Construction and Building Materials 435 (2024) 136847

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Decarbonization potential of steel fibre-reinforced limestone calcined clay cement concrete one-way slabs

Hisham Hafez [a,*], Beatrice Malchiodi [b], Nikola Tošić [c], Michal Drewniok [a], Phil Purnell [a], Albert de la Fuente [c]

[a] School of Civil Engineering, University of Leeds, Leeds LS2 9JT, United Kingdom
[b] Laboratory of Construction Materials, École Polytechnique Fédérale de Lausanne, EPFL, Lausanne CH-1015, Switzerland
[c] Universitat Politècnica de Catalunya, Civil and Environmental Engineering Department, Jordi Girona 1-3, Barcelona 08034, Spain

ARTICLE INFO

Keywords:
Limestone calcined clay cement
Fibre-reinforced concrete
Life cycle assessment
Recycled fibres
Carbonation
Functional unit

ABSTRACT

This study deals with a comparison of the environmental performance of one-way slabs utilizing steel fibre-reinforced limestone calcined clay cement (LC^3) concrete with the control case of Ordinary Portland cement concrete. The experimental program constituted compressive and residual strength testing of concrete mixes and beams reinforced with traditional longitudinal steel reinforcement as opposed to steel fibres. The code-compliant design of the one-way slabs confirmed that, by adding steel fibres, 45% replacement of longitudinal steel reinforcement could be achieved. The cradle-to-gate life cycle analysis proved that the use of LC^3 as a binder and integration of steel fibres lowers the environmental impact of one-way slabs by 10% despite the slight increase in the concrete cover of the steel fibre-reinforced concrete slabs for carbonation resistance purposes. Several scenario analyses were carried out to confirm that the savings could reach 40% depending on concrete mix design optimization and the potential use of recycled fibres.

1. Introduction

1.1. Background

The increasing demand for concrete to meet the growing urban requirements is alarming in light of the gross environmental burden attributed to the construction sector [1]. The need for a sustainable built environment is directing construction and building materials research towards exploring effective strategies decarbonize concrete production [2]. The structural components (concrete and steel) of reinforced concrete buildings are key to its carbon footprint reduction potential as they constitute 90% of its carbon footprint [3]. To be more specific, slabs contribute more than 50% to the concrete volume in a building and hence are responsible for approximately 60% of building's environmental impact [4,5]. One-way slabs are the most well-known flooring system for residential buildings in several countries [6] and hence this study focuses on studying two main strategies to enhance their decarbonization potential.

The first decarbonization strategy is to reduce the amount of clinker in the cement used in concrete [7]. The fact that 1 kg of clinker, the main component in Ordinary Portland cement (OPC) results in an almost equal amount of CO_2 emissions highlights the decarbonization potential of partially replacing it with low carbon Supplementary Cementitious Materials (SCMs) [8]. Typically, industrial by-products such as fly ash and ground granulated blast furnace slag are used as SCMs, but the reduction in coal-fired power plants and blast furnace steel production respectively means less future availability of both [9]. Hence, the decarbonization potential of utilizing Limestone Calcined Clay Cement (LC^3) as a binder in which up to 50% of clinker is replaced is considered significant [10]. Moreover, the limestone and kaolinitic clays required for LC^3 production are abundant worldwide, enabling a widespread deployment of this technology [11]. Previous studies show that LC^3 concrete utilizing clays with >40% kaolinitic content exhibits comparable compressive strength to a reference OPC concrete [12]. The addition of calcined clay is associated with lowering the workability of concrete, but specific water-reducing admixtures are proven to be effective in resolving this issue [13]. Regarding durability, LC^3 concrete was proven to have a substantially higher resistance to chloride ingress [14]. The structure performance of LC^3 concrete was assessed in precedent studies [15,16], but a gap remains on its specific use with steel

* Corresponsing author.
E-mail address: h.hafez@leeds.ac.uk (H. Hafez).

https://doi.org/10.1016/j.conbuildmat.2024.136847
Received 6 March 2024; Received in revised form 23 April 2024; Accepted 28 May 2024
Available online 30 May 2024

fibres in reinforced concrete applications.

The second decarbonization concrete production strategy is the integration of structural fibres to produce fibre-reinforced concrete (FRC) [17]. Several international standards and guidelines already allow for the usage of fibres in concrete for structural applications [18,19]. The addition of amounts ranging between 0.5% and 1.0% by volume of steel and/or macro-synthetic polymeric fibres has shown significant enhancement of the post-cracking) tensile strength [20], energy absorption [21] and post-cracking behaviour of structural concrete elements [22]. The ability to reduce the size of the structural reinforced concrete sections and partially replace the traditional steel reinforcement used in a member is hence considered as a promising decarbonization strategy [23].

An established method to calculate the environmental impact of concrete is Life Cycle Assessment (LCA). LCA is the study of the environmental impact resulting from resource use and emissions attributed to all processes defined within a specific scope of a concrete mix's life cycle [24]. A concrete mix designed for strength class C40/50 is reported to have an average Global Warming Potential (GWP) of 370 $kgCO_{2eq}/m^3$ [9], whereas the average of comparable (similar mixing proportions) concrete mixes based on LC^3 is reported to be 285 $kgCO_{2eq}/m^3$ [25]. Given similar transportation distances, LC^3 could also be up to 25% cheaper than OPC [25]. Reinforcing steel, on the other hand, is attributed to a significant carbon footprint ranging from 0.86 to 0.92 $kgCO_{2eq}/kg$ (Garcia-Segura et al., 2014; Proske et al., 2014) depending on the production process (blastfurnace/electric arc furnace), % of recycled steel and energy source. Comparatively, a few environmental product declarations from European producers (were found reporting a lower average for steel fibres (0.69–0.88) $kgCO_{2eq}/kg$ [26,27]. However, a previous paper assumed an equal value of carbon intensity for both (rebars and fibres) as a global average [21]. Hence, an environmental merit is expected when replacing the volume of steel rebars in a slab with a lower volume of steel fibres as long as the structural performance of concrete is maintained [28].

Previous LCA related studies have attempted to answer the question of the decarbonization potential of coupling low-carbon binder and fibre-reinforcement use in concrete. Abdulkareem et al. [29] reported that 1 m^3 of steel fibre reinforced alkali-activated concrete actually poses a higher carbon footprint than that of an OPC concrete, but the study did not include any structural performance comparisons. Similarly, Backes et al. [30] compared different types of fibre reinforced concrete walls for 3D printing applications and while structural performance was assumed equal across alternatives, mechanical testing to validate this assumption was lacking. Nonetheless, there is a clear gap in studying, based on a code-compliant case study, the decarbonization potential of partially replacing longitudinal steel rebars with steel fibres. Accordingly, a holistic evaluation of the functional and environmental performance of concrete and concrete structures is required [31]. Accordingly, this study is focused on exploring the environmental impact of steel fibre-reinforced LC^3 concrete compared with a reference OPC concrete.

1.2. Research objectives and significance

The main objective of this study is to assess the environmental performance of steel fibre-reinforced LC^3 concrete in one-way reinforced concrete slabs. The study is built on experimentally obtained mechanical properties of LC^3 and OPC concrete aimed at fulfilling specific structural design scenario requirements. The case-specific quantities of reinforced concrete are then integrated into a life cycle assessment (LCA) to evaluate the environmental performance of each alternative. The outcome is expected to present novel empirical evidence on the structural and environmental performance of LC^3 concrete as well as the decarbonization limitations of replacing longitudinal steel with steel fibres in reinforced concrete elements.

2. Materials and methods

2.1. Materials

As shown in Table 1, two groups of concretes were designed based on the use of OPC and LC^3. The OPC used in the study was CEM I 42.5 N and provided by Holcim (Schweiz) AG (Siggenthal, Switzerland). The LC^3-50 mix included: 1) 53% of the same OPC; 2) 30% calcined clay with 50% kaolinitic content sourced from a quarry in Northern Ireland and calcined at the labs at EPFL; 3) 15% commercial limestone powder; 3) 2% commercial gypsum. Both OPC and LC^3-50 concrete were designed for a strength class of C40/50 with 300 kg/m^3 binder content and a 0.5 water-to-binder ratio (W/B). Four fractions of natural aggregates (NA) were used, namely 0/4 (silica sand), 4/8, 8/16, and 16/32 mm of crushed limestone. The mass proportion of each of the four sizes in the aggregates portion of the concrete mix is 1:0.29:0.49:0.56 respectively.

A commercial polycarboxylate ether (PCE) based superplasticizer (Sika Viscocrete 1 LC^3) was used as a water reducer to achieve target workability. Within each concrete family, two mixes were produced: plain concrete, and steel fibre-reinforced concrete (SFRC). In particular, double-hooked steel fibres (Readymesh MF-500) supplied by Azichem were used in this research. The fibres are commercially available and display a nominal length of 50 mm and an aspect ratio (l/d) of 50. The tensile strength and modulus of elasticity of the fibres are reported by the manufacturer as 1.4 and 210 GPa respectively. The concrete mixes were designed to achieve a minimum slump of 50 mm. The volumetric content of fibres (0.75%) was selected as an average of the reported value in the literature to ensure the structural application of the steel fibre-reinforced concrete (SFRC).

2.2. Testing program

2.2.1. Slump

The slump cone test was conducted according to the EN 12350–2 standard [32] on each fresh mix. The mixes with a slump <50 mm were rejected and the SP content was adjusted accordingly.

2.2.2. Mechanical properties testing

Cylinders with a 160 mm diameter and 320 mm height were tested after 28 days for compressive strength according to EN 12390–3 [33] and modulus of elasticity as per EN 12390–6 [34]. In addition, 120×120×480 mm^3 unnotched beams were prepared and tested at 28 days for the pre- and post-cracking flexural strength performance according to the French national standard AFNOR or steel fibre-reinforced concrete (1999). This standard is one of several used for the post-cracking characterization of FRC, with the most commonly used

Table 1
The CEMI and LC^3 concrete family mixes with and without steel fibres (SF).

Mixes	W/B ratio	Cement type	Fibre % volume	Fibre type	Superplasticizer (%of binder by weight)
OPC	0.5	CEM I 42.5 N	-	None	0.00
OPC SF			0.75	SF	2.30
LC^3		LC^3-50	-	None	0.50
LC^3 SF			0.75	SF	2.50

one being the EN 14651 [35]. Nonetheless, the AFNOR (1999) standard is also compatible with a performance-based FRC design approach. A span of 360 mm and roller supports of 20 mm diameter and 250 mm length were adopted in a 4-point bending test setup. A 50 kN load cell was employed. The loading blades had a span of 120 mm, 130 mm length and hemispherical geometry (contact area) with a radius of 10 mm. The test was run with a constant displacement rate of 0.25 ± 0.03 mm/min until a deflection of at least 4 mm was achieved. A deflection transducer (LVDT) was used to track the deflection over time. Three specimens were tested for each concrete mix. Disposable cylindrical cardboard moulds with aluminium bottom were used to manufacture 160 mm diameter and 320 mm high specimens for compressive strength and elastic modulus tests. Before testing, the specimens for elastic modulus and compressive strength test were polished with an automatic polishing machine using a diamond brush. Specimens for flexural strength test were also prepared using stainless steel prismatic moulds with a size of 120x120x480 mm^3. The concrete were mixed for two minutes, cast and compacted by using a vibrating plate as from the standard prescription for steel fibre-reinforced concrete (AFNOR, 1999). All specimens were stored at 20 °C and 100% RH curing conditions.

2.3. Structural design scenarios

In this study, the choice was made to compare the environmental performance of the OPC and LC^3 mixes in the case of one-way steel-reinforced concrete slabs. As previously stated, one-way slabs can be considered as typical horizontal load-bearing elements in a variety of building structures and generally constitute the majority of concrete volume in a building structure [36]. In order to cover a wide range of possible scenarios, two slab effective depths (the distance between the slab edge and the centroid of the tension reinforcement, d) were selected for OPC reinforced concrete (RC) one-way slabs: 175 and 325 mm; and two span-effective depth ratios (L/d) typical for one-way slabs were also chosen: 20 and 25. Accordingly, the spans considered were 3500 and 4375 mm for slabs with $d = 175$ mm and 6500 and 8125 mm for slabs with $d = 325$ mm.

The slabs were designed for the following loads: self-weight g_{sw} (depending on the slab depth and considering a density of 2500 kg/m^3), additional dead load $\Delta g = 3$ kN/m^2, and a live load $q = 3$ kN/m^2 was assumed for use in residential buildings. The required reinforcement ($A_{s,req}$) was determined per Eurocode 2 [37] for an ultimate load $q_{Ed} = 1.35 \cdot (g_{sw} + \Delta g) + 1.5 \cdot q$ considering a unitary strip of the slab with a width $b = 1000$ mm and a characteristic compressive strength $f_{ck} = f_{cm} - 8$ MPa. Accordingly, the concrete mixes were designed for a strength class of C40/50. An exposure class of XC3 was assumed as typical for the interior of buildings so a nominal cover (c_{nom}) of 20 mm was assumed. Additionally, 20% of $A_{s,req}$ was considered as transverse reinforcement, i.e., reinforcement orthogonal to the main reinforcement of a one-way slab for covering secondary bending moments. Assuming the use of Ø10 mm reinforcement bars, the total slab heights for OPC slabs were $h = 175 + 25 = 200$ mm and $325 + 25 = 350$ mm.

In the case of LC^3 RC slabs, two differences were adopted relative to OPC RC slabs. Firstly, considering the obtained results on the modulus of elasticity (presented in Section 3.1) that showed a 10% lower modulus in the case of LC^3 concrete, a 5% increase in effective depth was imposed for the slabs to comply with the serviceability limit state of deflections. This is due to the fact that a 10% decrease in stiffness $E_c \cdot I$ caused by a 10% lower modulus can be compensated by a 5% increase in effective depth (since the moment of inertia (I) is linearly correlated with the cube of height). Hence, the effective depths for LC^3 RC slabs were 185 and 345 mm respectively, whereas the spans remained the same: 3500, 4375, 6500 and 8125 mm. It should be noted that this observation is based exclusively on the results experimentally obtained in this study. Previous work on LC^3-based concrete shows no significant differences in elasticity modulus compared to OPC [14].

Another change in LC^3 RC slabs was an increase in the concrete cover to ensure equal resistance to carbonation to OPC. This variation was driven by the different carbonation coefficients (K_{acc}) of OPC and LC3 concretes subjected to accelerated carbonation (3% of CO_2) as from previous evidence of Shah and Bishnoi [38]. For concretes with a w/c ratio of 0.5, the authors found average K_{acc} of 19.45 and 50.75 mm/year$^{1/2}$ for OPC and LC3, respectively. Considering the newly introduced concept of exposure resistance classes (XRC) [39], the concrete's performance against carbonation can be determined from an accelerated test using the following expression [40]:

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

Where $k(C)$ is the carbonation rate depending on the applied test (outdoor sheltered, chamber test, accelerated carbonation, respectively) determined in accordance with [41]; f_{exe} is the effect of execution (curing, compaction, and formwork after 50 years of exposure); f_{env} is the effect of different environmental conditions; f_{AC} is the correction factor for the accelerated test condition (includes the effect of high CO_2 concentration under curing and preconditioning); and n_{XRC} is the time exponent. In this case (exposure class XC3), all coefficients in Eq. (1) were set as 1.0, except n_{XRC}=0 [40]. Therefore, the values of XRC for OPC and LC^3 concretes were obtained as 2.25 and 5.86, respectively. As a consequence, OPC was classified as $XRC3$ and LC3 as $XRC6$, for which the new Eurocode 2 revision (2021) proposes covers of 20 and 35 mm, respectively. Therefore, the total height of LC^3 slabs was h= 185+40 =225 mm and 345+40= 385 mm, so 12.5% and 8.6% greater than the correspondent OPC slabs.

As for the FRC slab cases, the amount of reinforcement bars was partially replaced with steel fibres, considering the obtained residual strength of the FRCs (which produces a resisting bending moment due to FRC, M_{FRC}). Namely, considering a design external bending moment M_{Ed}, the amount of traditional steel reinforcement necessary to provide a resisting bending moment (M_{RC}) was calculated from [42]:

$$M_{RC} = M_{Ed} - M_{FRC} = M_{Ed} - 0.45 \bullet f_{eq,ctd,II} \bullet h \tag{2}$$

Where $f_{eq,ctd,II}$ is the equivalent design tensile strength of FRC, determined according to German guidelines DBV-Merkblatt Stahlfaserbeton [43], which is compatible with the P18–409 characterization test [44] as:

$$f_{eq,ctd,II} = f_{eq,ctk,II} \bullet \alpha_c^f \bullet \alpha_{sys} / \gamma_{ct}^f \tag{3}$$

With $f_{eq,ctk,II}$ being the characteristic value of the FRC residual tensile strength corresponding to a vertical mid-span deflection of 2.8 mm in the P18–409 test [44], $\alpha_c^f = 0.85$ for normal-weight concrete, α_{sys} being a coefficient dependent on the height of the specimen (varying from 1 for heights below 150 mm to 0.8 for heights above 600 mm) and γ_{ct}^f being the partial factor for SFRC equal to 1.25.

2.4. LCA study

2.4.1. Scope definition

The first stage of an LCA is to define the scope of the concrete life cycle to be considered. Typically, a cradle-to-gate scope would entail the inclusion of all the processes until the production of concrete constituents, delivery to the concrete batch plant and concrete production. For this case study, a cradle-to-gate scope is chosen as shown in the schematic in Fig. 2 while including the use phase, to validate the suitability of each concrete alternative to fulfil the service life requirement as per the reinforced concrete slab scenario.

The second part of the scope is to define the functional unit (FU), which is the LCA element responsible for the quantification of the environmental impact indicators and the alternatives under study. The FU of this LCA is selected as a square meter of the one-way slabs studied. The FU is calculated as the volume of concrete per square meter

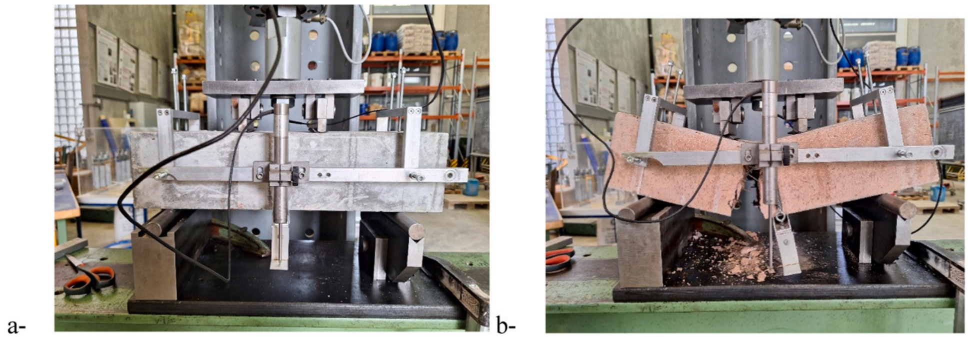

Fig. 1. Testing set-up following the AFNOR (1999) for the residual flexural strength test showing a) OPC sample before failure and b) LC^3 sample post-failure.

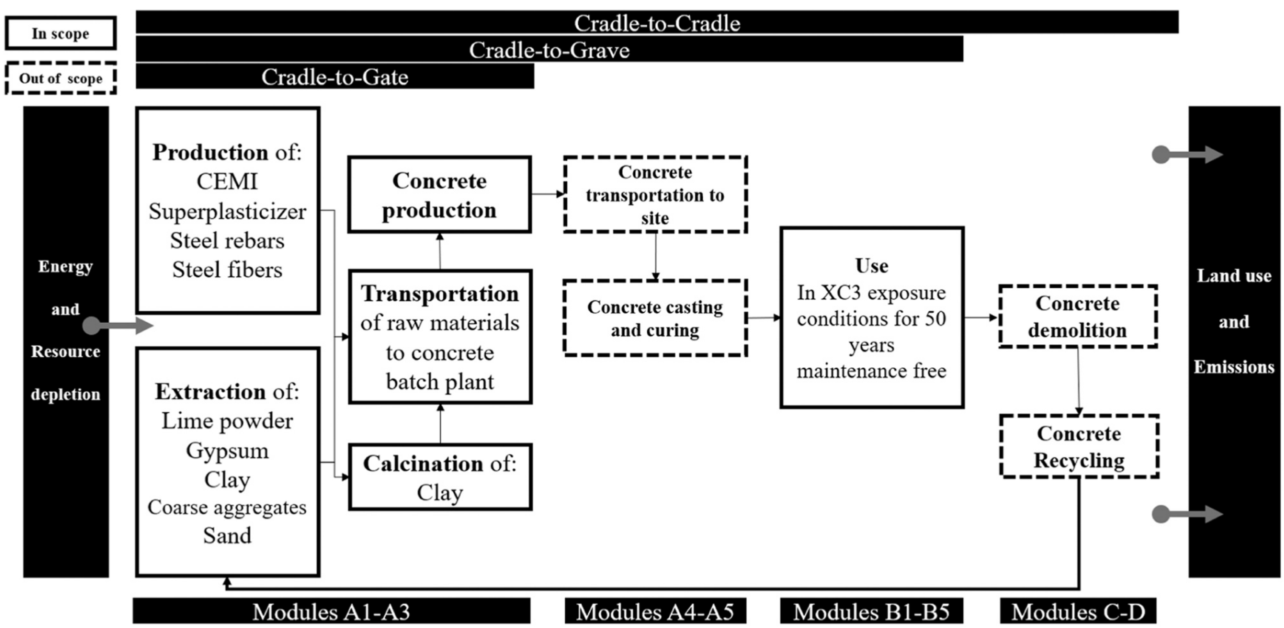

Fig. 2. A schematic figure of the LCA scope and modules selected in this study.

Table 2
Mixing proportions and literature based environmental inventory data for all concrete constituents of the experimental campaign.

Concrete constituent	Unit	OPC	OPC-SF	LC^3	LC^3-SF	Unit	GWP		
							kg CO_2 eq		
							A1 module		A1-A2 modules
							average	St.dev	average
CEM I 52.5 N	kg/ m^3	300	300	159	159	/kg	8.50E-01	3.17E-02	8.73E-01
Calcined Clay		-	-	90	90		2.32E-01	2.58E-01	2.54E-01
Limestone		-	-	45	45		5.87E-02	2.00E-02	8.11E-02
Gypsum		-	-	6	6		5.40E-02	6.90E-02	7.64E-02
SP		0	6.9	1.5	7.5		9.91E-01	9.00E-01	1.01E+00
Water		150	150	150	150		3.63E-04	5.70E-04	2.28E-02
Steel fibres*		-	60	-	60		1.08E+00	8.60E-01	1.11E+00
Sand 0/4		770	760	760	755		2.37E-03	2.00E-03	2.48E-02
Fine gravel 4/8		230	225	225	220		4.06E-03	2.90E-03	2.65E-02
Coarse gravel 8/16		375	375	375	370				
Coarser gravel 16/32		430	430	430	425				

* The GWP for steel rebars is considered similar to that of the steel fibres

multiplied by the total height (thickness in m) of the slab including the amount of steel and fibres (if any) required to fulfil each of the structural scenarios explained in Section 2.3. This includes the reinforcing steel volume compensation due to variation in the residual strength and Young's modulus as well as the durability against carbonation-induced corrosion for the assumed 50 years of service life. The alternatives being compared under this LCA scope are the concrete mixes for which the exact mixing proportions are described in Table 2.

2.4.2. Inventory data

The second stage of an LCA is to prepare the inventory database including the environmental impact of each of the concrete mix constituents. For each constituent, the upstream impact which is associated with the extraction and production as well as the delivery to the concrete batch plant, is allocated. A distance of 50 km was assumed for the transportation of the concrete raw materials to the batch plant. The source of the inventory data is a compilation of different published papers as shown in the supplementary information Table S1. The summary of the inventory data including the averages from the literature is shown in Table 2.

2.4.3. Impact assessment

The third and final stage of an LCA is to calculate the environmental impact of the studied product. This is performed by adding up the individual impacts of all the associated processes to calculate an environmental impact indicator; a number that makes the output of the impact assessment study more understandable to the user [45]. The selected impact indicators for this study were: Global warming potential (GWP).

3. Results and Discussions

3.1. Experimental results

The slump cone results of the six mixes were 180 mm and 170 mm for OPC mixes without and with steel fibres respectively, whereas it was 130 mm and 100 mm for the equivalent LC^3 mixes. The 28-day compressive strength results (Fig. 3) show minor increase (~17%) for the LC^3 and OPC concretes incorporating steel fibres, relative to the corresponding mixes without fibres. Considering that, at this dosage, fibres should not affect significantly compressive strength, and the modulus of elasticity results (discussed below), a probable explanation lies in the better compaction of concretes with fibres, as they were exposed to longer compaction because of the presence of fibres. At the same time, LC^3 exhibits comparable performance to OPC (-12% on average) and provides a compressive strength above 49.12 ± 1.82 MPa, allowing it to be classified as a C40/50 structural concrete.

As shown in Fig. 4, the addition of steel fibres did not strongly affect the elastic modulus of unreinforced OPC or LC^3 (within max. +7%), corroborating the explanation that the increase in compressive strength was due to the casting procedure and better compaction of the concretes with fibres. Overall, it is observed that LC^3 is a slightly less stiff matrix compared to OPC with a reduced elastic modulus value of -10% on average which was factored in the structural design considerations as explained in Section 2.3.

Overall, a low standard deviation is observed for all mechanical tests, supporting a good homogeneity of the concretes produced. In terms of equivalent flexural tensile strength, both SFRC mixes showed a suitable residual flexural performance for the used volume of fibres (0.75% of the binder volume). As seen in Table 3, the differences between OPC and LC^3 mixes in terms of flexural strength were consistent with the compressive strength results, showing slightly higher values for OPC – 3.58 MPa compared with 3.43 MPa. Nonetheless, for the LC^3 mix, a 20% and 30% decrease in equivalent tensile strengths $f_{eq,ctm,I}$ and $f_{eq,ctm,II}$ were noted, respectively: 3.37 and 2.41 Mpa for PC-SF and 2.67 and 1.65 Mpa for LC^3-SF, respectively.

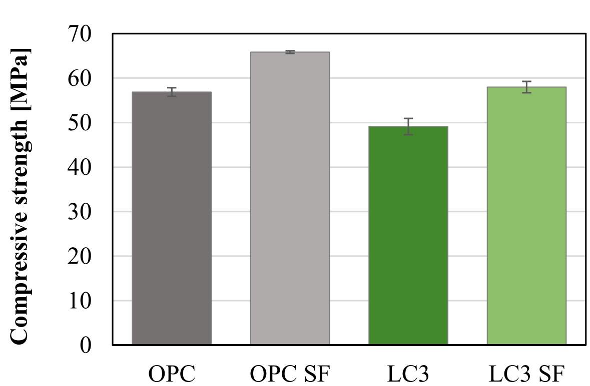

Fig. 3. Compressive strength results of unreinforced and steel fibre-reinforced OPC and LC^3 concrete mixes.

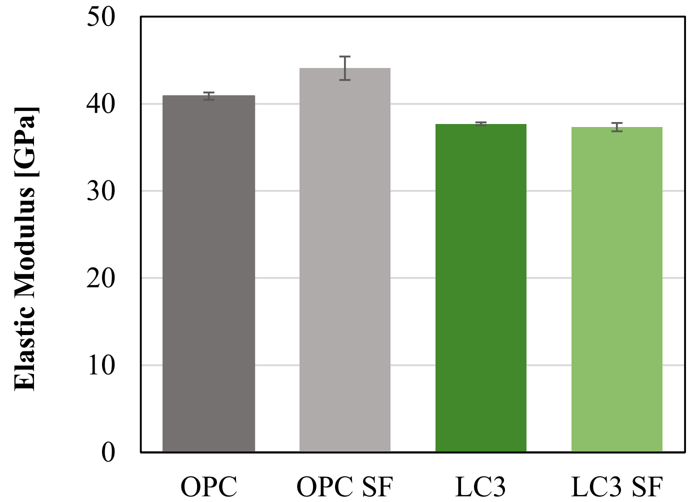

Fig. 4. Elastic modulus results of unreinforced and steel fibre-reinforced OPC and LC^3 concrete mixes.

Table 3
Equivalent tensile strengths of the tested SFRC mixes.

	$f_{ctm,fl}$ (MPa)		$f_{eq,ctm,I}$ (MPa)		$f_{eq,ctm,II}$ (MPa)	
Mixes	Average	CoV (%)	Average	CoV (%)	Average	CoV (%)
PC-SF	3.58	6.7	3.37	19.9	2.41	19.7
LC^3-SF	3.43	–	2.67	–	1.65	–

One possible explanation could be the potentially weaker bond between fibres and the LC^3 matrix. However, it should also be noted that for LC^3 the results are an average of only two tested specimens (since one specimen was lost due to equipment malfunction) and that the coefficient of variation for the OPC mix (which could not be determined for the LC^3 one since only two results were available) is relatively high (but usual for this type of test). Therefore, the statistical significance of the differences in $f_{eq,ctm,I}$ and $f_{eq,ctm,II}$ between OPC and LC^3 could not be assessed.

3.2. Structural design results

As explained in Section 2.3, the structural design was performed in each case to determine the required amount of steel reinforcement ($A_{s,req}$). For the SFRC mixes, characteristic values (5% allowed defectives) of the equivalent tensile strength $f_{eq,ctm,II}$ were determined using the average values and CoVs shown in Table 5 assuming a t-student distribution and that the observed CoV is equal to that of the population, so that $f_{eq,ctm,II,k} = f_{eq,ctm,II,m} - 1.645 \cdot \sigma_{R3}$ (where σ_{R3} is the standard deviation, i.e. CoV×average). For the LC^3 mixes, since CoV values could not be determined, they were adopted equal to OPC. The detailed results are shown in the supplementary information table S2.

The obtained results are shown in Table 4. In each case, minimum reinforcement for ductile failure was checked and always maintained, per Annex L of the new Eurocode 2 [46] meaning that for SFRC one-way slabs, a 50% reduction in minimum reinforcement was adopted. As expected, slightly higher amounts of reinforcement were needed for LC^3 RC one-way slabs compared with OPC ones: up to 13% and even less

Table 4
Results of the structural design of the one-way slabs.

Alternative	L/d	$f_{eq,ctd,I}$ (MPa)	L (mm)	d (mm)	h (mm)	g_{sw} (kN/m^2)	$A_{s,req}$ (mm^2/m)
OPC	20	0	3500	175	200	5.0	409
	25		4375	175	200	5.0	493
	20		6500	325	350	8.8	779
	25		8125	325	350	8.8	1228
OPC-SF	20	0.99	3500	175	200	5.0	223
	25		4375	175	200	5.0	228
	20		6500	325	350	8.8	413
	25		8125	325	350	8.8	817
LC^3	20	0	3500	185	225	5.6	387
	25		4375	185	225	5.6	552
	20		6500	345	385	9.6	879
	25		8125	345	385	9.6	1393
LC^3-SF	20	0.69	3500	185	225	5.6	216
	25		4375	185	225	5.6	329
	20		6500	345	385	9.6	556
	25		8125	345	385	9.6	1056

reinforcement was needed when minimum reinforcement was governing. However, in the case of LC^3 SFRC one-way slabs, up to 44% more reinforcement was needed than for the OPC SFRC slab, due to the 30% lower design equivalent tensile strength $f_{eq,ctd,II}$. Even so, the use of fibres could reduce reinforcement up to 45% relative to the RC cases.

3.3. LCA results

Following the life cycle impact assessment process explained earlier in Section 2, the values of the environmental impact per unit volume of each concrete mix came out as seen in Fig. 5. The impact is equivalent to the product sum of the processes in extracting/producing each of the concrete constituents multiplied by the ratio of these constituents in the concrete mix. The values confirm that for each type of concrete (no fibres or with steel fibres) LC^3 mixes exhibit a 35% lower carbon footprint per unit volume of concrete. The addition of 0.75 vol% of steel fibres increases the carbon footprint per m^3 by around 30%. Nonetheless, the steel fibre-reinforced LC^3 concrete has 10% less embodied carbon compared to the no-fibres OPC mix while exhibiting superior functional properties. The details of the calculations are shown in the supplementary information Table S3.

The unit volume impact results were then multiplied by the functional unit generated from the case study calculations of each of the specified one-way reinforced concrete slab scenarios. In all one-way slab scenarios analyzed in this case study, the LC^3 concrete slabs save 25% of the carbon footprint compared to OPC ones as shown in Table 5 below.

The second major finding is that the boundary conditions and selected variables in this case study conclude that through the synergy of using LC^3 as a binder and the addition of steel fibres, net carbon savings of a one-way slab are achieved. Although the steel-reinforced LC^3 concrete slab exhibits slight carbon reduction (~9%), it falls within the statistical variance in the inventory database used for the environmental impact assessment as shown in the error bars in Fig. 6. Moreover, the steel fibre addition, in either binder types, increases the GWP of a unit area of the designed one-way slabs by approximately 25%.

3.4. Discussions

It is established in the literature that the main incentive behind using steel fibre-reinforced concrete in structural applications is to bridge and limit the propagation of micro cracks (Liu et al., 2021) as well as increase the stiffness of the horizontal elements to enhance its serviceability (Nogales et al., 2021). However, this paper aimed to study the decarbonization potential of one-way slabs combining a low-carbon binder (LC^3) and steel fibres compared to reinforced OPC concrete. The results show that LC^3 FRC slabs reduce the carbon footprint by 5–10% compared to the control and that in the same binder the environmental cost of adding steel fibres increases the carbon footprint of a one-way slab by an average of 25% and 70% per m^2 respectively). In order to validate the promising environmental impact savings beyond the statistical variance, the four underlying parameters controlling the decarbonization potential of steel fibre reinforced mixes were studied and compared against precedent research. The detailed calculations of each of the discussions scenarios is shown in the SI table S4.

First, on the concrete level, the agglomeration potential of steel fibres requires a SP dosage of 2% by binder mass to achieve the target slump. However, the experimental results showed that the SFRC mixes achieve a 15% higher compressive strength compared to the plain concretes produced. This agrees with the findings from Liu et al., (2021). Hence, the SFRC mix designs could be optimized to increase the W/B ratio slightly to reduce the binder content by an equivalent 15% while achieving the same target compressive strength. The correlation between the paste volume and binder intensity achieving the same slump is established in the literature [47]. Hence, a scenario in which SFRC mixes would have 15% less binder was analyzed and the results in Fig. 7 show that the LC^{3}SFRC slab is 15% (instead of 9%) less than the control one (Fig. 7 – Binder content).

The second parameter that plays a direct role in defining the decarbonization potential of SFRC slabs is the differential carbon intensity of the steel fibres compared to the reinforcing steel rebars. Intuitively, the fibres and rebars are produced using the same electric arc furnace processes and hence in all the literature, including this paper, the same carbon intensity is attributed to both [21]. However, recent papers studied the potential use of recovered steel fibres from waste tires

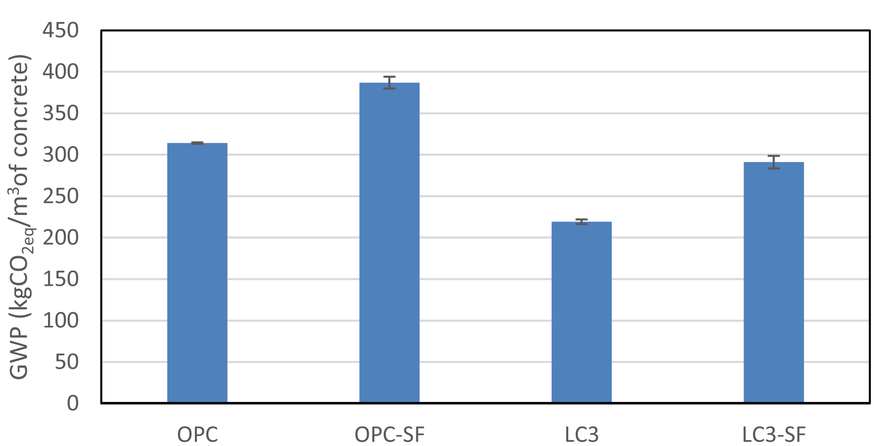

Fig. 5. The environmental impact assessment of OPC and LC^3 concrete mixes per unit volume.

Table 5
The environmental impact per m^2 of reinforced concrete slab of OPC vs LC^3 concrete.

Scenario	L(mm)	Indicator	Unit/FU (m^2)	PC	PC-SF	LC^3	LC^3-SF
1	3500	Concrete volume	m^3	0.20	0.20	0.22	0.22
		Steel reinforcement	kg	3.85	2.10	3.45	1.93
		GWP	kg $CO_{2\ eq}$	58.56	71.44	40.97	54.96
2	4375	Concrete volume	m^3	0.20	0.20	0.22	0.22
		Steel reinforcement	kg	4.64	2.15	4.82	2.80
		GWP	kg $CO_{2\ eq}$	59.42	71.50	42.46	55.90
3	6500	Concrete volume	m^3	0.35	0.35	0.37	0.37
		Steel reinforcement	kg	7.34	3.89	7.54	4.65
		GWP	kg $CO_{2\ eq}$	103.12	125.27	71.37	94.80
4	8125	Concrete volume	m^3	0.35	0.35	0.37	0.37
		Steel reinforcement	kg	11.57	7.70	11.94	8.95
		GWP	kg $CO_{2\ eq}$	107.71	129.39	76.15	99.46

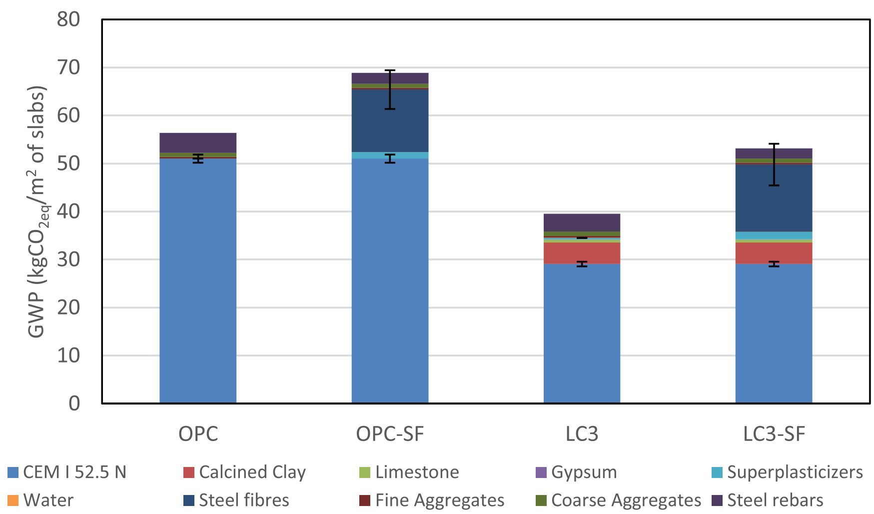

Fig. 6. Comparison of the carbon footprint per m^2 of slab of conventional vs steel fibre-reinforced OPC and LC^3 concrete.

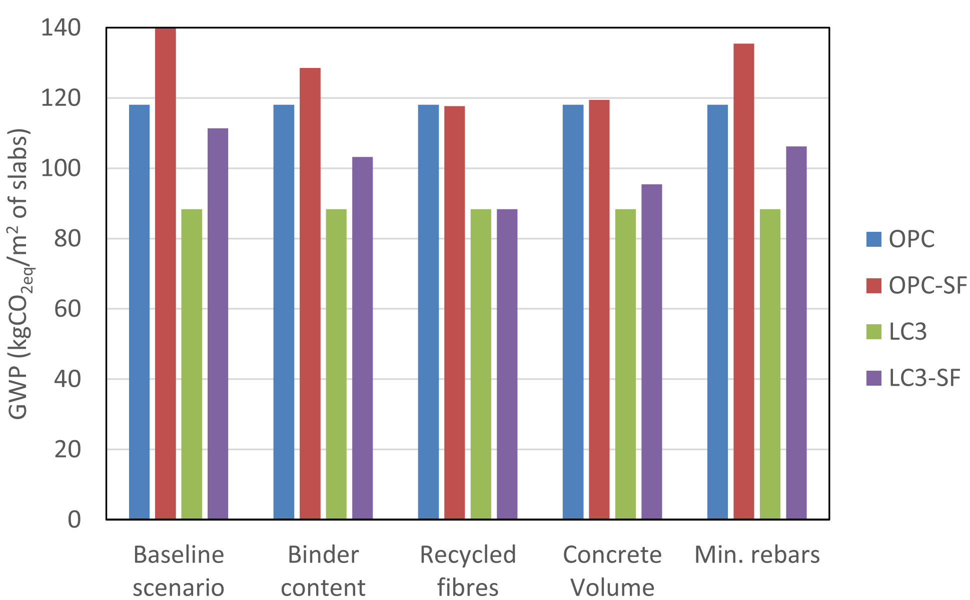

Fig. 7. Scenario analysis for relative decarbonization potential strategies for one-way steel fibre-reinforced LC^3 concrete compared to conventional steel reinforced OPC ones.

(Baricevic, et al., 2017; Bartolac et al., 2016) and from previous fibre-reinforced concrete [48-51] for which the carbon intensity is negligible, and they all showed enhanced tensile strength (50–100% better) compared to new steel fibres. A recent article attributes 54.74 gCO_{2eq}/kg for the recovered steel fibres due to the energy required for mechanical recovery process [52]. Accordingly, a second scenario was analyzed considering the use of recovered steel fibres and as shown in Fig. 7, the LC^{3}SFRC one-way slabs show 30% GWP savings compared to the control. The combination of the two realistic and easy-to-implement scenarios 1 and 2 could yield a differential of 40% in carbon footprint between LC^3SFRC and conventional OPC one-way slabs.

Thirdly, as explained in the methods section, this study is among the first to model the structural concrete element concrete cover based on the performance-based approach [39]. The increased cover due to the exposure resistance class in an XC3 environment caused a 12.5% increase in the volume of concrete per FU of the LC^3 slabs for compared to OPC ones. However, what was not taken into account was the contribution of SF to crack control and deformation, i.e., deflections. Although there are not many experimental results on this topic, available results suggest a contribution of steel fibres to reducing deflections in RC elements [53]. Additionally, theoretical research has provided models for calculating deflections of SFRC members [54] that demonstrate the reduction in deflections. Finally, Tošić et al. [55] developed a closed-form analytical solution to determine the maximum slenderness of SFRC members and showed a potential reduction in slab thickness when using SF. Since these studies are still preliminary and more experimental research is needed, in particular on long-term deflection behavior, the possible reductions in thickness were not considered in this study. Nonetheless, as seen in Fig. 7 – Concrete volume, assuming a reduction in the volume of concrete (through thickness reduction) of around 15% (plausible within the framework of the cited theoretical studies), could result in a 22% differential carbon footprint of the $SFRLC^3$ slab relative to the conventional OPCRC one.

The final parameter to be discussed is the structural performance of SF. The results showed that the addition of 0.75 vol% of SF to concrete enhances the flexural tensile strength of the studied slab scenarios by almost double. This is consistent with the findings from the results in Chen et al. [17] and Liu et al. [49]. However, as a safety precaution (to guarantee moment redistribution capacity and avoid cracking localization in lightly reinforced elements), the Eurocode 2 design process limits the replacement of steel reinforcement to maximum 50% of the minimum steel longitudinal reinforcement regardless of the enhanced residual strength of the mixes with fibres [56]. This result is a disadvantageous position for the FRC because the minimum steel rebar reinforcement in one-way slabs in the studied span widths is on average 20 kg/m^3 which is consistent with the findings from Jayasinghe et al. [57]. Therefore, since the studied one-way slabs, as shown in Table S2, have a maximum of 30 kg of rebar reinforcement per m^3 of concrete, the added weight of steel fibres would be 60 kg/m^3 to replace approximately a maximum of 20 kg of steel rebars. Accordingly, the third scenario designed was to assume a no-minimum reinforcement provision of the code and as seen in Fig. 7 - Min. rebars, this results in lowering the carbon footprint of the $SFRLC^3$ slab alternative potentially becoming 15% lower than the conventional OPCRC one. It is clear that the third and fourth discussion parameters are less likely as those require code coefficients adjustments, but it is important for further study of the topic within code provisions revisions for decarbonization purposes.

4. Conclusions

The case study carried out for this research was focused on exploring the decarbonization potential of combining the environmental savings from LC^3 based concrete compared to OPC and the structural performance enhancement of the addition of steel fibres. For this purpose, one-way slabs were chosen as a representative typology to apply the Eurocode for partially replacing steel rebars by structural steel fibres and use the results as the functional units for the life cycle assessment comparison between both alternatives. Based on the results, the following conclusions can be drawn:

- LC^3 concrete exhibits a comparable compressive strength performance to OPC and provides a compressive strength above 49.12 ± 1.82 MPa, allowing it to be used as a C40/50 structural concrete.
- LC^3 concrete exhibits a slightly less stiff matrix compared to OPC with a reduced elastic modulus value of -10% on average which was factored in the structural design.
- The slight increase in the concrete cover of LC^3 concrete elements to compensate for its lower carbonation resistance compared to OPC concrete is negligible considering the total volume of the structure.
- Following the Eurocode 2 design guidelines, the addition of steel fibres reduce the reinforcement rebars in one-way slabs by 45%. However, the partial steel rebar replacement required the addition of 0.75% steel fibres by volume which increased the carbon footprint per m^2 of the studied one-way slabs by approximately 25%.
- The most important conclusion is that the combination of LC^3 as a binder and steel fibre-reinforcement could save 10% of the carbon footprint of a one-way slab compared to OPC-reinforced concrete. The adjustment of the concrete mix for lower binder content and the reuse of steel fibres could increase the relative decarbonization potential to 40%.

The findings of the case study are only limited to the boundary conditions and assumptions considered. Accordingly, further research is needed to validate its conclusions. First, instead of fixing it at 0.75% by mass of binder, the experimental campaign could be extended to study 0.5 and 1% steel fibre additions to test the concrete properties and corresponding decarbonization potential. Also, as opposed to studying only a one-way reinforced concrete slab, other applications such as bridges or pavements could be analyzed to integrate the mechanical properties enhancements from the fibres even more. Finally, the carbon accounting boundary could also be extended in the future to include the potential reductions from the use of fibres in the construction and use phases by reducing the time and maintenance, respectively.

CRediT authorship contribution statement

Michal Drewniok: Writing – review & editing, Validation, Supervision, Software, Investigation, Funding acquisition. **Phil Purnell:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Albert de la Fuente:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition. **Nikola Tošić:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Funding acquisition, Conceptualization. **Hisham Hafez:** Visualization, Validation, Software, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Beatrice Malchiodi:** Writing – original draft, Investigation, Formal analysis.

Declaration of Competing Interest

None.

Data availability

The supplementary information is available in the following link: https://zenodo.org/records/11373481.

Acknowledgements

The authors acknowledge no conflict of interest and would like to acknowledge the support of the UK Engineering and Physical Sciences Research Council (EPSRC) through the “Engineered UK clays for production of low-carbon cements" project fund (Grant Reference EP/W021811/1). The authors also acknowledge Azichem for supplying the steel fibres used in this work.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.conbuildmat.2024.136847.

References

[1] F. Colangelo, A. Forcina, I. Farina, A. Petrillo, Life Cycle Assessment (LCA) of different kinds of concrete containing waste for sustainable construction, Buildings 8 (2018).
[2] H.S. Müller, M. Haist, M. Vogel, Assessment of the sustainability potential of concrete and concrete structures considering their environmental impact, performance and lifetime, Constr. Build. Mater. 67 (2014) 321–337.
[3] O.B. Carcassi, G. Habert, L.E. Malighetti, F. Pittau, Material diets for climate-neutral construction, Environ. Sci. Technol. 56 (8) (2022) 5213–5223.
[4] C. Hill, A. Norton, J. Dibdiakova, A comparison of the environmental impacts of different categories of insulation materials, Energy Build. 162 (2018) 12–20.
[5] J. Mata Falcón, P. Bischof, T. Huber, A. Anton, J.J. Burger, F. Ranaudo, A. Jipa, L. Gebhard, L. Reiter, E. Lloret-Fritschi, T. Van Mele, Digitally fabricated ribbed concrete floor slabs: a sustainable solution for construction, RILEM Tech. Lett. 7 (2022) 68–78.
[6] P.R. Lima, J.A. Barros, A.B. Roque, C.M. Fontes, J.M. Lima, Short sisal fibre-reinforced recycled concrete block for one-way precast concrete slabs. Constr. Build. Mater. 187 (2018) 620–634.
[7] K. Scrivener, F. Avet, H. Maraghechi, F. Zunino, J. Ston, W. Hanpongpun, A. Favier, Impacting factors and properties of limestone calcined clay cements (LC3), Green Mater. 7 (1) (2018) 3–14.
[8] S.A. Miller, Supplementary cementitious materials to mitigate greenhouse gas emissions from.concrete: can there be too much of a good thing? J. Clean. Prod. 178 (2018) 587–598.
[9] H. Hafez, R. Kurda, W.M. Cheung, B. Nagaratnam, A systematic review of the discrepancies in life cycle assessments of green concrete, Appl. Sci. 9 (22) (2019) 4803.
[10] R.G. Pillai, R. Gettu, M. Santhanam, S. Rengaraju, Y. Dhandapani, S. Rathnarajan, A.S. Basavaraj, Service life and life cycle assessment of reinforced concrete systems with limestone calcined clay cement (LC3), Cem. Concr. Res. 118 (2019) 111–119.
[11] F. Zunino, F. Martirena, K. Scrivener, Limestone Calcined Clay Cements (LC^3), Acids Mater. J. 118 (3) (2021).
[12] H. Du, S. Dai Pang, High-performance concrete incorporating calcined kaolin clay and limestone as cement substitute, Constr. Build. Mater. 264 (2020) 120152.
[13] K.L. Scrivener, V.M. John, E.M. Gartner, Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry, Cem. Concr. Res. 114 (2018) 2–26.
[14] F. Avet, L. Sofia, K. Scrivener, Concrete performance of limestone calcined clay cement (LC3) compared with conventional cements, Adv. Civ. Eng. Mater. 8 (3) (2019) 275–286.
[15] S. Barbhuiya, J. Nepal, B.B. Das, Properties, compatibility, environmental benefits and future directions of limestone calcined clay cement (LC3) concrete: A review, J. Build. Eng. (2023) 107794.
[16] X. Huang, Z. Jiao, F. Xing, L. Sui, B. Hu, Y. Zhou, Performance assessment of LC3 concrete structures considering life-cycle cost and environmental impacts, J. Clean. Prod. *436* (2024) 140380.
[17] L. Chen, W. Sun, B. Chen, Z. Shi, J. Lai, J. Feng, Multiscale study of fibre orientation effect on pullout and tensile behavior of steel fibre-reinforced concrete, Constr. Build. Mater. 283 (2021) 122506.
[18] Fib. Fib Model Code for Concrete Structures 2010; International Federation for Structural Concrete (FIB): Lausanne, Switzerland, 2013; ISBN 9783433030615. 2.
[19] Spanish Ministry of Public Works, Code on Structural Concrete, EHE-08, Permanent Commission of the Concrete; Spanish, Ministry of Public Works, Madrid, Spain, 2008.
[20] P. Müller, J. Novák, J. Holan, Destructive and non-destructive experimental investigation of polypropylene fibre-reinforced concrete subjected to high temperature, J. Build. Eng. 26 (2019) 100906.
[21] S. Aidarov, A. Nadaždi, E. Pugach, N. Tošić, A. de la Fuente, Cost-oriented analysis of fibre-reinforced concrete column-supported flat slabs construction, J. Build. Eng. (2022) 104205.
[22] A. Nogales, N. Tošić, A. De La Fuente, Rotation and moment redistribution capacity of fiber-reinforced concrete beams: Parametric analysis and code compliance, Struct. Concr. 23 (1) (2022) 220–239.
[23] A.M. Orellana, Estudio teórico-experimental de la aplicabilidad del hormigón reforzado con fibras de acero a losas de forjado multidireccionales. Doctoral dissertation. Universidad del País Vasco, Euskal Herriko Unibertsitatea (2013).
[24] E.K. Anastasiou, A. Liapis, I. Papayianni, Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials, Resour., Conserv. Recycl. 101 (2015) 1–8.
[25] R. Gettu, R. Pillai, M. Santhanam, A. Basavaraj, S. Rathnarajan, B. Dhanya, Sustainability-based decision support framework for choosing concrete mixture proportions, Mater. Struct. 51 (2018) 1–16.
[26] Dramix, 2021. Environmental Product Declaration Type III ITB No. 215/2021. https://bosfa.com/wp-content/uploads/2022/03/EPD_Bekaert_Dramix_Petrovice-2021_version-1.pdf.
[27] KrampeHarex, 2023. Steel fibre with hooked ends. Environmental Product Declaration In accordance with ISO 14025. https://api.environdec.com/api/v1/EPDLibrary/Files/8df595ab-3537-4817-a416-08daf9edfd5d/Data.
[28] O. Pons, M.d.M. Casanovas-Rubio, J. Armengou, A. de la Fuente, Sustainability-Driven Decision-Making Model: Case Study of Fibre-Reinforced Concrete Foundation Piles, J. Constr. Eng. Manag. 147 (2021) 10.
[29] M. Abdulkareem, J. Havukainen, M. Horttanainen, How environmentally sustainable are fibre reinforced alkali-activated concretes? J. Clean. Prod. *236* (2019) 117601.
[30] J.G. Backes, M. Traverso, A. Horvath, Environmental assessment of a disruptive innovation: Comparative cradle-to-gate life cycle assessments of carbon-reinforced concrete building component, Int. J. Life Cycle Assess. *28* (1) (2023) 16–37.
[31] H. Hafez, R. Kurda, N. Al-Ayish, T. Garcia-Segura, W.M. Cheung, B. Nagaratnam, A whole life cycle performance-based ECOnomic and ECOlogical assessment framework (ECO2) for concrete sustainability, J. Clean. Prod. 292 (2021) 126060.
[32] EN 12350-2, 2009. Testing fresh concrete. Slump-test.
[33] EN 12390-3, 2009. Testing hardened concrete—Part 3: Compressive strength of test specimens.
[34] EN 12390-6, 2009. Testing Hardened Concrete. Tensile Splitting Strength of Test Specimens.
[35] EN 14651. (2005). Test method for metallic fibred concrete — Measuring the flexural tensile strength (limit of proportionality (LOP), residual). *European Committee for Standardization*.
[36] N. Tošić, Y. Kurama, Parametric numerical study on service-load deflections of reinforced recycled aggregate concrete slabs and beams based on fib Model Code 2010, Struct. Concr. 21 (2020) 2854–2868.
[37] EN 1992-1-1, Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings, CEN, Brussels, 2004.
[38] V. Shah, S. Bishnoi, Carbonation resistance of cements containing supplementary cementitious materials and its relation to various parameters of concrete, Constr. Build. Mater. 178 (2018) 219–232.
[39] EN1992-1-1, Eurocode 2: Design of concrete structures – Part 1-1: General rules, rules for buildings, bridges and civil engineering structures, CEN, Brussels, 2021.
[40] CEN/TC 250/SC 2/WG 1/TG 10, 2021. Background Document for prEN1992-1-1: 2020 D7 clause 6 – Durability. Eur. Comm. Stand. Brussels.
[41] EN 12390-12, 2018. Testing hardened concrete – Part 12: Determination of the carbonation resistance of concrete – Accelerated carbonation method. Eur. Comm. Stand. Brussels.
[42] ACI 544.4-18. 2018. Guide to Design with Fibre-Reinforced Concrete. Farmington Hills, MI.
[43] DBV, Guide to Good Practice "Steel Fibre Concrete", German Society for Concrete and Construction Technology, Berlin, 2001.
[44] AFNOR, Beton avec fibres metalliques – Essai de Flexion, Normalisation Francaise P18-409, *L'associa- tion Franqaise de Normalisation (AFNOR)*, April 1993, 8 pp. (in French – Concrete with Steel Fibers – Flexural Strength Test).
[45] A. Bjørn, M.Z. Hauschild, Introducing carrying capacity-based normalisation in LCA: framework and development of references at midpoint level, Int. J. Life Cycle Assess. 20 (7) (2015) 1005–1018.
[46] FprEN 1992-1-1:2023, Eurocode 2: Design of concrete structures – Part 1-1: General rules, rules for buildings, bridges and civil engineering structures, CEN, Brussels, 2023.
[47] B.L. Damineli, F.M. Kemeid, P.S. Aguiar, V.M. John, Measuring the eco-efficiency of cement use, Cem. Concr. Compos. *32* (8) (2010) 555–562.
[48] B. Ali, H. Ahmed, H. Hafez, A. Brahmia, M.H.E. Ouni, A. Raza, Life cycle impact assessment (cradle-to-gate) of fiber-reinforced concrete application for pavement use: A case study of Islamabad City, Int. J. Pavement Res. Technol. *16* (2) (2023) 247–263.
[49] Guanzhi Liu, Martin Hunger, Nikola Tošić, Albert de la Fuente, Effect of free and embedded polypropylene fibres recovered from concrete recycling on the properties of new concrete, Constr. Build. Mater. 409 (2023) 134145.
[50] E. Martinelli, A. Caggiano, H. Xargay, An experimental study on the post-cracking behaviour of Hybrid Industrial/Recycled Steel Fibre-Reinforced Concrete, Constr. Build. Mater. *94* (2015) 290–298.
[51] Z. Zamanzadeh, L. Lourenço, J. Barros, Recycled Steel ReinforcedFibre-re Concrete failing in bending and in shear, Constr. Build. Mater. *85* (2015) 195–207.
[52] C. Frazao, J. Barros, J.A. Bogas, V. Garcia-Cortes, T. Valente, Technical and environmental potentialities of recycled steel fiber reinforced concrete for structural applications, J. Build. Eng. *45* (2022) 103579.
[53] K.H. Tan, P. Paramasivam, K.C. Tan, Instantaneous and long-term deflections of steel fiber reinforced concrete beams, Struct. J. *91* (4) (1994) 384–393.
[54] M.J. Watts, A. Amin, R.I. Gilbert, W. Kaufmann, F. Minelli, Simplified prediction of the time dependent deflection of SFRC flexural members, Mater. Struct. *53* (2020) 1–11.
[55] N. Tošić, M. Sanabra-Loewe, A. Nogales, A. de la Fuente, Effective Moment of Inertia and Slenderness Limits of Reinforced Concrete and Fiber-Reinforced Concrete Slabs, Acids Struct. J. 119 (5) (2022).
[56] V. Cugat, S.H.P. Cavalaro, J.M. Bairán, A. de la Fuente, Safety format for the flexural design of tunnel fibre-reinforced concrete precast segmental linings, Tunn. Undergr. Space Technol. *103* (2020) 103500.
[57] A. Jayasinghe, J. Orr, T. Ibell, W.P. Boshoff, Comparing the embodied carbon and cost of concrete floor solutions, J. Clean. Prod. 324 (2021) 129268.