Nordic Concrete Research – Publ. No. NCR 64 – ISSUE 1 / 2021 – Article 8, pp. 129-144

sciendo	Nordic Concrete Federation
© Article authors. This is an open access article distributed under the Creative Commons Attribution-NonCommercial-NoDerivs licens. (http://creaticecommons.org/licenses/by.nc-nd/3.0/).	ISSN online 2545-2819 ISSN print 0800-6377
DOI: 10.2478/ncr-2021-0006	Received: March 28, 2021 Revision received: June 21, 2021 Accepted: June 26, 2021

Decreasing Carbon Footprint of Block of Flats – Concrete Technology Possibilities

Elina Lahdensivu
MSc student
Tampere University
elina.lahdensivu@tuni.fi

Jukka Lahdensivu, Adjunct Professor, DSc
Leading Specialist
Ramboll Finland Oy
jukka.lahdensivu@ramboll.fi

ABSTRACT
Construction business along with other businesses have set carbon neutrality goals in the following years. To reach these goals a lot needs to be done fairly quickly. The high impact of concrete production on carbon emissions has been known for years and solutions for this problem are studied in this paper through supplementary cementing materials.

Ordinary Portland cement can be replaced partly but not completely with cement replacing materials since the strength properties are lost at replacement level higher than 80%. These replacing binders can be pulverized fly ash, blast furnace slag or silica fume.

The use of the new low-carbon products can half the embodied carbon for the bearing frame of the building. The total area of a certain structure type is important since replacing its cement can have much higher impact on the total carbon footprint than replacing it for a single structure type that has fairly small area in the building.

Key words: Carbon footprint, concrete, LCA, embodied carbon, supplementary cementitious materials

1. INTRODUCTION

1.1 General

In Finland the Ministry of the Environment is setting maximum levels for carbon footprint of buildings by 2025, but many cities have demands already now for low-carbon construction. Low carbon footprint is one evaluated issue together with architecture in public building land competitions. The Ministry of the Environment has released a guideline regarding the calculations of environmental impact of buildings a few years ago. Carbon footprint calculations are based on the standards EN-15978 and EN-15804. On first of March 2021 a national database on embodied carbon of mostly used construction materials and building components was released to combine calculation guideline.

The aim of this study is to look at the concrete technology possibilities the structural designer has in a basic block of flats design process. Only embodied carbon footprint was studied.

1.2 Case building

The case building is a block of flats with seven storeys and a basement located in Tampere, Finland. It is a typical Finnish apartment building with precast concrete sandwich elements as exterior walls and hollow core slabs combined with cast-in-place concrete intermediate floors. The building is founded with steel and concrete piles. Section of the building is illustrated in Figure 1 and the floor plan in Figure 2. The total area is 4583 m^2 of which 3962 m^2 are floor area. The building has a rectangular shape with four balconies per storey. The floor plan consists mostly of one- and two-room flats.

The base floor is 80-200 mm thick concrete slab with 100 mm expanded polystyrene (EPS) insulation.

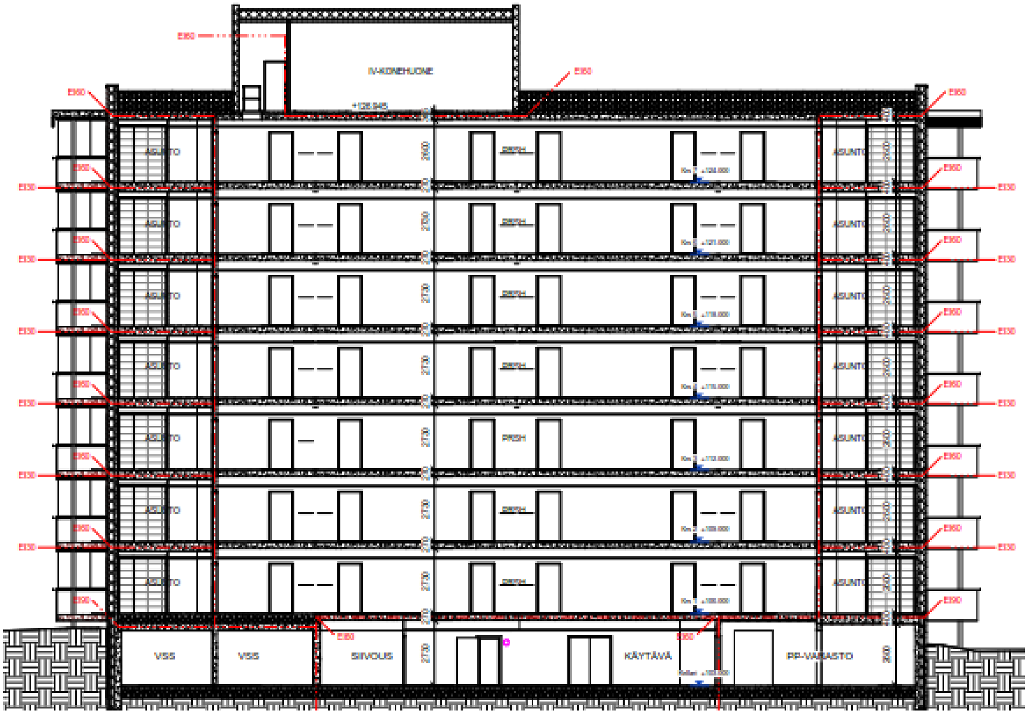

Figure 1 – Section of studied building.

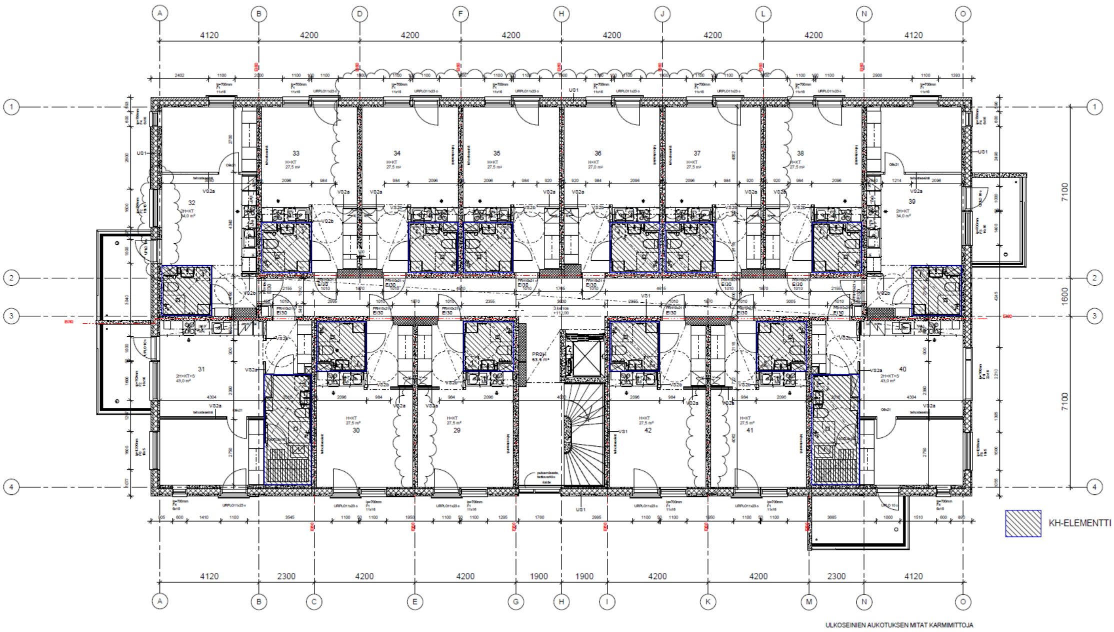

Figure 2 – Floor plan of studied building

Concrete grade used in hollow core slabs was C40/50 and the thickness of the slabs were 265, 320 and 370 mm. Concrete grade used in all other concrete structures was C30/37. These are the most common concrete grades used in Finnish blocks of flats.

Structure types used in the case building are listed in Table 1 along with material layers. Some simplifications were made for the purpose of the table, for example insulation layers were listed by their combined thickness.

Table 1 – Structure types and material layers used in case building.

Type of structure	Material layers				
Bearing sandwich panel 1	150 mm Inner concrete layer	200 mm Mineral wool insulation	85 mm Outer concrete layer		
Non-bearing sandwich panel 1	80 mm Inner concrete layer	200 mm Mineral wool insulation	85 mm Outer concrete layer		
Basement wall 2	300 mm Reinforced concrete wall	10 mm Bitumen polymer sheeting	160 mm Mineral wool insulation	100 mm Reinforced concrete	200 mm #6-16 crushed stone
Basement wall 2 (air raid shelter)	300 mm Reinforced concrete wall	10 mm Bitumen polymer sheeting	160 mm Mineral wool insulation	100 mm Reinforced concrete	300 mm #6-16 crushed stone
Bearing partition wall 1	200 mm Bearing reinforced concrete wall				
Bearing partition wall 1 (air raid shelter)	300 mm Bearing reinforced concrete wall				
Non-bearing partition wall 2	13 mm Gypsum plasterboard	66 mm Sheet metal frame	13 mm Gypsum plasterboard		
Intermediate floor 1	370 mm Hollow core slab	5-30 mm Leveling			
Intermediate floor 3	400 mm Reinforced concrete slab	220 mm EPS expanded polystyrene insulation	80 mm Concrete		
Intermediate floor 4	260 mm Bearing reinforced concrete slab	10 mm Leveling			
Intermediate floor 6	265 mm Hollow core slab	80 mm Concrete			
Base floor 1	300 mm #6-16 crushed stone	100 mm EPS expanded polystyrene insulation	80 mm Reinforced concrete slab		
Base floor 2	300 mm #6-16 crushed stone	100 mm EPS expanded polystyrene insulation	120 mm Reinforced concrete slab		

Base floor 3	300 mm #6-16 crushed stone	100 mm EPS expanded polystyrene insulation	200 mm Reinforced concrete slab		
Roof 1	320 mm Hollow core slab	950-1150 mm Expanded clay	Filter cloth	40 mm Concrete	Bitumen polymer sheeting
Roof 3	Profiled metal sheet	410 mm Mineral wool insulation	Bitumen polymer sheeting		
Balcony slab	200 mm Reinforced concrete slab				
Balcony side wall	180 mm Reinforced concrete wall				
Foundations	Reinforced concrete				
Piles	300*300 Reinforced concrete pile, total length 347 m	RD 140/8 steel pile, total length 235 m			

2. PROPERTIES OF CONCRETE MADE OF CEMENT REPLACING BINDERS

In Finland CEM I is the most used cement type for precast concrete for its quick curing time. This type of cement has less than 5 % non-clinker part in the cement [1]. Rapidsementti by Finnsementti has 0 % blast furnace slag and 6-15 % limestone filler. Its global warming potential (GWP) is between 712 and 764 $kgCO_2e$ (A1-A3) per tonne depending on the factory it was produced at. The average value from all four products is 742 $kgCO_2e$ (A1-A3) per tonne. [2]

CEM II is the most used cement type for cast-in-place concrete in Finland. It contains 6-20 % blast furnace slag [1]. For example, Plussementti by Finnsementti has 10-25 % blast furnace slag and its GWP is 611 or 624 $kgCO_2e$ (A1-A3) per tonne, again depending on the factory [2].

GWP numbers of commonly used cements and concrete in pre-cast concrete elements as well as ready mix concrete cast-in place can be lowered by replacing more clinker with binders such as pulverized fly ash or blast furnace slag. There have been studies how the strength development, durability and workability of concrete is affected when using up to 90 % cement replacing binders. The studies usually use combination of pulverized fly ash and blast furnace slag. These cement types would fit the CEM III criteria.

2.1 Pulverised fly ash

Fly ash is a by-product burning pulverised coal. It is collected electrostatically or mechanically from the flue gases [1]. Pulverised fly ash (PFA) is usually added to concrete for its workability and lower water consumption [3]. Cheah et al. [4] studies and Luke [5] show that the more PFA the binder mixture has, the less water it needs to achieve standard consistency. This is due to the lower surface area compared to that of ordinary Portland cement (OPC) or granulated blast furnace slag (GGBS).

Cheah et al.'s [4] experiments show that the more fly ash the mixture contains, the bigger the final compressive strength of the specimen is. This is the case until the mixture has over 80 % PFA. They also show that the early-stage strength is much weaker than the final strength. The compressive strength for mixture containing 80 % PFA at the age of seven days is approximately 25 MPa and at the age of 90 days it is 50 MPa.

After 80 % content of PFA, the strength of the concrete drops significantly. The strength of the mixture with 100 % PFA is basically 0 MPa and therefor useless. The cause for this is probably inability to form calcium aluminate silicate hydrate (C-A-S-H). This results in binder being loosely packed and unhydrated in the concrete mixture [4].

In these mixtures water to binder ratio decreased as PFA content increased. Mixture with 100 % GGBS water to binder ratio was 0.44. 50 % PFA to 50 % GGBS the water to binder ratio was 0.31 and for mixture with 100 % PFA it was 0.24. Flow of the mixture stayed constant, around 145-160 mm. Their mixtures had 0 % OPC and PFA to GGBS ratio varied. Other research done by Cheah et al. show the same decrease in early strength even when water to binder ratio is constant. In this study all the mixtures had 50 % OPC and the ratio between PFA and GGBS varied. The water to binder ratio was 0.5 [6]. Unfortunately, these studies were focused on the mechanical effects of concrete when replacing OPC so no long-term effects, for example carbonation rate, were studied.

When more than 60 % of binder is replaced with a combination of PFA and GBBS, the carbonation rate of concrete increases the more PFA the concrete has. The decrease in water content combined with the production of additional cementitious compounds reduces the pore interconnectivity of concrete, thus decreasing permeability. The reduced permeability results in improved long-term durability and resistance to various forms of deterioration. Lower permeability of fly ash containing concrete gives improved durability against sulphate attack, alkali-silica reaction (ASR) and corrosion of reinforcement despite of increased rate of carbonation [3, 7, 8].

According to [9] global warming potential of PFA is 0.2 $kgCO_2e$ (A1-A3) per tonne of hard coal fly ash. As the world is shifting away from using fossil fuels the availability of PFA will not be the same.

2.2 Blast furnace slag

Granulated blast furnace slag (GGBS) is a by-product of melting iron ore in a blast furnace. Suitable slag melt is rapidly cooled, making it glassy-like granules [1]. These granules are the pulverised to use as a binder. GGBS is used as a binder because it slows the setting time and improves workability [3].

In Finland the most commonly used cement type in precast concrete elements is CEM I 42.5 R. Lang [10] has compared the strength development of concrete using mentioned cement type and concrete using 73% GGBS and 27% Portland-cement (OPC). From this comparison it can be seen that at the age of two days the difference in strength is approximately 10 MPa. After seven days the strength development pace increases for the concrete containing slag. Around the age of 28 days the strength of both types is equal. At the age of 90 days the concrete containing slag is stronger by 5 MPa and the difference keeps growing. Unfortunately, there is no information about concrete recipe or its properties.

GGBS needs more water [10] since it is finer than OPC. Carbonation rate of concrete with high amount of GGBS is higher than that containing only OPC because of the reduced amount of carbonating calcium hydroxide ($Ca(OH)_2$) in concrete [3, 10]. Concrete containing higher volume of GGBS is known to be denser than concrete containing only OPC [10].

The Global Warming Potential for blast furnace slag is around 50-55 kgCO_2e (A1-A3) per tonne. depending on the production site [2].

2.3 Silica fume

Silica fume is also a by-product. It forms as high purity quartz is reduced with coal in electric arc furnaces in the production of silicon and ferrosilicon alloys [1].

Silica fume is used in concrete because it enhances early strength and has low penetrability. It also reduces bleeding since it coats the aggregate. This feature only benefits concrete containing up to 10 % silica, since aggregate ratio stays the same and there is no more aggregate to coat [3].

At 28 days the compressive strength of concrete containing 10-20 % silica fume is around 75 MPa while concrete containing only OPC has 56 MPa of strength. The difference in compressive strength between mixtures containing 10 or 20 % silica fume is not significant. These mixtures had 400 kg/m^3 of cementitious material combined with water to binder ratio at 0.36. Silica fume itself does not affect the carbonation rate directly, inadequate curing has bigger effect [3].

3. RESEARCH DATA AND METHODS

The study was carried out by calculating embodied carbon footprint independently of each structure type per square meter [kg CO_2e/m^2]. Multiplying that number with a total area of structure type, it was possible to get the total amount of embodied carbon of said structure type. Totally 18 structure types were calculated separately. Piles and foundations were calculated as one complex.

Phases A1-A5 and C1-C4 were included in LCA calculations. Service life for the building was 50 years, which is the most common design service life for block of flats in Finland. Phase B operation of the building was not included in this calculation, because the interest was in embodied carbon, not operational carbon.

The calculations of embodied carbon footprint are based on guidelines released by the Finnish Ministry of the Environment. Quantity surveying was done for each type of structure and with these results the carbon footprint was calculated using One Click LCA -software.

One Click LCA is a commercial, Finnish software for calculating carbon foot- and handprint. The software gives options for the calculation methods and in this study the Finnish Ministry of the Environment guidelines are used. All guidelines are based on EN-15978 [10] and EN-15804 [12] standards. One Click LCA has data for over 10 000 different building materials, some are from manufacturers and the rest are estimates. In this study basic calculations were carried out with the data available from One Click LCA software and the studies of low carbon concrete were carried out with the data available from ready-mix concrete suppliers and pre-cast concrete manufactures environmental product declarations (EPD).

The Finnish Ministry of the Environment guides which components should be taken account of and which to leave out of consideration. All temporary items, such as scaffolding and weather coverings, are left out. All fasteners are also left out since it is hard to estimate their use. All surface materials such as parquet or paint are not taken into consideration. The guideline also gives tabulated values for transportation, energy consumption and such. Tabulated values for some building products are given such as elevators.

Carbon footprint calculation for each type of structure was also carried out with typical cement mixtures and new low carbon cement mixtures. Examples are given in Tables 2 to 4. These three structure types had the biggest impact on overall embodied carbon footprint. In the Tables column three shows the carbon footprint for each part making the type of structure and column four combined carbon footprint of the parts for each module. The last bolded number is the carbon footprint per square meter.

Table 2 – Embodied carbon footprint of intermediate floor 1 [kgCO_2e/m^2].

Intermediate floor 1: levelling concrete 5…20 mm, hollow core slab 370 mm			
Module	Material	[kgCO_2e/m^2]	[kgCO_2e/m^2]
A1-A3	Leveling screed and render	4.25	
A1-A3	Hollow core slab, C40/50	81.63	85.88
A4	Leveling screed and render	0.09	
A4	Hollow core slab, C40/50	1.39	1.48
C1-C4	Leveling screed and render	0.09	
C1-C4	Hollow core slab, C40/50	5.74	5.83
All			**93.19**

Table 3 – Embodied carbon footprint of non-bearing concrete sandwich element.

Non-bearing sandwich panel 1: internal layer 80 mm, insulation 200 mm, external layer 85 mm			
Module	Material	[$kgCO_2e/m^2$]	[$kgCO_2e/m^2$]
A1-A3	Ready-mixed concrete, C30/37	21.51	
A1-A3	Ready-mixed concrete, C30/37	20.24	
A1-A3	Mineral wool	24.98	
A1-A3	Concrete reinforcement	3.8	
A1-A3	Concrete reinforcement	3.8	74.33
A4	Ready-mixed concrete, C30/37	1.86	
A4	Ready-mixed concrete, C30/37	1.75	
A4	Mineral wool	0.06	
A4	Concrete reinforcement	0.03	
A4	Concrete reinforcement	0.03	3.72
C1-C4	Ready-mixed concrete, C30/37	2.26	
C1-C4	Ready-mixed concrete, C30/37	2.13	
C1-C4	Mineral wool	0.89	
C1-C4	Concrete reinforcement	0.06	
C1-C4	Concrete reinforcement	0.06	5.40
All			**83.45**

Table 4 – Embodied carbon footprint of Roof 1.

Hollow core slab 320 mm, bitumen polymer sheeting, 950-1150 mm expanded clay aggregate, filter cloth, leveling concrete 40 mm, bitumen polymer sheeting			
Module	Material	[$kgCO_2e/m^2$]	[$kgCO_2e/m^2$]
A1-A3	Filter cloth	0.1	
A1-A3	Expanded clay aggregate	102.6	
A1-A3	Hollow core slab	58.47	
A1-A3	Bitumen polymer sheeting (water proofing)	5.09	
A1-A3	Bitumen polymer sheeting (vapour barrier)	7.36	
A1-A3	Ready-mixed concrete, C30/37	10.12	183.74
A4	Filter cloth	0	
A4	Expanded clay aggregate	0.4	
A4	Hollow core slab	0.99	
A4	Bitumen polymer sheeting (water proofing)	0.02	
A4	Bitumen polymer sheeting (vapour barrier)	0.02	
A4	Ready-mixed concrete, C30/37	0.87	2.31
B1-B5	Filter cloth	0.4	
B1-B5	Bitumen polymer sheeting (water proofing)	10.18	
B1-B5	Bitumen polymer sheeting (vapour barrier)	14.72	25.3
C1-C4	Filter cloth	0	
C1-C4	Expanded clay aggregate	0	
C1-C4	Hollow core slab	4.12	
C1-C4	Bitumen polymer sheeting (water proofing)	0.37	
C1-C4	Bitumen polymer sheeting (vapour barrier)	0.24	
C1-C4	Ready-mixed concrete, C30/37	1.06	6.03
All			**217.38**

In types of structures that included bitumen polymer sheeting, stages B1-B5 were also taken into account. Service life for the sheeting is 20 years so it needs to be replaced twice during the 50-year calculation period. The service life for filter cloth is even shorter, only 10 years.

Some components were left out of the calculations for a variety of reasons. All windows and doors were left out because they are irrelevant for this evaluation. Bathrooms were also excluded since they were one element and calculation would have been difficult. Air supply unit's walls were also left out, but the roof and floor were calculated. Underground structures are supposed to be reported separately but, in this calculation, these are reported in the same calculation.

In Table 5 the GWPs for each material used in the structure types are presented. The data is collected from One Click LCA as well as their service life. The unit used is typical for the specific material.

Table 5 – GWPs of used materials for modules A1-A3.

	GWP			
A1-A3	$kgCO_2e/m^3$	$kgCO_2e/m^2$	$kgCO_2e/m$	$kgCO_2e/kg$
Concrete C30/37	253			
Hollow core slab 370		64.6		
Hollow core slab 320		50.4		
Hollow core slab 265		47.8		
Mineral wool insulation	125			
Leveling				
Expanded clay aggregate	0.4			
Bitumen polymer sheeting		5.09		
Reinforcement				0.5
EPS expanded polystyrene insulation	50			
Profiled metal sheet		13.7		
Filter cloth		0.1		
#6-16 crushed stone	6.1			
Gypsum plasterboard		2.9		
Sheet metal frame			22.4	
Steel piles				2.5

For ready-mixed concrete and hollow core slabs made with low carbon concrete specific EPD values are gathered from manufacturers. These values are presented in Section 4.3.

4. RESULTS AND DISCUSSION

4.1 Embodied carbon in different building components

The results for each type of structure, their area and total carbon footprint are presented in Table 6. Foundations and piles are presented as total carbon footprint since they cannot be measured in square metres.

Table 6 – Embodied carbon footprint of different structures in basic case.

Type of structure	Carbon footprint [$kgCO_2e/m^2$]	Total area [m^2]	Total carbon footprint [$kgCO_2e$]
Bearing sandwich panel 1	104.6	455	47 593
Non-bearing sandwich panel 1	83.5	928	77 488
Basement wall 2	136.2	200	27 240
Basement wall 2 (air raid shelter)	166.3	195	32 429
Bearing partition wall 1	62.7	2243	140 636
Bearing partition wall 1 (air raid shelter)	92.9	113	10 498
Non-bearing partition wall 2	7.4	603	4 462
Intermediate floor 1	93.2	3814	355 465
Intermediate floor 3	159.8	255	40 749
Intermediate floor 4	87.9	428	37 621
Intermediate floor 6	82	56	4 592
Base floor 1	33.2	264	8 765
Base floor 2	45.3	48	2 174
Base floor 3	69.4	255	17 697
Roof 1	217.4	510	110 874
Roof 3	77.8	56	4 357
Balcony slab	87.2	200	17 440
Balcony side wall	58.1	130	7 553
Foundations			11 372
Piles			141 820

As can be seen from Table 4 and Figure 3, the highest carbon footprint, 217.4 $kgCO_2e$, per square meter is for Roof 1 which is regular type of roof structure. The biggest factor for its footprint is light-weight expanded clay with 102 $kgCO_2e/m^2$ for modules A1-A3. This can be swapped for some other insulation material with lower carbon footprint. This may affect the thickness of the structure, too. The second factor for Roof 1 is the hollow core slab with 58.5 $kgCO_2e/m^2$ for modules A1-A3. Replacing the cement in concrete for different binders has significant impact on the carbon footprint, as shown in Section 4.3.

The second highest carbon footprint is for Basement wall 2 surrounding air raid shelter with 166.3 $kgCO_2e/m^2$. The 300 mm thick concrete wall with relatively heavy reinforcement which forms the actual air raid shelter has the biggest effect, 75.9 $kgCO_2e/m^2$. This thick structure gains its final strength fairly slowly even when using 100% ordinary Portland cement. Then, again, air raid shelters are usually located in the basement of the building and are, therefore, built first. After completing the air raid shelter the construction of the building usually still takes place for more than one year so the shelter has time to get final strength and dry. When using replacement binders, it is important to make sure the shelter has gained enough structural strength before placing bearing structures on top of it.

On the other hand, the carbon footprint for Non-bearing partition wall 2 is significantly lower than any other type of structure with only 7.4 $kgCO_2e/m^2$. Since this kind of wall is used only inside flats, it consists of gypsum board and sheet metal frame without any insulation. Mineral wool insulation would make the carbon footprint much higher as can be seen from Table 3. Now the carbon footprint is mainly caused by gypsum board, 5.76 $kgCO_2e/m^2$ (modules A1-A3), with only 1.48 $kgCO_2e/m^2$ (modules A1-A3) from the sheet metal frame.

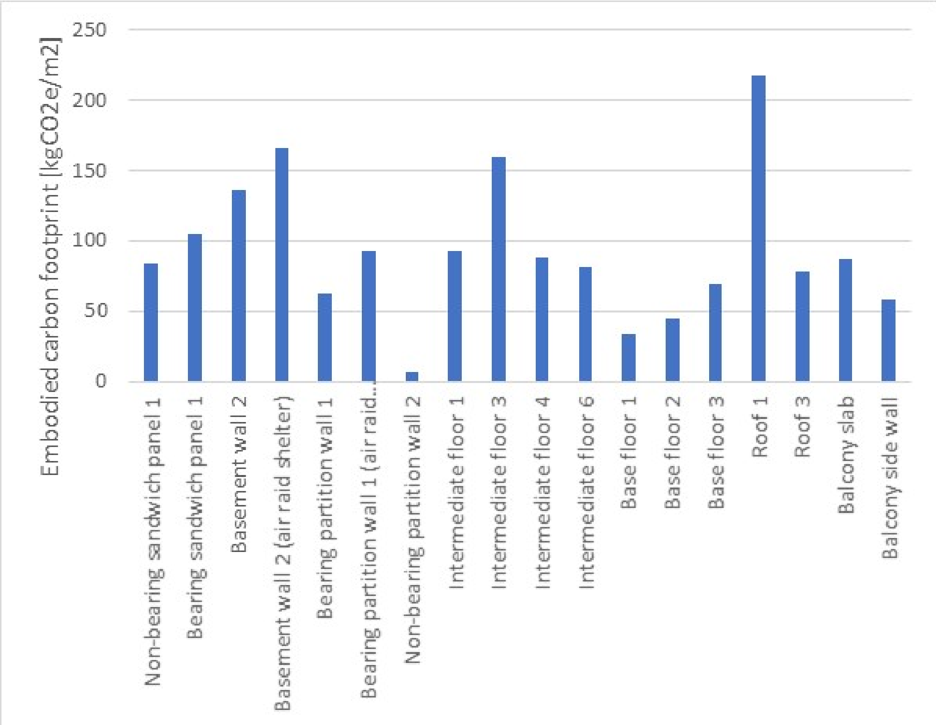

Figure 3 – Carbon footprint for each type of structure

From Tables 2, 3 and 4 it can be seen that modules A1-A3 are the ones that have the biggest impact on the carbon footprint. These modules are the production stages. Modules A4 and C1-C4 are just a small fraction not worth investigating. In this study the usage stage is not investigated although it is known to have even bigger impact than other modules. From the point of view structural design, the production phase and selection of structures and materials stages, A1-A3 are the most important ones.

4.2 Embodied carbon in whole building

In spite of having the highest carbon footprint per square meter the area for Roof 1 is not significant. Still, this has the fourth highest total carbon footprint with 110 874 kgCO_2e. The impact of different components of this structure are discussed in the Section 4.1.

The highest total carbon footprint of the building is for Intermediate floor 1, 355 465 kgCO_2e. This is expected because Intermediate floor 1 consists of only hollow core slab and levelling concrete and it has the largest area. Changing cement type for this structure impacts the overall carbon footprint more than changing it for Roof 1.

As it can be seen from Table 6 and Figure 4 the highest total carbon footprints are for the structures with large quantities of concrete. The second highest being the piles with 141 820 kgCO_2e. This is harder to impact since the foundation type and the type of piles used are so dependent on the type of soil on the construction site. The concrete used in piles has to be durable against sulphate attack of the soil if any. Some binders have enhancing qualities against chemical attacks.

The third highest carbon footprint is for Bearing partition wall with 140 636 kgCO_2e. These walls part flats from one another and create fire compartments. These walls also bear loads hence the 200mm thickness. 50.6 kgCO_2e/m^2 is embodied in concrete (modules A1-A3) with 2.38

$kgCO_2e/m^2$ (modules A1-A3) from reinforcement. The reinforcement usually has up to 100% recycled content. The structures are usually designed with minimum reinforcement so this cannot be affected any further.

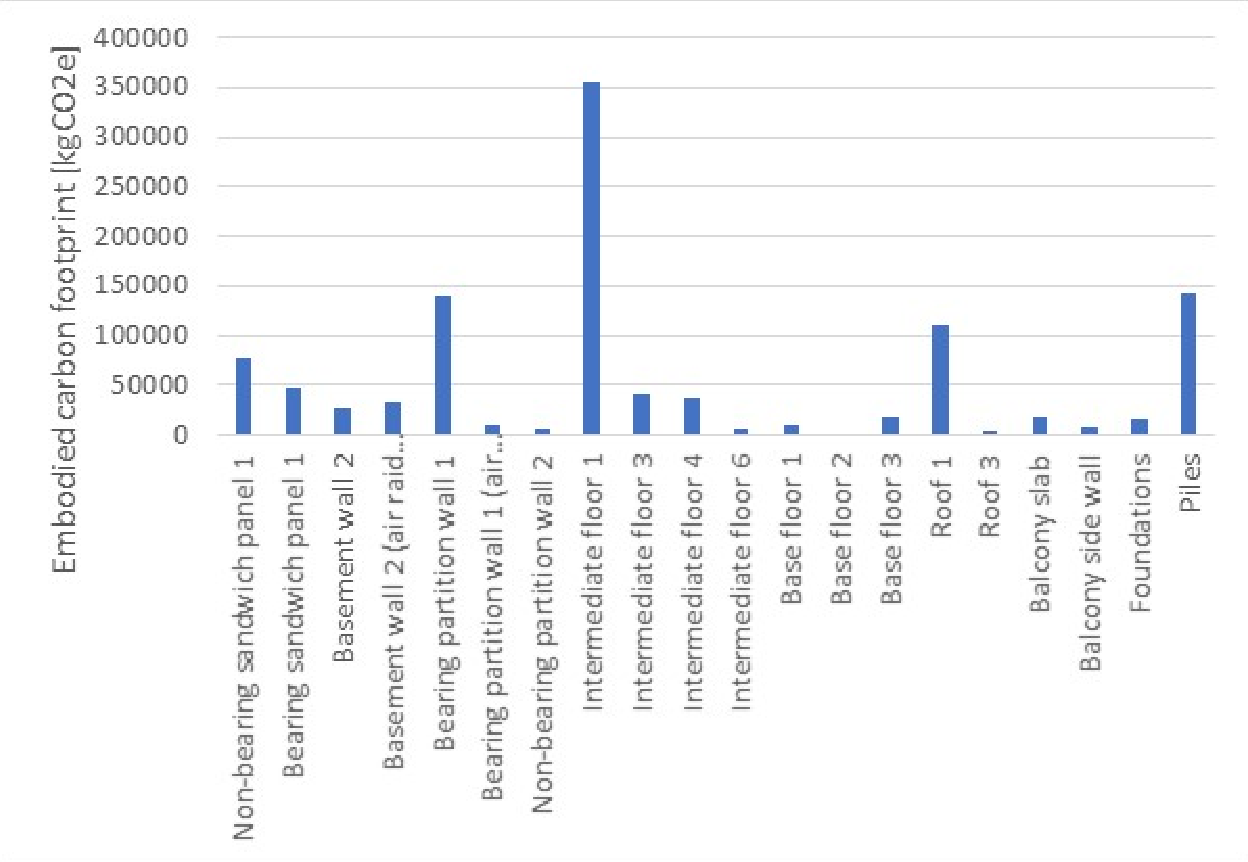

Figure 4 – Total carbon footprint for each type of structure

4.3 Effect of low carbon concrete

Embodied carbon footprint of structures with low-carbon ready-mix concrete and hollow core slabs were calculated in Table 7. GWP was calculated based on EPD's available from producers. GWP for one cubic meter of C30/37 concrete is 1150 $kgCO_2e$ (A1-A3) [13] and for one square metre hollow core slab 36,5 $kgCO_2e$ (A1-A3) [14]. In the calculations low-carbon concrete was used in foundations, concrete piles and concrete structures placed in dry indoor climate. Low-carbon concrete is not yet used in facade and balcony elements.

Table 7 – Embodied carbon footprint of different structures with low-carbon concrete.

Type of structure	Carbon footprint [$kgCO_2e/m^2$]	Total area [m^2]	Total carbon footprint [$kgCO_2e$]	Difference in basic case [%]
Bearing sandwich panel 1	77.0	928	35 035	-26.4
Non-bearing sandwich panel 1	71.2	455	66 074	-14.7
Basement wall 2	105.4	200	21 080	-22.6
Basement wall 2 (air raid shelter)	120.2	195	23 439	-27.7
Bearing partition wall 1	32.0	2243	71 776	-49.0
Bearing partition wall 1 (air raid shelter)	46.8	113	5 288	-49.6
Non-bearing partition wall 2	7.4	603	4 462	0
Intermediate floor 1	48.1	3814	183 301	-48.4
Intermediate floor 3	86.4	255	22 032	-45.9
Intermediate floor 4	47.9	428	20 501	-45.5
Intermediate floor 6	41.3	56	2 313	-49.6
Base floor 1	20.9	264	5 518	-37.0
Base floor 2	26.8	48	1 286	-40.8
Base floor 3	38.7	255	9 869	-44.2
Roof 1	187.4	510	95 574	-13.8
Roof 3	77.8	56	4 357	0
Balcony slab	87.2	200	17 440	0
Balcony side wall	58.1	130	7 553	0
Foundations			11372	-30.2
Piles			117883	-16.9

Total embodied carbon footprint of the building with low-carbon concrete was 726 152 $kgCO_2e$. It was 34.3 per cent less than in the basic case. As can be noticed from Table 7, there was remarkable decrease, usually more than 40 per cent, in carbon footprint in structures containing a lot of concrete. Despite of remarkable decrease of carbon footprint in intermediate floors and bearing partition walls, those got still the highest amount of embodied carbon because of the large volume of them.

By using low-carbon concrete embodied carbon of bearing concrete frame was 334 958 $kgCO_2e$, but it was 46.5 per cent less than in basic case, see Figure 5.

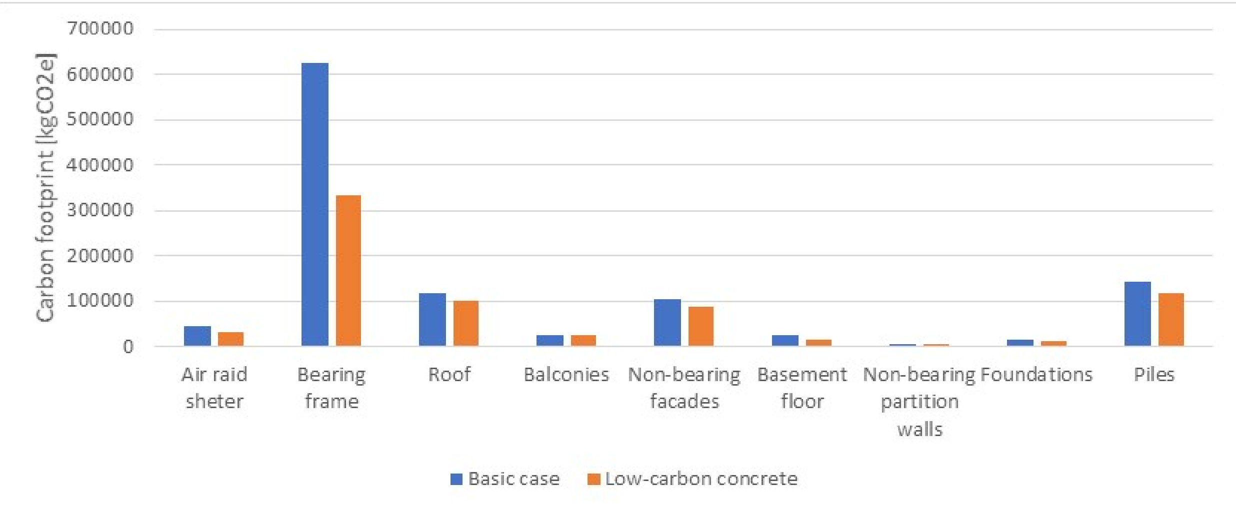

Figure 5 – Carbon footprint in basic case and building with low-carbon concrete.

Piles have still quite large proportion, 16.2 per cent, because of large share of steel piles. Non-bearing façade elements have low-carbon concrete only in inner layer, therefore decrease was minimal. Roof has 13.8 per cent share of all embodied carbon despite of low-carbon concrete and relatively small area compared to intermediate floors. The reason is thermal insulation, which is in this case light weight aggregate. In Nordic countries the thickness for thermal insulation is quite big, and, therefore the amount of light weight aggregate is big. The manufacture of light weight aggregate is relative energy intensive, which increases its GWP. The same phenomenon was seen in façade sandwich panels with mineral wool, too.

5. CONCLUSIONS

The carbon footprint for one type of structure can be high but if the total area for it is quite small the impact on total carbon footprint of the building is low. Knowing the total area of type of structure is important before optimizing the carbon footprint.

The effect of low-carbon concrete products on the bearing frame was significant since it was nearly halved. This is a quite important result. The effect on facades was fairly low since the developed products are not available outdoors. This product development is important so the carbon footprint can be halved for them, too.

The product development overall is needed. After concrete the second highest carbon footprint was for thermal insulation and there are not any low-carbon insulation products on the market, yet. The more environment friendly materials there is on the market, the easier it is for structural designer to choose these products over conventional products.

Many multimillion companies have declared carbon neutrality in the following decade. These goals can be helped by choosing low carbon products. This is a great first step, but it will not be enough alone.

ACKNOWLEDGEMENTS
Authors wish to acknowledge Ramboll Finland Oy for allowing the usage of the data.

REFERENCES

1. Finnish Standards Association: “Cement. Part 1: Composition, specification and conformity criteria for common cements”, SFS-EN 197-1, 2012, 35 p.
2. Finnsementti: ”Environmental data sheet on Cement and building limes (EN 16908)”, 2020, 3 p.
3. Neville AM: “Properties of concrete”, Longman Group Limited, Essex, England, 1995, 844 p.
4. Cheah C B, Samsudin M H, Ramli M, Part W K & Tan L E: “The use of high calcium wood ash in the preparation of Ground Granulated Blast Furnace Slag and Pulverized Fly Ash geopolymers: A complete microstructural and mechanical characterization”. *Journal of Cleaner Production*, Vol. 156, No. 10, 2017, pp. 114-123.
5. Luke K: “Pulverized fuel ash as a cement extender” Chapter 14, “Structure and performance of cements” (Edited by J Bensted & P Barnes), Taylor & Francis Group, London and New York, Great Britain and United States of America, 2002, pp. 353-371.

6. Cheah C B, Tiong L L, Ng E P, Oo C W: "The engineering performance of concrete containing high volume of ground granulated blast furnace slag and pulverized fly ash with polycarboxylate-based superplastizicer". *Construction and Building Materials,* Vol. 202, 2019, pp. 909-921.
7. Justnes H: "Condensed silica fume as a cement extender" Chapter 16, "Structure and performance of cements" (Edited by J Bensted & P Barnes), Taylor & Francis Group, London and New York, Great Britain and United States of America, 2002, pp. 399-408.
8. Thomas M: "Optimizing the Use of Fly Ash in Concrete", Portland Cement Association, United States of America, 2007, 24 p.
9. BauMineral GmbH: "Environmental data sheet for fly ash requirements on Environmental product declaration for fly ash (EN 15804)", 2017, 8 p.
10. Lang E: "Blast furnace cements" Chapter 12, "Structure and performance of cements" (Edited by J Bensted & P Barnes), Taylor & Francis Group, London and New York, Great Britain and United States of America, 2002, pp. 310-325.
11. Finnish Standard Association: "Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method", SFS-EN 15978, 2011. 60 p.
12. Finnish Standard Association: "Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products", SFS-EN 15804, 2012, 64 p.
13. Rudus: "Environmental data sheet on concrete and concrete elements (EN 16757)", 2020, 1 p.
14. The Building information foundation RTS: "Environmental data sheet on concrete and concrete elements (EN 16757)", 2020, 11 p.