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Cleaner production of the precast concrete industry: comparative life cycle analysis of concrete using recycled aggregates from crushed precast rejects

Yong Yu[a], Fernando Pacheco-Torgal[b], Xin-Yu Zhao[c] and Xiao-Lu Wang[a]

[a]School of Environment and Civil Engineering, Dongguan University of Technology, Dongguan, China; [b]C-TAC Research Centre, School of Engineering, University of Minho, Guimarães, Portugal; [c]State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou, China

ABSTRACT
The in-plant use of recycled aggregate concrete derived from precast rejects (termed PRAC herein) can promote a circular economy in the precast industry. However, the environmental implications associated with this practice remain poorly understood. A refined life cycle assessment (LCA) model was therefore developed to highlight the environmental benefits of using PRAC compared to natural aggregate concrete and conventional recycled aggregate concrete. Some key factors influencing PRAC's environmental performance were also examined. The results indicate that PRAC exhibits around 15% lower energy consumption and carbon dioxide emissions compared to other recycled materials. This reduction is attributed to the favourable quality of PRAC and the elimination of long-distance transport. However, emissions allocation and raw material prices play significant roles in determining the overall environmental impact of PRAC. The equivalent mortar volume mixing method is best suited for PRAC production, as it saves energy, reduces emissions, and maintains similar mechanical properties. Nevertheless, the high-temperature curing, which is often necessary in a precast factory setting, can be energy-intensive and thus diminishes the eco-friendliness of PRAC. Overall, the findings support the use of precast rework as recycled aggregate for cleaner production in the precast industry.

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Recycled aggregate concrete; precast rejects; fly ash; high-temperature curing; emissions allocation; casting methods

1. Introduction

Recent climate summits have sounded a clarion call for decarbonisation in the coming decades (Hanna & Victor, 2021; Ramakrishna & Jose, 2022; Stua et al., 2022). This has sparked significant interest in technologies supporting a circular economy (Li et al., 2022; Mhatre et al., 2021; Xu et al., 2021), which aims to establish a more balanced integration of economic, environmental and social aspects (Sousa-Zomer et al., 2018). As a consequence, a paradigm shift will ensue, necessitating the abandonment of traditional linear production systems (i.e. resources are extracted, consumed and finally discarded as waste) and advocating for the development of sustainable systems that prioritize resource reuse, recycling and energy conservation (Huysman et al., 2017; Rodríguez-Álvaro et al., 2021). Cleaner production represents a crucial step in the realization of a circular economy.

In the specific sector of construction, which contributes to approximately one-third of global emissions (Pan & Garmston, 2012), the active adoption of circular economy principles and low-carbon technologies

CONTACT Xin-Yu Zhao ctzhaoxy@scut.edu.cn State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou 510641, China.

holds immense significance. This endeavour not only serves to blunt the dire consequences of climate change (Gallego-Schmid et al., 2020; Orsini & Marrone, 2019), but also fosters technological innovations within the sector itself. Indeed, the transition towards a circular economy, wherein the outputs of construction processes can be repurposed as secondary resources, is being widely promoted on a global scale (Seara-Paz et al., 2022; Stephan & Athanassiadis, 2018).

Like many other countries, China has rolled out a series of sustainable construction policies in recent years (Zhang et al., 2021)—among them, embracing precast constructions stands out as a notable advancement (Chang et al., 2018; Gao & Tian, 2020). Precasting is well recognized for its ability to deliver high quality and efficiency while requiring fewer labour resources (Ghayeb et al., 2020; Priestley et al., 1999). Moreover, it contributes to the reduction of air pollution, noise and debris (Jaillon & Poon, 2008). The excellent surface finish of precast concrete elements enables them to remain untreated and exposed, maximizing the thermal mass benefits of concrete (Bagarić et al., 2020). From a strategic standpoint, pursuing such a construction pattern also aligns with the trajectory of modern industrialization.

In China, precast structural elements (primarily slabs) and non-structural elements (e.g. staircases and window sills) are widely used in new construction projects. The limited use of precast columns and walls is a result of seismic considerations. Optimistically, it is expected that the precast rate in new buildings of this country will reach 30% in the next decade (Luo et al., 2021). Globally, the precast concrete market is projected to grow from US$ 130.6 billion in 2020 to US$ 174.1 billion by 2025, at a compound annual growth rate of 5.9% (ReportLinker, 2021).

However, there are also challenges associated with implementing precast constructions (Baldwin et al., 2009; Revilla-Cuesta et al., 2022; Xu et al., 2021). One is the seismic performance of precast buildings (Kurama et al., 2018). Another concern is the significant consumption of concrete by the precast industry, which accounts for approximately 20% of the world's annual production (Cassagnabère et al., 2009). This proportion is expected to continue rising, potentially leading to significant environmental issues (Cao et al., 2015). Additionally, a substantial amount of concrete waste is generated in precast plants due to various reasons, such as leftover materials from casting and off-spec pieces (Fiol et al., 2021). The current rejection rate of precast products is about 15% on average, reaching as high as 20% in some projects (Kou, 2021). Proper disposal of these precast rejects has become a significant issue.

One potential solution is to crush the waste and off-spec elements to produce recycled aggregate (RA) for new prefabrications (Soares et al., 2014). The resulting products, referred to here as precast recycled aggregate concrete or PRAC, have demonstrated superior performance compared to those made with RA from other origins such as demolition sites. This is attributed to several factors, including the controlled conditions under which the precast elements were cast, their low impurity content, minimal air exposure (thus avoiding durability-related issues), and traceable production records.

The concept of recycling precast rejects has been around for years (Fiol et al., 2018; Pedro et al., 2015; 2017; Santos et al., 2019; Soares et al., 2014; Thomas et al., 2016; Zhao et al., 2020). Such in-plant recycling can lead to an efficient closed-loop flow of materials (Salesa et al., 2017). Two groups, led by de Brito and Thomas, were among the first to conduct a spate of studies on the properties of concrete made with aggregate from precast rejects; this aggregate type is termed PRA hereafter. For example, Soares et al. (2014) examined the workability, mechanical properties and durability of normal strength concrete using PRA. The findings indicated no significant differences in material properties between natural aggregate concrete (NAC) and PRAC. Moreover, it is widely recognized that the presence of old mortar and internal defects can present challenges in producing high-quality concrete using RA (Xiao et al., 2022; Yu et al., 2021). However, Pedro et al. (2017) successfully used PRA and silica fume to manufacture concrete with compressive strength up to 104 MPa. Furthermore, the benefits associated with PRAC enable the possibility of multi-generation recycling (Salesa et al., 2017). In light of these findings, some European building codes have commenced permitting increased usage and acceptance of PRA in engineering practice (Cenci et al., 2021; Fiol et al., 2023).

The preceding studies have greatly contributed to our understanding the material properties of PRAC. But not much is known about how this production process affects the environment. Although a number of studies—as summarized in Zhang et al., 2019a—have conducted environmental impact assessments for conventional recycled aggregate concrete, there is a lack of similar life cycle assessment (LCA) studies for the in-plant recycling of precast rejects.

To address this knowledge gap, the present study conducted a comparative analysis that elucidated the disparities in the environmental impacts between the production of NAC, PRAC and conventional recycled aggregate concrete (DRAC) using RA from demolition sites (that aggregate type is termed DRA). Furthermore, a comprehensive parametric study was undertaken showing the dependence of PRAC's environmental impacts on the mixture's water-to-binder ratio, the RA replacement level, the fly ash content, the concrete curing and enhancement techniques, and how the emissions were allocated. This exploration aimed to demonstrate the technical and environmental characteristics and advantages of using PRAC, thereby providing valuable insights for engineers' decisions on concrete recycling.

Apart from the aforementioned objectives, this study made several improvements in the following aspects compared to existing life cycle assessment for DRAC:

- A holistic and generally-applicable life cycle assessment tool was developed, covering direct production, supply chain production and transportation. It also considered regional variations and provided technical alternatives for raw material extraction, ingredient production and concrete batching. These distinctive features enhanced the credibility of the calculated results, allowing for the incorporation of a wide variety of parameters such as cement processing method, type and proportion of fossil and clean energy sources, transportation method, dust control measure, and recycling plant type of RA;
- The environmental impacts of industrial byproducts and demolition waste were given particular attention. This involved addressing two fundamental questions: (i) How to accurately assess the environmental impact of byproducts and solid waste? and (ii) How do the environmental benefits of using these materials change over time and in response to market demand? To answer these questions, different dynamic allocation scenarios were developed within this study;
- In actual conditions, a range of mixing and enhancement methods are commonly used for the production of RAC. In view of this, this study also focused on discussing the environmental impacts of concrete production using different mixing methods. To the best of the authors' knowledge, this study is the first of its kind to explore this specific topic.

2. Experimentation

The analysis in this study drew upon data from a previous experiment conducted by the authors (Yu et al., 2022), which extensively investigated the workability and mechanical properties of PRAC. However, that study only briefly discussed the economic and environmental benefits of PRAC production, using one cubic meter of concrete as the functional unit. Apparently, that hampers a comprehensive comparison of the environmental impacts between NAC, PRAC and DRAC. Moreover, the previous assessment did not consider crucial influential parameters such as the regional variations in PRAC raw materials and the allocation of recycled aggregates and industrial by-products. As a result, the previous work can be regarded as preliminary, limited in its scope and applicability.

In that study (Yu et al., 2022), the samples were cast using different water-to-binder ratios, fly ash contents and mixing methods. They were also cured at different temperatures. The inclusion of fly ash in different proportions was not only due to its frequent use in precast products (Alghazali et al., 2020), but also because of its benefits in reducing environmental impacts of concrete (Kurda et al., 2018). Some samples had added with steel fibre (fibre content = 1 vol.%) to improve their mechanical properties and durability (Kaplan et al., 2021). That resulted in 36 mixtures used to cast 216 cubes for compressive and splitting-tensile strength testing. The mix proportions and the measured strengths of all the blends are presented in Table 1. They are divided into five groups for easy comparison.

The specimen notation is of the form 'XW-η-ζ-H-M', where 'X' denotes the concrete type (X = N: NAC, X = D: DRAC, X = P: PRAC); 'W' indicates the water-to-binder ratio; 'η' is the replacement ratio of PRA or DRA; 'ζ' is the fly ash replacement ratio; 'H' represents the curing temperature in centigrade degrees; and 'M' stands for the mixing method (M = C for conventional mixing method; M = E for the equivalent mortar volume method; M = T for the two-stage mixing method). When steel fibre was added M becomes S, and M = ES indicates the equivalent mortar volume method with steel fibre added.

All the samples were produced at a precast plant located in Dongguan, China. Except for the superplasticizer and steel fibre, all raw materials were obtained from local suppliers. The demolition waste used for DRA was purchased from a local recycling plant, while the precast rejects were generated in the plant itself (refer to Figure 1). The superplasticizer and steel fibre were purchased commercially, which involved transportation of 1500 km for the superplasticizer and 1311 km for the fibres.

Table 1. Mix proportions and measured strengths.

Gr. no.	Specimen notation	Mix proportions (kg/m^3)								Strengths (MPa)	
		Cement	Fly ash	Sand	NCA	RCA[a]	Water[b]	SF[c]	SP[d]	f_c[e]	f_{st}[f]
I	N0.3-0-0.3-20-C	418.1	179.2	814.8	808.6	–	179.2	–	1.4	53.5	3.52
	N0.4-0-0.3-20-C	388.3	166.4	814.8	808.6	–	221.9	–	0.7	44.3	3.01
	N0.5-0-0.3-20-C	362.4	155.3	814.8	808.6	–	258.8	–	0.4	38.4	2.55
	N0.6-0-0.3-20-C	339.7	145.6	814.8	808.6	–	291.2	–	–	32.6	2.37
	D0.3-0.5-0.3-20-C	418.1	179.2	814.8	404.3	358.2	179.2	–	1.4	39.3	2.39
	D0.4-0.5-0.3-20-C	388.3	166.4	814.8	404.3	358.2	221.9	–	0.7	33.7	2.14
	D0.5-0.5-0.3-20-C	362.4	155.3	814.8	404.3	358.2	258.8	–	0.4	30.3	1.89
	D0.6-0.5-0.3-20-C	339.7	145.6	814.8	404.3	358.2	291.2	–	–	27.1	1.79
	P0.3-0.5-0.3-20-C	418.1	179.2	814.8	404.3	370.5	179.2	–	1.4	43.6	2.71
	P0.4-0.5-0.3-20-C	388.3	166.4	814.8	404.3	370.5	221.9	–	0.7	40.9	2.64
	P0.5-0.5-0.3-20-C	362.4	155.3	814.8	404.3	370.5	258.8	–	0.4	36.8	2.40
	P0.6-0.5-0.3-20-C	339.7	145.6	814.8	404.3	370.5	291.2	–	–	29.3	2.00
II	N0.4-0-0.3-20-C	388.3	166.4	814.8	808.6	–	221.9	–	0.7	45.3	3.01
	D0.4-0.3-0.3-20-C	388.3	166.4	814.8	566.0	214.9	221.9	–	0.7	38.5	2.41
	D0.4-0.5-0.3-20-C	388.3	166.4	814.8	404.3	358.2	221.9	–	0.7	33.7	2.14
	D0.4-0.7-0.3-20-C	388.3	166.4	814.8	242.6	501.5	221.9	–	0.7	31.4	1.74
	D0.4-1.0-0.3-20-C	388.3	166.4	814.8	–	716.4	221.9	–	0.7	26.7	1.29
	P0.4-0.3-0.3-20-C	388.3	166.4	814.8	566.0	222.3	221.9	–	0.7	43.8	3.03
	P0.4-0.5-0.3-20-C	388.3	166.4	814.8	404.3	370.5	221.9	–	0.7	40.9	2.64
	P0.4-0.7-0.3-20-C	388.3	166.4	814.8	242.6	518.7	221.9	–	0.7	37.7	2.43
	P0.4-1.0-0.3-20-C	388.3	166.4	814.8	–	741.0	221.9	–	0.7	36.3	2.31
III	P0.4-0.5-0-20-C	554.7	–	814.8	404.3	370.5	221.9	–	0.7	48.3	3.47
	P0.4-0.5-0.15-20-C	471.5	83.2	814.8	404.3	370.5	221.9	–	0.7	46.5	3.18
	P0.4-0.5-0.3-20-C	388.3	166.4	814.8	404.3	370.5	221.9	–	0.7	40.9	2.64
	P0.4-0.5-0.45-20-C	305.1	249.6	814.8	404.3	370.5	221.9	–	0.7	32.7	2.34
	P0.4-0.5-0.6-20-C	221.9	332.8	814.8	404.3	370.5	221.9	–	0.7	23.0	1.68
IV	P0.4-0.5-0.3-20-C	388.3	166.4	814.8	404.3	370.5	221.9	–	0.7	46.5	3.18
	P0.4-0.5-0.3-50-C	388.3	166.4	814.8	404.3	370.5	221.9	–	0.7	48.7	3.54
	P0.4-0.5-0.3-70-C	388.3	166.4	814.8	404.3	370.5	221.9	–	0.7	51.6	3.71
	P0.4-0.5-0.3-90-C	388.3	166.4	814.8	404.3	370.5	221.9	–	0.7	52.4	3.92
	P0.4-0.5-0.6-20-C	221.9	332.8	814.8	404.3	370.5	221.9	–	0.7	40.9	2.64
	P0.4-0.5-0.6-50-C	221.9	332.8	814.8	404.3	370.5	221.9	–	0.7	43.1	2.97
	P0.4-0.5-0.6-70-C	221.9	332.8	814.8	404.3	370.5	221.9	–	0.7	45.8	3.15
	P0.4-0.5-0.6-90-C	221.9	332.8	814.8	404.3	370.5	221.9	–	0.7	47.9	3.49
V	P0.3-0.5-0.3-20-C	418.1	179.2	814.8	404.3	370.5	179.2	–	1.4	43.6	2.71
	P0.3-0.5-0.3-20-T	418.1	179.2	814.8	404.3	370.5	179.2	–	1.4	44.8	2.82
	P0.3-0.5-0.3-20-E	380.8	163.2	742.2	580.0	370.5	163.2	–	2.0	46.3	2.75
	P0.3-0.5-0.3-20-S	418.1	179.2	814.8	404.3	370.5	179.2	78.6	1.4	44.7	3.15
	P0.3-0.5-0.3-20-ES	380.8	163.2	742.2	580.0	370.5	163.2	78.6	2.2	45.3	2.98
	P0.4-0.5-0.3-20-C	388.3	166.4	814.8	404.3	370.5	221.9	–	0.7	40.9	2.64
	P0.4-0.5-0.3-20-T	388.3	166.4	814.8	404.3	370.5	221.9	–	0.7	41.8	2.76
	P0.4-0.5-0.3-20-E	353.7	151.6	742.1	580.0	370.5	202.1	–	1.2	43.9	2.64
	P0.4-0.5-0.3-20-S	388.3	166.4	814.8	404.3	370.5	221.9	78.6	0.7	42.1	3.11
	P0.4-0.5-0.3-20-ES	353.7	151.6	742.1	580.0	370.5	202.1	78.6	1.5	44.6	2.96

[a]RCA: recycled coarse aggregate from either demolished members or precast rejects; [b]Water: effective water; [c]SF: steel fibre; [d]SP: superplasticizer; [e]f_c: compressive strength; [f]f_{st}: splitting-tensile strength.

The experimental campaign yielded several significant findings, which are outlined as follows:

i. The measured compressive strengths of PRAC were between 8% and 36% higher than those of DRAC at similar water-to-binder ratios. Still, the strength of PRAC was comparable to that of NAC;
ii. As anticipated, with the increase of fly ash content, PRAC's strength decreased. But that loss would be compensated for by the former's better environmental benefits (Hafez et al., 2020);
iii. Increasing the curing temperature of the PRAC improved its strength by up to 32%;
iv. Compared with conventional mixing, the modified 'E', 'T', 'S' and 'ES' methods only moderately affected the PRAC's strengths (by up to 11%). Among these methods, the equivalent mortar volume method was proved to be the most effective in enhancing the strength of PRAC;

(a) Precast rejects stockpiled in plant's yard (b) Crushing of precast rejects in the workshop

Figure 1. Source and production of PRA (a) Precast rejects stockpiled in plant's yard and (b) Crushing of precast rejects in the workshop.

v. The test data were used to develop formulas for predicting the compressive and tensile strengths considering the comprehensive set of parameters varied in the tests. These equations were then applied in the current LCAs.

$$f_c = \alpha_c \beta_c^{RA} \gamma_c^{FA} \delta_c^{T} (aWB + b) = \alpha_c (1 - 0.20\varphi_c \eta)(1 - 0.76\zeta)(0.96 + 0.002T)(87.48 - 74.08WB) \quad R2 = 0.953 \tag{1}$$

$$f_t = \alpha_t \beta_t^{RA} \gamma_t^{FA} \delta_t^{T} (cWB + d) = \alpha_t (1 - 0.23\varphi_t \eta)(1 - 0.80\zeta)(0.92 + 0.004T)(5.60 - 4.15WB) \quad R2 = 0.963 \tag{2}$$

where α_c and α_t are fitting coefficients allowing for the effects of different mixing methods on RAC's strengths. In specific, for the 'C', 'T', 'E', 'S' and 'ES' methods, α_c is equal to 1.00, 1.03, 1.07, 1.03 and 1.06, while α_t is equal to 1.00, 1.04, 1.01, 1.18 and 1.11, respectively; η and ζ represent the replacement ratios of coarse RA and fly ash, respectively; φ_c and φ_t are factors considering the coarse RA type (φ_c and φ_t are both equal to 1.00 for PRA, while the corresponding values for DRA are 2.12 and 2.51, respectively); T is the curing temperature; and WB is the water-to-binder ratio.

3. Life cycle assessment (LCA) methodology

GreenConcrete is a tool developed by researchers at the University of California, Berkeley (Gursel, 2014), which was modified and utilized in this study. A typical LCA consists of four steps: defining goals and scope, establishing a life cycle inventory, evaluating environmental impacts, and interpreting the results of the analysis (Klüppel, 1998).

3.1. Goal and scope definition

The objective of this study was to evaluate the environmental impacts of the production of PRAC, highlighted by comparisons with NAC and DRAC production. This goal defined the system boundaries: the life cycle analysed included the production and transport of different concretes (NAC, DRAC and PRAC) and their ingredients (cement, fly ash, aggregate, steel fibre, etc.), as shown in Figure 2. However, the study did not consider the environmental impacts resulting from the concrete's use at the construction site or its maintenance and replacement over time. As a result, a cradle-to-gate approach (Zhang et al., 2019b) was adopted for the current LCAs.

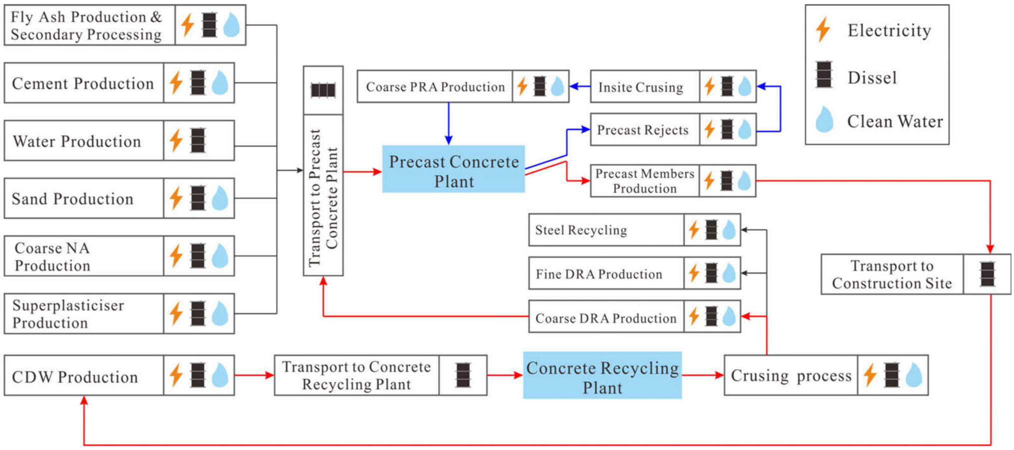


Figure 2. Scope of the present LCA tool.

3.2. Life cycle inventory (LCI) data

The functional unit for this study was defined as one cubic meter of concrete at the exit gate of the precast plant. The compressive and tensile strengths of various mixtures, as estimated by Eqs. (1) and (2), were utilized as metrics or constraints in the analysis.

Taking 'P0.5-0.5-0.3-20-C' as an example, its predicted compressive and tensile strengths were 35.0 and 2.37 MPa, respectively (Please note that there may be slight variations between the predicted and measured strengths). To achieve an equivalent strength, the water-to-binder ratio for a DRAC mixture should be reduced to 0.3, as determined by Eqs. (1) and (2). Consequently, a hypothetical new DRAC mixture called 'D0.3-0.5-0.3-20-C' was created. The same procedure can be applied to obtain a comparable NAC mixture called 'N0.58-0-0.3-20-C' by increasing the water-to-binder ratio for comparison purposes. The *GreenConcrete* tool can then be employed to calculate the consumption of raw materials, fuels, electricity and emissions for the different mixtures, facilitating a fair comparison of the environmental impacts of NAC, DRAC and PRAC.

The electricity grid mix and transportation used in those calculations are listed in Table 2. Note that the PRA had no transport distance as it was generated and recycled within the precast plant. The transport distance from Dongguan's one concrete recycler was slightly longer than the distance to the gravel pit in use at that time (140 km vs. 101 km). The Appendix details the main equipments used in precrushing, primary jaw crushing, secondary impact crushing and screening and their respective efficiencies for the two types of RA.

The complete life cycle inventories of the LCA are provided in the Appendix, but here are some key points. The production of cement involves a series of steps (Hafez et al., 2021) that offer various technical options at different stages (Gursel, 2014). The energy and emissions associated with cement production therefore vary widely. Fortunately, the *GreenConcrete* tool is designed to account for these variations and incorporate them into the analysis.

The manufacturing process of fly ash mainly includes primary ash production and secondary processing (Kurda et al., 2018). For the life cycle inventory of the secondary processing, survey data published by Chen et al. (2010) was utilized in this analysis. Regarding the treatment of environmental impacts related to primary ash production, there are three approaches—no allocation, mass allocation, and economic allocation. In this study, economic allocation was predominantly employed. The impact of the allocation choice will be discussed in Section 5.2

Producing DRA and PRA is generally simpler and uses less energy than producing NA because no blasting is involved. Diesel and electricity are the main fuels driving the crushers. Three allocation scenarios can again be used. For this study, an economic allocation coefficient of 72.4% was assumed for most LCA calculations. The effect of this choice will also be discussed in Section 5.2.

The production of steel fibre typically involves several processes such as electric steel production, hot rolling, descaling, dry or wet wire drawing, tempering, strand fabrication, and cutting to length (Stengel & Schießl, 2014). Unfortunately, there is no published data on the energy use and emissions specifically

Table 2. Assumed NAC and RAC inputs.

User input information	
Cement	P.O.42.5
Admixture	Superplasticizer
Power of the electric heater	600 Watt

Electricity grid mix of Guangdong Province (Yang et al., 2022)						
Fuel type	Bituminous coal	Hydro-power	Nuclear power	Wind power	Solar power	Biomass power
Contribution	61.9%	11.1%	15.5%	4.2%	5.8%	1.5%

Transportation details*	Mode	Distance (km)[#]
Cement raw materials to cement plant	Class 8b truck	70
Gypsum to cement plant	Class 8b truck	70
Fly ash to cement plant[&]	Class 8b truck	52
Cement to precast plant	Class 8b truck	124
Fly ash to precast plant	Class 8b truck	140
Natural sand to precast plant	Class 8b truck	130
NA to precast plant	Class 8b truck	101
Demolition waste to recycling plant	Class 8b truck	40
DRA to precast plant	Class 8b truck	140
PRA to precast plant	–	0
Steel fibre to precast plant	Train	1500
Admixture to precast plant	Train	1311
Technology options		
Cement raw material prehomogenisation	Wet process, raw storage	
Cement raw materials grinding	Dry, raw grinding, tube mill	
Cement raw meal blending/homogenisation	Raw meal homogenisation, blending and storage	
Clinker pyroprocessing	Average China kiln	
Clinker cooling	Rotary tube cooler	
Clinker finish milling and grinding and blending	Roller press	
Cement plant particulate matter (PM) control	Fabric filter	
Conveying in the cement plant	Screw pump (20 m between all processes)	
Mixing method in concrete batching plant	Mixer loading (central mix)	
Concrete batching plant PM control technology	Fabric filter	

*Fresh-water is pumped from a river by electricity.
[#]All road distances include the return trip, as the truck may be empty, but the rail trips are one-way.
[&]Some fly ash is often incorporated as mineral admixture in producing ordinary Portland cement.

associated with these processes in the Chinese context. The composite life cycle inventory data provided in the Appendix was sourced from Jiang's research (Jiang et al., 2021). According to their estimates, the production of one metric tonne of steel fibre consumes 423.41 MJ of energy and generates a total of 50.33 kg of greenhouse gas emissions.

The *GreenConcrete* tool is designed to take into consideration both road and rail transportation (Yang et al., 2022). The lack of transport needed to produce PRA is one of the material's principal advantages.

But precast products are generally very bulky. To get them out of the plant as quickly as possible, high-temperature curing is normally used. Scholars (Bergman et al., 2017; Shobeiri et al., 2021) suggest the following formula to estimate the curing energy (E_{curing}) needed to produce one cubic metre of concrete when the curing temperature is above 20 °C:

$$E_{curing} = Pt_{curing} + mc(T_{curing} - 20) \text{ when } T_{curing} > 20\ ^{\circ}C \qquad (3)$$

where P is the power of the oven or furnace (J/s) and m is the mass of the cubic metre of concrete; T_{curing} and t_{curing} are the curing temperature (°C) and time (s), respectively; c denotes the specific heat capacity of the concrete, which was simply assumed to be 700 J/(kg·°C) in this study (Yang et al., 2022).

4. Assessment results and interpretation

The evaluated environmental impact categories included embodied energy (EE), carbon dioxide equivalent emissions ($CO_{2\text{-}eq}$), nitrogen oxides (NO_x), sulphur dioxide (SO_2), wastewater (H_2O), solid waste (SW) and total particulate matter (PM_{total}). It is worth noting that numerous LCA studies (e.g. de Brito et al., 2022; Dias et al., 2022) have demonstrated discrepancies in natural resource consumption between NAC and RAC, as evident by indicators such as abiotic depletion. However, the current study's calculation

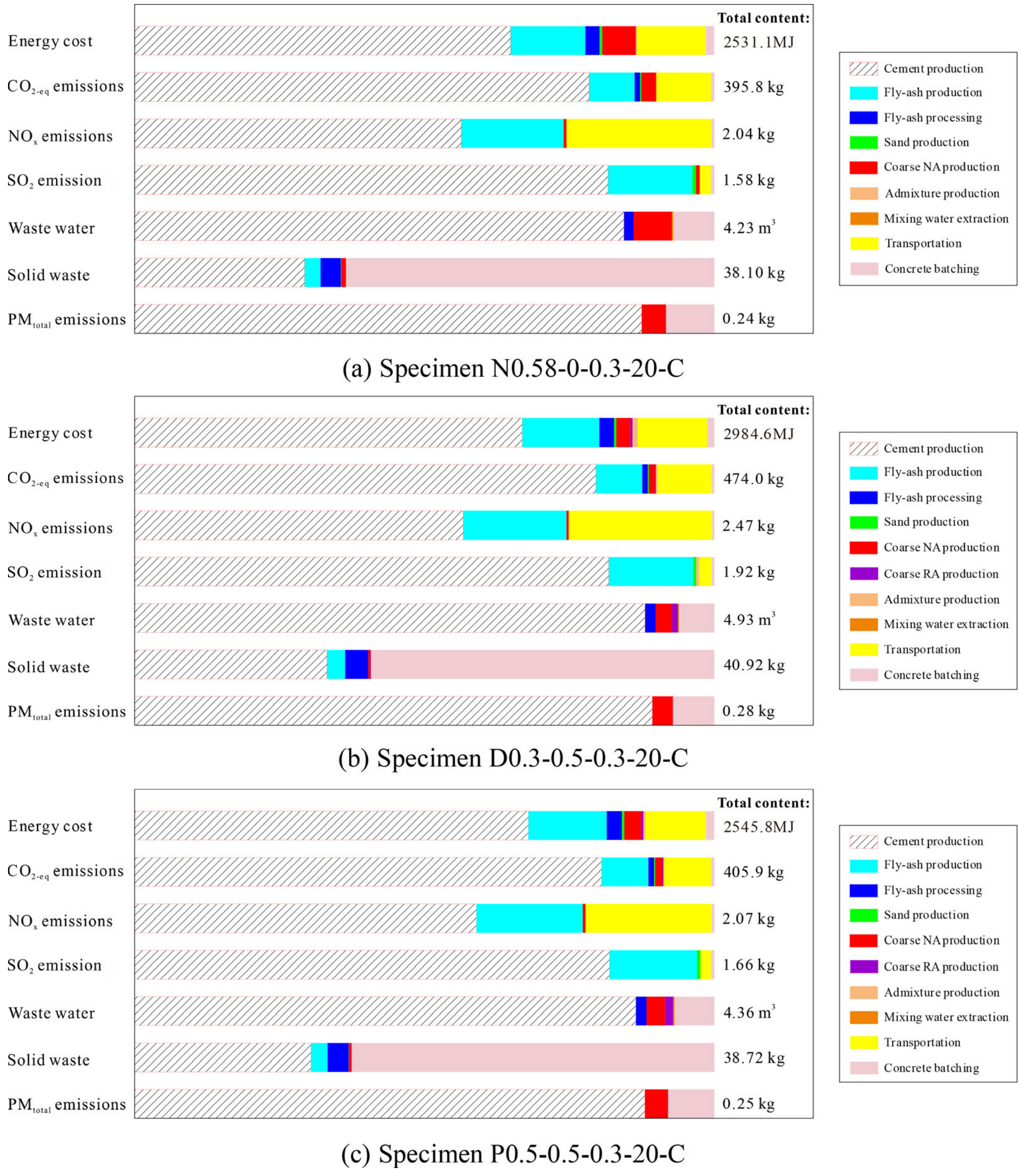


Figure 3. Environment impacts for different samples with comparable strengths. (a) Specimen N0.58-0-0.3-20-C, (b) Specimen D0.3-0.5-0.3-20-C, and (c) Specimen P0.5-0.5-0.3-20-C.

model did not include such indicators, and this limitation should be given particular attention in future relevant studies.

Figure 3 compares the environmental impacts of three samples: N0.58-0-0.3-20-C, D0.3-0.5-0.3-20-C, and P0.5-0.5-0.3-20-C, which serve as typical cases. Cement production clearly has the greatest impact in all aspects with the exception of solid waste. The majority of solid waste comes from concrete batching. Note, though, that the absolute emissions of SO_2, H_2O, and PM_{total} from cement production were not particularly serious. Nonetheless, cement production accounted for the lion's share of energy consumption and $CO_{2\text{-eq}}$ emissions, followed by fly ash production and transportation. The contributions of NO_x and SO_2 from fly ash production and transportation were also relatively high. Figure 3 shows that overall the type of aggregate did not significantly influence the contributions from different production processes in each environmental impact category.

However, when compared to N0.58-0-0.3-20-C, the absolute environmental impacts of D0.3-0.5-0.3-20-C were on the whole higher. For instance, producing a cubic metre of DRAC is predicted to consume 2984.6 MJ of energy and emit 474.0 kg of carbon dioxide, which are 17.9% and 19.7% higher than the estimates for N0.58-0-0.3-20-C, respectively. These increases indicated that the use of DRA may be less sustainable in certain cases. Visintin et al. (2020) report similar conclusions. The specific reason for this could be attributed to the fact that DRA requires more transportation than NA, and additional cement and fly ash are needed (approximately 22% more in this scenario) to compensate for DRAC's weaker strength. Naturally, a replacement rate of 100% would further amplify the environmental impact.

Figure 3c illustrates the predicted environmental impacts associated with P0.5-0.5-0.3-20-C. These impacts are closer to those of N0.58-0-0.3-20-C than to those of D0.3-0.5-0.3-20-C. The production of one cubic meter of PRAC is estimated to consume 2545.8 MJ of energy and emit 405.9 kg of carbon dioxide, about 14% less than D0.3-0.5-0.3-20-C in both cases. Eliminating the need for long-distance transportation and reducing the usage of additional cement clearly provide benefits for PRA. The superior quality of PRA compared to DRA contributes to the reduced cement usage. Moreover, the energy consumption during the production of PRA's binder was only slightly higher than that of NAC (2139 vs. 2030 MJ), while the fuel and transportation were significantly decreased (from 594 to 350 MJ). This trade-off resulted in similar energy consumption between NAC and PRAC. It implies that recycling precast rejects is not only technically feasible but also environmentally friendly. As the substitution rate of PRA increases, this comparative advantage over using DRA will become more pronounced.

But cement production remains the most significant factor, as indicated by the predictions presented in Table 3. Clinker pyroprocessing is the most influential step. Its energy consumption (83.6%), CO_2 emissions (94.6%), solid waste generation (87.4%), SO_2 emissions (95.1%) and NO_x emissions (96.5%) eclipse all other contributions from cement production. These predictions align closely with the analytical findings reported by Worell's group (Worrell et al., 2001). The high-temperature environment necessary for the chemical decomposition and synthetic reactions during clinker pyroprocessing makes this step energy-intensive and polluting.

Figure 4 provides further assessment of the embodied energy and carbon dioxide emissions associated with NAC and PRAC with similar strength. In this figure the replacement ratio of PRA and the water-to-binder ratio are varied. At 50% PRA replacement, the total energy consumption of PRACs with different water-to-binder ratios is very close to that of NAC. The differences are only between −1 and 5%. The same goes for the $CO_{2\text{-eq}}$ emissions. With 70% replacement the differences are still less than 5%, but when the replacement rate increases to 100%, the environmental impacts show a moderate rise (about 15%) relative to those of NAC. This trend remains consistent irrespective of the water-to-binder ratio.

Table 3. Absolute and relative (%) energy cost and waste emissions for producing 344 kg of cement[#].

		Waste emissions (kg and %)					
Production processes	EE (MJ)	$CO_{2\text{-eq}}$	NO_x	SO_2	Water	SW	PM_{total}
Raw material quarrying	40.2 (2.4)	2.6 (0.9)	0.01 (0.4)	0.01 (0.5)	171.3 (4.8)	0.14 (1.3)	0.01 (4.0)
Meal prehomogenization	1.1 (0.1)	0.1 (0)	0.00 (0)	0 (0)	8.9 (0.2)	0.01 (0.1)	0 (0.2)
Raw materials grinding	54.4 (3.3)	3.4 (1.1)	0.01 (0.7)	0.01 (1.0)	439.7 (12.3)	0.3 (2.7)	0.02 (10.0)
Meal homogenization	3.2 (0.2)	0.2 (0.1)	0 (0)	0 (0.1)	25.7 (0.7)	0.02 (0.2)	0 (0.6)
Clinker pyroprocessing	1372.4 (83.6)	293.5 (94.6)	1.11 (96.5)	1.23 (95.1)	1554.1 (43.5)	9.76 (87.4)	0.11 (53.9)
Clinker cooling	16.9 (1.0)	1.0 (0.3)	0 (0.2)	0 (0.3)	136.7 (3.8)	0.09 (0.8)	0.01 (3.1)
Finish milling and grinding	92.7 (5.6)	5.7 (1.8)	0.01 (1.2)	0.02 (1.8)	748.9 (21.0)	0.51 (4.6)	0.04 (17.1)
Cement plant conveying	0.6 (0)	0 (0)	0 (0)	0 (0)	4.6 (0.1)	0 (0)	0 (0.1)
Other electricity use	60.0 (3.7)	3.7 (1.2)	0.01 (0.8)	0.01 (1.1)	484.7 (13.6)	0.33 (3.0)	0.02 (11.0)

[#]Note: 344 kg cement is used in fabricating 1.0 m^3 of concrete mixture N0.58-0-0.3-20-C.

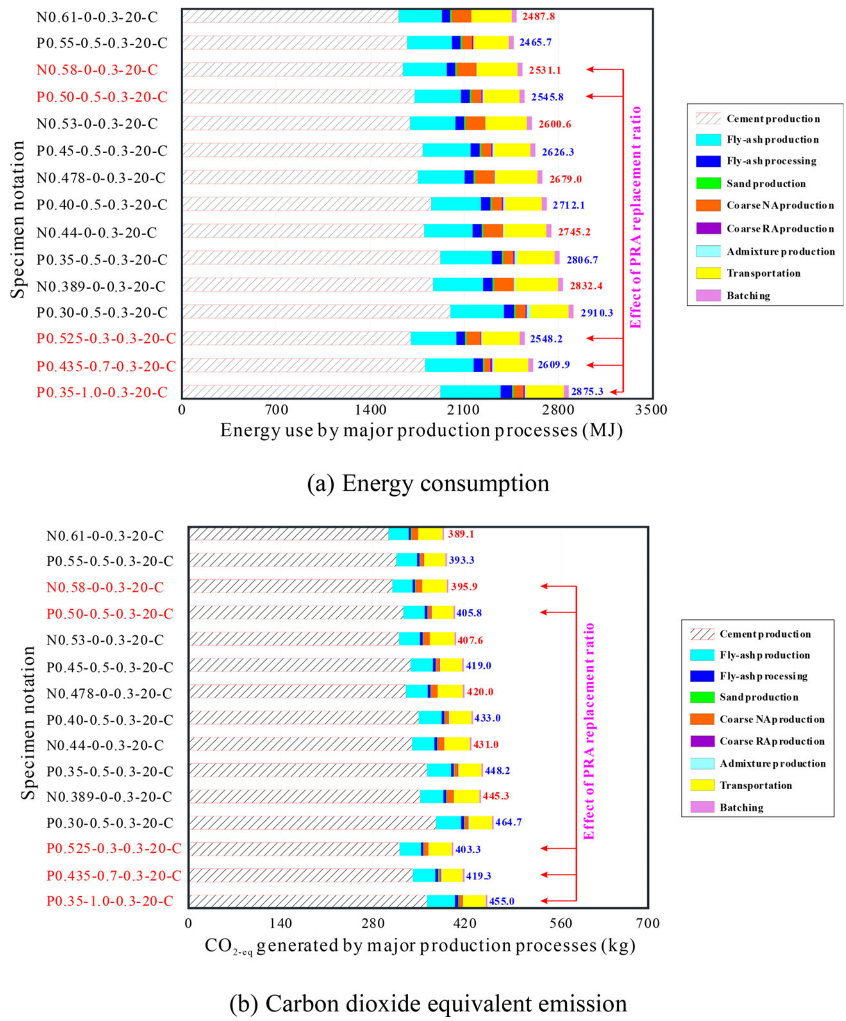


Figure 4. Environmental impacts of NAC and PRAC with various water-to-binder ratios and PRA replacement ratios. (a) Energy consumption and (b) Carbon dioxide equivalent emission.

5. Sensitivity analysis

Concrete production is susceptible to numerous uncertainties that can pose challenges to conducting a robust LCA, as highlighted by Zhao et al. (2021). To address these uncertainties, a sensitivity analysis was conducted in this study to evaluate the impacts of some key factors such as high-temperature curing, emissions allocation scheme and PRAC formulation methods on the LCA outcomes.

5.1. Influence of high-temperature curing

Fly ash is considered more environmentally friendly than cement, which favours using more of it in formulating concrete (Kurda et al., 2018; Yang et al., 2022). But in practice there are difficulties. One challenge is that concrete containing fly ash may exhibit inferior early-age mechanical properties. High-temperature curing is capable of remedying this, and it is in any case widely adopted in precast industry to improve the throughput of precast members. Nevertheless, from an environmental impact perspective, several questions arise: What is the trade-off? Which is more environmentally unfriendly, using high-temperature curing or increasing cement content? And can the reduced environmental impacts of using fly ash offset the increased environmental impacts of using high-temperature curing?

Table 4. Predicted environmental impacts for concrete with various binder amounts and curing temperatures.

		Strengths (MPa)*			Waste emissions (kg)					
Case no.	Specimen notation	f_c	f_t	EE (MJ)	$CO_{2\text{-eq}}$	NO_x	SO_2	Water	SWs	PM_{total}
1	P0.5-0.5-0.3-20-C	35.0	2.37	2545.8	405.8	2.07	1.66	4351.3	38.72	0.25
2	P0.526-0.5-0.3-40-C	35.1	2.48	2718.8	412.4	2.07	1.69	6011.7	39.65	0.33
3	P0.551-0.5-0.3-60-C	35.0	2.59	2765.7	411.6	2.06	1.68	6630.3	39.89	0.36
4	P0.568-0.5-0.3-75-C	35.0	2.66	2802.8	411.4	2.05	1.68	7098.2	40.09	0.38
5	P0.584-0.5-0.3-90-C	35.0	2.73	2842.4	411.6	2.04	1.68	7571.3	40.30	0.40
1	P0.5-0.5-0.3-20-C	35.0	2.37	2545.8	405.8	2.07	1.66	4351.3	38.72	0.25
6	P0.5-0.5-0.34-40-C	35.0	2.45	2694.4	402.1	2.07	1.66	5844.8	39.46	0.32
7	P0.5-0.5-0.375-60-C	35.1	2.53	2738.2	395.1	2.06	1.64	6345.5	39.63	0.34
8	P0.5-0.5-0.4-75-C	35.1	2.58	2772.5	390.3	2.06	1.63	6728.0	39.77	0.36
9	P0.5-0.5-0.425-90-C	35.0	2.63	2806.7	385.4	2.05	1.62	7109.5	39.91	0.38

*Strengths predicted by Eqs. (1) and (2).

To address these questions, a theoretical evaluation was conducted on nine concrete mixtures (referred to as cases 1–9 in Table 4) using Eqs. (1) and (2). Mixture P0.5-0.5-0.3-20-C (case 1) was the control one. The replacement ratio of fly ash in cases 2 to 5 was kept at 30% (identical to case 1), but the curing temperature was increased from 40 to 90 °C, with the water-to-binder ratio adjusted to maintain the same strength. On the other hand, in cases 6–9 the fly ash replacement rate was increased while maintaining the water-to-binder ratio.

It is interesting that P0.5-0.5-0.3-20-C was predicted to have the lowest energy cost and the best emissions indexes among cases 1 to 5. This strongly suggests that high-temperature curing is not an effective approach to reducing cement consumption from an environmental perspective. In other words, increasing the curing temperature results in more significant environmental impacts than increasing the cement content. Similarly, comparing case 1 with 6–9 shows that the reduced environmental impacts of using fly ash cannot counteract the increased environmental impacts of using high-temperature curing, because both energy consumption and waste water increase substantially with higher fly ash content and curing temperature, despite a slight decrease in $CO_{2\text{-eq}}$ emissions.

5.2. Influences of the emission allocation scheme

Recycled aggregate is usually broken from difficult-to-handle demolition waste and fly ash is an industrial byproduct. This allows for different ways of considering the environmental impacts of the production of these materials. The simplest approach is called the no-allocation method, where the fuel consumption and waste emissions are entirely attributed to the primary economic activities (e.g. electricity generation in the case of fly ash), while secondary economic activities are assumed to have no bearing on the environment. Such an allocation scheme is easy to implement but not very realistic in the case of RAC (Chen et al., 2010; Marinković et al., 2013, 2014). In mass allocation emissions are allocated to the main and secondary economic activities according to the quantity of the products (precast forms and waste disposal for PRA production). Formally,

$$C_{m,s-product} = \frac{m_{s-product}}{m_{s-product} + m_{m-product}} \tag{4}$$

where $C_{m,s\text{-product}}$, $m_{m\text{-product}}$, and $m_{s\text{-product}}$ are the mass allocation coefficient of the secondary product, the mass of the main product, and the mass of the secondary product. In this study the calculations were based on the life cycle inventory values reported by Chen and his colleagues (Chen et al., 2010). They estimated that burning 0.36 kg of hard coal produces 0.052 kg of fly ash and 1.0 kWh of electricity. Visintin's group similarly estimated (Visintin et al., 2020) that 1.0 kg of construction and building waste (CDW) can ultimately yield 0.6 kg of coarse recycled aggregate. Those estimates produce a $C_{m,\ s\text{-product}}$ of 0.126 for primary fly ash and 0.375 for CDW disposal.

In economic allocation the environmental impacts of the primary and secondary economic activities are estimated as (Chen et al., 2010):

$$C_{e,s-product} = \frac{(u_p \times m)_{s-product}}{(u_p \times m)_{s-product} + (u_p \times m)_{m-product}} \tag{5}$$

Table 5. Emission allocation coefficients for fly ash and PRA (unit: %).

			Economic allocation									
Material	No allocation	Mass allocation	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Fly ash	0	12.40	0.46	0.51	0.56	0.62	0.69	0.72	0.84	0.93	1.03	1.15
PRA	100	37.50	44.01	47.22	50.44	53.67	56.86	60.00	63.06	66.02	68.85	72.36

where u_p is the product's unit price. In this study the price of fly ash in China was taken as increasing from ¥49.5/tonne in 2012 to ¥109.3/tonne by 2021 (Guangdong Engineering Cost Information Platform, 2022). The electricity price was stable over that time period from the China electricity market report (TongCheng Finance News, 2022). Based on an AGR of 22.9%, the price of a tonne of recycled aggregate increased from ¥16.8 in 2012 to ¥118.6 in 2021 (Guangdong Engineering Cost Information Platform, 2022). And the cost of handling a tonne of CDW increased from ¥12.8 in 2012 to ¥23.7 in 2021. Using those prices, the economic allocation coefficients $C_{e,s\text{-product}}$ for fly ash and PRA shown in Table 5 were calculated.

Table 5 reveals that the economic allocation coefficients for both fly ash and PRA climbed over the years. This indicates that an increased proportion of the environmental impacts caused by the production of the two materials will be assigned to products utilizing them. The C_e of fly ash grows faster than that of PRA (by 150% compared with 64.5%) from 2012 to 2021. This discrepancy stems from the fact that the price of fly ash relative to electricity has risen much quicker than the price of PRA relative to the cost of demolition waste disposal.

Now consider the effects of the allocation scenarios on the energy consumption and $CO_{2\text{-eq}}$ emissions associated with three categories of concrete mixtures designed as Group A, Group B and Group C. Please refer to Figures 5 and 6 for detailed information. In these figures, '1' represents the no allocation scenario, '2' represents the mass allocation scenario, and '3' to '12' are the results of the economic allocation scenario from 2012 to 2021.

Clearly, the allocation scheme and the year of use have substantial impacts on the assignment of environmental impacts. Overall, regardless of the concrete type, the no allocation scenario consistently attributes the least energy consumption and $CO_{2\text{-eq}}$ emissions and mass allocation attributes the most.

With no allocation or economic allocation, the embodied energy (or $CO_{2\text{-eq}}$ emissions) attributed to PRAC consistently increases relative to NAC as the PRA substitution rate rises. The mass allocation of emissions exhibits a similar trend.

Figure 6c shows that PRAC with more fly ash fares better with no allocation or economic allocation. For instance, the $CO_{2\text{-eq}}$ emissions attributed are about 12% less with no allocation as the fly ash replacement ratio increases from 30% to 50%. With mass allocation, however, the effect is the opposite. And the attribution can be as high as 41% greater.

These examples highlight that the environmental benefits ascribed to using fly ash or PRA depend heavily on the allocation scheme assumed and market prices.

5.3. Influence of the PRAC's formulation method

Different formulation methods have been suggested to enhance the mechanical properties of RAC (González-Fonteboa et al., 2021; Yu et al., 2021). In order to assess their environmental impacts, ten mixtures with different water-to-binder ratios and formulation methods, as detailed in Table 6, were examined in terms of their predicted energy consumption and waste emissions.

Overall, the two-stage casting method ('T') and the addition of steel fibres ('S') have minimal effects on the environmental impacts of PRAC. On the other hand, the equivalent mortar volume method ('E') is predicted to have much less environmental impact than the other formulation methods. Additionally, the hybrid method ('ES') also shows relatively minimal environmental impact.

To gain deeper insights, an extensive analysis of each main production procedure was conducted using mixtures 6–10 in Table 6. The results are plotted in Figure 7. The environmental impact indices for each production step of the 'C', 'T' and 'S' methods are relatively similar, indicating that the total environmental impact of these three casting methods does not differ significantly. However, the 'E' method demonstrates an average reduction of 7% in production energy costs and $CO_{2\text{-eq}}$ emissions compared to the 'C' method. Such a drop is mainly related to the lower environmental impact of the 'E' method's cement

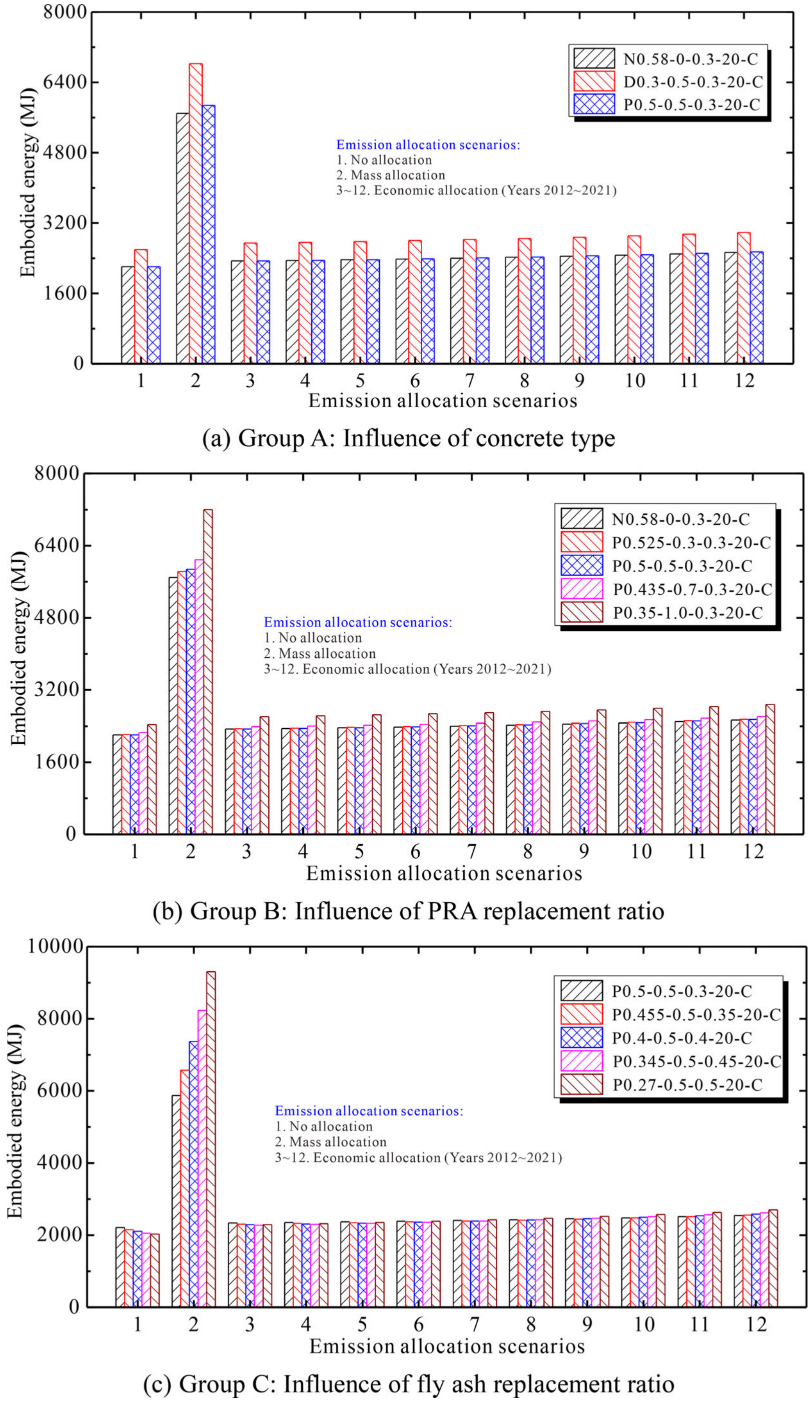
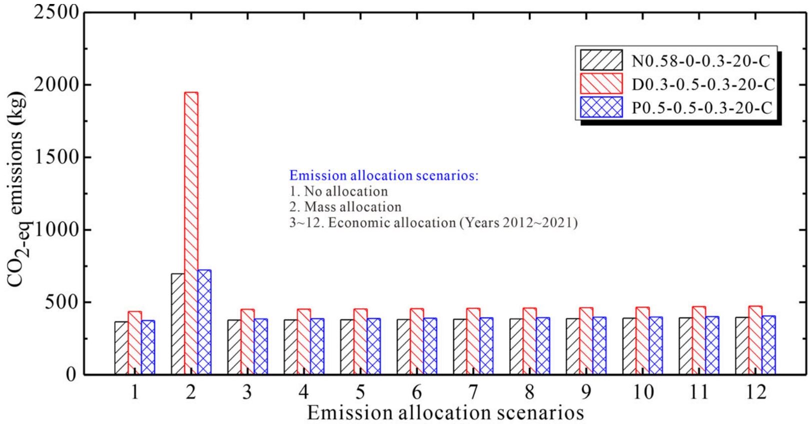
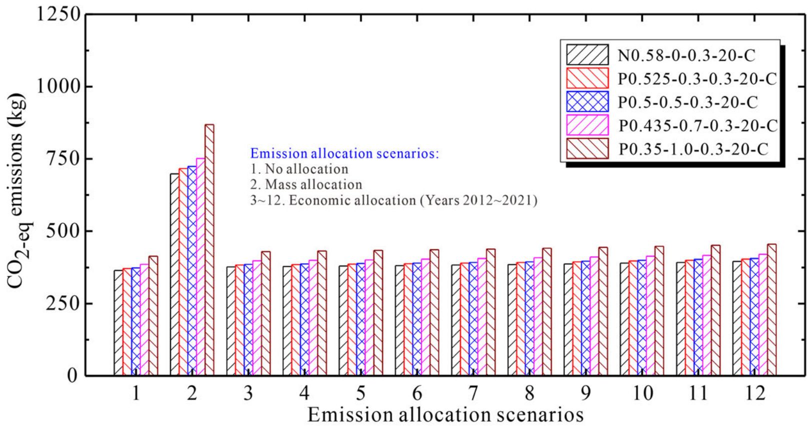


Figure 5. Effects of allocation scenario on energy consumption. (a) Group A: Influence of concrete type, (b) Group B: Influence of PRA replacement ratio, and (c) Group C: Influence of fly ash replacement ratio.

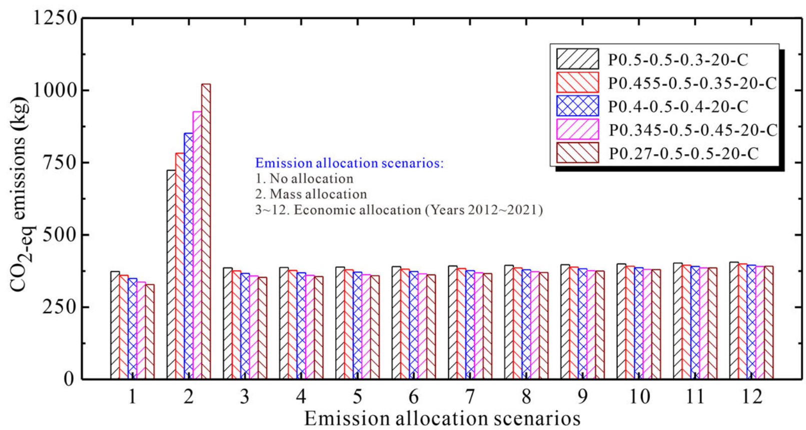
production. The inclusion of old cement mortar in the 'E' method serves as an indirect recycling of cement, resulting in a smaller overall environmental effect when compared to the 'C', 'T' and 'S' methods.



(a) Group A: Influence of concrete type



(b) Group B: Influence of PRA replacement ratio



(c) Group C: Influence of fly ash replacement ratio

Figure 6. Effects of allocation scenario on $CO_{2\text{-eq}}$ emissions. (a) Group A: Influence of concrete type, (b) Group B: Influence of PRA replacement ratio, and (c) Group C: Influence of fly ash replacement ratio.

Furthermore, the 'ES' method enhances the tensile and compressive strengths of RAC, which reduces the amount of cement used. Considering that the cement production constitutes the primary source of

Table 6. Environmental impacts for PRAC samples cast with various improvement methods.

		Strengths (MPa)*			Waste emissions (kg)					
Case no.	Specimen notation	f_c	f_t	EE (MJ)	$CO_{2\text{-eq}}$	NO_x	SO_2	Water	SWs	PM_{total}
1	P0.30-0.5-0.3-20-C	45.3	2.92	2910.3	464.7	2.35	1.92	4939.6	40.93	0.29
2	P0.327-0.5-0.3-20-T	45.3	3.03	2854.4	455.7	2.30	1.88	4850.9	40.60	0.28
3	P0.309-0.5-0.3-20-E	48.1	2.93	2713.5	426.8	2.17	1.74	4578.4	39.44	0.27
4	P0.326-0.5-0.3-20-S	45.3	3.37	2926.0	463.2	2.37	1.89	4854.0	40.61	0.28
5	P0.35-0.5-0.3-20-ES	45.3	3.10	2715.8	422.2	2.17	1.70	4457.0	38.99	0.26
6	P0.40-0.5-0.3-20-C	40.2	2.65	2712.1	433.0	2.20	1.78	4624.8	39.74	0.27
7	P0.423-0.5-0.3-20-T	40.2	2.74	2674.9	426.6	2.17	1.75	4558.3	39.50	0.26
8	P0.41-0.5-0.3-20-E	42.5	2.65	2530.4	398.0	2.03	1.62	4292.2	38.36	0.25
9	P0.423-0.5-0.3-20-S	40.2	3.05	2744.7	433.8	2.23	1.76	4558.3	39.50	0.26
10	P0.445-0.5-0.3-20-ES	40.1	2.80	2553.2	396.6	2.05	1.59	4202.5	38.03	0.24

*Strengths as predicted by Eqs. (1) and (2).

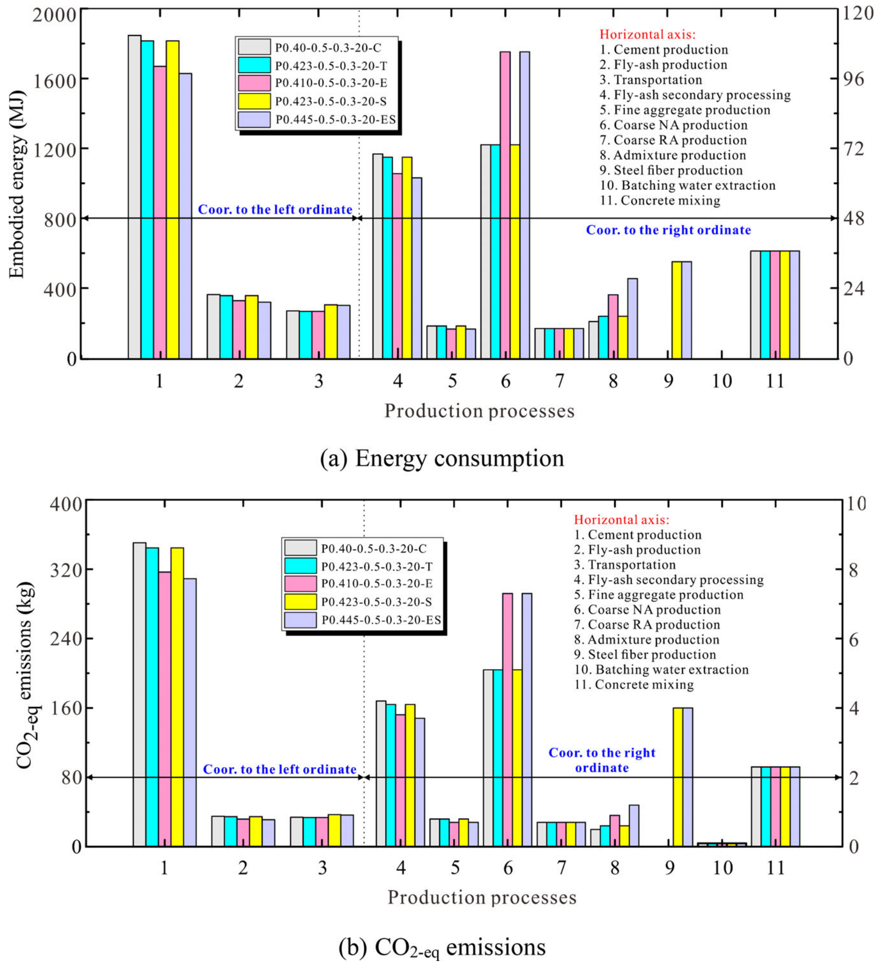


Figure 7. Effect of casting method on environmental impacts of PRAC's major production processes. (a) Energy consumption and (b) $CO_{2\text{-eq}}$ emissions.

pollution in the entire production system, the 'ES' method proves to be beneficial in minimizing environmental impacts.

6. Implications for PRAC production

Based on the aforementioned LCAs, the following implications for PRAC production can be drawn:

a. The use of PRAC in new prefabrications offers an excellent sustainable solution for precast factories. Moreover, it proves to be economically viable, if considering the profitability of construction material productions and the rising prices of aggregate products;
b. The choice of mixing method is crucial for PRAC production. Both the equivalent mortar volume method and the two-stage mixing method can effectively enhance the mechanical properties of the products, leading to reduced binder use and less negative environmental impact;
c. The environmental benefits of incorporating industrial byproducts are significantly influenced by the market prices of binder materials. So regulators should be well prepared for future price swings;
d. If storage space is available, high-temperature curing is not recommended from an environmental standpoint. Fortunately, new curing techniques, such as CO_2 curing, are currently being developed (e.g. Ahmed et al., 2021), offering promising solutions to overcome this challenge.

7. Conclusions

A refined LCA model was developed to compare the environmental impacts of PRAC, NAC and DRAC. From both environmental and economic perspectives, crushing precast rejects into coarse PRA for use in new concrete is an excellent practice for precast factories. In general terms, PRAC exhibits similar production energy consumption and $CO_{2\text{-eq}}$ emissions compared to NAC, while being around 15% lower than DRAC. Enhancing PRAC's mechanical properties while reducing the environmental impact can be achieved by using the equivalent mortar volume method or the two-stage mixing method. The environmental effects attributed to PRAC depend heavily on the method used for allocating emissions and the market prices of fly ash and CDW. Moreover, the environmental benefits of using industrial byproducts as binder are strongly influenced by the market price of the byproduct. Thus, buying and hoarding fly ash when the price is low has environmental as well as economic benefits. Additionally, if only considering the aspect of improving early strength of concrete, high-temperature curing is not recommended in the precast industry practice. In summary, recycling precast rejects can help precast factories improve their environmental performance substantially.

Authors contribution

Yong Yu: Conceptualization, Methodology, Investigation, Formal analysis, Writing – Original draft, Funding acquisition. Fernando Pacheco-Torgal: Conceptualization, Investigation, Writing – Reviewing and Editing. Xin-Yu Zhao: Conceptualization, Methodology, Investigation, Formal analysis, Writing – Reviewing and Editing, Funding acquisition, Supervision. Xiaolu Wang: Conceptualization, Investigation, Writing – Reviewing and Editing.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability statement

The LCA models supporting the findings of this study are available from the corresponding author by reasonable request.

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Appendix

This file provides the detailed life cycle inventories for determining the production environmental impacts of PRAC and DRAC. If interested, readers can refer to Gursel's PhD thesis (2014) for more introductions on the main principles of life cycle assessment simulations.

Table A. Cement plant technology options.

Cement production phases	Product of each phase	Technology selection
Raw materials prehomogenization	Raw meal	Wet process_raw storing
Raw materials grinding	Ground meal	Dry raw grinding_tube mill
Raw meal blending and homogenization	Blended meal	Raw meal homogenization, blending and storage
Pyroprocessing	Clinker	China-average kiln
Clinker cooling	Cooled clinker	Rotar (tube) cooler
Finish milling, grinding and blending	OPC/blended cement	Roller press
Clinker cooling PM control	—	Fabric filter (FF)

Table B. Fuel use options for cement pyroprocessing.

Fuel type	Proportion
Bituminous coal	64.1%
Petroleum coke (pet coke)	21.2%
Natural gas	3.7%
Residual (heavy) fuel oil	0.2%
Distillate (diesel or light) fuel oil	0.8%
Waste oil	0.3%
Waste solvent	4.0%
Waste tires (whole)	1.8%
Waste tires (shredded)	1.8%
Waste (other) (non-hazardous)	2.3%

Table C. Life cycle inventory for Freight transportation (Gursel, 2014; GB30510, 2018).

Transport mean	Road_class 8b	Road_class 5	Road_class 2b	Rail_interstate	Water_general cargo
Energy cost (MJ/ton/km)	1.03E + 0	1.77E + 0	2.97E + 0	3.10E-1	2.49E-1
Air emissions (kg/ton/km)					
$CO_{2\text{-eq}}$	1.28E-1	1.58E-1	1.98E-1	2.74E-2	1.72E-2
CO_2	1.28E-1	1.58E-1	1.98E-1	2.74E-2	1.65E-2
CO	4.11E-4	8.22E-4	1.26E-3	2.88E-4	0
NO_x	1.76E-3	1.12E-3	1.21E-3	5.07E-4	3.80E-4
PM_{10}	2.40E-4	3.22E-4	4.04E-4	3.42E-5	0
SO_2	1.03E-4	2.05E-4	3.08E-4	8.22E-5	7.30E-5

Table D. Life cycle inventory for cement raw Materials quarrying (Gursel, 2014).

Energy or raw material use	Unit	Single quantity (per tonne of raw material)
Bituminous (hard) coal	kg	0.036
Natural gas	m^3	0.140
Distillate (diesel or light) fuel oil	l	0.584
Gasoline	l	0.051
Electricity	kWh	4.230
Water	m^3	4.351

Table E. Life cycle inventory for cement raw Meal preparation (Gursel, 2014).

Process and technology option	Electricity (kWh/tonne clinker)	Water (m^3/tonne material)	PM_{10} (m^3/tonne material)
Raw materials prehomogenization			
Wet process_raw storing	0.375	0	0.750
Raw materials grinding			
Dry raw grinding_tube mill	18.5	0	7E-4
Raw meal blending and homogenization			
Raw meal homogenization, blending and storage	1.08	0	0

Table F. Life cycle inventory for cement pyroprocessing (Gursel, 2014).

Thermal energy consumption (MJ/kg clinker)			
Avg.	Max.		Min.
3.5	3.8		3.1
Electricity use (kWh/tonne clinker)			
Avg.	Max.		Min.
25.0	25.0		25.0
Water consumption (kg/tonne cement)			*PM_{10} emission* (kg/tonne cement)
Avg.			Avg.
88.0			0.232
	Avg.	Max.	Min.
CKD generation (kg/tonne cement)	38.6	38.6	38.6
CO_2 emission (kg/tonne cement)	522.0	522.0	522.0

Table G. Life cycle inventory for cement Cooling (Gursel, 2014).

PM control technology and amount (-/tonne cement)				
	Electricity use (kWh)			
Technique option	Avg.	Max.	Min.	PM amount (kg)
Fabric filter (FF)	1.902	2.092	1.712	6E-5

Electricity use for clinker cooling (kWh/tonne cement)			
Technology option	Avg.	Max.	Min.
Rotar (tube) cooler	3.563	3.800	3.325
Water use for clinker cooling (m^3/tonne clinker)			
Technology option	Avg.	Max.	Min.
Rotar (tube) cooler	0.030	0.060	0

Table H. Life cycle inventory for clinker finish Milling and grinding (Gursel, 2014).

Electricity use (kWh/tonne cement)			
Technology option	Avg.	Max.	Min.
Roller press	27.5	33.0	22.0

Table I. Life cycle inventory for cement plant Conveying (Gursel, 2014).

Conveyor technology	Screw pump	Airlift	Dense phase pump	Bucket elevator
Electricity use (kWh/kg/m)	1.2E-6	1.1E-5	5.9E-6	4.1E-6

Table J. Life cycle inventory for Gypsum production (Gursel, 2014).

Energy use and waste emission	Single quantity (per kg of gypsum)
Diesel (distillate) fuel oil (l)	4.67E-4
Electricity (kWh)	9.16E-4
PM_{10} (kg)	1.12E-4

Table K. Life cycle inventory for fly-ash secondary processing (Chen et al., 2010).

Energy use and waste emission	Single quantity (per tonne of fly ash)
Natural gas (m^3)	7.59
Distillate (diesel or light) fuel oil (l)	1.03
Electricity (kWh)	6.82
PM (kg)	3.23
Solid waste (kg)	8.48

Table L. Life cycle inventory for GBFS secondary processing (Chen et al., 2010).

Energy use and waste emission	Single quantity (per tonne of GBFS)
Natural gas (m^3)	8.96
Distillate (diesel or light) fuel oil (l)	1.26
Electricity (kWh)	94.70
Water (m^3)	0.92
PM (kg)	0.22
Solid waste (kg)	0.31

Table M. Life cycle inventory for Sand production (Gursel, 2014).

Energy cost and waste emissions	(per kg of aggregate)
Electricity (kWh)	0
Natural gas (m^3)	0
Residual (heavy) fuel oil (l)	2.86E-4
Distillate (diesel or light) fuel oil (l)	0
Gasonline (l)	0
Water (m^3)	0

Table N. Life cycle inventory for coarse natural aggregate production (Ghanbari et al., 2018).

Machine and model	Numbers required in 200 tons/h plant	Power (kW)	Energy source	Efficiency
Bulldozer. Komatsu D155A-2	2	238.6	Diesel	0.71
Hydraulic excavator. Komatsu PC 600-7	3	287	Diesel	0.75
Wheel loader. Komatsu WA420-3	2	162	Diesel	0.75
Rigid dump truck. Komatsu HD325-6	1	364	Diesel	0.8
Lorry truck. Benz Wh 2624	4	179	Diesel	0.82
Backhoe loader. HEPCO B90B	1	72	Diesel	0.65
Primary-jaw crusher	1	165	Electricity	1
Secondary-hydro cone crusher	2	125	Electricity	1
Tertiary-impact crusher	1	195	Electricity	1
Vibrating feeder	2	16	Electricity	1
Vibrating screening	3	19	Electricity	1
Bucket-typed sand washing machine	1	18	Electricity	1
pan-typed aggregate washing machine	3	20	Electricity	1
Conveyor belt 1.2×35	4	18	Electricity	1
Conveyor belt 1.2×21	4	12.5	Electricity	1
Conveyor belt 1×15	3	8	Electricity	1
Conveyor belt 1×8	2	6.5	Electricity	1
Conveyor belt 1.2×4	1	5	Electricity	1
Conveyor belt 1×3.5	2	4	Electricity	1

Table O. Life cycle inventory for coarse recycled aggregate production (Ghanbari et al., 2018).

Machine and model	Numbers required in 200 tons/h plant	Power (kW)	Energy source	Efficiency
Hydraulic excavator. Komatsu PC 200-7	1	107	Diesel	0.7
Wheel loader. VOLVO L120F	1	179	Diesel	0.73
Vibrating feeder	1	15	Electricity	1
Primary-jaw crusher	1	90	Electricity	1
Secondary-impact crusher	1	250	Electricity	1
Vibrating screening	1	30	Electricity	1
Magnetic separator	1	3	Electricity	1
Soft products separator	2	5.5	Electricity	1
Dust collector	1	85	Electricity	1
Conveyor belt 1 × 11	1	7.5	Electricity	1
Conveyor belt 1.2 × 10	1	5.5	Electricity	1
Conveyor belt 1 × 19	1	11	Electricity	1
Conveyor belt 1 × 25	1	15	Electricity	1
Conveyor belt 1 × 10	1	4	Electricity	1
Conveyor belt 0.8 × 16	1	7.5	Electricity	1
Conveyor belt 0.65 × 20	2	7.5	Electricity	1
Conveyor belt 0.65 × 12	1	5.5	Electricity	1
Conveyor belt 0.65 × 15	1	5.5	Electricity	1
Conveyor belt 0.65 × 18	1	5.5	Electricity	1

Table P. Life cycle inventory for Admixture production (Gursel, 2014).

Admixture type	Plasticiser	Superplasticiser	Retarder	Accelerator	Air entraining	Waterproofing
Single quantity (per kg of admixture)						
Energy use (MJ)	4.60	1.83E + 1	1.77E + 1	2.28E + 1	2.1E + 0	5.60E + 0
Solid waste (kg)						
Non-hazardous solid waste (kg)	3.40E-3	2.10E-2	9.10E-2	3.20E-3	2.90E-4	2.40E-5
Hazardous solid waste (kg)	1.70E-4	4.50E-4	7.40E-4	1.20E-4	5.90E-5	7.40E-5
Air emissions						
$CO_{2\text{-eq}}$ (kg)	2.29E-1	7.67E-1	1.42	1.26	1.03E-1	3.74E-1
As (kg)	4.70E-8	5.80E-8	1.60E-8	1.80E-7	8.60E-9	4.40E-8
CO_2 (kg)	2.20E-1	7.20E-1	7.60E-2	1.20	8.60E-2	2.50E-1
CO (kg)	1.10E-4	5.50E-4	8.10E-4	1.00E-3	1.10E-4	5.70E-4
Cr (kg)	6.80E-10	1.60E-8	5.60E-9	6.70E-8	3.30E-9	1.70E-8
Hg (kg)	2.80E-9	9.40E-8	2.90E-8	3.40E-8	1.90E-8	9.20E-9
CH4 (kg)	3.80E-4	1.20E-3	5.80E-2	2.50E-3	6.20E-4	2.80E-3
Ni (kg)	9.30E-7	4.60E-7	1.50E-7	1.70E-6	4.60E-8	4.20E-7
NO_x (kg)	5.20E-4	1.80E-3	1.70E-3	2.30E-3	3.50E-4	1.60E-3
N_2O (kg)	0	6.70E-5	3.50E-5	0	8.60E-6	2.00E-4
SO_2 (kg)	8.50E-4	3.60E-3	1.40E-3	2.80E-3	3.20E-4	8.80E-4
VOC (unspecified) (kg)	1.70E-4	2.90E-4	0	0	0	0

Table Q. Life cycle inventory for water Extracting and treatment (GaBi Software, 2020; Stokes & Horvath, 2009).

	Single quantity (per m^3 of water)			
User choice	Electricity (kWh)	CO_2 (kg)	CH_4 (kg)	N_2O (kg)
Self-supplied industrial surface water	7.90E-2	0	0	0
Public surface water	4.82E-1	2.90E-2	0	0
Self-supplied industrial groundwater	1.85E-1	0	0	0
Public groundwater	6.61E-1	7.37E-3	0	0
Seawater	7.90E-2	0	0	0

Table R. Life cycle inventory for concrete mixing and batching (Gursel, 2014).

Energy and water	Single quantity (per m^3 of concrete)
Natural gas (m^3)	3.28E-9
Distillate (diesel or light) fuel oil (l)	4.38E-7
Electricity (kWh)	4.11
Water, excluding batch water (m^3)	6.50E-1
Waste emissions	
Solid waste (kg)	2.40E + 1
PM	See Table S

Table S. PM emission inventory for concrete mixing and batching (Gursel, 2014).

	Single quantity (kg per tonne of material)			
	Emission control with FF		Uncontrolled	
Material	PM_{10}	PM_{total}	PM_{10}	PM_{total}
Cement	1.70E-4	5.00E-4	2.40E-1	3.60E-1
Water	0	0	0	0
Fine aggregates	0	0	5.10E-4	1.10E-3
Coarse aggregates	0	0	1.70E-3	3.50E-3
FA	2.40E-3	4.50E-3	6.50E-1	1.57
GBFS	2.40E-3	4.50E-3	6.50E-1	1.57
Superplasticiser	0	0	0	0
Mixer loading (central mix)	2.80E-3	9.20E-3	7.80E-2	2.86E-1
Truck loading (truck mix)	1.31E-2	4.90E-3	1.55E-1	5.59E-1
Fine aggregates loading weight hopper	0	0	1.30E-3	2.60E-3
Coarse aggregates-loading weight hopper	0	0	1.30E-3	2.60E-3

Life cycle inventories for *fuel pre-combustion and combustion* can see Gursel (2014) for more details.