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WHAT IS SUSTAINABLE OR LOW IMPACT CONCRETE?

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Abstract

This paper compares a range of new and proposed 'greener' concretes and evaluates their environmental impact via quantification of their embodied energy. These new concretes are further compared with bio based concretes so as to develop a broad picture of the relative environmental impact of the increasing array of concretes now available to building designers. Some uses, advantages and disadvantages of each type are discussed. Particularly the quantity and volume of concrete material for each specific use case is considered for comparison of the embodied energy for a square meter of building envelope structure.

Results show that bio based concretes have considerably lower impact than standard concretes, as exhibited by much lower embodied energies per kilogram of material. However, those values documented in only a few studies, and further repeatedly referenced in the wider literature, are approximate at best and sometimes inaccurate. Ultra high performance and geopolymer concretes have higher embodied energies but due to their high strengths less material is used, giving them a low environmental impact advantage over standard concrete materials. However, claims that these concretes are many multiples less impactful is widely inaccurate, and misleading promotion.

In a similar vein, this work also questions the claims of carbon negativity of popular bio based concretes, such as hemp-lime. Investigation of the means of carbon sequestration and the difficulties in its quantification are discussed. More realistic estimates of the energy embodied of hemp-lime are used for calculation of the embodied energy, and carbon, for walls sized appropriate to low energy architecture.

Keywords:
UHPC, hemp lime, biobased, hempcrete, embodied energy, sustainable concrete

1 INTRODUCTION

Concrete is a broad term for a wide range of composite materials that include a powder binder, an aggregate and water. They chemically combine to form a workable mixture that can be moulded and will subsequently solidify and gain strength. Most commonly a ready-mix of concrete (~30MPa) combines cement (~10%), sand and gravel (~25% and 40%), and water (~18%). Alternatives to this common concrete with varied strengths and constituents exist. Innovative alternatives with higher strength (HPC, UHPC, geopolymer etc.) enable reduced material quantity usage in the achievement of the same function. Biobased concretes replace, increasingly limited, sand and gravel with biobased aggregate such as flax or hemp shiv.

These authors are currently in the final stage of a H2020 project named IMPRESS focused on developing innovative solutions for precast claddings. This work encompassed the development of a range of novel concrete materials. Investigation of low-impact Ultra High Performance Concrete (UHPC) typologies led these authors to the development of High-Performance Fibre Reinforced Concrete (HPFRC) that met client, industry and project requirements [O'Hegarty et al. 2019]. This concrete is here compared to a standard or normal concrete (NC) as the control, and to an example bio-based hemp-lime mix previously developed [Walker and Pavia 2014] and analysed [Kinnane et al. 2016, Reilly and Kinnane (2017), Reilly et al 2019].

2 THE CRISIS OF CONCRETE

The gargantuan development of urban environments, and their connecting infrastructure, in the last century and a half has resulted in considerable environmental problems and degradation. Future cataclysmic events are predicted as a result. The emissions deriving from the fuel for this development are warming the planet and changing the climate. This development has been realised using concrete. Its usage swelled in the mid twentieth century. Unfortunately modernist masterpieces, and subsequent brutalist wonders, were trailed by a near ubiquitous and commonly shoddy usage of the material. Today concrete is used more commonly than any other man made material and more than its preceding industrial age marvel – steel. In recent years it has again found popularity as a cladding material for building facades. The production of concrete is increasing, and increasing rapidly.

The problem with this situation is that concrete embodies considerable carbon in its production, particularly as a result of the cement content. Other constituents of concrete, such as sand and gravel - although not embodying the same carbon in production or processing - are limited resources and their continued usage is fundamentally unsustainable.

Alternative binders, and aggregates, need increased research. Alternative lower-impact concretes need to rapidly replace the standard, if emissions are to reduce for the concrete used. However, the fact remains that we are using far too much concrete and identification of a low impact alternative will not be a silver bullet in itself.

3 NOVEL OR ALTERNATIVE CONCRETES

3.1 UHPC

UHPC is claimed as a concrete with more sustainable credentials than typical concretes. This claim primarily derives from the fact that UHPC is of much higher strength and therefore less concrete needs to be used for the same function. However, a much greater percentage of cement is used in a UHPC mix when compared to a standard concrete mix. This study investigates what is termed a High-Performance Fibre Reinforced Concrete (HPFRC) with a compressive strength of ~ 100MPa. The concrete was developed with the dual aims of low embodied energy and high strength, particularly in flexure.

Slag (GGBS) is a by-product, or co-product, material of the steel production process that when pulverised can be used as a cement replacement. GGBS is included as a cement replacement in the mixes analysed in this study, to quantify the embodied energy reduction it offers.

3.2 Geopolymer

Given its cement free constitution geopolymer is certainly likely to play a large part in the conversation about low impact concretes. A past study [Hyde et al. 2017] took a cursory look at the embodied carbon content of geopolymer, using waste material. It (in $kgCO_2e/m^2$ rather than in $kgCO_2e/m^3$) compared the embodied carbon for a specific locally sourced geopolymer mix and promoted it as a low embodied carbon alternative to a random UHPC mix. The concretes encompassed different fibre types (stainless steel and polypropylene for UHPC and geopolymer respectively) and this inconsistency resulted in wide divergence of EC values. To understand the actual low embodied potential of geopolymer technically rigorous studies are required, particularly of the plethora of chemical activators involved.

3.3 Biobased

Both of the described preceding novel high-strength concretes use sand as small aggregate within the mix. However, due to recent excessive quarrying sand is an increasingly limited resource and large-scale future excavation needs to considered if environmental degradation, in sand quarrying areas, is to be avoided.

An alternative to sand and gravel as binders is the use of biobased aggregates in their stead. These aggregates represent the greatest possible ‘greening’ of this concrete alternative. Lime can be mixed with pozzolanic materials and used as a binder alternative to cement. It is often proposed as a more environmentally friendly or ‘sustainable’ alternative to cement, however its embodied carbon is listed as similar to cement (5.3 MJ/kg (0.73 $kgCO_2e/kg$) against 4.51 MJ/kg (0.74 $kgCO_2e/kg$)) in the ICE database. The greatest sustainable benefit of using lime instead of cement likely derive from its superior ability to enable deconstruction at the end of the building life. Also over its lifetime in-situ lime binders recarbonise and therefore might be viewed as a long-term sink for carbon.

4 COMPARATIVE ANALYSIS

A comparative analysis of a selection of concretes is undertaken to evaluate the real EE impact of each. The concretes are compared on a per volume basis, but also in an ‘as-built’ scenario on a meter squared of wall section. Considering a good practice U-value of 0.18 W/m^2K a high performance based concrete is compared with a biobased concrete wall build up.

The materials considered in this comparative analysis are a Normal Concrete (NC) and a High-Performance Fiber Reinforced Concrete (HPFRC), with and without GGBS, and a hemp-lime concrete. Details of the constituents are given in Tab 1.

4.1 1 m^3 of concrete

This study compares the embodied energy and carbon of 1 m^3 of concrete materials.

The NC is designed as a typical ~30MPa concrete with a w/c ratio of 0.58 and a 3:4:6 ratio of cement paste, sand and aggregate respectively. The specifically analysed HPFRC has been designed with a w/b ratio of 0.25, a 50:50 ratio of cement to GGBS, high SP (superplastizer) content, locally sourced sand and aggregates, and microsilica. Glass fibres are used as the fibre in the mix in place of more traditional steel fibres.

The compressive strength of the NC is 32 MPa after 28 days while the compressive strength of the HPFRC is 96 MPa. The flexural strength of the HPFRC is 10 MPa. A flexural test on the NC was not conducted but a flexural strength of 10% of the compressive strength is assumed.

The embodied energy and carbon of the constituents of the different mixes (and the associated sources of this information) are listed in Tab 1. This data is primarily taken from the ICE database [Hammond and Jones, 2008)]. For comparison a NC mix with 50% GGBS content, by weight of powder content, is also considered for analysis.

A full comprehensive study of the embodied energy of the individual components is outside the scope of this paper and so a number of assumptions have been made to simplify the analysis:

- The tabulated values, used in this analysis, are predominantly taken from the ICE database.
- If values are not available in the ICE database a secondary referenced source is used.
- It is assumed the glass fibres have the same embodied energy/carbon as fibreglass
- General steel (as listed in the ICE database) is assumed in the analysis.

The embodied energy and carbon of 1 m^3 of the two mixes are presented in Tab 2. It is interesting to note that for this specific HPFRC the embodied energy is almost double that of the NC. The embodied carbon difference isn't as considerable however. This is most likely due to the high GGBS content in the HPFRC mixture, which has a reduced .

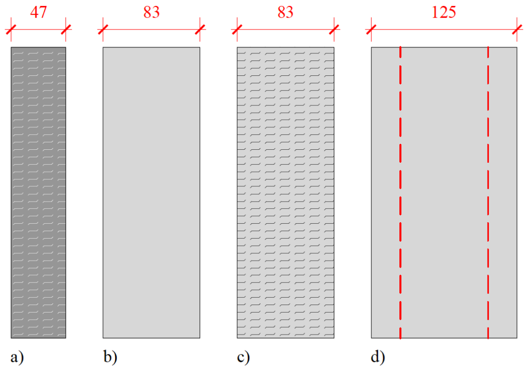
4.2 1m² of concrete cladding

This section looks at 1 m^2 of concrete material in as-built-up wall section examples. The walls under consideration in the IMPRESS project are 3m high concrete walls and thereby fixed top and bottom to floor slabs. Hence they do not require additional structure. To enable a structurally realistic analysis, each wall is designed to meet wind loading conditions. Wind loading conditions vary from one location to the next but the FIB (2017) recommend a design pressure of 1.6kPa and this value is assumed in this study. That is equivalent to a design moment, *M*, of 1.8kNm for the given 3 m high walls. The required thicknesses, *t* (m), of the walls are then calculated according to Eq 1 where □ the design flexural strength of the material which is set as half the measured flexural strength.

$t = \sqrt{\frac{6M}{\sigma}}$ Eq 1.

The four walls are listed below and displayed in Fig 1.

a) A HPFRC wall,
b) A normal concrete wall designed according to the same methodology,
c) A normal concrete wall with fibres to allow for a ductile failure, and,
d) A typical construction of for example a precast reinforced concrete wall with two layers of 8mm steel mesh (250 mm spacing).



a) b) c) d)

Fig. 1: Different wall types assessed.

Based on these wall typologies the embodied energy and carbon are estimated per m^2 of area and the results are presented in Tab 3.

On a per m^2 basis the embodied carbon of all the NC walls is greater than the HPFRC wall which is stronger and therefore thinner. The embodied carbon of the standard wall (Fig 1(d)) embodies more than 3.5 times the carbon of the HPFRC wall. Much of this carbon is attributed to the steel reinforcement bar. The embodied energy of the NC wall without any fibres or reinforcement bar is the lowest. However given that this wall has no form of reinforcement, if it were to fail the failure would be brittle and potentially disastrous. Hence, for this reason, wall type b from Fig 1 is not a realistic option, and only assessed for comparison purposes. The HPFRC wall performs best of those walls that offer post cracking ductility (either via the fibres or rebar (walls c and d respectively)).

4.3 1m² of wall with U-value of 0.18 W/m²K

The embodied energy and embodied carbon of two different wall build ups are compared here. The walls chosen encompass a) a high-strength concrete and b) a biobased concrete. Both walls are designed to meet a thermal resistance lower than Irish (or UK) regulation requirements, but representative of good practice and hence often used in compliance calculations. The thermal transmittance is set to 0.18 W/m^2K. The required thicknesses are displayed in Fig 2 and the walls are briefly described below.

- Wall a) includes a HPFRC rain screen layer cladding and a layer of Expanded Polystyrene (EPS) insulation with an internal layer of plaster board. For simplicity a ventilation cavity is not included.
- Wall b) includes an outer lime render over with a thick layer of hemplime concrete, finished with a layer of plaster on the internal. This is the same wall as that presented in (Reilly and Kinnane, 2017) but with a greater thickness of hemp-lime to meet the 0.18 W/m^2K U-value.

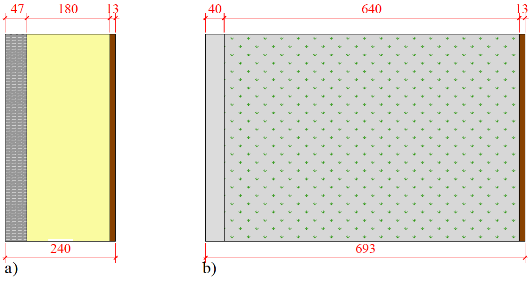


Fig. 2: Different wall build-ups assessed.

The material properties required for the analysis are presented in Tab 4. It is immediately apparent from Fig 2 that the hemp-lime concrete wall is of considerable sectional thickness. This is even though a hemp-lime concrete of relatively low thermal conductivity value is chosen for analysis. Other studies recorded conductivity values in the region of 0.5 W/mK (Elfordy et al. 2008) for higher density concretes.

Some authors attempt to quantify carbon sequestration values for hemp. Pervaiz and Sain [2003] estimate 0.67 ton/hectare/year but this value is derived from values for timber, multiplied by factors that are broad estimates of comparable growth capacity and biodegradation. Amziane and Sonebi [2016] review a number of studies that have attempted to place a value on sequestration levels, and many report a positive overall impact of hemp growth, and incorporation with a binder, on the greenhouse effect. These authors do not contradict these study findings. Instead we state that quantification, or estimation, of the level of carbon sequestration by the hemp plant during its lifetime is outside the scope of this paper. However in the absence of a thoroughly comprehensive and persuasive study we have chosen to use values of 10MJ/kg – based on embodied energy of timber averages in the ICE database. The rationale for this is explained at length in Reilly and Kinnane [2017]. Elsewhere values as low as 1.4 MJ/ton have been documented [Rhydwen, 2015] and for comparison a value of 0 MJ/kg is used. This presumes the carbon sequestered balances the input energy of production. This study does assume that hemp-lime concrete is carbon neutral [as per Florentin et al., (2017)]. In this case any energy used for harvesting or drying is also balanced by the carbon sequestered. The embodied carbon and embodied energy of two hemplime wall build ups are presented in Tab 5. The high embodied of Wall b) is due primarily to the thickness of the hemplime concrete (0.64 m^3 * 3 MJ/kg * 508 kg/m^3 = 975 kg/m^2 of wall area. Such a thick concrete section, encompasses considerable lime content.

5 SUMMARY

Alternatives to standard concretes offer potential for embodied energy savings when used in concrete wall systems. Although high strength concretes have a per mass higher embodied energy this study shows that they offer the best confidentially quantifiable option for decreasing the overall embodied energy of a wall build up, even when aligned with synthetic insulation products.

The embodied energy advantages of hemp-lime construction are strongly dependent on the value of carbon sequestration assumed. Definitive quantification of this would be most helpful to the field of biobased material research. It should be noted that lime and/or cement binders still embody considerable energy in a full sized, thick, wall. For example, hemp-lime concrete (with EE hemp (perhaps more realistically) taken as 10MJ/kg) embodies considerably less energy than the HPFRC option on a per unit volume basis. However, the embodied energy of the hemp-lime concrete wall build-up is greater than the high-performance concrete wall with EPS insulation, when sized to meet contemporary building regulations. This is a consistent problem for biobased concretes. Building regulations have focused almost exclusively on reducing the U-value of walls and ignored other thermal performance characteristics including thermal mass and hygrothermal benefits. These benefits are often claimed for hemp-lime. Such regulation makes hemp-lime a challenging material to use in contemporary high performance buildings for example in near Zero Energy Buildings.

The negative impact of concrete is very much in the news currently [Reilly and Kinnane, 2019[. Replacement of sand and stone aggregate by biobased materials can help reduce the use of increasingly limited natural resources that are currently over consumed. However, the binders in both standard and biobased concretes embody the majority of energy. Binder replacements, such as GGBS can considerably reduce the embodied energy – in this study from 5.3 MJ/kg for binder to 4.1 MJ/kg. It should however be noted that GGBS should not be viewed as a long-term solution to the overuse of cement as it exists in limited supply and its usage is hence unsustainable. GGBS is not typically used in the precast industry as it results in a concrete with a slower setting time, and therefore can’t be lifted from the vibration tables as quickly as a standard concrete. This study was focused on developing a low-impact, high-strength concrete and therefore GGBS is included.

In the analysis undertaken no ventilation cavity is included for ease of analysis. The HPFRC concrete under investigation is designed for a full vertical sections. In an alternative typical rainscreen system constituting smaller arrayed panels, a rail or fixing system would be required to carry the rainscreen cladding. Importantly from a thermal perspective these fixings would penetrate the thermal insulation layer resulting in considerable thermal bridging that should be accounted for. This would negatively affect the thermal calculation, for the HPFRC, and might instead therby favour biobased concretes that are monolithically cast. This is an essential advantage of a biobased concrete wall system and should not be undervalued. Analysis of this will be a focus of future work. This study is part of a wider analysis of the embodied energy of walls. This focuses on the concrete component of the wall and looks at a select few options. The question - what is a sustainable or low impact concrete? - remains an open one. This study shows that varied concretes embodied a wide range of energy values. It simply shows that concretes should not be judged on a per weight, or even a per volume, basis when considering the impact of these, but should be considered in a realistic wall build up that meets structural and thermal standards of contemporary construction.

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Tab. 1: Equivalent embodied energy of constituent materials (MJ/kg)

Constituent	EE (MJ/kg)	Ref	EC ($kgCo^2/kg$)	Ref
PC	4.6	ICE	0.83	ICE
GGBS	1.33	ICE	0.07	ICE
MS	0.036	Aysha	0.028	TR74
Water	0.2	ICE	0	ICE
Sand	0.1	ICE	0.005	ICE

Aggregate	0.1	ICE	0.005	ICE
Superplasticizer	9	Aysha	0.01	Flowers
Glass fiber	28	ICE	6	ICE
Steel	24.4	ICE	1.53	ICE

Tab. 2: Equivalent embodied energy per cubed meter of material

Concrete type	**EE (MJ/m^3)**	**EC (kgCO^2/m^3)**
HPFRC	4441	462
NC	1888	308
NC (GGBS)	1299	172

Tab. 3: Equivalent embodied energy per m2 of wall area.

Concrete type	**EE (MJ/m^2)**	**EC (kgCO2/m^2)**
HPFRC	209	22
NC	157	26
NC- fibres	299	33
NC - steel	389	76
NC (GGBS) - steel	315	59

Tab. 4: Material properties of wall build ups. All data is taken directly from this study or ICE database unless specified.

Concrete type	**EE (MJ/kg)**	**EC (kgCO$_2$/kg)**	**k (W/mK)**	**ρ (kg/m^3)**
HPFRC	1.85	0.19	1.5	2400
EPS	88.6	2.5	0.034	20
Plasterboard	6.75	0.38	0.16	950
Lime render[1]	0.97	0.13	0.8	1600
Hemp-lime concrete[2]	3[2]	0[3]	0.12[4]	508[4]

[1] The lime render is assumed to be a 1:3:2 ratio of lime, sand and water respectively.

[2] Mix proportions and associated EE from (Reilly and Kinnane, 2017)

[3] The embodied carbon varies dramatically from one source to the next and study to the next as an example Florentin et al. (2017) found it to be carbon neutral.

[4] (Walker and Pavía, 2014)

Tab. 5: Equivalent embodied energy per m2 of wall area to achieve a U-value of 0.18 W/m^{2}K.

Concrete type	**EE (MJ/m^2)**	**EC (kgCO2/m^2)**
HPFRC wall	611	35
Hempcrete wall (EE of hemp at 10 MJ/kg)	1057 (975 excl. render)	11
Hempcrete wall (EE of hemp at 0 MJ/kg)	522 (440 excl. render)	11