for 14 days in a climate chamber at temperature 20 ± 2 °C and air humidity 65 ± 5%. After that, the specimens were placed for 28 days in a carbonation chamber exposed to a CO_2 concentration of 2% by volume under controlled temperature and air humidity [53]. Finally, carbonation depth measurements were performed with a phenolphthalein solution sprayed on the freshly broken concrete surface [54] on eight points per side. Measured carbonation depths were used to calculate the values of the carbonation coefficients and concrete cover depths.

2.3. *Applying the ECO_2 framework*

2.3.1. *LCA scope definition*

The first stage of an ECO_2 analysis consists in defining the scope for the LCA study, the scenarios; then define the alternatives which are the concrete mixes being compared, and collecting the necessary inventory data. The scope of an LCA study is the boundary which separates the included concrete activities out of the whole life cycle from the excluded ones. A typical scope could be Cradle-to-Grave, which includes the “Production”, “Use” and “End-of-Life” phases. However, there is no, to the best knowledge of the authors, reliable model to predict the amount of carbon dioxide sequestered by a high-volume limestone powder concrete mix. Hence, it was decided to exclude the “Use” phase in the LCA scope. Also, regarding the concrete production phase, transportation and casting, there is enough similarity across all alternatives to justify disregarding those without this leading to unrepresentative results and unrepresentative comparisons. Finally, the end-of-life activities, whether it is the demolition and landfilling or recycling into aggregates due to large uncertainties depending on the future waste management technologies, scenarios, recovered materials application, etc., was excluded from the calculations. Accordingly, for the purpose of this study, it was decided to accept a Cradle-to-Gate scope, Fig. 2. Having in mind all the previously adopted limitations and simplifications, it implies including all processes and emissions from the production of different concrete constituents and its transporting to the concrete batching plant.

2.3.2. Definition of alternatives and scenarios

The alternatives under comparison in LCA are all the concrete mixes that passed the criteria specified in section 2.1 including the authors’experimental results shown in section 2.2.

Structural elements of an RC structure (e.g. building) can be divided into vertical and horizontal according to their position, as well as linear and plate elements, according to their dimensions. Horizontal elements are predominantly loaded in bending and shear, whereas vertical elements are dominated by axial load. In order to perform a comprehensive analysis and include a sufficient number of parameters, two types of structural elements (slabs and columns) with two different geometries (loading) were analyzed. In this way, a total of four possible scenarios were formed.

2.3.3. Functional unit calculations

The functional unit (FU) is part of the LCA goal and scope definition responsible for the quantification of the environmental and economic impact indicators. In most LCA or LCC (Life Cycle Cost) frameworks, the functional unit is assumed as simply a unit volume (1 m^3) of concrete [55–58]. However, an FU that includes strength, durability, as well as serviceability, allows alternatives being properly evaluated and compared [59]. The volume of concrete per 1 m^2 of surface area of an RC slab and 1 m’ of length/height of an RC column, required for same strength, service life and serviceability, was adopted for the FU.

The first stage was to calculate, for each scenario of structural element and loading, the minimum concrete cover that would be enough to fulfill the required service life of 50 years without needing for significant maintenance or replacement. In this paper, the exposure class XC3 which includes concrete elements inside buildings with moderate humidity and not permanent high humidity, as well as external elements sheltered from rain was chosen. In the second stage the FU was corrected for strength and serviceability.

To the best knowledge of the authors, there are no models for assessing the durability of concrete with a high LS powder content, so the proposal given in the draft of the new version of Eurocode 2 [60] was used. In the mentioned document, concrete is classified in exposure resistance classes (ERC) against deterioration in the form of corrosion induced by carbonation (XRC) or chlorides (XRDS). ERC represents a set of requirements for concrete that are necessary to resist a certain exposure class [61]. For resistance against corrosion induced by carbonation – XRC [mm/$\sqrt{}$(years)] can be derived from the characteristic value (90% percentile) of carbonation depth [mm] assumed to be obtained after 50 years under reference conditions (400 ppm CO_2 in an environment with a constant RH of 65% and temperature of 20 °C), Equation (1):

$$XRC = k_{XRC} + 1.282 k_{XRC} CoV \approx 1.256 k_{XRC} \tag{1}$$

where k_{XRC} is the mean value of carbonation rate under XRC conditions and the coefficient of variation (CoV) is 20%. Depending on the test method used, the carbonation rate k can be compared to the XRC resistance class using Equation (2):

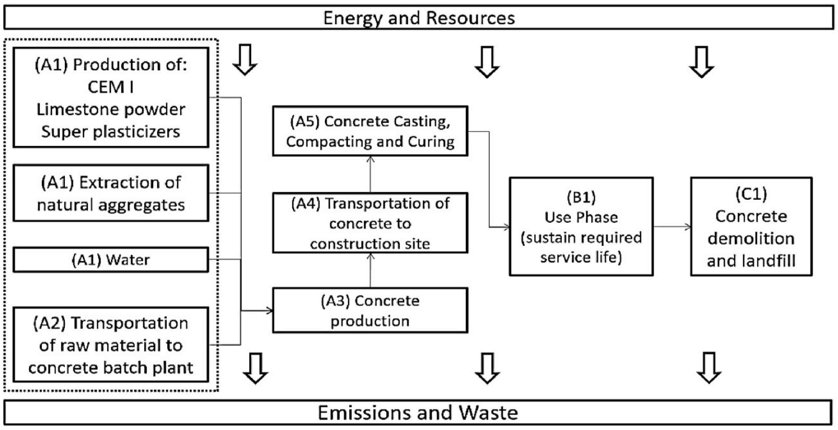

Fig. 2. LCA boundary and the scope selected for this study.

$$XRC > k(A)f_{exe}\left(\frac{1}{50}\right)^{n_{XRC}} = k(B)f_{env}f_{exe}\sqrt{\frac{0.04}{c_N}}\left(\frac{1}{50}\right)^{n_{XRC}} = k(C)f_{env}f_{exe}f_{AC}\sqrt{\frac{0.04}{3}}\left(\frac{1}{50}\right)^{n_{XRC}} \tag{2}$$

where:

k(A), k(B), k(C) - the carbonation rate depending on the applied test (outdoor sheltered, chamber test, accelerated carbonation, respectively) is determined in accordance with [62,63].

f_{exe} - effect of ***exe***cution (curing, compaction, and formwork after 50 year of exposure)
f_{env} - effect of different ***env***ironmental conditions (different from XRC)
f_{AC} - correction factor for the ***acc***elerated test condition (includes the effect of high CO_2 concentration under the curing and preconditioning)
c_N - is the ***n***atural CO_2 ***c***oncentration (sheltered outdoor conditions)
$\left(\frac{1}{50}\right)^{b_{XRC}-0.5} = \left(\frac{1}{50}\right)^{n_{XRC}}$ - time law, *bXRC* and *nXRC* time exponent under XRC

Numerical values of these factors depend on a number of parameters, and the most important are the applied test method and in some cases the exposure class. This paper considers the following (medium or conservative) values:

$f_{exe} = 1.1$ for A, *1.45* for B and C approach
$f_{env} = 0.7$ - *1.3* for XC3 (*1.0* is adopted)
$f_{AC} = 1.0$ for A and B, *1.26* for C approach
$n = 0.0 – 0.15$ for XC3 (0.0 is adopted)

For the purposes of this study, the recommended values for XRC classes range from 0.5 to 7 were extrapolated for two degrees, up to 9 according [61]. The assumption was adopted that concretes with value $XRC > 9$ cannot be used for structural applications due to poor carbonation resistance and potential corrosion of reinforcement. Finally, the value of *XRC* was converted to a minimum concrete cover $c_{\min,dur}$ by reading corresponding values from the table given in Ref. [61]. Values given herein are determined by calibration and verification based on experimental results, for the projected service life with a reliability index for the durability limit state $\beta = 1.5$ which implies initiation followed by a certain part of the corrosion propagation phase. The nominal concrete cover is defined according to Eq. (3).

$$c_{nom} = c_{\min,dur} + \Delta c_{dev} \tag{3}$$

The allowance in design for deviation, depending on tolerance class is $\Delta c_{dev} = 5–10$ mm. However, in this paper $\Delta c_{dev} = 0$ is adopted, which will be discussed in the sensitivity analysis.

As already mentioned, in the case of slabs, the volume of concrete per 1 m^2 of RC slab required for same strength, service life and serviceability was adopted for the FU. For slabs, design flexural resistance of RC slab M_{Rd} can be determined on the basis of Equation (4):

$$M_{Rd} = A_s f_{yd} d\left(1 - 0.513\frac{A_s f_{yd}}{bdf_{cd}}\right) \tag{4}$$

where:

A_s – cross sectional area of reinforcement
$f_{yd} = f_{yk}/\gamma_s$ – design value of longitudinal reinforcement yield strength
f_{yk}, $\gamma_s = 1.15$ – characteristic value of longitudinal reinforcement yield strength and partial safety factor for reinforcement, respectively
$b = 1000$ mm - overall width of slab cross section
d - effective depth of slab cross section
$f_{cd} = \alpha_{cc} f_{ck}/\gamma_c$ – design value of concrete compressive strength
$\alpha_{cc} = 1.0$ – taking account long term effects on the compressive strength (recommended)
$f_{ck} = f_{cm}$ – 8 MPa – the characteristic value of concrete compressive strength
f_{cm} – the mean concrete compressive strength at 28 days (cube converted into the cylinder)
$\gamma_c = 1.5$ – partial safety factor for concrete

For known common values of area and quality of reinforcement, as well as effective slab depth, by varying the strength of concrete in the range of C20/25 to C45/55, an increase of the ultimate flexure resistance of 4–7% was obtained. Therefore, it is reasonable to assume that the compressive strength of concrete has small effect on the load-bearing capacity of the slab and, hence, for this research purposes this beneficial effect is neglected. In this case, the compressive strength of the concrete is only indirectly (through carbonation resistance) included by the size of the concrete cover $h = d + c_{nom}$. If the same type and amount of reinforcement is assumed in all scenarios, flexural strength of slab depends only on effective depth d and reinforcement can also be excluded from further analysis. In order to consider the influence of different slab geometries and loads, 2 scenarios were considered. In scenario 1, with $d = 200$ mm, and scenario 2, with $d = 300$ mm. Required service life of 50 years was provided with adequate concrete cover for each alternative. Finally, similar serviceability (slab deflections) was assumed for all alternatives since reduced amount of cement paste mainly results in reduced shrinkage and creep of LS concrete [14,46,64].

In the case of columns, which are a typical vertical linear elements, the volume of concrete per 1 m' of column height required for same strength, service life and serviceability has been adopted for the FU. The design axial strength of a reinforced concrete column N_{Rd} can be expressed as:

$$N_{Rd} = N_{Ed} = A_c f_{cd} + A_s \sigma_s \tag{5}$$

where:

N_{Ed} – ultimate axial load in the column
$A_c = bh$ – cross sectional area of concrete (the square is assumed $b = h$)
σ_s – compressive stress in the reinforcement

The influence of reinforcement amount (A_s) on the resistance of the cross-section is the same in all alternatives since the minimum area resulted the same (dependent of the cross sectional dimensions, which coincides in all alternatives) and, consequently, it was neglected in the analysis. In this way, for a known axial load N_{Ed} and compressive strength of concrete, the required cross-sectional area can be determined, and thus the FU for each of the alternatives. In this general case of axially loaded RC columns, column's axial strength is insensitive to concrete cover size since this part of section also contributes to the mechanical performance of the column. As for RC slabs, similar serviceability (column displacement) was assumed for all alternatives. In scenario 3, the column on the ground floor of a 4-storey building was analyzed, and in scenario 4, the column of a 10-storey residential and commercial building. The

Table 2
Properties of selected concrete mixtures (alternatives, scenarios).

						FU - slab [m^3]/[m^2]		FU - column [m^3]/[m']	
Reference	Concrete Mix	Flow [mm]	Slump [mm]	$f_{cm,150}$ [MPa]	c_{nom} [mm]	Scenario 1	Scenario 2	Scenario 3	Scenario 4
						$d = 200$ mm	$d = 300$ mm	4 storey	10 storey
Radović et al., 2021	RS-0%-330		230	49.5	20	0.220	0.320	0.073	0.185
	RS-30%-230		250	50.0	25	0.225	0.325	0.073	0.185
	RS-45%-180		240	45.4	35	0.235	0.335	0.084	0.203
	RS-55%-150		210	46.4	35	0.235	0.335	0.084	0.203
Palm et al., 2016/Neufert et al., 2014	DE-0%-320	400		64.7	40	0.240	0.340	0.058	0.137
	DE-35%-208	380		50.1	45	0.245	0.345	0.073	0.185
	DE-50%-190	550		61.8	50	0.250	0.350	0.058	0.144
Lollini et al., 2014	IT-0%-300		200	56.5	40	0.240	0.340	0.063	0.160
	IT-15%-212		190	52.3	45	0.245	0.345	0.073	0.176
	IT-15%-255		180	43.7	50	0.250	0.350	0.090	0.221
	IT-30%-210		170	58.0	40	0.240	0.340	0.063	0.152
	IT-30%-245		165	55.1	40	0.240	0.340	0.068	0.168
Collepardi et al., 2004	IT2-0%-400		220	64	15	0.215	0.315	0.058	0.137
	IT2-0%-350		200	53.6	35	0.235	0.335	0.068	0.168
	IT2-0%-300		210	43	40	0.240	0.340	0.090	0.221
	IT2-15%-340		220	53.9	15	0.215	0.315	0.068	0.168
	IT2-15%-297		200	45	40	0.240	0.340	0.084	0.212
	IT2-15%-255		210	36.9	50	0.250	0.350	0.109	0.270
	IT2-25%-300		220	50.6	25	0.225	0.325	0.073	0.185
Leemann et al., 2015	CH-0%-335	420		58.7	45	0.245	0.345	0.063	0.152
	CH-0%-315	460		47.2	40	0.240	0.340	0.078	0.194
	CH-15%-270	420		49.7	40	0.240	0.340	0.073	0.185
	CH-15%-264	500		42.4	40	0.240	0.340	0.090	0.221
Dhir et al., 2007/Meddah et al., 2014	GB-0%-355		80	47.5	25	0.225	0.325	0.078	0.194
	GB-15%-302		80	43.2	40	0.240	0.340	0.090	0.221
	GB-25%-266		80	35.6	45	0.245	0.345	0.116	0.281

-where $f_{cm,150}$ is the mean value of concrete cube (150 mm) compressive strength.

estimated axial forces in the columns are $N_{Ed} = 1600$ kN and $N_{Ed} = 4000$ kN, for scenario 3 and scenario 4 respectively. Table 2 shows the individual properties of all alternatives, including workability, compressive strength, nominal value of the concrete cover depth, as well as the calculated FU for 4 different scenarios.

Graphical representations of FUs are given in Fig. 3. The FUs in scenarios 3 and 4 are dominantly affected by the compressive strength of concrete, rather than cement content. It seems that the lower the cement content, the lower carbonation resistance is, which is also affected by the *w/c* ratio. This requires a higher concrete cover depth to ensure the required services life of structures. However, the increase in concrete cover is negligible compared to the total volume of the RC element and its influence on the FUs is minimal.

2.3.4. Inventory data

As per the defined scope, the next step in an LCA is to source the energy and emissions associated with all activities and materials included. It is advised that users rely on primary inventory data such as environmental product declarations (EPD) of the concrete raw materials or source measurements whenever possible. However, in this case due to the scatter of the experimental data sources, secondary inventory databases were used. In order to increase the reliability of the utilized secondary inventory data, the authors opted to calculate an average of a combination of established databases such as Ecoinvent and previously published papers [39,65–67]. The environmental impact could be demonstrated through absolute measurements of emissions, deposits and waste. It is more common to show it through mid-point environmental impact indicators, which are numbers that correlate the calculated impact to a specific change in the environment such as global warming potential to make the output of the impact assessment study more understandable to the user [68]. Six mid-point indicators are used in this study: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Abiotic Depletion Potential (ADPE), Photochemical ozone creation potential (POCP), and Cumulative Energy Demand (CED).

The economic impact is conveyed through the market price, which includes all constituent materials and transportation costs. The concrete production, transportation, and casting phases are the same for all alternatives and, consequently, these were discarded in the analysis. The inventory database of the average values for each concrete constituent across the selected indicators is found in Table 3.

2.3.5. Impact assessment

As explained, the concrete production phase is excluded, so the Cradle-to-Gate scope includes only what is labeled as upstream impact including only the production and transportation of concrete mix constituents. Hence, for each concrete mix, the environmental and economic impact per unit volume is calculated by multiplying the inventory impact of producing and transporting every constituent by its mixing proportion for every alternative as per Equation (6).

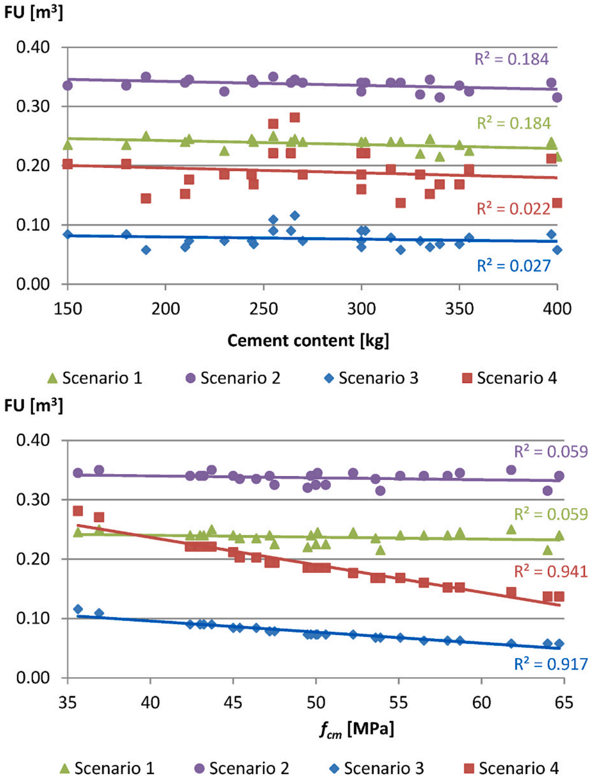

Fig. 3. FU regarding cement content (a) and compressive strength (b) for all 4 considered scenarios.

Table 3
Summary of the environmental and economic inventory data and transportation distances/types for the LCA study.

	Constituent	CEM I	LS powder	Nat Coarse Agg	Nat Fine Agg	Super Plasticizers	Water	Large truck
	Unit	/kg	/kg	/kg	/kg	/kg	/kg	/tkm
GWP	kg CO_2 eq	8.96E–01	1.21E–01	1.03E–02	6.72E–03	8.61E–01	2.50E–04	3.09E–01
AP	kg SO_2 eq	2.90E–03	1.61E–04	1.53E–05	8.10E–06	5.44E–02	4.68E–07	2.71E–04
EP	kg PO_4 eq	4.16E–04	3.23E–05	5.39E–06	2.82E–06	9.23E–04	1.26E–07	1.74E–04
ADPE	kg Sb eq	1.35E–03	1.66E–04	1.49E–05	5.07E–05	4.94E–03	6.83E–07	5.79E–04
POCP	kg C_2H_4 eq	1.14E–04	5.32E–06	4.53E–06	9.83E–07	1.88E–04	6.32E–08	5.18E–05
CED	MJ	4.19E+00	7.64E–01	7.19E–02	5.78E–02	1.98E+01	2.95E–04	1.74E+00
MP	€	9.60E–02	3.44E–02	1.39E–02	1.48E–02	1.78E+00	3.28E–03	5.83E–02
TD	Km	5.91E+01	9.30E+01	9.30E+01	9.30E+01	5.39E+02	0.00E+00	–

GWP - Global warming potential; **AP** - Acidification potential; **EP** - Eutrophication potential; **ADPE** - Abiotic Depletion Potential; **POCP** - Photochemical ozone creation potential; **CED** – Cumulative Energy Demand; **MP** – Market price; **TD** – Transportation distance by truck.

$$\frac{GWP_i}{m^3} = \sum\nolimits_{j=1}^{n} \left(\frac{GWP_{j,upstream}}{kg} \times \frac{kg_j}{m^3} \right) \tag{6}$$

The total impact per unit volume is then multiplied by the functional unit of each alternative in order to account for the discrepancies in the concrete performance across the different mixes. The six environmental indicators and single economic indicator are then normalized, according to Equation (7):

$$GWP_n = \frac{1.1 \cdot \max(GWP_i) - GWP_i}{1.1 \cdot \max(GWP_i) - 0.9 \cdot \min(GWP_i)} \tag{7}$$

The maximum values of indicators were enlarged and the minimum ones were reduced by 10%, for each value function [38]. Hence, the alternative with the lowest impact in each indicator gets a maximum value (<1) and the one with the highest impact has a minimum value (>0).

2.3.6. ECO_2 score calculations

A single environmental impact indicator, *V* is then calculated by averaging all six normalized environmental impact indicators as per Equation (8). Finally, the ECO_2 score is calculated for each alternative as a weighted average of the scores of its normalized single

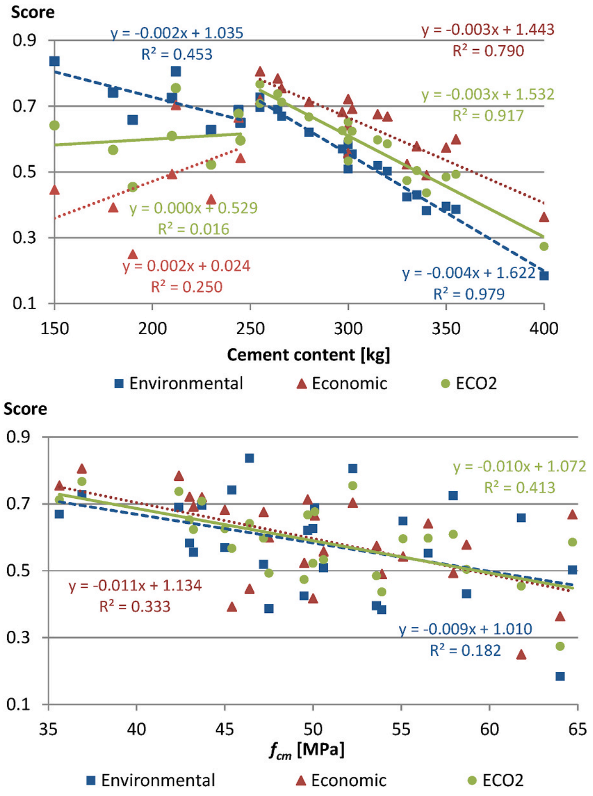

Fig. 4. Environmental, economic, and sustainability (ECO_2) scores for 1 m^3 ready-mix concrete considering cement content (a) and compressive strength (b).

environmental score V and the normalized market price X as per Equation (9).

$$V_i = \frac{1}{6} \times (GWP_n + AP_n + EP_n + ADPE_n + POCP_n + CED_n) \tag{8}$$

For this study, ECO_2 scores of each scenario were calculated in 3 different ways i.e. weight distributions: the “default” one where weights W_1 and W_2 are equal, the environmental advantage distribution (2:1) where W_1 is 0.667 and W_2 is 0.333, and the economic advantage distribution (1:2) where the weights are reversed.

$$ECO_{2,i} = V_i \times W_1 + X_i \times W_2 \tag{9}$$

3. Results and discussion

3.1. Sustainability assessment per unit volume

For each alternative, calculations were first performed at the volume level of 1 m^3 of ready-mix concrete, in order to compare results obtained in such a way with results obtained with proper FUs. ECO_2 scores for 1 m^3 of ready-mix concrete in relation to cement content and compressive strength are shown in Fig. 4.

A large scatter of results is evident, especially comparing ECO_2 scores and compressive strength. Relationships between environmental, economic and ECO_2 scores versus cement content ($R^2 = 0.98$; 0.79; 0.92; respectively) are pretty clear and reliable for concretes with $\geq$250 kg cement. The decreasing trend of all mentioned scores with an increase in the amount of cement is obvious. Other relations cannot be reliably determined because the coefficients of determination are too low. In some number of mixtures with a relatively small amount of cement ($<$250 kg), a low value of the economic score ($<$0.5) is observed, which is a consequence of the increased content of plasticizers (the most expensive constituent) in order to achieve satisfactory workability. As the ecological and economic criteria equally participate in the ECO_2 score, this significantly reduces the final sustainability score. These mixtures are mainly responsible for the dispersion of results. Observing the whole range of cement content, trendlines seem to follow a bilinear (environmental and ECO_2) or even triangle distribution (economic). It means that technology related to a concrete with high LS powder (reduced cement) content is not completely mastered yet. Therefore, the economic benefit brought by lower cement content is not always guaranteed. If only volume is considered for FU, the following ranking of alternatives was obtained (Fig. 5):

- The five concrete mixtures with the highest ECO_2 score were: IT2-15%-255 (G2), IT-15%-212 (G3), CH-15%-264 (G2), GB-25%-266 (G2), and IT-15%-255 (G2). Four of the top five mixtures are from the G2 (250–300 kg) group, and one is from G3 (200–250 kg).
- These mixtures have almost equal sustainability scores (0.71–0.77), i.e. the difference in ECO_2 score between the first and second mixture is negligible at 0.02 and between the first and fifth mixture is only 0.06.
- The differences between first and fifth mixtures in the environmental and cost criteria are slightly higher than ECO_2 ones and amounts 0.14 and 0.1 respectively. Also, the relatively high differences between economic and environmental criteria in the one mixture are possible. That is why these mixtures are sensitive to the change in weight coefficients, so in the case of environmental advantage, IT-15%-212 is slightly more favorable than IT2-15%-255, while in the case of economic advantage, CH-15%-264 is in the second place after IT2-15%-255.

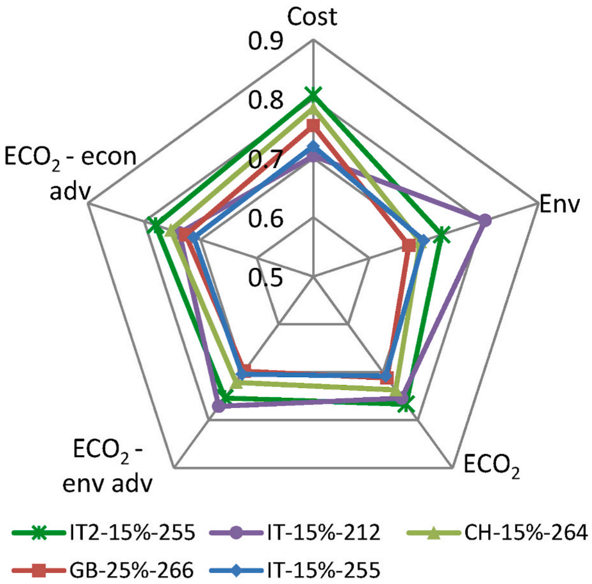

Fig. 5. Environmental, economic, and sustainability (ECO_2) scores for 1 m^3 - the best five mixtures.

- The fourth and fifth mixtures have the same value of the ECO_2 score of 0.71 regardless of the weight coefficients values. In this case, a change in the weight coefficients (2:1) in favor of environmental or economic criteria has virtually no impact on the value of the ECO_2 score.
- There is no G1 (>300 kg) and more interestingly, there is no G4 (<200 kg) concrete in the best five mixtures. The best G1 mixture (IT2-0%-300) is in the eighth, and the best G4 (RS-55%-150) is in the ninth place. Characteristic of the RS-55%-150 is the highest environmental (0.84) and almost the lowest economic (0.45) score, which affects the final ECO_2 score.
- Here it should be kept in mind that 1 m^3 of compared alternatives cannot fulfill the same functional requirements – these results are only indication of their sustainability potential, while sustainability assessment should be based on the FU which encompasses all functions of the structure.

3.2. *Sustainability assessment per functional unit*

The environmental, economic and sustainability scores were calculated per FU versus cement content for scenarios 1 and 2 and compressive strength for scenarios 3 and 4 as plotted in Fig. 6.

Similar to the FU equal to 1 m^3 of ready mix concrete, the most pronounced trend is the decrease of the environmental score with the increase in the amount of cement, only for scenarios 1 and 2, with a significantly lower coefficient of determination ($R^2 = 0.63$). On the other hand, relationships between economic and ECO_2 scores versus cement content are unclear neither for concretes with ≥250 kg cement. Interestingly, for scenarios 3 and 4, a very good correlation of all considered criteria with concrete compressive strength is observed. The dominant influence of this parameter on FU is evident. Trendlines with relatively high coefficients of determination (0.69–0.85) of environmental, economic, and ECO_2 scores almost coincide. The increase in strength for every 5 MPa results in a fairly high average increase in all scores of about 0.1.

Fig. 7 presents the variability of the calculated ECO_2 scores per FU (from highest to lowest) for alternatives from each G1–G4 group and different scenarios. Also, the mean compressive strength (f_{cm}) of each alternative was shown as a point. Comparing the results of scenarios 1 and 2, it can be concluded that the volume of FU can affect the relative relations of individual scores, and the order of alternatives but only when their scores are very close. The range of results within a group can vary significantly. Groups G2 and G3 have the smallest score value variation of 0.12–0.13 in scenarios 1 and 2 which gives reliability to the judgment. Groups G1 and G4 have more than twice the result range for the same scenarios. Generally, the results of scenarios 1 and 2 seem less scattered statistically.

The influence of concrete compressive strength on the order of alternatives in scenarios 3 and 4 is dominant, so the variation of the results is even more pronounced. The difference in strength of alternatives within G1 of about 20 MPa resulted in a difference in the sustainability score of 0.41–0.88. In group G2 for smaller strength differences (about 15 MPa), the difference in scores is even more

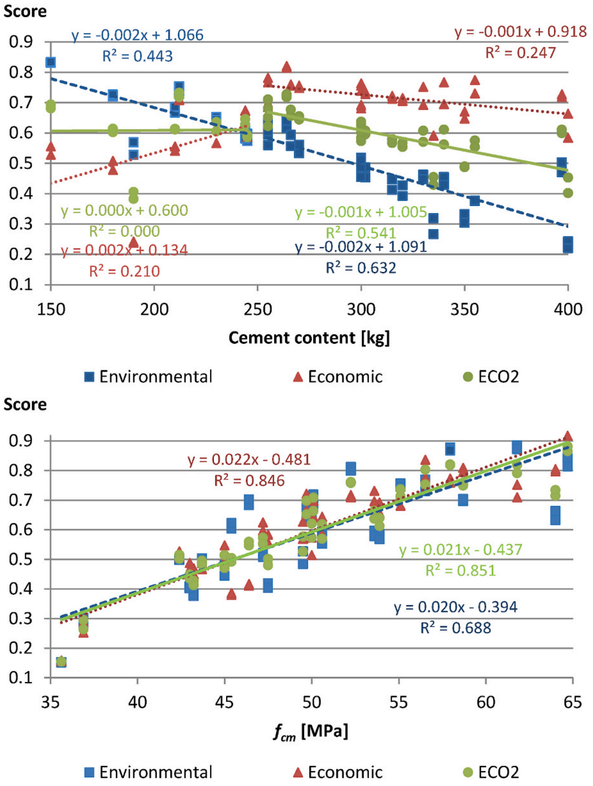

Fig. 6. Environmental, economic, and sustainability (ECO_2) scores per FU versus cement content for scenarios 1 and 2 (a) and compressive strength for scenarios 3 and 4 (b).

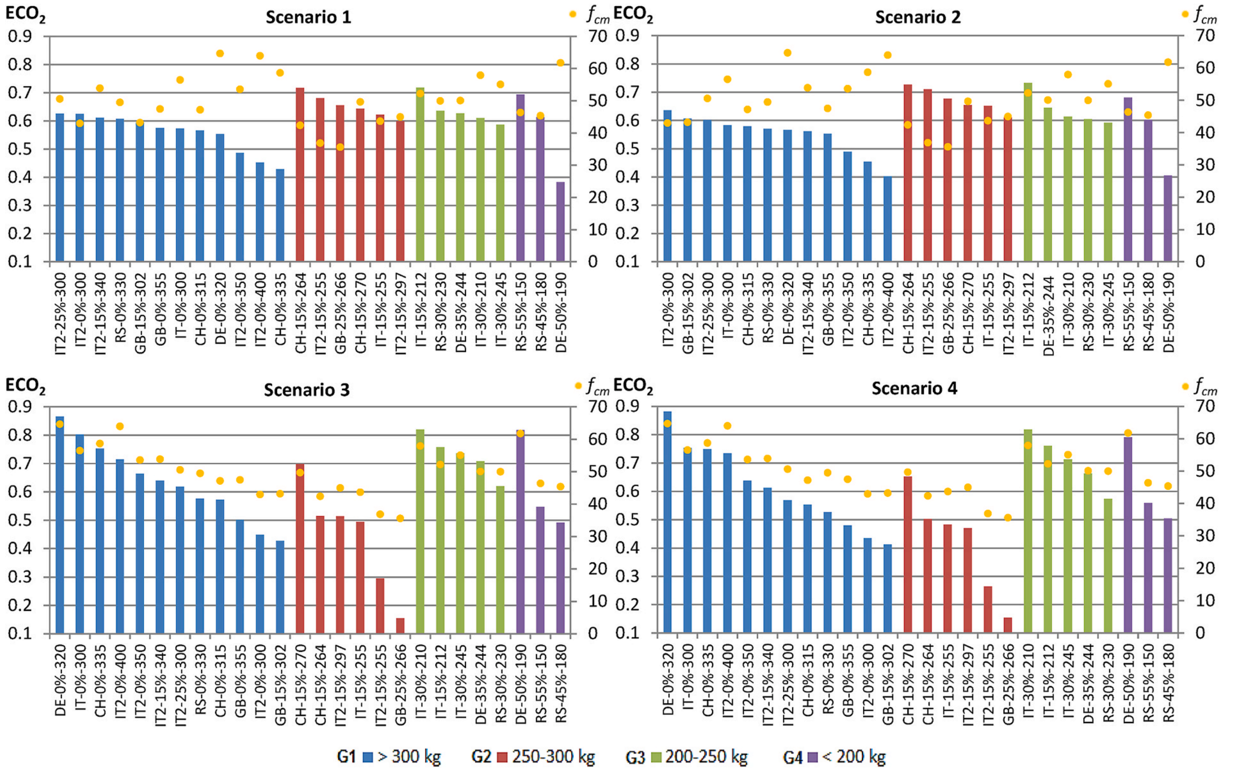

Fig. 7. Sustainability (ECO$_2$) scores per FU for G1-G4 alternatives and different scenarios: a) Scenario 1; b) Scenario 2; c) Scenario 3; d) Scenario.

pronounced, 0.15–0.70. The smallest variation of the scores (0.57–0.82) was recorded in the alternatives from G3, due to the smallest difference in strength (8 MPa). Strength of concretes from group G4 (45–62 MPa) resulted in an ECO$_2$ score value in the range 0.49–0.82. In scenarios 3 and 4, if mixtures from the same group are compared, with similar compressive strength, the advantage is mostly on the side of the one with lower cement content.

Environmental, economic, and sustainability scores per FU for the best five concrete mixtures (with the highest ECO$_2$ scores) and different scenarios are shown in Fig. 8. For both scenarios 1 and 2, all these mixtures contain LS: IT-15%-212 (G3); CH-15%-264 (G2); RS-55%-150 (G4); IT2-15%-255 (G2); GB-25%-266 (G2). Three of the top five mixtures are from the G2 (250–300 kg) group, and one each from groups G3 (200–250 kg) and G4 (<200 kg), i.e. there is no OPC (G1) concrete. All these mixtures have practically equal sustainability scores, more precisely, the differences between the first IT-15%-212 and fifth GB-25%-266 mixture in ECO$_2$ score is about 0.06. This difference is small enough that no mixture can be declared the best, so all five should be considered potentially optimal solutions. It is worth mentioning that the mixture RS-55%-150 (G4) was in the ninth place when observing 1 m^3, and now is in the third and fourth place in scenarios 1 and 2 respectively. The mixture with the highest ECO$_2$ score from the group G1 is in ninth place.

Conversely, the differences between the first and fifth mixture in the environmental and cost criteria are significantly higher than the ECO$_2$ ones, up to 0.3. In case of environmental criteria, the mixture with the highest score (0.83) was RS-55%-150, and mixture with the lowest one (0.56–0.59) was GB-25%-266. The best economic score (0.78–0.82) had the mixture CH-15%-264, and the worst (0.53–0.56) had RS-55%-150. The high difference in environmental and economic scores makes alternatives sensitive to changing weight coefficients. This effect is particularly pronounced in the mixtures which have a large deviation of the economic and environment scores, such as RS-55%-150 (0.53–0.83) and CH-15%-264 (0.61–0.82). So, in the case of environmental advantage, RS-55%-150 has the best ECO$_2$ score in scenario 1 and shares the first place with IT-15%-212 in scenario 2. The order of other alternatives is unchanged. When criteria weights are changed in favor of the economy, CH-15%-264 became a mixture with the highest score and RS-55%-150 with the lowest, in both scenarios. The very close values of the ECO$_2$ scores (0.66–0.73) of the best alternatives in these scenarios additionally affect sensitivities to weight change.

Generally, the effect of the change in the FU values due to different carbonation resistance, in both scenarios 1 and 2, has minimal effect on the order of top five mixtures according to any criteria, but affects the relative difference between individual scores. The increase in slab heights due to different concrete covers, expressed as a percentage of total height, is small enough not to change the ranking of alternatives for both scenarios: the benefits brought by a reduced amount of cement overcome larger FU volume. If compared with FU based on unit volume, results are not significantly altered: the difference between the first and fifth mixture is the same, but the ranking is slightly changed due to very small differences in ECO$_2$ scores. The most significant transition is the relegation of the IT-15%-255 mixture from the top 5, and the entry of RS-55%-150. This suggests that the choice of FU volume is not significantly

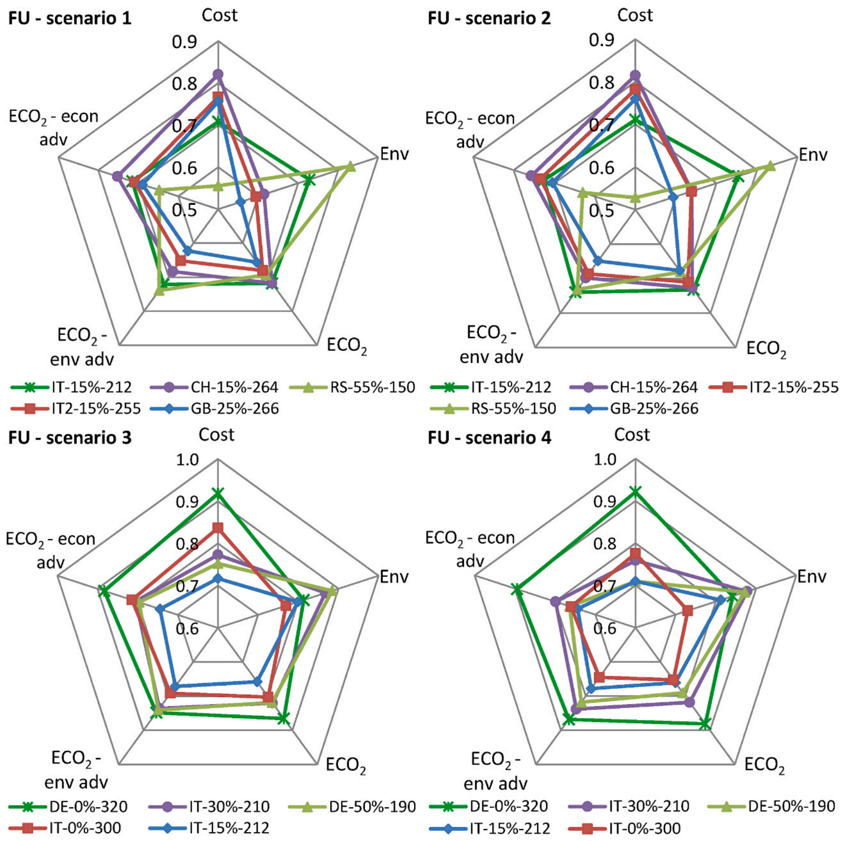

Fig. 8. Environmental, Economic, and Sustainability (ECO_2) scores per FU for the best five mixtures in each scenario: a) Scenario 1; b) Scenario 2; c) Scenario 3; d) Scenario 4.

important if it is affected only by service life and not by strength and serviceability requirements.

Analyzing the results obtained for scenarios 3 and 4, a different order of alternatives, compared to FU based on unit volume, was observed. The five concrete mixtures with the highest ECO_2 score were: DE-0%-320 (G1), IT-30%-210 (G3), DE-50%-190 (G4), IT-0%-300 (G1), and IT-15%-212 (G3). Two of the top five mixtures are from the G1 (>300 kg) group and three others containing LS: two from the G3 (200–250 kg), and one is from G4 (<200 kg), but there is no concrete from G2 (250–300 kg) due to the lowest compressive strengths of mixtures from this group. The differences between the first and fifth mixture in the ECO_2 scores are about 0.12, twice as large as in the previous two scenarios. The first four mixtures in scenario 3 have similar ECO_2 scores (0.80–0.87), so there are four potentially optimal solutions in this scenario. The larger size of the FU in scenario 4 brings the higher differences in ECO_2 score, without changing the order. Due to the best economic and relatively good environmental score, a mixture DE-0%-320 with the ECO_2 score of 0.88 in scenario 4, followed by IT-30%-210 with a score of 0.82 represent potentially the most sustainable choice.

The differences between the first and fifth mixture in the environmental and cost criteria are smaller than in the previous two scenarios. In scenarios 3 and 4, the highest environmental score (0.87–0.88) had mixtures IT-30%-210 and DE-50%-190, while the highest economic score (0.92) had DE-0%-320. The mixture with the lowest environmental score (0.73–0.77) was IT-0%-300 until the lowest economic score (0.71) had mixtures IT-15%-212 and DE-50%-190.

Smaller differences in the environmental and economic indicators make alternatives less sensitive to changes in weight coefficients in scenarios 3 and 4. Moreover, the order of alternatives is almost unchanged regardless of the value of the weights, but the relative differences are subject to change.

In scenarios 3 and 4, due to the nature of the structural performance requirements in columns, the dominant influence of the compressive strength of concrete, is evident. These results are significantly different compared to results obtained for FU equal to 1 m^3. This suggests that for structural applications where the strength of an element primarily depends on the concrete compressive strength, FU based only on unit volume should not be used in assessments.

4. Sensitivity analysis

In order to determine the influence of critical variables on the final sustainability scores, a sensitivity analysis was performed. By changing each of the key parameters separately, while all other values remain constant, the entire calculation procedure is repeated and the effect is determined. The influence of concrete cover depth, cost of cement, LS powder and superplasticizer were tested.

In the first step, the influence of the concrete cover depth was analyzed. By varying the input parameters in Equation (2), different values of the concrete cover can be obtained from those calculated. Adopting values $n > 0$ and $f_{env} < 1$, resulted in a 30–50% reduction in the concrete cover, but the FU reduction effect was significantly lower, 4–6% for scenarios 1 and 2. In addition, the number of mixtures that meet the condition $XRC < 9$ increased by 10–15. However, this had no effect on the final order of alternatives. The adoption of $\Delta c_{dev} > 0$ did not affect the results also, because practically the same effect was achieved with all alternatives. Additionally, any change in the size of the concrete cover does not affect the size of the FU in scenarios 3 and 4. Based on the above, it can be concluded that all adopted assumptions are justified.

In the second step, the influence of variation in the cost of the main component materials - cement, LS powder and superplasticizer - was investigated. Sensitivity analysis results are shown in Fig. 9.

Because of the very small difference between ECO_2 scores of some alternatives in scenarios 1 and 2, with a 25% increase in the price of cement, the order of alternatives is slightly changed. Namely, a mixture with lower cement content RS-55%-150 had the highest score in scenario 1, and the third score in scenario 2. In scenario 3 DE-50%-190 had a bit higher score than IT-30%-210, while in scenario 4 the order of alternatives is not changed.

The price of LS powder primarily depends on the fineness of grinding, i.e. particle size distribution, and can vary significantly from the adopted average value in Table 3. An increase in the price of LS powder by 50% has no significant effect on the results in scenarios 3 and 4, but it has in scenarios 1 and 2. In scenario 1 alternative RS-55%-150 had the fifth place, while in scenario 2, shared fifth place with 4 other alternatives that were not from the top five.

Although it is one of the most expensive components, the effect of superplasticizers is often neglected due to its small content in the mixture. However, in the case of concrete with a high content of LS powder (Table 1), its impact, especially on the economic score, can be significant and should be considered. Reducing the price of superplasticizers by 25% in all mixtures led to some changes in the order of alternatives in all scenarios, mostly in benefit of alternatives with high LS content (RS-55%-150; DE-50%-190). With a further reduction in the price of superplasticizers, 50% of the initial value, RS-55%-150 becomes the best choice in scenario 1 and shares first place in scenario 2; also some new mixtures (RS-45%-180, RS-30%-230, IT-30%-210) appear in the top 5. In scenario 3, the best choice becomes DE-50%-190, while in scenario 4 this mixture is in the second place and has a practically equal score as IT-30%-210. It is obvious that LS concretes come to the fore with the reduction of the price (and/or amount) of superplasticizers.

It is worth mentioning, that the best mixtures in scenarios 1 and 2 (IT-15%-212) as well as 3 and 4 (DE-0%-320), have almost constant sustainability scores in all analyzed cases.

The previous results are not surprising; since the scores of certain alternatives are very close, small changes in the input data can affect their ranking. Therefore, the variation of individual parameters does not lead to excessive changes in the sustainability scores, but relatively small changes are sufficient to affect the existing order.

5. Conclusions

Achieving low-carbon concrete is one of the priorities on the path of sustainable construction development. In that sense, the

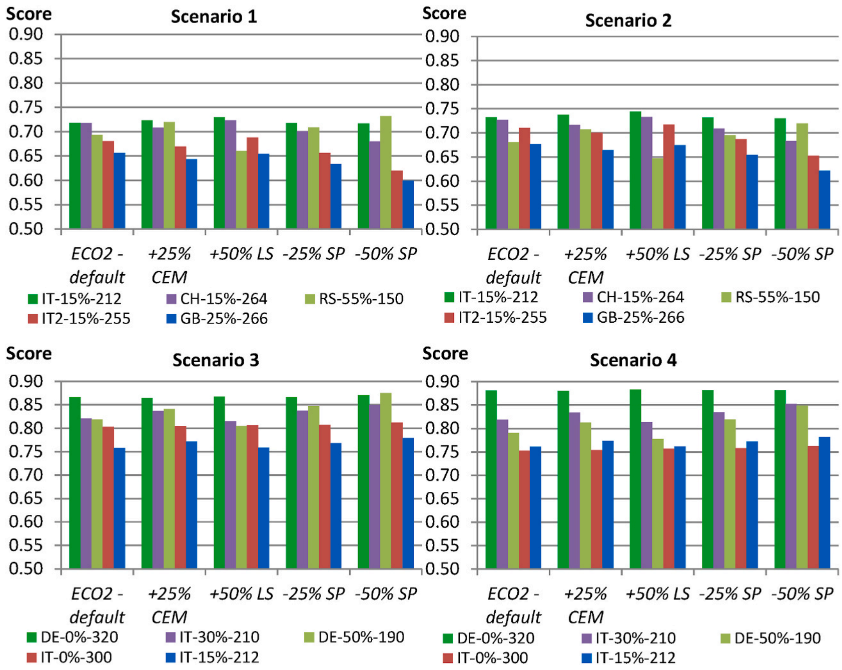

Fig. 9. Sustainability (ECO_2) scores regarding sensitivity analysis for the best five mixtures in each scenario: a) Scenario 1; b) Scenario 2; c) Scenario 3; d) Scenario 4.

application of structural concrete with reduced cement and high LS powder content can be a response to modern tendencies of conserving natural resources and reducing the negative impact of the concrete industry on the environment. In this study, 26 experimentally verified, different kinds of concrete mixtures in which LS powder was used as OPC replacement and comparable OPC concretes were evaluated in their sustainability aspect which includes economic, environmental, as well as performance-based criteria. The assessment of the collective sustainability score based on the previous criteria was performed using the multi-criteria decision analysis framework ECO_2. The potential application of these concretes was analyzed through two types of selected structural elements, with different stress state and geometry (slabs and columns), which made a total of four possible scenarios. Mixtures were grouped according to the total amount of cement in four groups: >300 kg (G1); 250–300 kg (G2); 200–250 kg (G3): <200 kg (G4).

Based on the research conducted in this paper, the following conclusions can be drawn:

- Since compared concretes can potentially have different performances, the results can vary greatly depending on the FU adopted. Therefore, it is necessary to include mechanical properties as well as durability parameters in the FU. The compressive strength of concrete does not have a direct effect on FU for structural elements loaded in bending (i.e. slabs), whereas in the case of columns this connection is linear.
- The average compressive strength of concrete containing LS powder for all groups (G2, G3 and G4) was about 10% lower, while the concrete cover depth for the designed service life of 50 years was higher for 27% compared with OPC concretes (G1). This resulted in a slightly higher FU of concrete with LS powder, for about 2% and 8% in the case of RC slabs and RC columns, respectively.
- Although concretes with a high LS powder and reduced cement content, primarily groups G4 and G3 (RS-55%-150; DE-50%-190; IT-30%-210) have a clear environmental advantage, their economic potentials are practically the lowest (highest cost), which significantly affects the overall score, especially in scenarios 3 and 4. This is due to a large amount of relatively expensive superplasticizer in these mixtures, as shown in the sensitivity analysis. In order to fully exploit the large environmental potential, further research should focus on optimizing the G4 and G3 mixtures, as well as on the development of more powerful superplasticizers. The application of some of the particle packing optimization methods can also reduce the content of superplasticizers without jeopardizing the workability of the mixture, which would significantly improve their economic score and make them competitive in all areas.
- When it comes to slabs, concretes containing LS are a more favorable choice in terms of sustainability than OPC concrete. Three of the best five mixtures (with the highest ECO_2 scores, for equal weight coefficients) are from the G2 group (CH-15%-264; IT-15%-255; GB-25%-266), and one each from groups G3 (IT-15%-212) and G4 (RS-55%-150), i.e. there is no OPC (G1) concrete. These mixtures have practically equal scores (0.66–0.72); therefore, all five should be considered potentially optimal solutions. Such close overall scores, as well as a large difference between environmental and economic scores within some mixtures, make these relatively sensitive to possible changes in input parameters or weights.

  •When considering columns (for equal weight coefficients), there are four potentially optimal solutions DE-0%-320 (G1), IT-30%-210 (G3), DE-50%-190 (G4), IT-0%-300 (G1) in scenario 3, and only two in scenario 4 (DE-0%-320, IT-30%-210). The equal presence of LS and OPC concretes in these two scenarios is a consequence of a slightly higher compressive strength of OPC concrete. The mentioned optimization of mixtures from G4 and G3 groups could also increase the compressive strength of LS concrete which is most important for columns. The increase in strength for every 5 MPa leads to a high average increase in all (environmental, economic and ECO_2) scores of about 0.1. This can affect the order of alternatives and prevail in favor of concrete with a high LS powder content.

The results of this study depend on a number of adopted assumptions, sources of input data and all uncertainties related to those, which mean that these should not be generalized when interpreting conclusions. The sensitivity analysis showed that adopted assumptions are justified, but also potentially narrows the stability intervals of some variables. Further research in this area with a higher number of alternatives and a wider range of input parameters is necessary in order to draw more general conclusions. Finally, the development of a model for estimating CO_2 uptake for concretes with a high LS powder content would enable the analysis of a whole life cycle of the concrete structure.

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CRediT authorship contribution statement

Andrija Radović: Conceptualization, Formal analysis, Investigation, Writing – original draft. **Hisham Hafez:** Conceptualization, Formal analysis, Investigation, Writing – original draft. **Nikola Tošić:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Snežana Marinković:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Albert de la Fuente:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Supplementary data is provided for this article

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Appendix A. Supplementary data

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