# Impact Indexes Comparison Study Using Environmental Product Declarations (EPDs) on Innovative Cement Bound Granular Material Pavement Layers

Andrea Serpi(✉), James Rombi, Francesca Maltinti, and Mauro Coni

Department of Civil Environmental Engineering and Architecture, University of Cagliari, Via Marengo 2, 09123 Cagliari, Italy
andrea.serpi93@unica.it

**Abstract.** In the last decades, the need to perform experiments with innovative new materials to be used in civil engineering and replace Portland Cement (PC) by embracing the concept of circular economy and environmentally sustainable engineering. PC production is responsible each year of 8% of the total $CO_2$ emitted into the atmosphere, for this reason, it is vital to find valid alternatives to PC. Such innovative materials must not only have good mechanical and physical performances if compared with PC but also be obtained with very low $CO_2$ emissions. In this research innovative mix designs for road Cement Bound Granular Material (CBGM) layers were analyzed to evaluate the environmental impact, in which PC was partially replaced with Anhydrous Calcium Sulphate (ACS), a by-product of the hydrofluoric acid industrial production process. This paper analyzes the Environmental Product Declarations (EPD) of two main mixes, one with 3% of ACS and 2% of cement and the other one with 4% ACS and only 1% of cement. The selected mixes had already been studied from a mechanical and physical point of view. Laboratory and in situ tests ensured good mechanical and physical performances. This paper wanted to analyze the environmental impacts of such mixes using the EPD of each material forming the CBGM layers. For comparison, two reference mixes one with only 5% of PC and the other with 5% of Green Cement (GC) were also analyzed. The research aims to compare the blends and evaluate the mix design with less environmental impacts. Twelve mix designs were considered, varying the type of hydraulic binders, that is PC, GC, and ACS and also the type of aggregates divided into Natural Aggregate (NA) and Recycled Aggregate (RA). The best design solution for the Global Warming Potential (GWP), which is one of the EPD parameters, was the mix incorporating 1% GC, 4% ACS and only RA.

**Keywords:** Environmental Product Declarations · Pavement Layers · By-Product

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## 1 Introduction

This study aims to demonstrate the feasibility of using Anhydrous Calcium Sulphate (ACS) as a viable alternative to Portland Cement (PC). To this end, twelve different mix designs were compared by varying the type and quantity of the hydraulic binder PC, Green Cement (GC), ACS, and the type of Natural Aggregate (NA) and Recycled Aggregate (RA). The purpose of the research is to evaluate the environmental impact indices of the various design solutions with the aim of highlighting their positive and critical aspects, shedding light on the strengths of innovative solutions and those of traditional solutions. The current paper aims to demonstrate the feasibility of the use of ACS as a valid alternative to PC. PC production has an elevated impact on abiotic depletion, global warming potential, ozone depletion, human toxicity, freshwater aquatic ecotoxicity and other impacts [1]. The International Energy Agency [2] states that the amount of energy spent on cement production is currently 105 kWh/t for a material production of 4300 Mt per year. Cement production is responsible of about 7–8% of the $CO_2$ emissions released globally, which is the construction material with the highest $CO_2$ emissions, but an industrial product essential for the economic growth of a country [3]. The PC preheating and calcination process generates on average 0.85 kg of $CO_2$ per 1 kg of cement [4]. Furthermore, the use of cement involves serious risk factors for humans, such as hexavalent chromium, exposure to allergens or crystalline-free silica, which can cause damaging consequences as chemically hazardous substances [5]. For this reason, new approaches have been developed that limit the negative environmental impacts related to cement production aiming at developing advanced methodologies in the processes of raw material processing and clinker manufacture, improving energy efficiency and decreasing emissions to the atmosphere [6, 7]. The use of energy-efficient materials that can moderately replace PC in binders can be considered one of the possible methods to mitigate environmental risks [8]. Also various types of supplementary cementitious materials were used in the past to partially replace PC and other pozzolanic materials are tested with the same aim [9, 10]. In recent decades, European policy has increasingly aimed to support environmental policies and environmental protection, first with the Treaty of Amsterdam (1999), then with the Treaty of Lisbon (2009) and finally with the Paris Agreement 2015. In Italy, the new Public Procurement Code [11] came into force in 2016, which transposes Directives 2014/23/EU [12], 2014/24/EU [13], 2014/25/EU [14] of the European Parliament, providing guidelines and specifications for the three levels of infrastructure design. In June 2022, Decree No. 256 [15] emphasized the minimum environmental criteria for construction, which are based on circular economy and eco-sustainable architecture, enabling contracting authorities to reduce the impacts related to works for the maintenance, renovation and construction of public buildings and the management of related construction sites. The Action Plan for Environmental Sustainability of Consumption in the Public Administration Sector, the National Action Plan on Green Public Procurement (PANGPP) [16] contains the Minimum Environmental Criteria (MEC) to be included in public tenders. These criteria include new approaches to the design and use of materials such as Life Cycle Assessment (LCA) and include EPD (Environmental Product Declaration) certification of the material used in the construction works. This last document describes the environmental impact generated by the product taken into consideration, analyzing different impact categories, resources use,

and waste production. The PANGPP [16] inserts a correlation for awards on a tender basis for projects with LCAs with improvements in environmental indicators. Significantly linking the monetary and environmental aspects, implying a preference for environmentally sustainable solutions over those that cost less but care less for the environment. Is discussed how investments made for the beauty and health of landscape and nature are repaid in terms of social consensus and have a strong return from the business community [17]. As far as the road sector in Europe is concerned, the GPP for road design, construction and maintenance emphasizes the possibility for administrations to take into account design experience and competence in relation to environmental aspects relevant to the subject matter of the contract, excluding operators who violate environmental laws. In Italy, the PANGPP criteria for design and works services for new road construction and maintenance are currently being defined. The work covered in this paper fits into this context, attempting to analyze the best solution in terms of lower environmental impact and performance. Some recent studies highlighted how ACS can partially replace PC in Cement Bound Granular Pavement (CBGM) layers and also in cementitious mortars. On the bases of laboratory tests [18, 19] which demonstrated good mechanical and physical performances and in situ tests performed on a trial embankment [20]. This paper studies the EPD of two main mixes, one with 3% of ACS and 2% of PC and the other one with 4% ACS and only 1% of PC, and for comparison two reference mixes were also analyzed one with 5% of PC and the other with 5% of Green Cement (GC). GC is an innovative type of cement, that uses less amount of non-renewable resources and emits less $CO_2$. LCAs and EPDs present themselves as a functional tool in precisely and objectively defining the environmental impacts of a product or process [21] to be used in compliance with environmental policies as a parameter in tenders according to the documents mentioned above [15]. In the road sector, the LCA study involved comparative material analyses, studying, as in the case of [22], the impacts on climate and the depletion of fossil resources resulting from the reduction of asphalt production temperatures, not only focusing on the carbon footprint. The research [23] carrying out studies on modified bitumen states that the use of 15% recycled pavement decreases impacts, climate change, fossil depletion, and total cumulative energy demand by 13–14%. While [5] addresses a comparison of four different types of cement by comparing them using criteria that fall into the three macro areas of environmental impact, worker health and socio-economic impact. The study [24] compares the impacts of recycled aggregates versus natural aggregates by analyzing the entire process and demonstrating that recycling one ton of material ensures fewer $CO_2$ emissions and fewer impacts regarding eutrophication and acidification. Other topics [25] propose an analysis of the environmental, construction and maintenance costs of various design alternatives using virgin materials, stabilized materials, and recycled materials. This study shows that it is possible to obtain the 34% reduction in energy and the 30% reduction in $CO_2$ with the use of RA if compared to NA, and to reduce the environmental impact with stabilization using lime, and the reduction in total costs with the use of RAP. In the study [26] with the help of the ECOCER tool and its database assesses how impacts vary with the consumption of materials. The current paper analyses twelve different mix designs using traditional and innovative materials such as PC, low carbon emissions cement GC, ACS, NA and RA. For all the mixes the total binder percentage was 5% by weight of

the aggregates. The analyses were conducted by re-weighting the environmental impact indices in the EPDs of the products used according to the quantities of each individual material used for the mix design taken into consideration, in order to be able to conduct a comparative analysis of the strengths and weaknesses of the mixtures analyzed.

## 2 Methodology

The paper presents comparative analyses of various mix designs that can be used for the road base course layer. The environmental impacts of the composite product were analyzed by studying the EPDs issued by the manufacturers of the materials used in the mixes. The various mixes that were chosen for the analysis, were derived from previous studies in which good mechanical and physical performances were demonstrated [18–20].

Following the standard EN 15804 2019 [27], ten impact categories were considered, and it was evaluated which mix design was more impactful to the environment. The binder materials used for the various cement mixes are PC (European Cement Association Cembureau, owner of EPD), GC (produced by the company Italcementi), and ACS (produced by the company Fluorsid), which were combined in various percentages. The aggregates used are NA and RA (produced by the company Nuova Demi).

## 3 Case Study

Starting from the need to reduce emissions from cement production, it was decided to design mixes for road layers in which cement was partially replaced with ACS. ACS can be considered chemical gypsum, a by-product of the chemical industry obtained from the production of hydrofluoric acid. The material is obtained by the chemical reaction of sulphuric acid and fluorspar without additional energy expenditure, by mass of 80 percent vs. 20 percent hydrofluoric acid [28]. Its use in roads meets the concept of circular economy and environmentally sustainable engineering.

As a by-product it is on the market as a material with low production costs [28] and low emissions [29] as all emissions from the chemical process are attributed to the core product of the production process. Mix designs using in a total of 5% of hydraulic binders were analyzed, and two reference mix one with 5% of PC and the other with 5% of GC were compared with innovative mixes respectively 3% of ACS and 2% of cement that could be PC or GC, and 4% ACS and 1% of cement that could be once PC and then GC. Ensuring the specifications of standard EN 15804 2019 [27], the following environmental impact indices were taken into consideration.

- GWP: Global Warming Potential.
- ADPE: Abiotic depletion potential of non-fossil resources.
- ADPF: Abiotic depletion potential of fossil resources.
- AP: Soil and water acidification potential.
- ODP: Stratospheric ozone depletion potential
- EP-FRESHWATER. Freshwater eutrophication potential
- EP-TERRESTRIAL: Terrestrial eutrophication potential

- EP-MARINE: Seawater eutrophication potential
- POCP: Tropospheric ozone formation potential
- WDP: Water Deprivation Potential

Each index was taken from the following EPDs:

- Portland Cement EPD (Cembureau) [30]
- Green Cement EPD (Italcementi) [31]
- Anhydrous Calcium Sulphate EPD (Fluorsid) [29]
- Aggregate EPDs [32]

Combinations were made:

– PC mix (5% cement by weight of the aggregates), in two combinations, respectively with only NA, and only RA. Total number of mixes two.
– GC mix (5% cement by weight of the aggregates), in which Italcementi's green cement (Italcementi EPD Termocem green Type CEM III-A 42.5 N) was used and also combined first with NA aggregates, and then with RA. Total number of mixes two.
– Innovative cement mixes (3% ACS and 2% cement) with, respectively: NA-PC, NA-GC, RA-PC and RA-GC. Total number of mixes four.
– Innovative cement mixes (4% ACS and 1% cement) with, respectively: NA-PC, NA-GC, RA-PC and RA-GC. Total number of mixes four.

The analyses of the various mix designs were charted for both the 3% ACS and 2% cement and 4% ACS and 1% cement quantities and compared accordingly. The mix designs are numbered from 1 to 12, each mix proportion was named in terms of hydraulic binder percentage, followed respectively by the type of binder (PC, GC and ACS) and then the type of aggregate NA or RA.

In the first group of mixes only NA are used:

- 1) CBGM with 5% PC and only NA (Labelled 5PC_NA)
- 2) CBGM with only 5% GC and only NA (Labelled 5GC_NA)
- 3) CBGM with 3% ACS and 2% PC and only NA (Labelled 3ACS_2PC_NA)
- 4) CBGM with 4% ACS and 1% PC and only NA (Labelled 4ACS_1PC_NA)
- 5) CBGM with 3% ACS and 2% GC and only NA (Labelled 3ACS_2GC_NA)
- 6) CBGM with 4% ACS and 1% GC and only NA (Labelled 4ACS_1GC_NA)

In the Second group of mixes only RA are used:

- 7) CBGM with 5% PC and RA (Labelled 5PC_RA)
- 8) CBGM with 5% GC and RA (Labelled 5GC_RA)
- 9) CBGM with 3% ACS and 2% PC and only RA (Labelled 3ACS_2PC_RA)
- 10) CBGM with 4% ACS and 1% PC and only RA (Labelled 4ACS_1PC_RA).
- 11) CBGM with 3% ACS and 2% GC and only RA (Labelled 3ACS_2GC_RA)
- 12) CBGM with 4% ACS and 1% GC and only RA (Labelled 4ACS_1GC_RA).

As a result, graphs were analyzed for each index according to the 12 mixes.

It follows that: to Global Warming Potential Index (GWP) (Fig. 1):

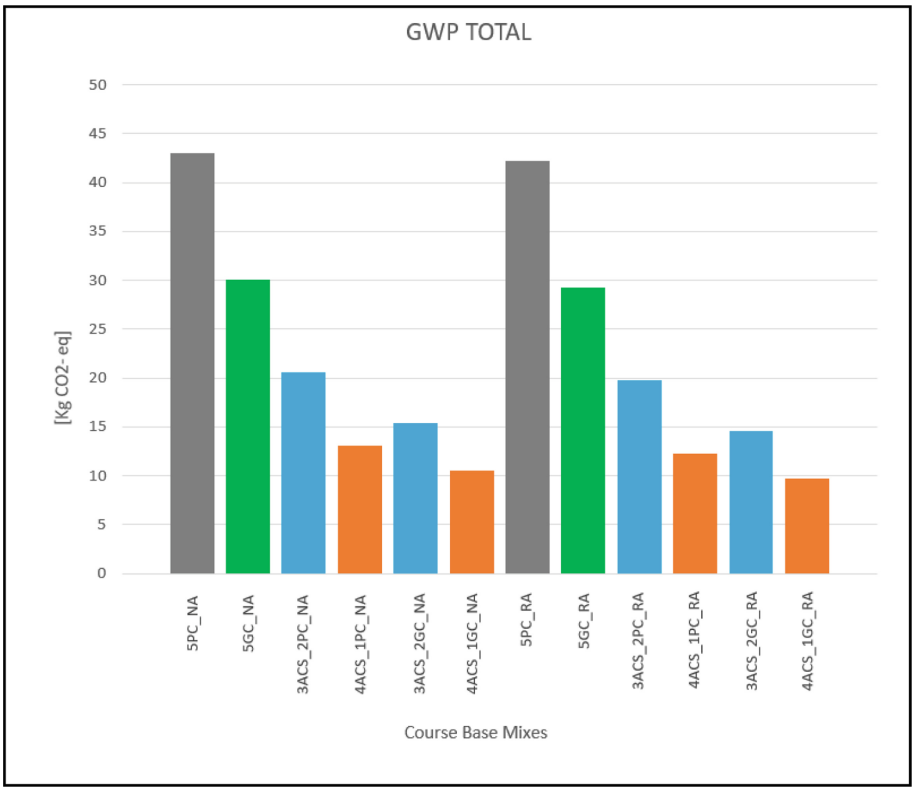


**Fig. 1.** This figure shows the different mix design impacts for the GWP (Global Warming Potential) Total Index.

- Traditional PC solutions are the most impactful (5PC_NA and 5PC_RA), there is no big difference if NA or RA are used in the mix.
- GC solutions (5GC_NA and 5GC_RA) are less impactful than those using PC (5PC_NA and 5PC_RA). In mix designs where part of the cement is replaced with ACS (3ACS_2PC_NA, 3ACS_2GC_NA, 4ACS_1PC_NA, 4ACS_1GC_NA), impacts are lower than in mixes where cement is the only binder. Solutions using recycled aggregates (3ACS_2PC_RA, 3ACS_2GC_RA, 4ACS_1PC_RA, 4ACS_1GC_RA) are slightly less impactful than those using natural aggregates (3ACS_2PC_NA, 3ACS_2GC_NA, 4ACS_1PC_NA, 4ACS_1GC_NA).
- For innovative mix designs (mixes with ACS percentage) lower impacts are found for the 4% and 1% mix than for the 3% and 2% mix. This evidence stems from the fact that ACS is less impactful than cement, and that the first design solution uses one point more of ACS at the expense of cement.
- It follows that the least impactful solution turns out to be the solution 4ACS_1GC_RA.

Abiotic Depletion Potential of non-Fossil Resources (ADPE) (Fig. 2):

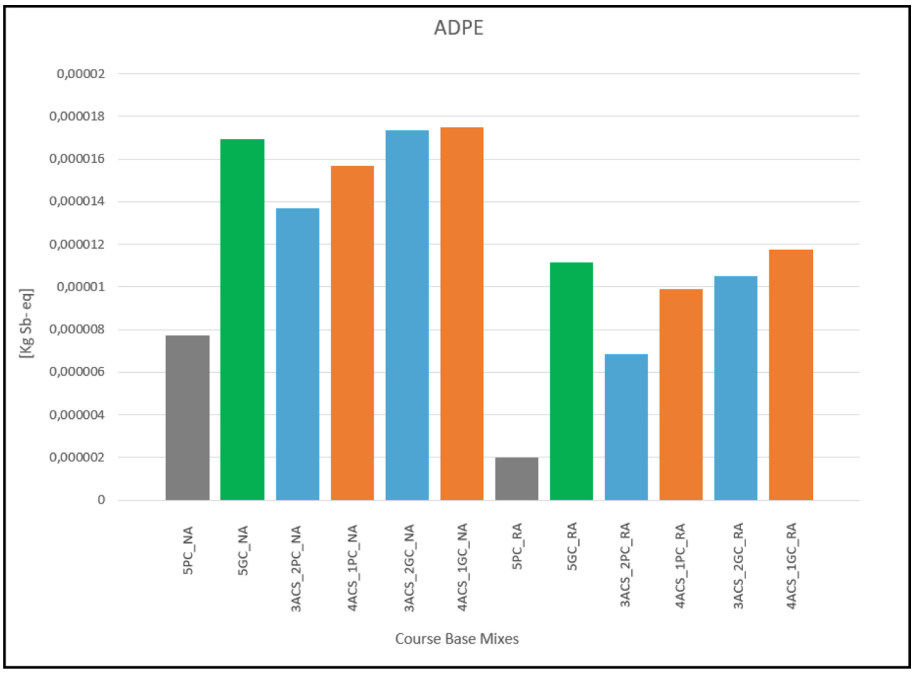


**Fig. 2.** This figure shows the different mix designs impacts for the ADPE (Abiotic depletion potential of non-fossil resources) Index.

- Again, solutions using RA are less impactful than those using NA.
- In this case, mix designs with GC and ACS have a greater impact than those with PC alone. In fact, the ADPE index of GC and ACS is an order of magnitude higher than that of conventional PC.
- RA also prove to be less impactful than NA.
- The best solution is 5PC_RA, which involves the use of PC and RA, but without the use of ACS.
- The most impactful solutions are the ones using GC and ACS (4ACS_1GC_NA), which have higher ADPE values than the other alternatives.

Abiotic Depletion Potential of Fossil Resources (ADPF) (Fig. 3):

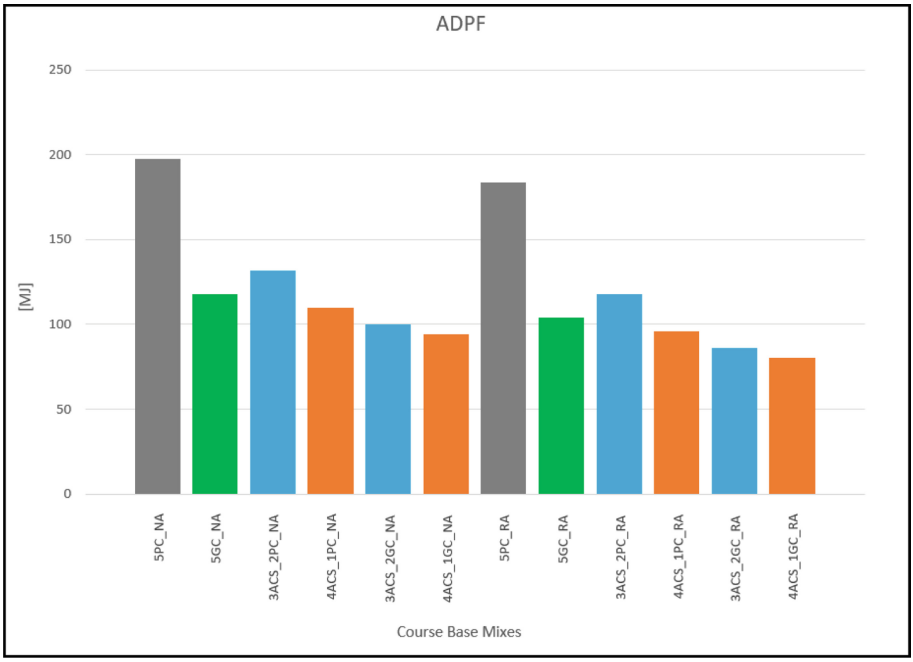


**Fig. 3.** This figure shows the different mix designs impacts for the ADPF (Abiotic depletion potential of fossil resources) Index.

- Mix designs using PC alone are the most impactful (5PC_NA and 5PC_RA), while options with GC alone are significantly less (5GC_NA and 5GC_RA).
- Using RA slightly lowers the impacts of cement mixes if compared with mixes with NA.
- A similar argument can be made regarding the use of ACS instead of cement in fact where is used 4% ACS and 1% PC rather than 3% ACS and 2% PC impact are lowest.
- It follows that the least impactful solution is 4ACS_1GC_RA.

Soil and Water Acidification Potential (AP) (Fig. 4):

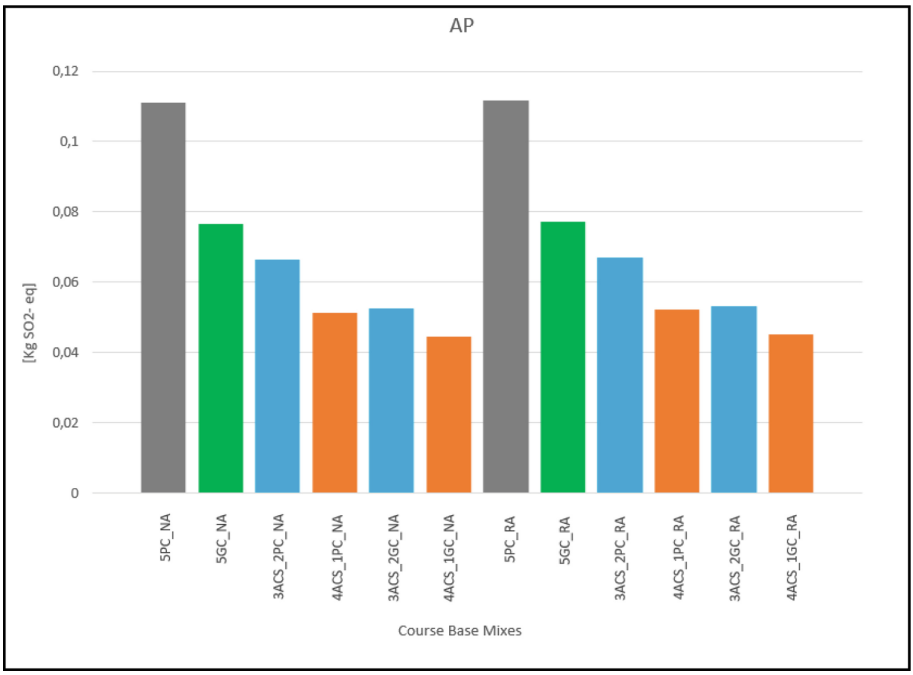


**Fig. 4.** This figure shows the different mix design impacts for the AP (Soil and water acidification potential) Index.

- The design solution using PC (5PC_NA and 5PC_RA) is always more impactful than the innovative ones using GC and ACS (3ACS_2GC_NA, 4ACS_1GC_NA, 3ACS_2GC_RA, 4ACS_1GC_RA).
- The difference between 3% ACS and 2% cement and 4% ACS and 1%, proves that the mix incorporating less percentage of cement is the best solution. In fact, although green solutions (5GC_NA and 5GC_RA) are preferable to the traditional cement mix (5PC_NA and 5PC_RA), the use of ACS reduces impacts compared to non-innovative solutions and obviously reaches the optimum when using GC and ACS (4ACS_1GC_NA, 4ACS_1GC_RA).
- RA have no visible influence compared to NA, in fact, the AP index for the two categories is almost the same.

Stratospheric Ozone Depletion Potential (ODP) (Fig. 5):

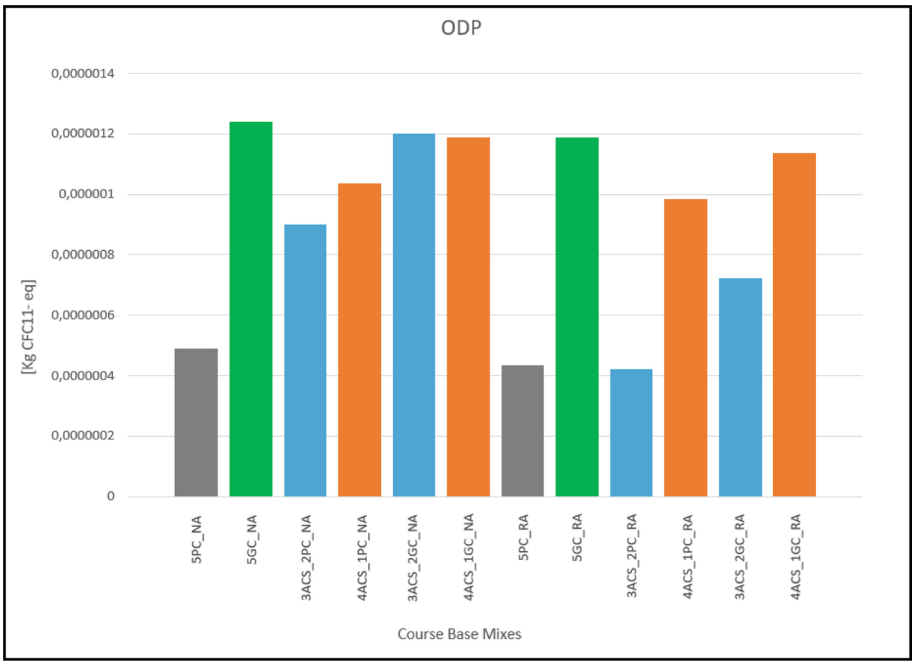


**Fig. 5.** This figure shows the different mix designs impacts for the ODP (Stratospheric ozone depletion potential) Index.

- In the case of this index, there is an opposite trend to the investigations of the other indices considered.
- RA bring a present but insignificant improvement. (RA mixes versus NA mixes)
- The mixes with PC (5PC_NA and 5PC_RA) are less impactful than GC mix without ACS (5GC_NA and 5GC_RA), which are the most impactful.
- Analyzing the ODP indices of ACS and GC shows that they are two orders of magnitude higher than those of PC. Therefore, in this case, the innovative solutions with ACS are more impactful than the reference mix with PC (5PC_NA and 5PC_RA), among which a slight improvement can be seen with the use of recycled aggregates (RA group).

Freshwater Eutrophication Potential (EP-FRESHWATER) (Fig. 6):

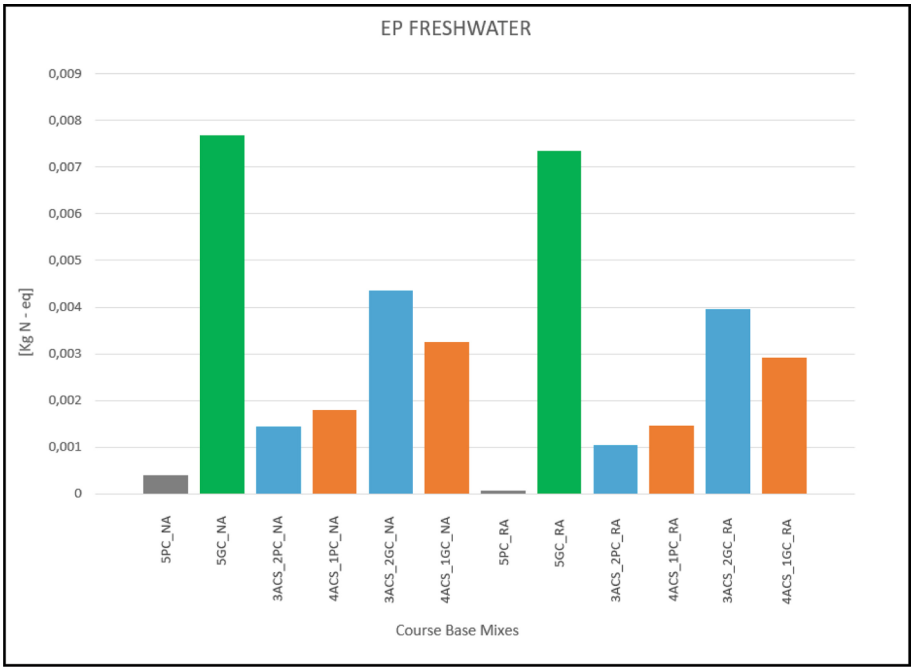


**Fig. 6.** This figure shows the different mix design impacts for the EP FreshWater (Freshwater eutrophication potential) Index.

- Options using RA (RA group) were found to be less impactful than those using NA (NA group).
- The most impactful solutions are those in which GC is used (5GC_NA and 5GC_RA). ACS has a higher EP FW index than PC but lower than GC, so its use offsets the impact of GC in innovative solutions (3ACS_2GC_NA,4ACS_1GC_NA, 3ACS_2GC_RA, 4ACS_1GC_RA).
- GC has four orders of magnitude more than PC and one more than ACS. This means that when using PC, the 3% and 2% solution is less impactful than the 4% and 1%, while when using GC, in this case, the most impactful, a greater amount of ACS lowers the impacts of the 4% and 1% compared to the 3% and 2%.

Terrestrial Eutrophication Potential (EP TERRESTRIAL) (Fig. 7):

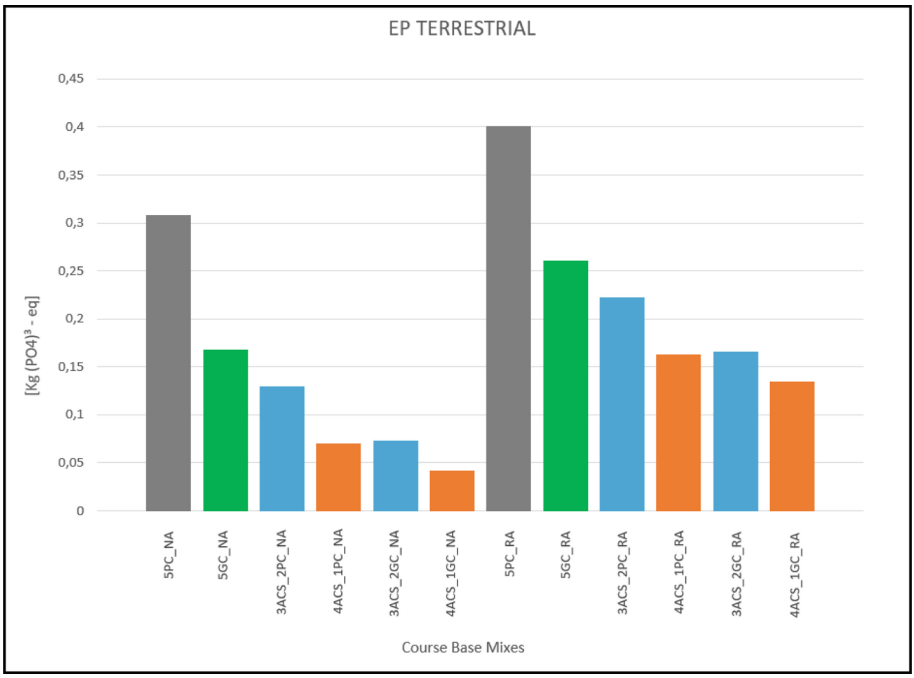


**Fig. 7.** This figure shows the different mix design impacts for the EP T (Terrestrial eutrophication potential) Index.

- RA have a large impact on the EP index of various mix designs compared to when NA are used.
- The use of ACS goes towards reducing impacts (mixes with ACS).
- The solution with PC and RA is very impactful 5PC_RA.
- By using more ACS at the expense of cement, 4% - 1% solutions are better than 3% -2%.
- Solutions with GC (5GC_NA and 5GC_RA) are less impactful than those with only PC (5PC_NA and 5PC_RA).
- The best solution is with GC, NA and ACS (4ACS_1GC_NA).

Seawater Eutrophication Potential (EP MARINE) (Fig. 8):

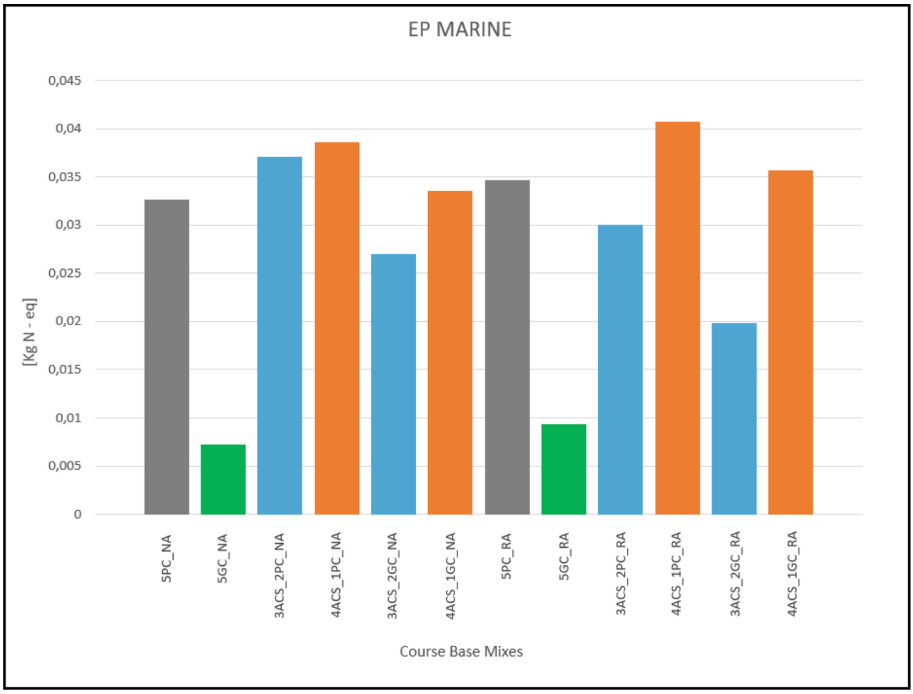


**Fig. 8.** This figure shows the different mix design impacts for the EP Marine (Seawater eutrophication potential) Index.

- The greatest impacts occur with the use of ACS in the innovative solutions, it follows that the 4% and 1% solution is more impactful than 3% and 2%.
- Higher relative impacts are seen with the use of only PC (5PC_NA and 5PC_RA) compared to only GC (5GC_NA and 5GC_RA).
- RA group is more impactful than the NA group.
- The best solution turns out to be 5GC_NA, with GC and NA. Looking at the indices, it can be seen that GC has 100 times less impact than PC and ACS.

Tropospheric Ozone Formation Potential (POCP) (Fig. 9):

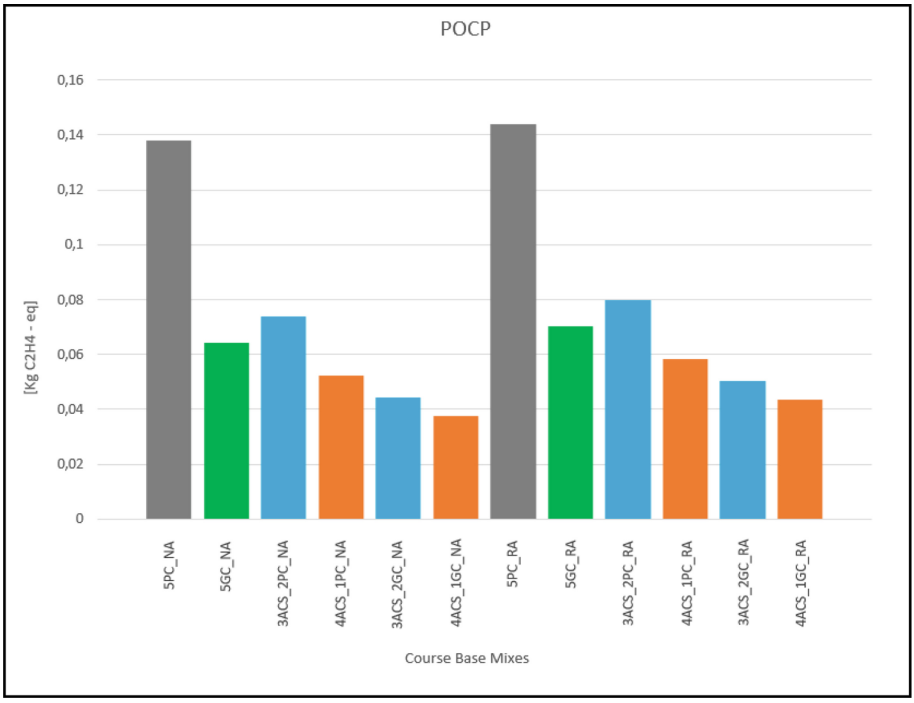


**Fig. 9.** This figure shows the different mix design impacts for the POCP (Tropospheric ozone formation potential) Index.

- The most impactful solutions are those with PC (5PC_NA and 5PC_RA).
- RA group is slightly more impactful than the NA group.
- The lowest impacts occur with the use of GC and ACS, particularly on the 4% and 1% ratio (4ACS_1GC_NA, 4ACS_1GC_RA). This result is associated with GC being less impactful than PC and ACS.

Water Deprivation Potential (WDP) (Fig. 10):

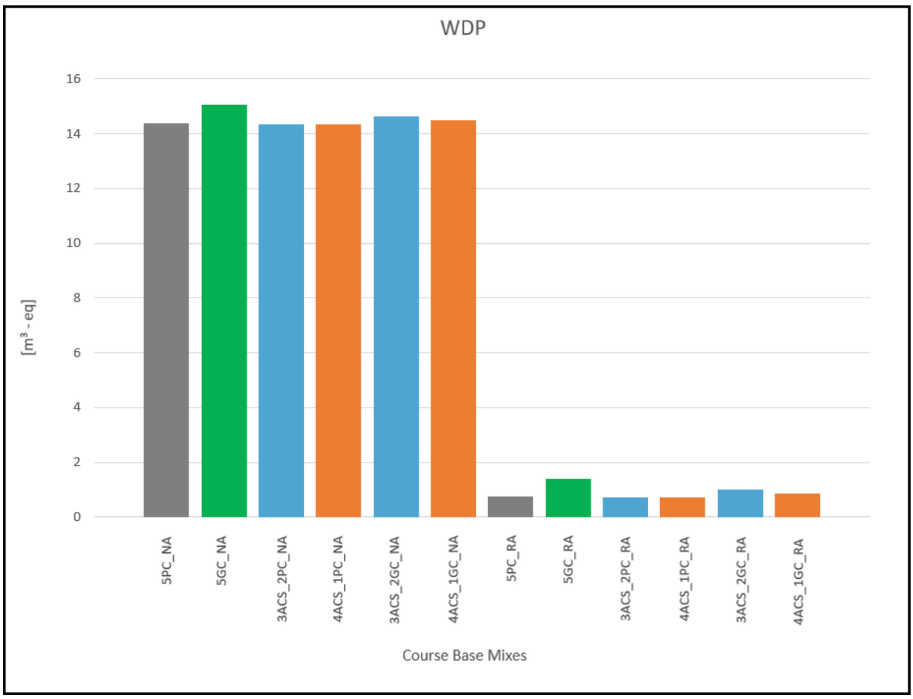


**Fig. 10.** This figure shows the different mix design impacts for the WDP (Water Deprivation Potential) Index.

- Solutions using NA have much heavier impacts than options using RA. The reason lies in the size of their water consumption index, which is 100 times higher for NA. It follows that all solutions with RA are preferable.
- PC and ACS have almost the same impacts. Solutions with GC are slightly more impactful (5GC_RA, 3ACS_2GC_RA, 4ACS_1GC_RA).
- There is a slightly higher level of impact for 4% and 1% solutions than for 3% and 2%.

## 4 Discussion

The results of the analysis on each individual index are summarized in the following table, the best solution contains the binder and the mix percentage indicated with the green tick "√", (where the percentage is not indicated the best solution provides only single 5% binder use), while options to be inconvenient are indicated with a red cross "X". The equal sign "=" indicates that there is no difference between the options (Table 1).

**Table 1.** Positive and negative contribution of materials for each Index.

| Materials Index | Portland | Green | ACS | 3%ACS_2%C_NA | 4%ACS_1%C_NA | 3%ACS_2%C_RA | 4%ACS_1%C_RA |
|---|---|---|---|---|---|---|---|
| WGP | X | √ | √ | X | X | X | √ |
| ADPE | √ | X | X | X | X | X | X |
| ADPF | X | √ | √ | X | X | X | √ |
| AP | X | √ | √ | X | = | X | = |
| ODP | √ | X | X | X | X | √ | X |
| EP FW | √ | X | X | X | X | X | X |
| EP TER | X | √ | √ | X | √ | X | X |
| EP MAR | X | √ | X | X | X | X | X |
| POCP | X | √ | √ | X | √ | X | X |
| WDP | √ | X | √ | X | X | = | = |

From the analysis of each index, it emerged that there is no specific use of materials preferable to another, the impacts vary according to the material used, but in almost all the indices it appears that recycled aggregates are less impacting than the natural ones, even if slightly. While between the two innovative formulations, the mix with 4% ACS and 1% (GC or PC) is preferable to alternative 3% ACS and 2% (GC or PC) in a greater number of cases. Only in the case of ADPE and EP FW indexes, the solution that provides for the only use of PC is less impacting than the innovative solutions, while in the case of EP MAR, the solution with the GC is less impacting than the other alternatives.

## 5 Conclusion

Analyzing the various mix designs, it emerged from the environmental impact index analyses that there is no mix that is preferable over the others. From the study conducted, it emerged that considering the two alternatives mix design where ACS is used to replace partially PC and GC is possible to see that the mix design with 4% ACS and 1% (PC or GC) is less impactful than 3% ACS and 2% (PC or GC) except for ODP (Stratospheric ozone depletion potential) and EP MARINE (Seawater eutrophication potential) indexes. While to ADPE (Abiotic depletion potential of non-fossil resources) and EP FW (Freshwater eutrophication potential) the use of only PC binder is the better solution. The study shows that RA are less impactful than NA except to AP (Soil

and water acidification potential) index, where both solutions are equal, and to EP TER (Terrestrial eutrophication potential), EP MAR (Seawater eutrophication potential) and POCP (Tropospheric ozone formation potential) index, where RA have a greater impact than NA. To WDP index RA are clearly the better choice. The use of ACS is a good design choice when considering indices GWP (Global Warming Potential) –ADPF ( Abiotic depletion potential of fossil resources) -AP (Soil and water acidification potential) -EP TER (Terrestrial eutrophication potential) -POCP (Tropospheric ozone formation potential)-WDP (Water Deprivation Potential). Consequently, for such indices, it will be convenient to use the 4%ACS - 1%PC mix design as more of the same material is expected. Analysis shows that GC is preferred over PC in 60 percent of the cases, except for the indices ADPE (Abiotic depletion potential of non-fossil resources) -ODP (Stratospheric ozone depletion potential)-EP FW (Freshwater eutrophication potential) and WDP (Water Deprivation Potential). In conclusion, it must be said that the analyses of EPDs indices are a valid tool to better understand environmental impacts when analyzing the introduction of by-products as potential alternative materials in the construction sector. The suggested methodology and the reliable sources from which the data were taken allowed a detailed view of the strengths and weaknesses of innovative and traditional mix designs with regard to environmental implications related to the use of various binders and the use of aggregates. Proposing further parameters on which to base design choices useful in identifying the most suitable materials from an environmental point of view.

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