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Environmental Assessment of Frost-resistant Concrete with Superabsorbent Polymers



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ABSTRACT
Air-entraining agents (AEA) are normally used to improve the frost resistance of concrete. However, it is not possible to accurately control the air void system in concrete with AEA. Thus, a significant loss of concrete strength is caused by over-dosing voids, and this increases the environmental impact from concrete structures. Superabsorbent polymer (SAP) can also be used to produce frost-resistant concrete. Compared to AEA, it can be used to precisely engineer the air void structure of concrete, promote cement hydration, and mitigate self-desiccation cracks. In this study, life cycle assessment methodology is applied to evaluate the overall environmental impact of frost-resistant concrete based on AEA and SAP, respectively. The results illustrate that frost-resistant concrete with SAP has a lower environmental impact than frost-resistant concrete with AEA if the strength and durability of concrete are considered in the defined functional unit. In addition, frost-resistant concrete with SAP reduces the environmental burdens of the vertical elements such as columns, but it increases the environmental load of the horizontal elements such as slabs, where the strength increase cannot be utilized. Moreover, the inventory data for AEA and SAP can affect the impact assessment results.

Key words: Frost-resistant concrete, air voids, compressive strength, environmental impact, superabsorbent polymers, life cycle assessment.

1. INTRODUCTION

In cold climates, frost action may result in internal cracking and surface scaling of concrete, which in turn poses a threat to the long-term durability and service life of concrete structures [1-3]. It is well established that entrained air in concrete can protect concrete structures against frost damage, because the air voids release the expansion pressure induced by ice formation [4-5]. Therefore, most standards prescribe a minimum total air content of frost-resistant concrete in its fresh and hardened states to ensure adequate frost resistance of concrete. For example, DS/EN 206 DK NA: 2019 [6] prescribes that the total air content in fresh and hardened concrete should be at least 4.5% and 3.5%, respectively. Contemporary air-entraining agents (AEA) are the standard practice to establish the required air void structure in concrete. However, it is difficult to accurately control the air void system in concrete based on AEA. For example, the use of other surfactants or supplementary cementitious materials can influence the effect of AEA [7-9]. In addition, the transport, placement, and compaction of fresh concrete can affect the stability of the entrained air voids. Consequently, the target air content of fresh frost-resistant concrete in practice is normally 6-7% to ensure the 3.5% level in the hardened concrete. This causes a significant loss of concrete strength, because an increase in the air content of 1% leads to a loss of compressive strength of 4-5% [10]. In order to compensate for the loss of concrete strength, solutions like increasing the cement content in concrete or the concrete volume in structural members are normally adopted, and this increases the environmental impact from concrete structures [11-12].

Superabsorbent polymer (SAP) is a multifunctional concrete admixture. During the mixing of concrete, SAPs absorb part of the mixing water and swell. The absorbed water is later released from the SAP to the surrounding, hydrating cement paste. This results in SAP voids in the hardened concrete [13-15]. These SAP voids enhance the frost resistance of concrete in a similar way as the entrained air voids [16-17]. In comparison with the AEA voids, the water-filled SAP particles in the fresh concrete are stable and thus result in a designed, well-defined void structure in the hardened concrete. The more precise control of the air void structure based on SAP eliminates the need for over-dosing voids and thereby reduces the strength loss. In addition, for concrete at a low water-to-cement ratio, the use of SAPs promotes cement hydration and mitigates

crack formation caused by autogenous shrinkage. This may outbalance the loss of strength induced by the SAP voids [18-19]. Therefore, there is a potential reduction of the environmental impact from concrete structures if SAPs are used to produce frost-resistant concrete.

Life cycle assessment (LCA) is a methodology for evaluating the environmental performance of a system or a product. It has been used to assess the environmental impact of different construction materials in the past decades [20-23]. In this study, LCA is applied to evaluate the environmental performance of the SAP technology in the production of frost-resistant concrete. To limit the study it does not include Life Cycle Costing (LCC). Furthermore, it will be difficult to carry out LCC, as there is no mature commercial market of SAP for concrete and its price is thus uncertain. Three case studies are conducted to compare the environmental impact between frost-resistant concrete based on SAP and AEA.

2. MATERIALS AND METHODS

Table 1 shows the mix designs of frost-resistant concrete with different chemical admixtures. Unicon A/S, the largest Nordic supplier of ready-mixed concrete, has provided the mix design of frost-resistant concrete with AEA. The cement type is CEM I 52.5N from Aalborg Portland. The w/c ratio of frost-resistant concrete with AEA is 0.38. The concrete has the following properties:

- strength class: C40/50
- slump: 120 mm
- total air content of fresh concrete: 6% (including 1% natural air)
- exposure class: XF4

It is the intention to propose a concrete mix with SAP that has the same durability as the concrete mix with AEA, so that the mixes are comparable in relation to the length of service life. To obtain this, the mix with SAP shall have the same w/c ratio as the mix with AEA. Dry SAP will absorb some of the water during the mixing process. Therefore, extra water needs to be added. This water does not contribute to the w/c ratio of the paste in the fresh concrete. In this study, the following terminology is used:

$$(w/c)_{total} = w/c + (w/c)_e \quad (1)$$

Where the water (relative to the cement mass) in each of these designations refers to:
w/c water in the pure water-cement mixture of the concrete, i.e. excluding water held by SAP
$(w/c)_e$ water held by SAP in the fresh concrete ("entrained water")
$(w/c)_{total}$ water dosed to the mix ("total water")

The use of SAP instead of AEA does not change the workability of fresh concrete significantly, when extra water is added to compensate for the SAP absorption [17]. The target air content in hardened concrete is 4.5% (consisting of 1% natural air and 3.5% voids created by SAPs). Even though the air void structure is engineered more precisely with SAP, it allows for some variation, while the requirement of frost-resistant concrete in DS/EN 206 DK NA: 2019 [6] is still met. Moreover, it is assumed that the SAP used is a covalently cross-linked copolymer of acrylic acid/acrylamide produced by suspension polymerization and with absorption capacity 17 g/g [24]. The absorption capacity does not matter in relation to calculating the extra water that needs to be added, as this will in any case be 35 kg/m^3 concrete to create a void volume of SAP voids equivalent to 3.5% of the concrete volume. However, it is necessary to know the absorption

capacity in order to be able to calculate the amount of dry SAP in the concrete mix, which is an input for LCA modelling. Since the void content is lower for frost-resistant concrete with SAP than frost-resistant concrete with AEA, the content of all other components in frost-resistant concrete with SAP is slightly higher than that in frost-resistant concrete with AEA.

Table 1 - Mix proportions of two types of frost-resistant concrete (1 m³)

	Concrete with AEA	Concrete with SAP
Cement (kg/m³)	445.0	451.8
Tap water (kg/m³)	164.7	204.6
Fine aggregate (kg/m³)	711.9	722.7
Coarse aggregate (kg/m³)	965.6	980.3
Plasticizer (kg/m³)	0.9	0.9
Superplasticizer (kg/m³)	2.9	2.9
Air-entraining agent (kg/m³)	2.4	-
Superabsorbent polymers (kg/m³)	-	2.06
Target air content, fresh concrete (%)	6.0	1.0*
w/c	0.38	0.38
$(w/c)_e$	0.00	0.08
$(w/c)_{total}$	0.38	0.46

* The content of SAP voids is not registered in fresh concrete, as they are water-filled.

2.1 Estimation of compressive strength of concrete

The mean value of compressive strength of concrete f_{cm} is estimated by Bolomey's formula [25]:

$$f_{cm} = k_1(1/(w/c) - k_2) \quad (2)$$

Where w/c is the water-to-cement ratio of concrete. k_1 and k_2 are constants, which depends on the cement type. For cement (CEM I 52.5N) from Aalborg Portland, k_1 is 30 MPa and k_2 is 0.5 [26].

When the effect of the entrained air voids is taken into account, Bolomey's formula modifies to [10]:

$$f_{cm} = k_1(1/(w/c) - k_2)(1 - B(a - a_0)) \quad (3)$$

Where a is the total air content of fresh concrete (% relative to concrete volume) and a_0 is the natural air content of fresh concrete (% relative to concrete volume). Since 1% increase of the air content in concrete causes the loss of compressive strength of 4-5%, the correction factor B is set to 0.045 [10, 26]. Therefore, for frost-resistant concrete with AEA, the mean value of compressive strength f_{cm} is 49.5 MPa. The characteristic compressive strength f_{ck} of concrete can be calculated by the mean value of compressive strength f_{cm} according to Eq. (3) [28].

$$f_{ck} = f_{cm} - 8(MPa) \quad (4)$$

Thus, the characteristic compressive strength f_{ck} of frost-resistant concrete with AEA is 41.5 MPa, supporting that its strength class is indeed C40/50.

For frost-resistant concrete with SAP, Bolomey's modified formula is not suitable to estimate its compressive strength directly because of the complex effect of SAP on the concrete strength. The study reported in [29] used the same cement type as the mix shown in Table 1 (CEM I 52.5N from Aalborg Portland). Therefore, it is assumed that the strength measurements from this study can be used to estimate the effect of SAP addition on compressive strength. In [29], the absorption

capacity of SAP is 12.5 g/g, so the $(w/c)_e$ for concrete with 0.6% SAP (relative to cement mass) is 0.075. The results illustrate that compared to reference concrete without SAP, the reduction of compressive strength of concrete with SAP is 16% when the w/c is 0.40 and the reduction of compressive strength is 8% when the w/c is 0.35. Consequently, when the w/c is 0.38, the reduction of the compressive strength is 12.8% through linear interpolation. In this study, the $(w/c)_e$ for frost-resistant concrete with SAP is 0.077. It means that these two cases are comparable. For reference concrete with w/c of 0.38 and only 1% natural air, the mean value of compressive strength is 63.9 MPa according to Bolomey's formula. Therefore, for frost-resistant concrete with SAP, the expected mean value of compressive strength is 55.7 MPa and the characteristic compressive strength is 47.7 MPa. Since the difference in the characteristic compressive strength between frost-resistant concrete based on SAP and AEA is larger than 5 MPa, the strength class of frost-resistant concrete with SAP changes from C40/50 to C45/55.

2.2 Life cycle assessment methodology

LCA evaluates the environmental impact of different systems or products from a life cycle perspective. According to the methodological framework for LCA described in ISO 14040 [30], an entire LCA study contains four separate phases, see Figure 1. The goal and scope definition is the first phase and the basis of an LCA study. It defines the purpose of the LCA study, and frames and outlines the product system to be studied. The inventory analysis involves collecting and compiling the data in relation to the elementary flows in the studied product system. As for the life cycle impact assessment, knowledge and models from environmental science are employed to translate the elementary flows and the interactions of the product system into the environmental impact scores. In the interpretation, all results are interpreted in line with the definition of goal and scope.

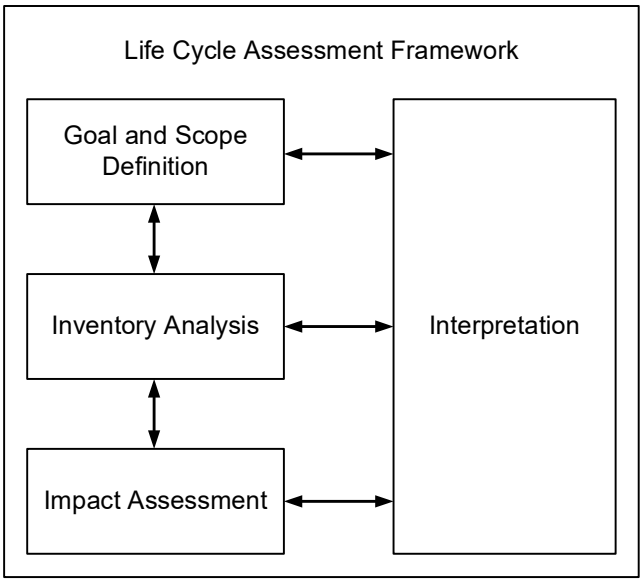


Figure 1 - Methodological framework of LCA [31].

Goal and scope definition

Three LCA case studies are carried out. The goal of all case studies is to compare the environmental impact of frost-resistant concrete based on SAP and AEA.

A well-defined functional unit is vital for an LCA study. For structural concrete, the functional unit should take the strength, durability and serviceability of concrete structural elements into consideration [32-33]. In the present study, the frost resistance and strength of concrete are considered in the definition of the functional unit. In case study 1, the environmental performance of different types of frost-resistant concrete is evaluated on the material level. Considering the function (strength and durability) of concrete, the functional unit is defined as "m^3 frost-resistant concrete per MPa of compressive strength". This functional unit is defined based on the method in [34] and the calculation results are presented in Table 2. In case studies 2 and 3, the environmental impact of frost-resistant concrete based on SAP and AEA is compared on the structural element level. Considering the influence of the concrete strength on the failure of different kinds of structural elements, columns and slabs are chosen to be assessed. The functional unit in case study 2 is "A concrete column with a height of 4 meters which sustains an axial load of 3000 kN and serves under the exposure class XF4 for 100 years". The functional unit in case study 3 is "A concrete slab (span: 5 meters, width: 1 meter) which sustains a live load of 5 kN/m^2 and serves under the exposure class XF4 for 100 years".

Table 2 - Calculated functional units for case study 1

Type of concrete	Characteristic compressive strength (MPa)	Functional unit (m^3 frost-resistant concrete per MPa)
Concrete with AEA	40	0.025
Concrete with SAP	45	0.022

The design of the columns and slabs follows the principles in Eurocode 2 [28]. The strength class of frost-resistant concrete based on AEA and SAP is C40/50 and C45/55, respectively. The characteristic strength of steel f_{yk} is 500 N/mm^2. The partial factors for action on concrete are prescribed in DS/EN 1990 DK NA: 2019 [35]. The partial factors of materials are prescribed in DS/EN 1992-1-1 DK NA: 2017 [36]. The exposure class of the structural members is XF4.

The "cradle-to-gate" approach is used in all case studies. It means that the system boundary includes the processes from the extraction of raw materials to the manufacturing of the product. The use and maintenance of the product are excluded, as well as the disposal of the product. It is anticipated that this will not change the conclusions. The maintenance scenario is expected to be the same because frost-resistant concrete based on AEA and SAP have the same durability and equivalent service life. As for the disposal of concrete, the demolition waste produced by frost-resistant concrete with SAP is not exceeding frost-resistant concrete with AEA in any case. It is also possible to reuse concrete after demolition, instead of disposing it in the landfills. Compared to frost-resistant concrete with AEA, frost-resistant concrete with SAP can be reused to the same extent, because relevant SAPs are non-toxic and may be made biodegradable [37-38].

Life cycle inventory (LCI) data

With respect to the LCIs for common concrete components including cement, tap water, sand (fine aggregate), gravel (coarse aggregate) and plasticizer, the Ecoinvent database serves as the main source. The LCI for superplasticizer is *Polycarboxylates, 40% active substance {RER}| market for Polycarboxylates, 40% active substance | APOS, U*. The environmental impact related to the manufacturing process of concrete is taken into account. In the Ecoinvent database, there is an LCI (LCI name: *Concrete, for de-icing salt contact {CH}| concrete production, for drilled piles, with cement CEM I | APOS, U*). This LCI represents the entire production procedure of 1 m^3 of concrete exposed to aggressive conditions (XF4 and XC4) on an industrial scale. It includes the raw materials (cement, sand, tap water, etc.) and the manufacturing process to produce ready-mixed concrete (concrete mixing factory, energy consumption, etc.). Therefore, a new LCI for the

manufacturing process of concrete can be obtained by eliminating the concrete components in this LCI. For reinforcement bars, adapted inventory data are built based on an LCI for reinforcing steel (LCI name: *Reinforcing steel {RER}| production | APOS, U*). The transport of reinforcement bars from the manufacturing factory to the market is considered. Since the reinforcement bars used in Denmark are mainly imported from Norway and Sweden, the transport distance is set to 1000 km. The environmental product declaration provides information about the transport type [39]. Regarding the LCI for AEA, an LCI for non-ionic surfactant (LCI name: *Non-ionic surfactant {GLO}| market for non-ionic surfactant | APOS, U*) is used because the ethylene oxide-based non-ionic surfactant can be used as AEA for concrete [40]. There is no LCI for SAP available in the Ecoinvent database. Therefore, the LCI for the acrylic acid/acrylamide based SAP developed by Mignon [41-42] is adopted. However, the LCI for acrylamide (LCI name: *Acrylamide (Chemicals UPR_draft, ecoinvent)*) is not available. As a result, an LCI for acrylonitrile (LCI name: *Acrylonitrile {GLO}| market for | APOS, U*) is used because acrylonitrile is the major raw materials for the production of acrylamide [43].

Life cycle impact assessment

Instead of merely focusing on the carbon footprint, this study intends to compare the overall environmental impact between frost-resistant concrete based on SAP and AEA. The problem-oriented method CML-IA baseline developed by the Center of Environmental Science (in Dutch: Centrum voor Milieuwetenschappen, CML) of Leiden University is implemented for life cycle impact assessment [44]. This impact method contains eleven impact categories. The characterization factor and indicator unit for each impact category are presented in Table 3.

Table 3 - Overview of impact categories in the CML-IA baseline impact method [44]

Impact category	Characterization factor (Indicator unit)
Abiotic depletion	Abiotic depletion potential (kg Sb eq)
Abiotic depletion (fossil fuels)	Abiotic depletion (fossil fuels) potential (MJ)
Global warming (GWP100a)	Global warming potential (kg CO_2 eq)
Ozone layer depletion (ODP)	Ozone layer depletion potential (kg CFC-11 eq)
Human toxicity	Human toxicity potential (kg 1,4-DB eq)
Fresh water aquatic ecotoxicity	Fresh water aquatic ecotoxicity potential (kg 1,4-DB eq)
Marine aquatic ecotoxicity	Marine aquatic ecotoxicity potential (kg 1,4-DB eq)
Terrestrial ecotoxicity	Terrestrial ecotoxicity potential (kg 1,4-DB eq)
Photochemical oxidation	Photochemical ozone creation potential (kg C_2H_4 eq)
Acidification	Acidification potential (kg SO_2 eq)
Eutrophication	Eutrophication potential (kg PO_4 eq)

3. RESULTS

3.1 Design of structural members

Since the strength class of frost-resistant concrete can be increased from C40/50 to C45/55 by using SAP, a smaller cross-section for the concrete column is accepted, as shown in Table 4. Consequently, the amount of concrete used is reduced by 10%. The number of reinforcement bars is unchanged while the number of ties for the column constructed by concrete with SAP increases due to the decrease of the spacing of the ties. However, the amount of reinforcing steel needed is almost the same because the perimeter of ties in the column constructed by frost-resistant concrete with SAP is smaller. For the concrete slab mainly subjected to bending, the increase of compressive strength is not valorised and reinforcement bars act as the main contributor.

Therefore, the design of the slabs constructed by different types of frost-resistant concrete is the same (Table 5). It means that the amounts of concrete and reinforcement bars used for the two slabs are identical.

Table 4 - Design of columns constructed by frost-resistant concrete based on AEA and SAP

Type of concrete	Concrete with AEA	Concrete with SAP
Strength class of concrete	C40	C45
Height of column (m)	4	4
Length of cross section (mm)	450	450
Width of cross section (mm)	300	270
Reinforcement		
- bars, dimension	4Ø16 mm	4Ø16 mm
- ties, dimension	17Ø6 mm	18Ø6 mm
- total mass (kg)	30.8	31.0

Table 5 - Design of slabs constructed by frost-resistant concrete based on AEA and SAP

Type of concrete	Concrete with AEA	Concrete with SAP
Strength class of concrete	C40	C45
Span of slab (m)	5	5
Width of slab (m)	1	1
Thickness of slab (mm)	210	210
Reinforcement		
- bars, dimension	Ø12@167mm	Ø12@167mm
- total mass (kg)	27.5	27.5

3.2 Impact assessment

Case study 1: Frost-resistant concrete

When the functional unit is "m^3 frost-resistant concrete per MPa of compressive strength", frost-resistant concrete with SAP performs better than frost-resistant concrete with AEA for 10 out of 11 impact categories, see Figure 2. By using SAP instead of AEA, the environmental impact of frost-resistant concrete is reduced 6-8% for impact categories abiotic depletion, global warming, ozone layer depletion, human toxicity, photochemical oxidation and acidification. The environmental impact of concrete with SAP for terrestrial ecotoxicity is around 38% lower than concrete with AEA. The abiotic depletion (fossil fuels) potential of concrete with SAP is 2% lower than concrete with AEA. The impact of concrete with SAP is negligibly lower than concrete with AEA in terms of the marine aquatic ecotoxicity potential and fresh water aquatic ecotoxicity potential. In contrast, concrete with SAP has a slightly higher impact (about 1%) for eutrophication.

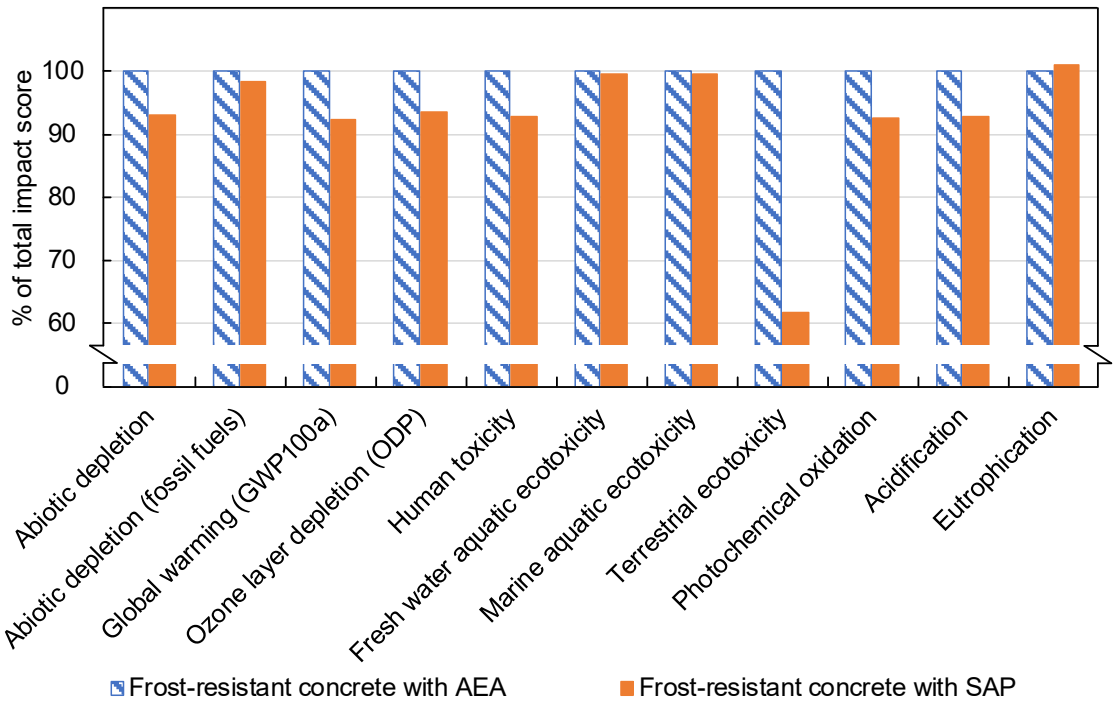


Figure 2 - Comparison of the environmental impact between two frost-resistant concretes for each impact category when the functional unit is "m^3 frost-resistant concrete per MPa of compressive strength".

Figure 3 presents the characterized impact assessment results of two types of frost-resistant concrete with the defined functional unit. The results show that cement is the largest contributor for all impact categories. Due to the use of a concrete mixing factory, the manufacturing process of concrete contributes significantly to abiotic depletion, human toxicity, marine aquatic ecotoxicity and fresh water aquatic ecotoxicity. For concrete with AEA, the contribution of AEA to all other impact categories is negligible apart from human toxicity (4%) and terrestrial ecotoxicity (34%). By contrast, SAP accounts for 2-4% of the total environmental impact of concrete with SAP for impact categories abiotic depletion, global warming, ozone layer depletion, terrestrial ecotoxicity, photochemical oxidation and acidification. In addition, it represents around 6% of the total impact of concrete with SAP for human toxicity, 8% for abiotic depletion (fossil fuels), 10% for marine aquatic ecotoxicity, and 11% for fresh water aquatic ecotoxicity and eutrophication. Owing to the extra water added, the impact of tap water in concrete with SAP is 9% higher than concrete with AEA for all impact categories but the contribution of tap water to the total impact of concrete is inappreciable. The impact of other components in concrete with SAP is about 10% less than concrete with AEA for all impact categories.

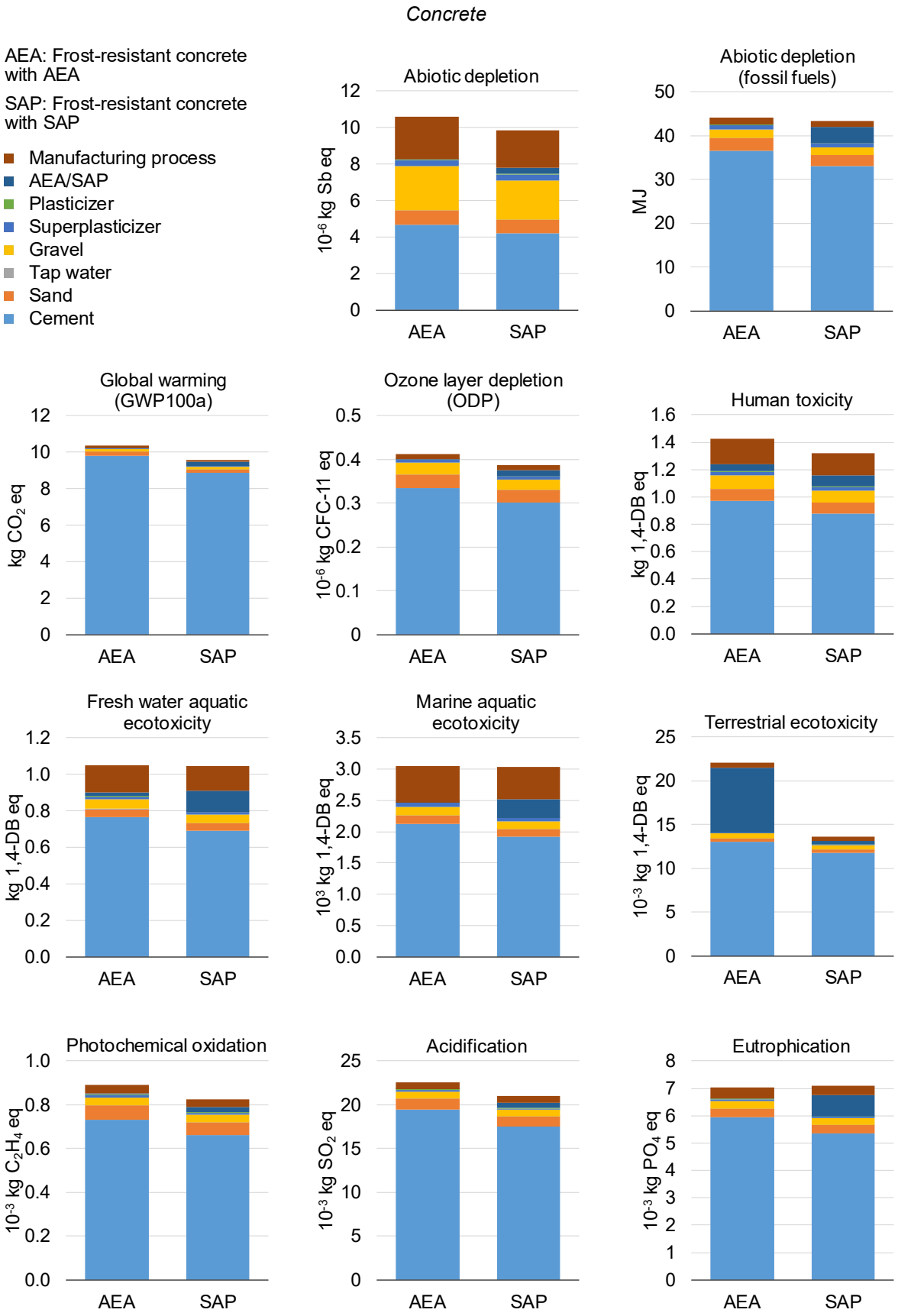


Figure 3 - Characterized impact assessment results of two frost-resistant concrete with the defined functional unit "m^3 frost-resistant concrete per MPa of compressive strength".

Case study 2: Column constructed by frost-resistant concrete

Figure 4 compares the overall environmental impact of columns constructed by different types of frost-resistant concrete. The results show that the column constructed by concrete with SAP (SAP column) has a lower impact for 8 out of 11 impact categories, compared to the column constructed by concrete with AEA (AEA column). The terrestrial ecotoxicity potential of the SAP column is 19% lower than the AEA column. When frost-resistant concrete with SAP is used, the total impact of the column decreases around 5% for global warming, 4% for ozone layer depletion and acidification, 2% for abiotic depletion and photochemical oxidation, and 1% for human toxicity. The reduction of the impact of the SAP column for abiotic depletion (fossil fuels) is negligible, as well as the increase of the impact of the SAP column for marine aquatic ecotoxicity and fresh water aquatic ecotoxicity. In comparison with the AEA column, the eutrophication potential of the SAP column increases over 1%.

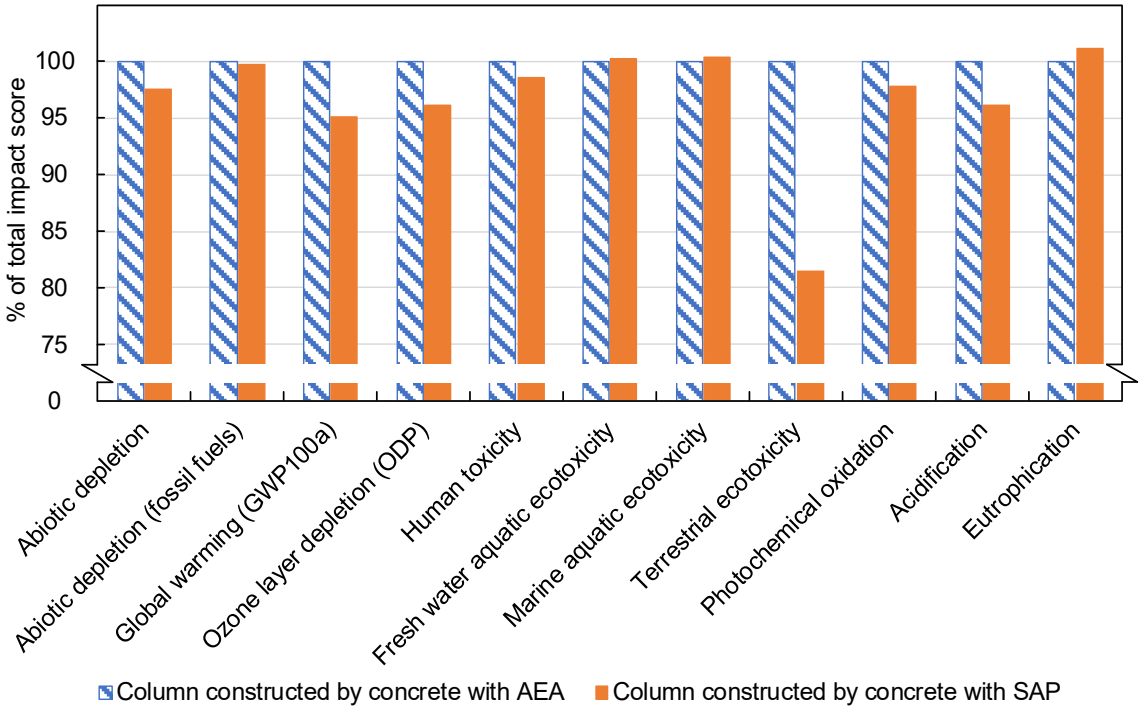


Figure 4 - Comparison of the environmental impact between columns constructed by frost-resistant concrete based on AEA and SAP for each impact category.

Characterized impact assessment results of columns in Figure 5 illustrate that cement is the most important component for abiotic depletion (fossil fuels), global warming, ozone layer depletion and acidification. The environmental impact of two columns for the rest of impact categories is mainly driven by reinforcing steel. For the AEA column, AEA contributes negligibly to all other impact categories except for terrestrial ecotoxicity (17%). For the SAP column, the contribution of SAP to impact categories abiotic depletion, human toxicity, terrestrial ecotoxicity and photochemical oxidation is small (about 1%). SAP represents around 2% of the total impact of the SAP column for global warming and acidification, 3% for ozone layer depletion, 4% for fresh water aquatic ecotoxicity and marine aquatic ecotoxicity, 5% for abiotic depletion (fossil fuels) and 6% for eutrophication. The impact of reinforcing steel is almost the same for the two columns. The impact of tap water in the SAP column is 10% higher than the AEA column for all impact categories. The impact of other components in the SAP column is around 9% less than the AEA column for all impact categories.

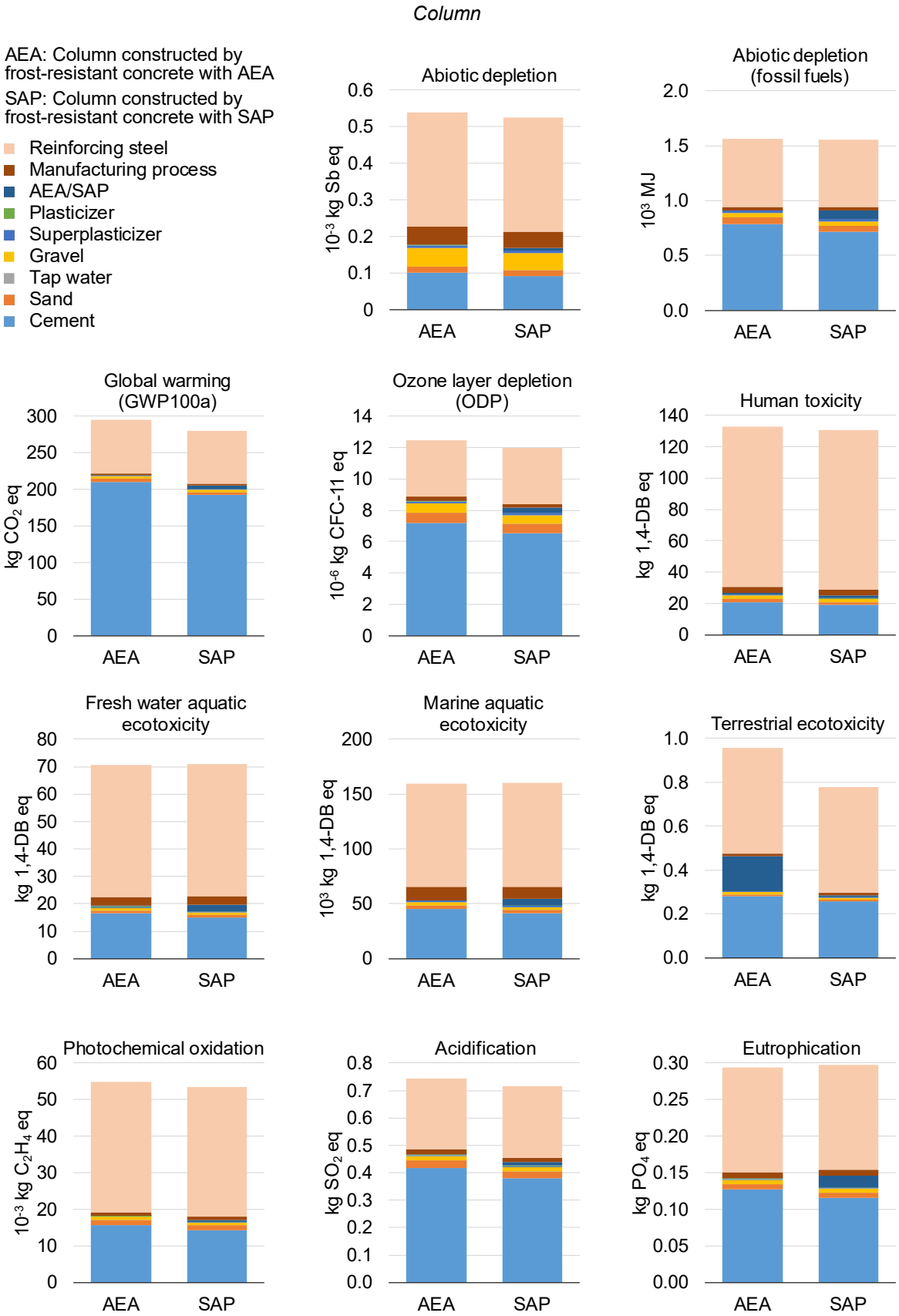


Figure 5 - Characterized impact assessment results of columns constructed by frost-resistant concrete based on AEA and SAP.

Case study 3: Slab constructed by frost-resistant concrete

In Figure 6, the slab constructed by frost-resistant concrete with SAP (SAP slab) has a higher environmental impact than the slab constructed by frost-resistant concrete with AEA (AEA slab) for 10 out of 11 impact categories. The results present that the environmental impact of the SAP slab is 22% lower than the AEA slab for terrestrial ecotoxicity. Frost-resistant concrete with SAP increases the environmental impact of the slab 2-4% for impact categories abiotic depletion, global warming, ozone layer depletion, human toxicity, photochemical oxidation and acidification. In comparison with the AEA slab, the total impact of the SAP slab increases about 6% for fresh water aquatic ecotoxicity, 7% for marine aquatic ecotoxicity, 8% for abiotic depletion (fossil fuels), and 10% for eutrophication.

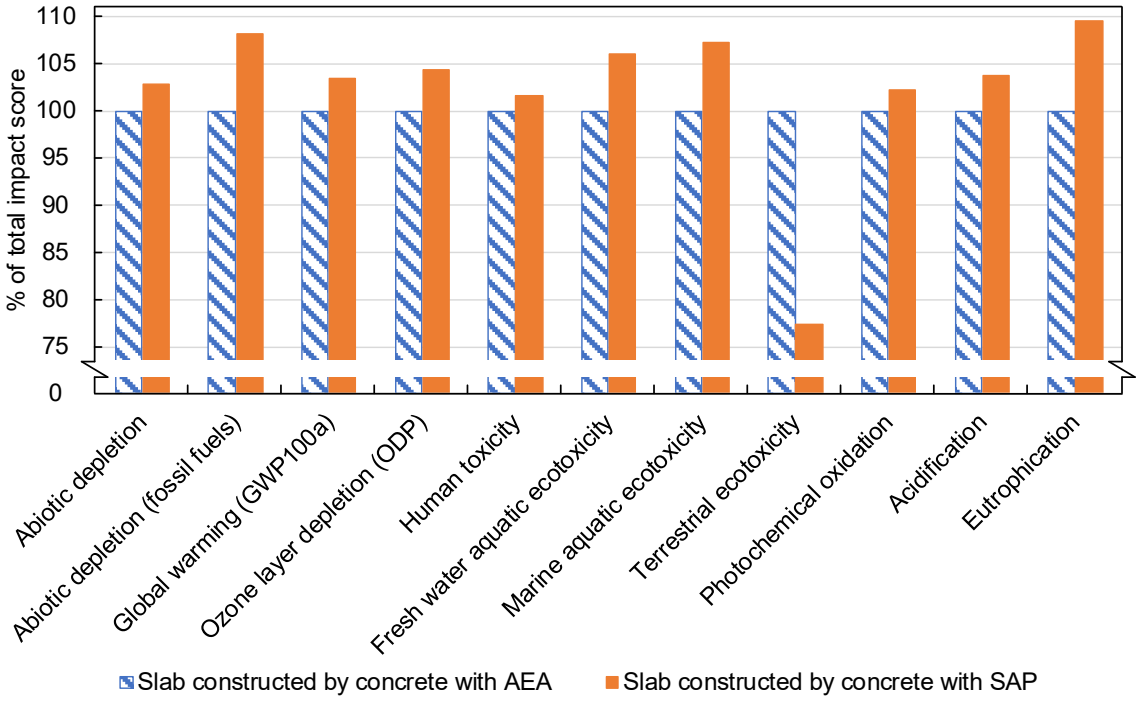


Figure 6 - Comparison of the environmental impact between slabs constructed by frost-resistant concrete based on AEA and SAP for each impact category.

Figure 7 shows the characterized impact assessment results of slabs constructed by different frost-resistant types of concrete. The environmental impact of two slabs for impact categories abiotic depletion (fossil fuels), ozone layer depletion, global warming, marine aquatic ecotoxicity, terrestrial ecotoxicity, eutrophication and acidification is primarily due to the cement. Reinforcing steel is the main contributor for impact categories abiotic depletion, human toxicity, photochemical oxidation and fresh water aquatic ecotoxicity. For the AEA slab, the terrestrial toxicity potential of AEA is over 24% while its impact for the rest of the impact categories is inappreciable. For the SAP slab, SAP contributes 2-3% to the impact categories abiotic depletion, global warming, ozone layer depletion, human toxicity, terrestrial ecotoxicity, photochemical oxidation and acidification. Moreover, SAP represents around 6% of the total impact of SAP slab for fresh water aquatic ecotoxicity and marine aquatic ecotoxicity, 7% for abiotic depletion (fossil fuels), and 8% for eutrophication. For the two slabs, the impact of the manufacturing process, as well as reinforcing steel, is the same. The impact of other components in the SAP slab is around 2% higher than the AEA slab.

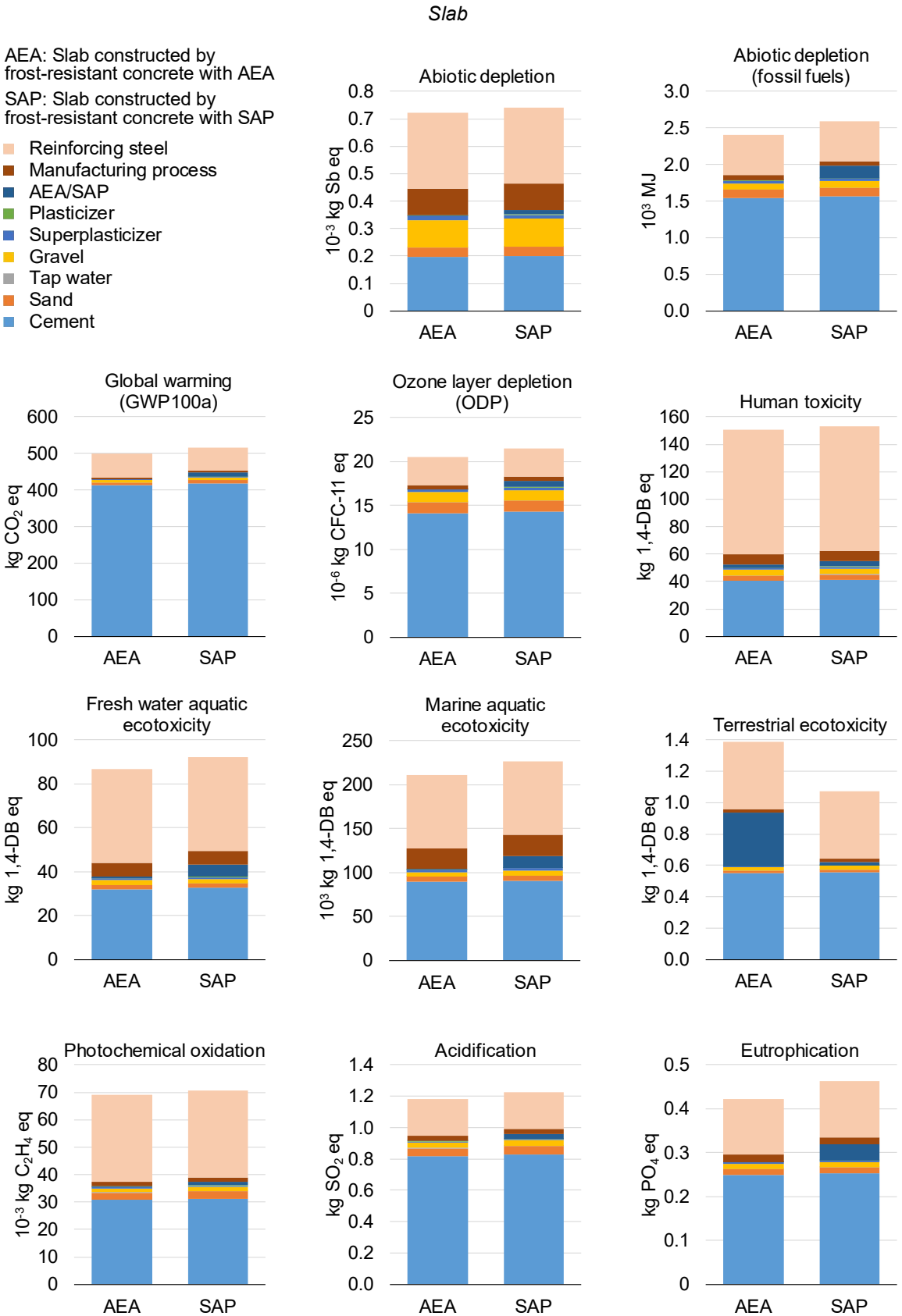


Figure 7 - Characterized impact assessment results of slabs constructed by frost-resistant concrete based on AEA and SAP.

4. DISCUSSION

The defined functional unit makes a fundamental difference to the environmental impact results. In the past decades, the functional unit "1 m^3 of concrete" is commonly used for the LCA study of concrete materials [45-47]. If this functional unit is used, there is no doubt that the environmental impact of frost-resistant concrete with SAP is higher than frost-resistant concrete with AEA. This is because the amount of all other components in frost-resistant concrete with SAP is higher than that in frost-resistant concrete with AEA, as shown in Table 1. However, this functional unit is in most cases irrelevant, as it does not consider the real functions (e.g. strength and frost resistance) of concrete. Instead, the functional unit "m^3 frost-resistant concrete per MPa of compressive strength" is applied in case study 1. Since the amount of concrete needed decreases with the increase of concrete strength (Table 2), frost-resistant concrete with SAP has a better environmental performance than frost-resistant concrete with AEA (Figure 2).

The results indicate that the environmental performance of frost-resistant concrete with SAP depends on the type of structural elements. For the considered vertical elements such as columns, frost-resistant concrete with SAP reduces their total environmental impact, even though the environmental impact of SAP is higher than AEA for most of the impact categories. The results in [12, 48] also confirm that the increase of compressive strength of concrete decreases the environmental burdens of the vertical elements. However, the reduction potential may be affected by the decisive failure mode of the column which depends on factors like load type, load size, slenderness ratio, etc. For example, a short column under pure compression gains more benefit from a higher strength concrete than a slender column subjected to compression with the risk of buckling. In contrast, frost-resistant concrete with SAP increases the environmental load of the considered horizontal elements such as slabs. The main reason is that the increase of concrete strength does not contribute to the bending resistance. In addition, the environmental impact of frost-resistant concrete with SAP is higher than frost-resistant concrete with AEA when the amount of concrete is identical.

The results in Figure 3 show that the reduction of the environmental impact of frost-resistant concrete varies for each impact category, mainly due to the difference in the environmental impact of AEA and SAP. In addition, for some impact categories like abiotic depletion (fossil fuels), marine aquatic ecotoxicity, fresh water aquatic ecotoxicity and eutrophication, the contribution of SAP cannot be neglected. These indicate that the inventory data for SAP and AEA could affect the comparative results to some extent. Actually, the LCI developed by Mignon [41-42] is employed for SAP in the modelling. However, the LCI for acrylonitrile is used instead of the LCI for acrylamide. This could have an influence on the calculated environmental impact of SAP, but the influence is expected to be limited. In addition, it should be noted that the LCI for SAP in the LCA modelling depends on the type of SAP used. The compositions and manufacturing processes of SAP can vary [42]. For all impact categories, the environmental impact of other types of SAP can be up to 1-3.5 times higher compared with the impact of SAP used in this study. Besides, the absorption capacity of dry SAP is an important parameter, as it decides the amount of dry SAP needed. Previous research [14, 49] reports that the absorption capacity of dry SAP in cementitious materials is 10-30 g/g. It means that the environmental impact of SAP for all impact categories could vary approximately 0.6-1.7 times compared to the calculated results. Similarly, there are several types of AEA [40]. In [22], the LCI for superplasticizer is used as the LCI for AEA. Figure 8 shows a comparison of the overall environmental impact of frost-resistant concrete based on AEA and SAP with the defined functional unit. The LCI for AEA is the LCI for superplasticizer instead of non-ionic surfactant. Compared to the results in Figure 2, it can be seen that different inventory data of AEA do not make a significant difference to the results for most of the impact

categories. A visible change can only be found in terms of the fresh water aquatic ecotoxicity potential and the terrestrial ecotoxicity potential.

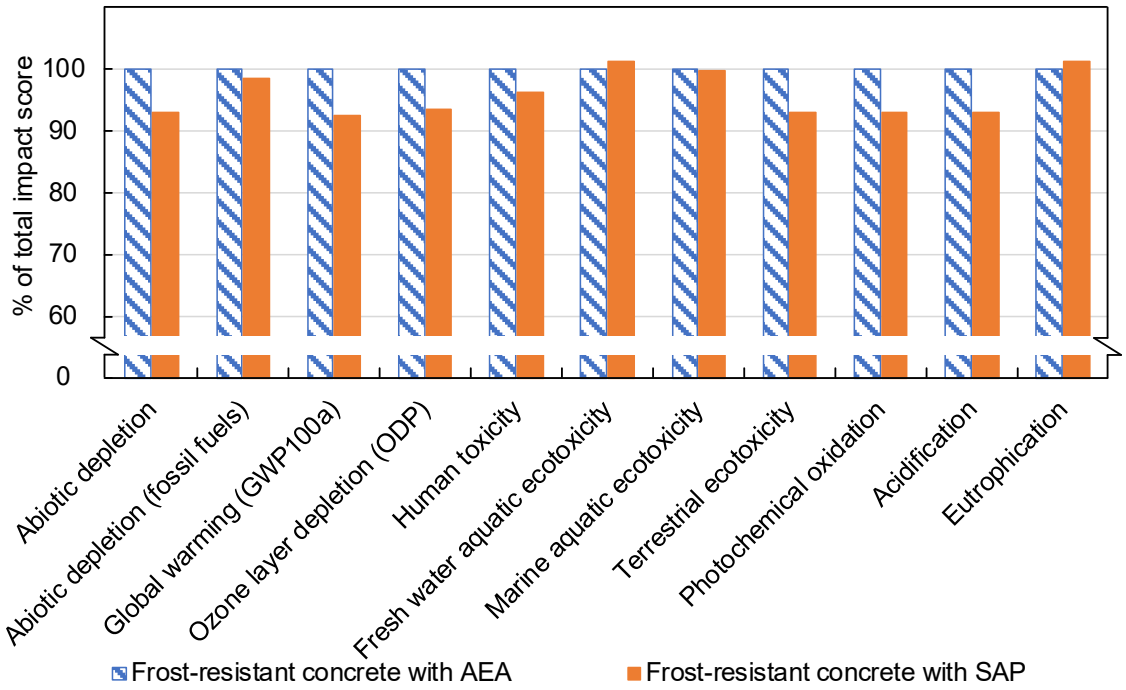


Figure 8 - Comparison of the environmental impact between two frost-resistant concrete for each impact category when the functional unit is "m^3 frost-resistant concrete per MPa of compressive strength". (Note: The LCI for AEA is the LCI for superplasticizer).

Cement is the main contributor to the environmental impact of concrete, primarily because of the clinker production. This means that reducing cement content or using supplementary cementitious materials to decrease clinker content in binder can lead to a reduction in the environmental burden of concrete. However, this will not change the conclusion which relates to a comparison between frost-resistant concrete based on SAP and AEA.

The variation of the total air content is taken into account although the SAP voids are stable. This is why the target air content in hardened frost-resistant concrete with SAP is set to 4.5% in the current study. In fact, according to the requirement in DS/EN 206 DK NA: 2019 [6], the target air content in hardened frost-resistant concrete with SAP can be set to the marginal value 3.5% (containing 1% natural air and 2.5% SAP voids). Since SAP makes it possible to engineer the size of the voids [17, 50], it can be used to create a finer air void structure in concrete. It means that it should be possible to produce frost-resistant concrete with the total air content less than 3.5% by using SAP. This is because the coarse air voids have a limited contribution to the frost protection of concrete compared to the fine air voids, but they significantly increase the total air content and the value of the so-called "spacing factor" which is recommended to be smaller than 200 µm. However, based on the calculation in section 2.1 and the results in [29], the strength class of frost-resistant concrete with SAP is expected to be unchanged even though the total air content is further decreased from 4.5% to 3.5%. It also should be noticed that the internal curing effect of SAP could be negatively affected because of the less extra water added. Despite the strength change of concrete, the further reduction of the total air content allows a decrease (around 25%) of the amount of SAP. As a result, the environmental load of frost-resistant concrete with SAP for each impact categories could be further reduced.

5. CONCLUSION

Frost-resistant concrete with SAP has a higher compressive strength than frost-resistant concrete with AEA. When the life cycle assessment study is carried out on the material level and the strength and durability of concrete are considered in the functional unit, the environmental impact of frost-resistant concrete with SAP is lower than that of frost-resistant concrete with AEA. On the structural element level, whether the effect of concrete with SAP is positive or negative depends on the type of structural members, i.e. to what extent a strength increase of concrete can be utilized. Compared to frost-resistant concrete with AEA, frost-resistant concrete with SAP reduces the environmental burdens of the structural elements exposed to compression (typically vertical elements), but the reduction potential may be influenced by the decisive failure modes of the studied elements. In contrast, frost-resistant concrete with SAP increases the environmental impact of structural elements subjected to bending (typically horizontal elements). The environmental impact of AEA and SAP has an influence on the impact assessment results. Thus, better inventory data for AEA and SAP need to be established in the future. In addition, the further decrease of the total air content can further reduce the environmental burdens of frost-resistant concrete with SAP because of the reduction of SAP content.

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