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ENVIRONMENTAL EVALUATION OF A SELF-COMPACTED CLAY BASED CONCRETE WITH NATURAL SUPERPLASTICIZERS

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Abstract

Cement concrete is the most widely used construction material worldwide due to its favourable mechanical characteristics. However, it is responsible for 8% of the total carbon emissions in the world, which are generated mainly during the production of clinker. Due to that fact, finding alternatives to cement for some applications in which it is not strictly needed should be a priority. In this study, a self-compacted clay-based concrete with natural superplasticizers based on natural tara tannins is presented. The main objective of the study is to determine if this clay-based concrete can be a sustainable alternative to conventional cement concrete as the main component in structural slabs. The methodology of the study is divided into two parts. First, the self-compacting clay concrete is characterized to determine its mechanical properties. Secondly, a comparative Life Cycle Assessment is conducted to determine the difference between the impacts generated by one square meter of self-compacting cement concrete and one of self-compacting clay concrete. The characterization of the material showed that this self-compacting clay concrete is suitable for some building elements such as structural slabs while avoiding the energy consumption needed to produce conventional concrete. The environmental impact results showed that using self-compacting clay concrete instead of the cement-based material decreases 90% of the carbon emissions and 80% of the overall environmental impact. After the completion of the study, it can be stated that the presented material is a sustainable alternative to conventional concrete for building structural slabs.

Keywords: earth construction, clay concrete, self-compacted clay-based concrete, Life Cycle Assessment, sustainability.

1. Introduction:

Cement concrete is the most used building material in the world [1]. Its favourable mechanical properties paired with its affordable price makes cement concrete the easy choice for building any kind of structure. However, an immense quantity of CO_2 is emitted into the atmosphere during its production process. The production of cement concrete by itself generates 8% of the total carbon emissions in the world [2]. The reaction between limestone and clay to produce clinker is responsible for most of those emissions. Reducing the worldwide carbon emissions is one of the most pressing challenges society faces. Since the first climate emergency declaration, the effects of climate change have become apparent, and mitigating them is indispensable to protect the ecosystems [3]. Therefore, finding alternatives to conventional cement concrete is key to a sustainable future.

One of those alternatives is soil. Soil is used as a construction material by approximately half of the global population, with highly diverse techniques. It is the most abundant natural construction material in most regions in the world. The use of soil as a construction material is a constant in low-resource areas, and it is becoming increasingly popular in contemporary sustainable construction [4]. However, due to the lack of standardization in the different parts of the world, it is difficult to scale up its production.

Now more than ever, research on techniques to take advantage of the benefits of soil worldwide is a subject of great interest.

In this study, a soil-based concrete is presented. This concrete replaces cement by an illitic soil in its formulation. This concrete, named Self Compacting Clay Concrete (SCCC), has been thought as an alternative to cement concrete in some favourable scenarios. This technique has been studied previously, using chemical superplasticizers [5] or drying accelerators such as lime or cement [6] to improve the formwork removal. The idea behind this study has been to achieve a similar effect to that of the chemical superplasticizers in reducing the amount of water, but using a natural compound, gallic acid (hereinafter GA) from tara tannin (Caesalpinia spinosa).

The objective of this study is to determine if SCCC can, in some cases, be used as a sustainable replacement of conventional concrete. The methodology followed to achieve that goal can be divided into two parts. The first one is the mechanical characterization of SCCC. Evaluating the mechanical behaviour of the material gives the possibility of knowing which building typologies would be adequate for its use. After characterising the material, the second part consists of a comparative Life Cycle Assessment (LCA) between SCCC and conventional self-compacting concrete. By this comparison, it is possible to assess the actual existing difference between the impacts that both materials have over the environment. The LCA methodology has been applied to other earth-based construction systems on previous occasions [7]. The working methodology for the final LCA results is set out in (Fig. 1)

Figure 1. Methodology

1 Raw materials sampling

The illitic soil (IL) was provided by PYBC in Ribarroja (Valencia, Spain). The Tara tannin was supplied by the company SILVACHIMICA S.R.L (Italy).

2 Raw material characterization

A characterization of the soil and aggregates was carried out through laboratory tests in order to obtain decisive conclusions after mechanical tests.

3 SCCC. Search for the optimal water content in the mixture

A batch of SCCC mixes was performed according to the described procedure. The fluidity test was carried out to determine the % mixing water according to the desired workability.

4 Fresh SCCC. Specimen preparation

With the fresh mass, the specimens were prepared to check that the shrinkage of the SCCC was within the required parameters. Then the compressive and flexural strength samples were prepared.

5 Hardened SCCC. Mechanical tests

Compressive and flexural strength tests were performed after the guarantee that the dosage complied with the % linear shrinkage within the established parameters.

6 Lyfe cycle analysis (LCA)

A comparative LCA was performed between the SCCC and a cement concrete with similar workability characteristics applied as a structural slab.

2. Materials

2.1. Soil

The illitic soil (IL) was provided by the company PYBC from Ribarroja del Turia (Valencia, Spain). The following characterisation tests were performed to establish an adequate dosage and reactivity evaluation strategy. The two goals of the characterisation tests (Table 1) were: to study the granular skeleton of the material either by density or particle size and to understand the chemical composition of the material. The characterisation was complemented using a sedimentation test to obtain complete information about the real percentage of clay and silt between the fine particles. A granulometric laser analysis was performed with a Mastersizer2000 Hydro 2000SM (A) and one minute of ultrasound as a dispersant agent.

A major component analysis was made through the quantitative interpretation of an X-ray diffraction test (XRD) to identify the crystalline phases of the object soils, using the Diffrac Plus Xrd Commander Software system with the JCP3 database of the ICDD (International Centre for Diffraction Data). To the basic dust pattern test were added the oriented clay aggregates, the glycol aggregates diagram/pattern, and the calcined aggregates diagram at 550ºC.

2.2 Aggregates

The aggregates were supplied by La Torreta, a quarry in Castellón de la Plana (Spain). Dolomitic limestone and washed crushed stone aggregates were used so that the fines did not interfere in the proposed granulometric curve. The quarry provided data related to the properties of each aggregate to adequately adjust the dose needed (Table 2).

***Table 2**. Soil and aggregates properties*

Soil Parameters	Unit	Soil
Grain size		
Gravel (> 5000 μm)	%	0.0
Sand (63–5000 μm)	%	0.3
Fines (< 63 μm)	%	99.7
Silt	%	45.6
Clay	%	54.1
Atterberg limits		
Liquid limit (W_L)	-	17.7
Plastic limit (W_P)	-	12.5
Plasticity index (PI)	-	5.2
Soil classification - USCS	-	CL-ML
Specific gravity (G_S)	-	2.712
Calcium carbonate content	%	11.0
Organic matter content	%	0.02

Aggregate Parameters	AF-0/2 AF-0/4	AG-4/11
Granulometry: Category (UNE-EN 12620:2003+A1:2009) [35]	G_F 85	G_C 90/15
Fines, % (< 0.063 mm) (UNE-EN 933-1:2012) [36]	≤ 10	≤ 1.5
Particle shape: elongation index, % (UNE-EN 933-3:2012) [37]	-	≤ 15
Sand equivalent (UNE-EN 933-8:2000) [38]	≤ 75	-
Resistance to fragmentation (LA), (UNE-EN 1097-2:2010) [39]	-	≤ 35
Specific gravity, Mg/m^3 (UNE-EN 1097-6:2001) [40]	2.700	
Water absorption, % (UNE-EN 1097-6:2001)	≤ 1.5	
Chloride content, % (UNE-EN 1744-1:2010) [41]	≤ 0.03	
Total sulphur content, % (UNE-EN 1744-1:2010)	≤ 1.0	
Total soluble sulphates, % (UNE-EN 1744-1:2010)	≤ 0.2	
Light organic pollutants, % (UNE-EN 1744-1:2010)	≤ 0.5	

2.3 Gallic acid

The tannin powder (product name Tan'Activ T80) was supplied and produced by Silvachimica SRL (Italy) from a raw material imported from Perú, Tara (Caesalpinia spinosa). The product was supplied as dry powder packed in 5 kg packages. We chose this product for its high gallic acid concentration in the extract (reaching up to 53%) [8].

3 Methods

3.1 SCCC Dosage

The protocol for the SCCC dose is based first on the readjustment and adaptation of the granulometric curve of the raw material to ensure an improved cohesion of the components of the concrete; and, secondly, on the reduction of mixing water, and therefore, the minimisation of the probability of microcracking (due to the shrinking effect) that decreases resistance.

Taking into account the singular curves of each component of the concrete, the percentages of each were adjusted to recreate an ideal curve that was close to the proposal made by Bollomey [9], which proposes an ideal granulometric curve based on the consistency of the concrete. The procedure of recognising the reactivity of the GA with the clayey soil IL according to [10] was followed to obtain an ideal pH of the mixing water and an ideal percentage of the GA as a superplasticizer.

The mixing procedure for the SCCC concrete was as follows: the first step was to add N_aOH to the water to compensate the pH according to the results of the reactivity test. The aggregates, the IL, and the GA additive were homogenised in a dry state with an electric concrete mixer model HGN 150 for 30 s. The pH compensated water was added to the concrete mixer with the rest of the components. The mixture was then mixed as a concrete for 2 min until the materials reach a homogenised consistency.

3.2 Mechanical tests

The tests carried out are displayed in Table 1. It was proposed that the mechanical tests for the SCCC mixture under research be compared with the results of a sample without additive (henceforth NA), set as a constant to obtain the same flow index for both mixtures.

Table 1. *Soil characterisation and mechanical tests*

Soil characterisation tests	Regulations
Grain size	ASTM D7928-17 [28]
X-Ray powder diffraction	ICDD (International Centre for Diffraction Data)
Sedimentometry	UNE-EN ISO 17892-4:2019 [29]
Attemberg limits	ASTM D4318 [30]
Soil classification – USCS	ASTM D2487 [31]
Specific gravity (G_S)	ASTM D854 [32]
Calcium carbonate content	ASTM D4373 [33]
Organic matter content	ASTM D2974 [34]

Mechanical tests	Regulations	Dimensions (cm)	Samples
Slump test	PNE-EN 12350-2 [11]	20x30 (top) 10x 30 (base)	3
Shrinking test	DIN 18952 [42]	7x10x70	3
Compressive strength test	DIN 18555-5 [43]	ø15x30	9
Flexural strength test	DIN 18555-5	10x10x030	9
Young's modulus test	UNE-EN 12390-13:2014 [44]	ø15x30	9

3.2.1 Fluidity and shrinkage test

The flow test was performed just after the mixing process in the concrete mixer. The fluidity to be achieved was of a 15-16 cone or fluid-liquid consistency according to the PNE-EN 12350-2 [11] for self-compacting concrete.

The next step was to perform the shrinkage test. A sample from the flow test was collected, and a parallelepiped specimen mould of 7x10x70 cm was filled. A distance of 20 cm and the line defining that distance were marked on the upper plane of the specimen using a knife and a pattern.

The specimen was placed then on a glass surface, previously greased with oil, for three days at a temperature not higher than 20º C. The drying was then completed in an oven at 60º for 24 h. The dry shrinkage value was determined by the average of the two tests, which should not differ by more than 2 mm, and given that the SCCC is applied in continuous structural elements, the average of the total lineal shrinkage should not exceed 1%.

3.2.2 Compressive *and flexural strength*

The specimens were prepared for the mechanical tests following the regulations shown in Table 1.

Given that the clay-based concrete does not need high ambient humidity for hardening, the samples were kept in a controlled environment chamber under constant conditions of 20 °C and 50% RH. The SCCC does not have any time-dependent stabiliser or hardener, so the break date was set to its full hardening state (Table 3) and hygroscopic equilibration of 28 days. The compression test was performed using a testing machine with a range of 2000 kN and a speed of 0.60 kN/s, with a servo-hydraulic control console for axial load application and Mecatest-16 data acquisition. Also, strain gauges type PL-60-11 were used with a gauge factor of 2.09±1% and an HBM Spider 8 daq data acquisition module to measure microstrains (to obtain Young’s and Poisson coefficient under the standard regulations). The flexural test was performed using a testing machine model CODEIN MC0-30 with a range of 2000 kN and a speed of 2,5 kN/s.

Table 3. *Mineralogical composition interpretation*

Components	Illitic soil
% Smectites	0.00
% Illitic	55.71
% Chlorite	6.23
% Kaolinitic	38.06

4 Methodology for the Comparative Life Cycle Assessment

A comparative Life Cycle Assessment (LCA) between Self-compacting clay concrete (SCCC) and regular self-compacting cement concrete has been performed. This study analyzes the life cycle from cradle to gate, accounting for all the impacts generated during the production of both materials. This LCA has been performed following the framework provided by the ISO 14040 [12].

4.1 Functional unit

The functional unit used for this study is one square meter of slab with a 10 cm thickness. Therefore, the comparative unit for both slabs is 0.1 cubic meters. This building element was chosen as the comparative unit since both materials meet the mechanical requirements to be used as a slab according to ACI 360R-92 [13] and Code on Structural Concrete EHE-08 [14]. A structural verification calculation was performed with Cype3D v. 2021.a. where the SCCC met the structural requirements for a standard single family-house established in the Technical Building Code (CTE SE-AE) [15] for residential use within the following conditions:

Slab dimensions: 10x6x0,1 m

Gravitational actions: Own weight 24,00 kN/m^3; Dead loads 2,00 kN/m^2

Variable actions: Surface load 2,00 kN/m^2; Punching shear load 2,00 kN applied in 5x5 cm^2

To obtain the solicitations, the principles of Rational Mechanics and the classical theories of the Resistance of Materials and Elasticity have been considered. The calculation method applied was the Limit States.

4.2 Inventory analysis

A Life Cycle Inventory (LCI) was performed to account for every activity, raw material, and process that can have an impact on the environment. The tool used to model the LCI was Simapro 8.3.1.0, one of the most well-known software used for LCA calculations. The dosages of both SCCC and self-compacting cement concrete are specified in Table 6.

Table 6. *Concrete dosage for 1m² of a 10cm thick slab*

	Materials	Mass (%)
Cement concrete	Water	7.50
	Portland cement	15.00
	Sand 0/2, grinded	20.62
	Sand 0/4, grinded	15.46
	Sand 0/4, washed	15.46
	Gravel, round, washed	25.78
	Superplasticiser	0.15
	Anti-washout admixture	0.03
	Total mass	100.00
SCCC	Sand 0/4, washed	32.92
	Sand 0/2, grinded	17.68
	Gravel, round, washed	28.05
	Clay	13.90
	Tap water	7.32
	Galic acid	0.09
	Sodium hydroxide	0.04
	Total mass	100.00

4.2.1 Data quality

The data used for the Life Cycle Inventory was collected during the testing and the production process of the SCCC. The cement concrete dosage was provided by industry partners. Additional data used to conduct this study was extracted from the Ecoinvent V3.5 database [16]. Ecoinvent is a not-for-profit association founded in the early 90s by the domain of the Swiss Federal Institutes of Technology. It compiles real data about the impacts generated by every industry field with over 14700 LCI datasets. The peerreview process that every piece of data undergoes before being approved as a part of the database makes it a highly reliable source [17].

4.2.2 Production phase model

An overview of the production processes of the materials involved both in the SCCC and in the self-compacting cement concrete is included in this section.

Self-compacting cement concrete inventory

Cement: The most common technique for manufacturing cement is the dry method. First, limestone and clay are quarried. After the extraction, the rocks are crushed in two steps. The first step consists of crushing the rock to a maximum diameter of 152 mm. The rock then goes to hammer mills where it is reduced to around 76 mm or less. After that process, the rocks are combined with iron ore and fly ash and then ground. Once these materials are mixed, they are fed into a cement kiln and heated to around 1500 ºC. After the heating process, the elements in the mix unite to form a new substance called clinker. Clinker comes out of the kiln as small grey balls the size of marbles. The clinker goes through various coolers to lower its temperature. In the final step, the clinker is then ground and mixed with small amounts of gypsum and limestone [18][19][20].

Sand and gravel: Sand is usually mined in open excavations. This process is carried out with power shovels, draglines, front end loaders, and bucket wheel excavators. In some rare cases, light charge blasting is required to loosen the deposits. After mining, the sand is then suctioned and transported to processing plants. Although sand is sometimes used straight from the quarry, it usually requires further processing. After being transported to the processing plant, the sand is directly loaded into a hopper, typically covered with parallel bars to screen out big cobbles or boulders. Then the sand is transported on a conveyor belt to scalping screens. Scalping screens separate the oversize material from the smaller marketable sizes. The oversize material is usually crushed and returned to the process. The material is then fed into a battery of vibrating multi-deck sizing screens. Rotating trommel screens with water wash the sand and gravel. After the screening, the sized material is transported to stockpiles or storage bins. Then, water classification is then used to separate the different granulometry, and then the material is dewatered using hydro-separators. The resulting material is transported to stockpiles or storage bins on conveyors belts [21].

Superplasticiser: a polycarboxylate-based superplasticizer is considered for the production of the cement concrete in this study. Polycarboxylate ethers (PCE), which are linear polymers, contain groups with polyoxyalkylene (especially polyethylene or polypropylene glycol groups**)** as well as carboxylic acid or carboxylic acid anhydride monomers. Several components are submitted to a polymerization process to obtain polycarboxylate. Polyethylene glycol, acrylic acid, and maleic acid are obtained from crude oil. Hydrogen peroxide is extracted from natural gas and sodium hydroxide from rock salt. The batch polymerisation process requires a polymerisation plant and suitable industrial buildings [22].

Anti-washout admixture: admixtures are based on cellulose ether. Cellulose ethers are made by reacting cellulose first with aqueous sodium hydroxide and then with an alkyl halide [23].

Self-compacting clay concrete (SCCC)

Illitic soil: illitic soil is mined using excavators and load-hauling trucks. It is usually extracted with a bench-mining technique that enables the clay to be quarried separately. Depending on its category, clay is then aged for 3 to 12 months. The aged clays are then blended according to the desired formulation and roll crushed to a diameter of 5 cm. The clay is then put in a fluid bed dryer to reduce the moisture content to 10%. Once the drying process finishes, the last step is to use a roller mill to obtain clay powder [24].

Sodium hydroxide: commonly called caustic soda, is mainly produced by the electrolysis of soda. Currently, the most common procedure in the industry is called the ion-exchange membrane method. The process starts by dissolving salt in water and removing its impurities. Then the solution is fed to an electrolyser. The electrolysation process produces caustic soda and chlorine. The concentration of caustic soda obtained in the cathode is around 32%. The solution is taken to an evaporator that produces concentrated caustic soda. Thanks to a density meter installed in the evaporator, it is possible to control the steam temperature and the pressure inside the evaporator to maintain a suitable concentration of caustic soda [25].

Gallic acid: This can be obtained from Tara Spinosa. Tara is a small leguminous tree**,** native to Peru. The production process begins with the harvest. The pods are cleaned to remove impurities, and then deseeded and separated from the beans. After the deseeding, the pods become a mixture of powder and fibre**,** which then undergoes an extraction process using water at 70ºC. The liquid extract is purified by decantation and filtration. The final product is obtained by submitting the purified liquid extract to an atomisation process [26].

4.3 Life impact assessment

4.3.1 Allocation principle

The allocation principle followed in this study is cut-off by classification, based on the cut-off system model. This model relies on the idea that the original producer of the material is responsible for the waste generated, not receiving any credit for using materials that can be recycled. The consequence of this is that recycled materials are burden free environmentally-wise [27]. Even though this study does not consider any recycled materials, this choice directly affects those pieces of data extracted from Ecoinvent. This model is considered to be the most adequate for this study.

4.3.2 Evaluation methods

Among all the available methods for performing the life cycle assessment, two are selected: The IPCC.GWP 100a [28], and the Environmental footprint (EF) method. Developed by the intergovernmental panel on climate change, the IPCC GWP 100a method is used to calculate the greenhouse gas emissions (equivalent CO_2 Kg) emitted by each material. The EF method was developed by the European Platform on Life Cycle Assessment. This method calculates the impacts of 19 different impact categories. The method describes the methodology for normalizing and weighting the results. By that process, it is possible to compare the results adequately and also to join them together in a single score result [29].

5 Results

The results of the tests carried out on the raw materials and on the specimens prepared for the mechanical tests are presented below.

5.1 Soil characterisation tests

The results of the soil characterisation tests are shown in Table 2. From the results, the soil has been classified as a silty-clay (CL-ML) of low plasticity according to USCS soil classification.

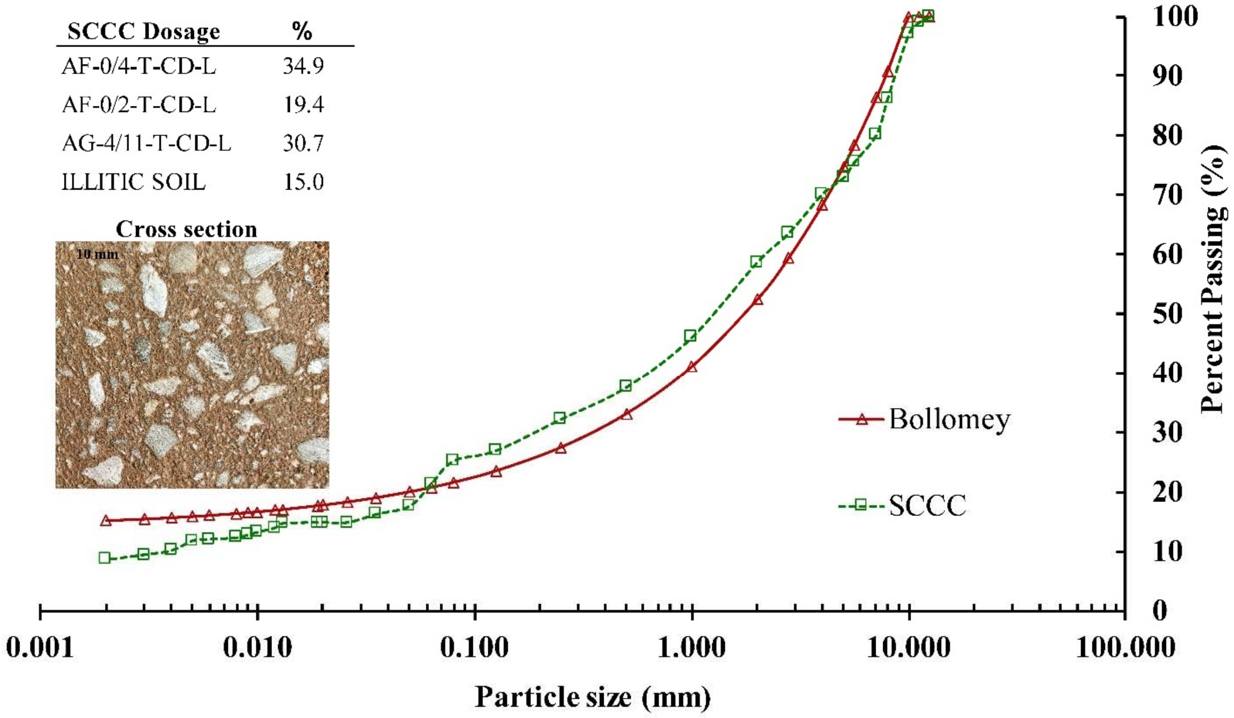
The results of the X-ray diffraction test showed an elevated percentage of K_2O, which is natural in illitic soils. The comparison of the mineralogical composition with the ICDD database revealed a high percentage of illite and kaolinite (Table 3). The phyllosilicate structure of this colloid is appropriate for construction due to its high adherence and dimensional stability under RH% environmental variability. The sedimentation test provided us with the real percentage of clays and fines to complete the fines area of the granulometric curve of our designed concrete. These percentages verify that the soil is silty-clay (CL-ML).

5.2 SCCC preparation

The design of the granular skeleton of our SCCC with the available materials produced a curve similar to the ideal proposed by the Bolomey method (Fig. 2). The distribution of the aggregate in the SCCC can be seen in the cross-section as shown in Figure 2.

For the preparation of the SCCC, the following dosage of additives under investigation was treated as ideal: 0.8% AG/IL and 0.5% NaOH/H_2O both by weight.

Figure 2. Granular skeleton proposal and SCCC cross-section



5.3 *Mechanical tests*

5.3.1 Fluidity test and shrinkage test

For the SCCC, with a decrease of the Abrahams cone of 16 cm, the results of linear shrinkage after drying at room temperature and after extraction from the oven are displayed in Table 4.

Table 4. *Lineal shrinkage*

Sample	24h T 20ºC	7d T 20ºC	24h T 60ºC
SCCC	0.15	0.72	0.76

5.3.2 Compressive and flexural strength

The compressive and flexural strength results are presented in Table 5. These values were entered in the calculation simulation to verify that SCCC mechanical properties meet the requirements for the chosen functional unit according the Code on Structural Concrete (EHE-08) [14].

Table 5. *Compressive strength (fc) and Young's modulus results*

Sample	ρ (Kg/m^3)	f_{cm} (MPa)	f_{ctm} (MPa)	E_{cm} (MPa)	Poisson's ratio, v
SCCC	2,308	6.3	1.43	2,686	0.13

Flexural ultimate limit state result 0,30 MPa and Punching ultimate limit state 0,120 MPa. These results confirm that a 10 cm SCCC slab complies with the Ultimate Limits State criterion of flexotraction by point load of 2 kN and supports the punching shear limit state for the 2 kN load applied to a 5x5 cm surface, values within the acceptance parameters of the Technical Building Code (CTE SE-AE) for residential use.

Young's modulus and flexural test for the NA specimen did not show representative results given the volumetric inconsistency and irregularity of the specimens and given that the mixing moisture to retain a constant flow rate caused a significant shrinkage of the mixture without additive.

A comparison of the horizontal structural element (the slab) was made, and the requirement was its dead load, its weight, as well as its live load, the structure in operation, of ±10 KN/m^2 for a standard single family-house.

5.4 LCA results

The LCA calculations were carried out using two highly trusted methods. The first one is the IPCC GWP method, developed the Intergovernmental Panel on Climate Change. The carbon dioxide equivalent emissions are obtained through this method. The second one is the Environmental Footprint method v2, developed by the European Platform on Life Cycle Assessment of the European Commission. This method offers a comprehensive set of results in different impact categories.

5.4.1 IPCC GWP

Networks representing the different processes involving the production of the two kinds of concrete and their contribution to the total carbon emissions are depicted in Figure 3 and Figure 4. In the case of the cement slab, it can be observed that almost 90% of the emissions occur during the production of clinker. In the case of the SCCC, the emissions are mostly related to the extraction of sand and gravel.

Figure 3. Network of cement concrete slab

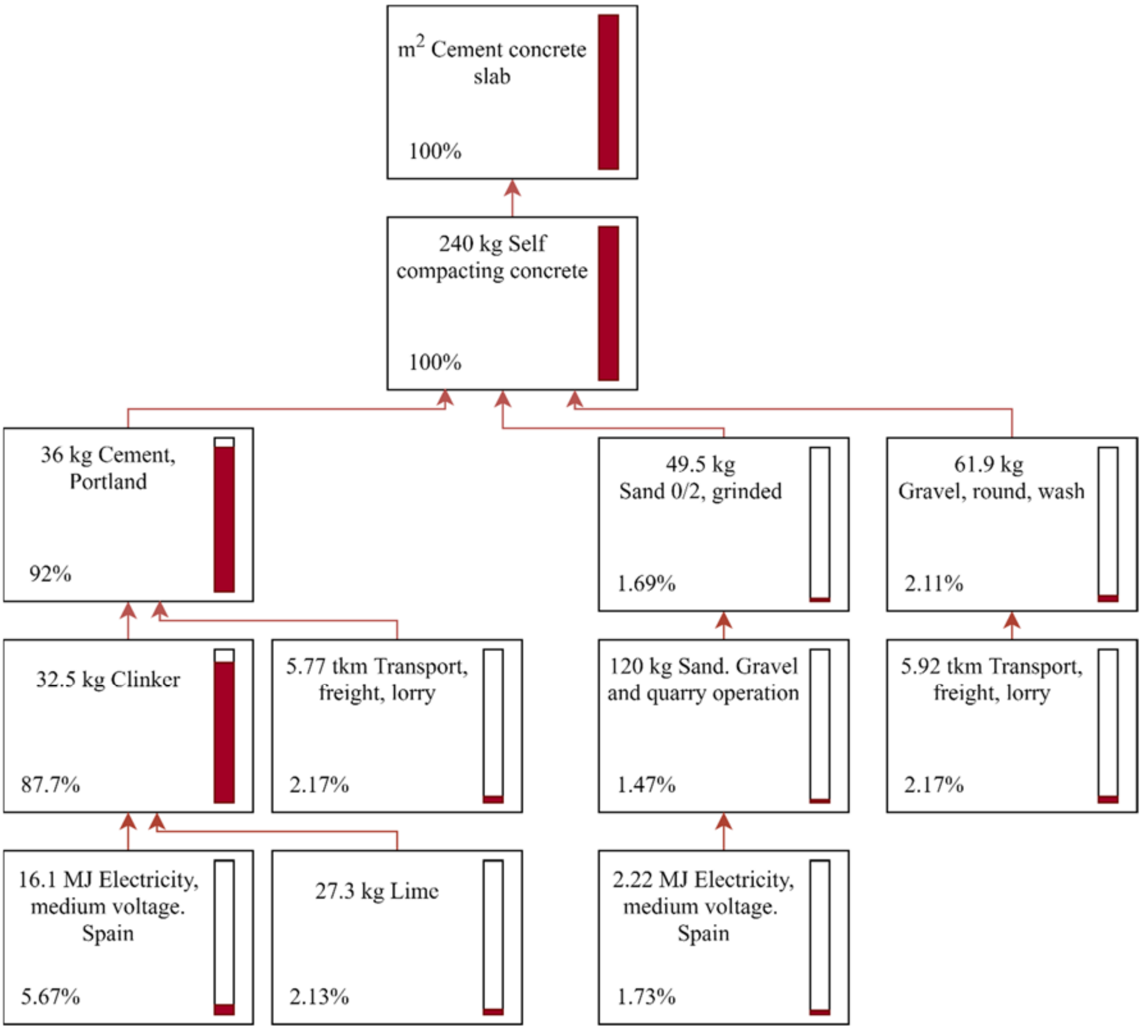
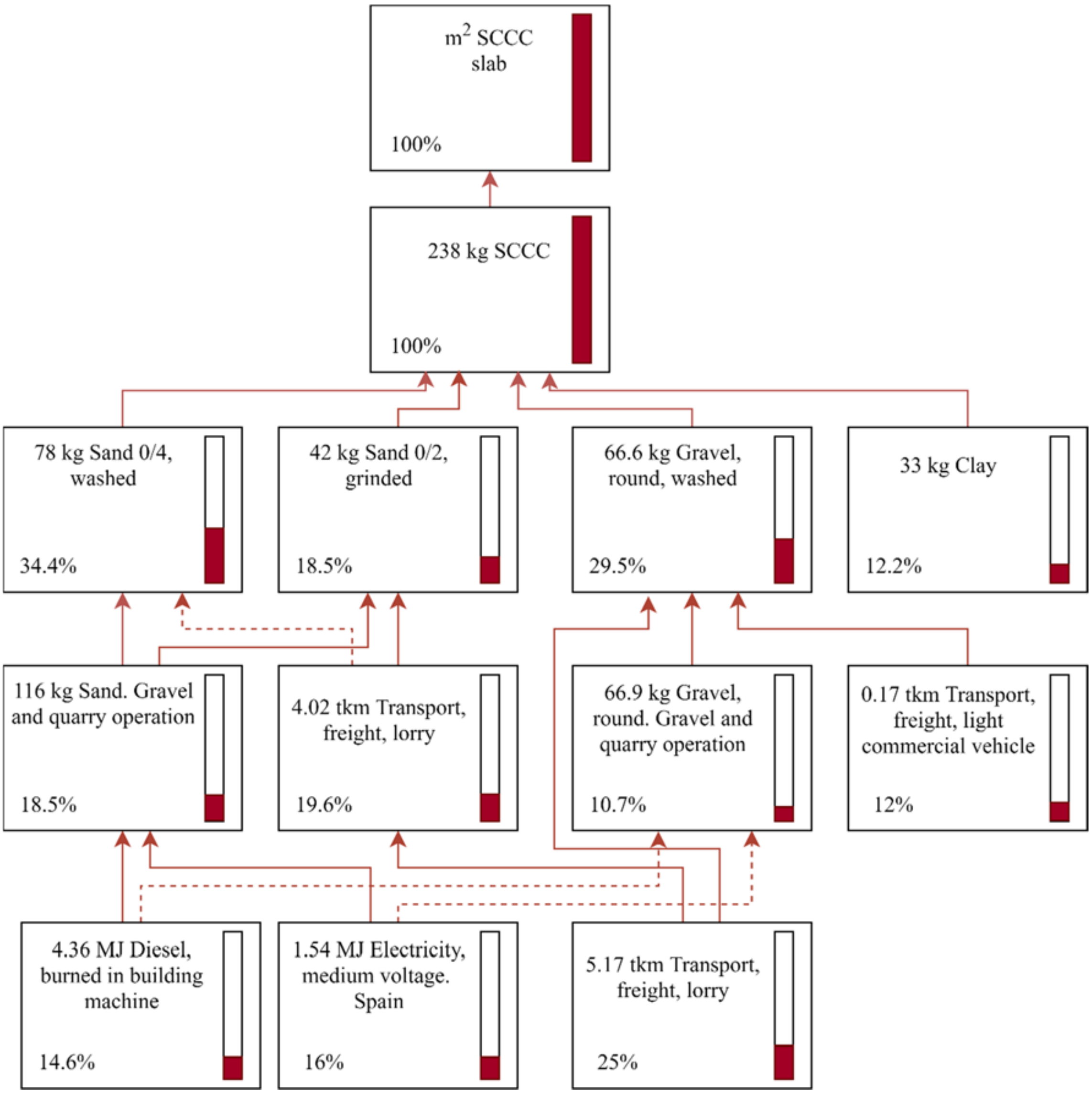
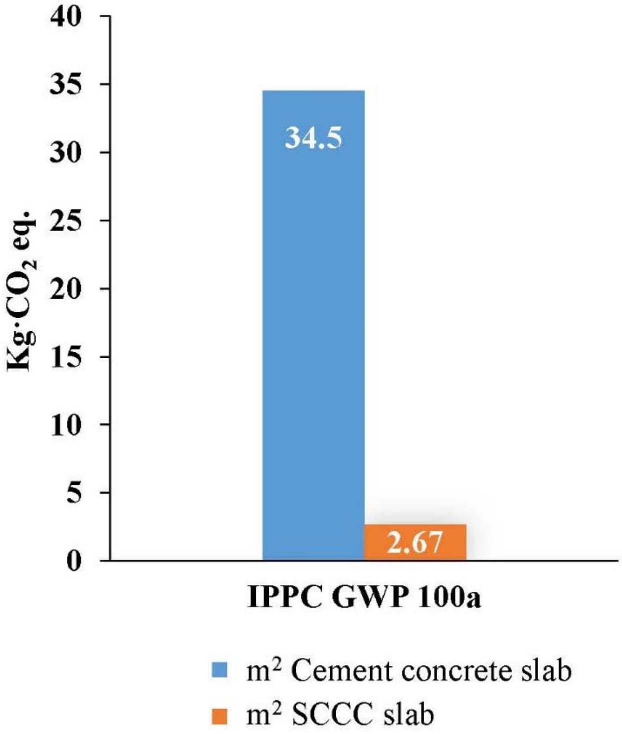


Figure 4. Network of SCCC slab



The total CO_2 equivalent emissions produced by 1 square meter of each typology are depicted in Figure 5. While building a slab using cement concrete generates 34.5 Kg of CO_2 eq. per square meter, using SCCC to build the slab only generates 2.67 Kg of CO_2 eq.

Figure 5. Comparison between 1m^2 cement concrete and SCCC



5.4.2 Environmental Footprint v2 results

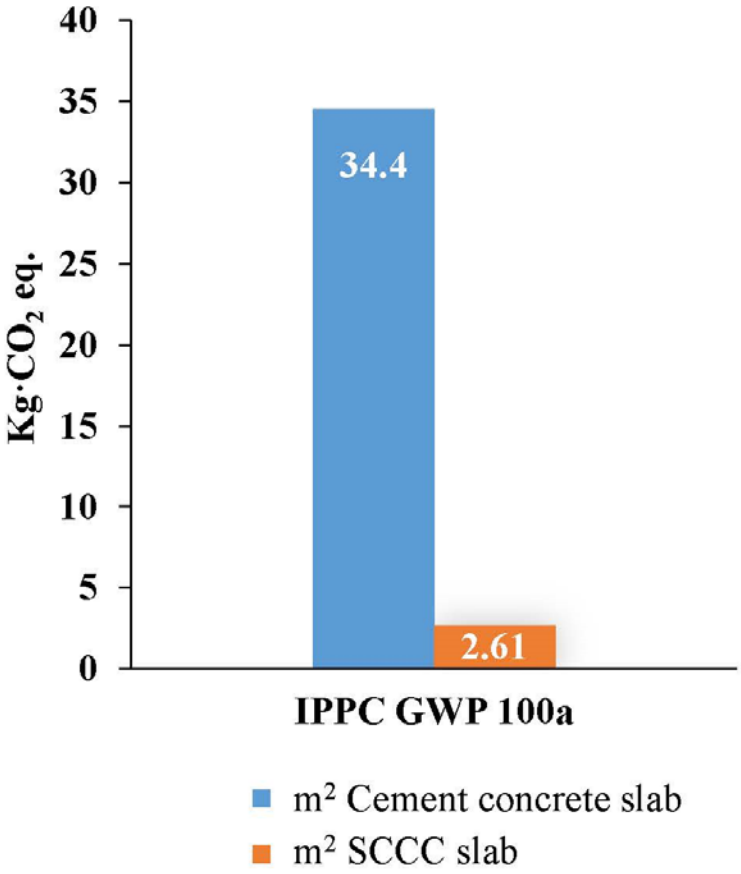
Besides assessing the carbon emissions, other environmental impacts have been analyzed as a part of this study. As said in previous sections, the Environmental Footprint method (EF) has been used to perform the calculations. The characterization results, where the impacts are presented in different impact categories, are reflected in Table 7. As will be discussed in subsequent sections, the results show that the impact generated by the SCCC is lower in every category studied.

Table 7. *EF characterisation*

Impact category	Unit	m^2 slab cement concrete	m^2 slab clay concrete
Climate change	kg CO2 eq	34.36	2.61
Climate change - fossil	kg CO2 eq	34.33	2.61
Climate change - biogenic	kg CO2 eq	0.0188	0.0039
Climate change - land use and transform.	kg CO2 eq	0.0077	0.0025
Ozone depletion	kg CFC11 eq	1.63E-06	4.98E-07
Ionising radiation, HH	kBq U-235 eq	0.7549	0.1638
Photochemical ozone formation, HH	kg NMVOC eq	0.0787	0.0190
Respiratory inorganics	disease inc.	6.84E-07	2.75E-07
Non-cancer human health effects	CTUh	1.90E-06	4.20E-07
Cancer human health effects	CTUh	1.14E-07	6.40E-08
Acidification terrestrial and freshwater	mol H+ eq	0.1041	0.0213
Eutrophication freshwater	kg P eq	0.0006	0.0001
Eutrophication marine	kg N eq	0.0259	0.0060
Eutrophication terrestrial	mol N eq	0.3166	0.0691
Ecotoxicity freshwater	CTUe	7.00	3.52
Land use	Pt	104.52	51.09
Water scarcity	m3 depriv.	14.36	13.46
Resource use, energy carriers	MJ	182.36	37.88
Resource use, mineral and metals	kg Sb eq	2.73E-05	1.60E-05

The EF method offers the possibility to normalize the results, which makes it easier to compare the importance that every category has over the total environmental impact. As observed in the normalization results, depicted in Figure 6, the difference between the two typologies in most categories is significant.

Figure 6. EF normalization. Comparison between 1m^2 of cement concrete and SCCC



The EF can also weigh the results, increasing the importance that some categories have over the total environmental impact. The weighted results are depicted in Figure 7. Once the results have been normalized and weighted, the different categories can be added up to obtain a single score result, Figure 8. The impact score obtained by the SCCC slab is 80% lower than the one obtained with the cement concrete slab.

Figure 7. EF weighting. Comparison between 1 m^2 of cement concrete and SCCC

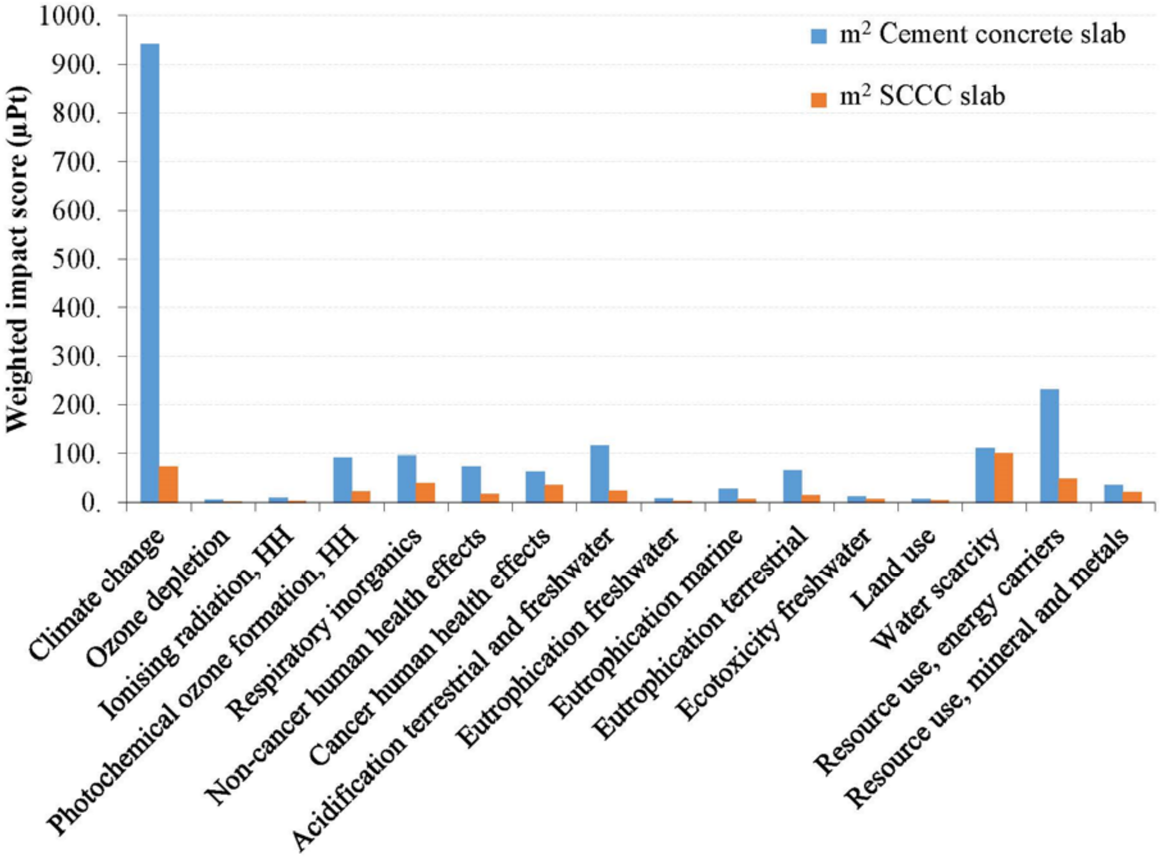
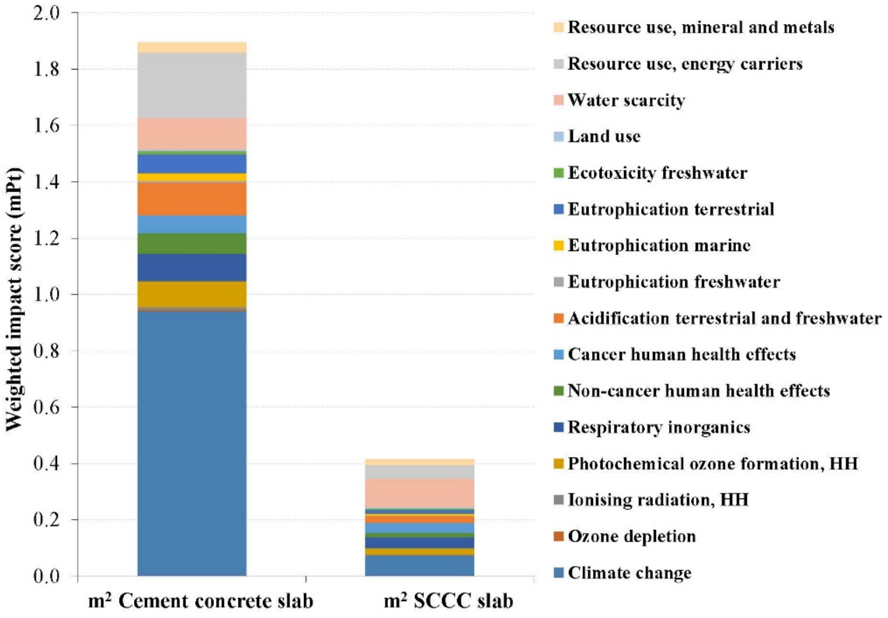


Figure 8. EF single score. Comparison between 1 m^2 of cement concrete and SCCC



6 Discussion

After the completion of the study, it is apparent that using SCCC to replace conventional cement concrete is not only better environmentally wise but also adequate in terms of mechanical properties. The results of compressive strength, shrinkage, and fluidity of the SCCC with the natural superplasticizers (GA) studied have been satisfactory for construction purposes in the case of slabs, bearing in mind that the main objective was to achieve liquid concrete without shrinkage for continuous elements. The results are satisfactory because the GA, in conjunction with the chosen illitic soil, at a certain pH, enables clay dispersion with less water such that the concrete becomes highly fluid – and so reduces the amount of mixing water while maintaining the same density as in drier consistencies.

The arrangement of the clay microstructure can also explain the improvement of the compressive and flexural strength. The sorting of the clay changes its electrical charge, as opposed to the case of having an aleatoric arrangement with positions that do not favour the transmission of compressive loads.

In order to obtain conclusive results, a follow-up of the evolution and aging of the material should be carried out in future investigations, also studying the gallic acid reaction in different types of exposure and combination with auxiliary materials.

When it comes to the LCA results, both methods show a big difference between the impacts of the two materials. The results obtained using the IPCC GWP method show a 90% reduction in the carbon emissions when using SCCC to build a square meter of slab. This is due to the massive amount of carbon emitted during the production of clinker. The EF method also shows a big difference in every impact category studied. The results obtained in categories relevant to human health such as cancer and non-cancer human health effects show the positive impact that using SCCC can have on human health. Other categories related to the ecosystems, for example, resource use and acidification, also reflect the environmental benefits that its use would bring. This becomes apparent when all the categories are summed up after the normalization and weighting process. As it was mentioned in section 5.4.1, the biggest contributor to the environmental impacts of the cement concrete slab is the cement itself, due to the emissions generated during the clinker production. In the case of the SCCC slab, sand and gravel are responsible for almost 90% the total carbon emissions of the slab. These environmental results show consistency with other studies dealing with the environmental impacts of cement [30]. Despite the efforts made by some manufacturers, research indicates that there is a limit to how much the environmental impacts of cement production can be lowered [31]. Using SCCC instead of conventional cement concrete, when the technical conditions are favorable, could have environmental benefits both locally, by attenuating the environmental impacts in places where clinker is produced, and globally, by helping to mitigate climate change.

Conventional cement concrete is an incredibly valuable material but due to its high impact over the environment, finding alternatives to it in some applications is a subject of great relevance. The SCCC presented in this study can be useful to avoid overusing cement in applications where it is not necessary. Furthermore, combining the use of biological materials such as wood, and sustainable geological ones such as SCCC, it is possible to build green constructions.

7 Conclusions

This research aimed to analyze the feasibility of replacing conventional self-compacting cement with a new kind of clay-based concrete. This self-compacting clay concrete

(SCCC) uses soil to replace cement in its composition and chemical additives with natural additives in those scenarios in which the mechanical loads are favourable. The study combined the characterization of the mechanical behavior of the SCCC and a comparative LCA between an SCCC and self-compacting cement concrete slab.

The improvement that this construction technique offered in comparison with its clay-based counterparts is that it maintains a valid compressive strength as a structural element, improving the setting and speed of installation of the material (an important condition in contemporary construction markets) and not shrinking and cracking when used in continuous construction elements such as slabs.

When it comes to the SCCC characterization, the comparison of two types of concrete with different compositions demonstrates the possibility of substituting the cement binder for clay or chemical additives for natural ones in certain scenarios, which emphasizes the technical feasibility of this type of ecological and sustainable construction solutions.

The results obtained in the LCA clearly show that using SCCC instead of cement concrete is hugely beneficial for the environment. By an impact assessment of two comparable typologies, it is possible to identify the existing difference of the materials environmentally wise. In this case, the typology chosen was a concrete slab. The results show a 90% decrease in carbon emissions and an 80% decrease in the overall environmental impact. It can be concluded that using SCCC instead of self-compacting cement concrete to build slabs is not only feasible mechanically wise but also hugely beneficial for the environment and human health.

In future research, the dosages of clay concrete with natural superplasticizers in drier consistencies will be further studied to improve compressive strength instead of workability.

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.

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Figure Captions

Figure 1. Methodology

Figure 2. Granular skeleton proposal and SCCC cross-section

Figure 3. Network of cement concrete slab

Figure 4. Network of SCCC slab

Figure 5. Comparison between 1m^2 cement concrete and SCCC

Figure 6. EF normalization. Comparison between 1m^2 of cement concrete and SCCC

Figure 7. EF weighting. Comparison between 1 m^2 of cement concrete and SCCC

Figure 8. EF single score. Comparison between 1 m^2 of cement concrete and SCCC