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A Low-Impact Development Strategy for Green Urban Infrastructure

Singh, Avishreshth; Biligiri, Krishna Prapoorna

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Use of recycled rubber and composite wastes in pervious concrete: a low-impact development strategy for green urban infrastructure

16

Avishreshth Singh[1] *and Krishna Prapoorna Biligiri*[2]
[1]Section of Pavement Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands, [2]Department of Civil and Environmental Engineering, Indian Institute of Technology, Tirupati, Andhra Pradesh, India

16.1 Introduction

In recent years climate change mitigation, resource conservation and ecosystem preservation have become the key challenges for scientists and policymakers. A variety of industrial sectors and processes are responsible for these ever-increasing risks to the planet. For instance, the United States Environmental Protection Agency has reported that the building and transportation sectors contribute to more than 20% of the total greenhouse gas (GHG) emissions [1]. Further, the global temperature in 2020 was 1°C higher than the preindustrial levels [2], and is expected to rise to at least 1.5°C between 2030 and 2050 [3]. Such rising temperatures and augmented GHG emissions are consequential of increase in the sea levels, which is anticipated to rise by up to 2 m at the end of this century [4], endangering billions of people living in the hinterland areas either 1 m below the sea level or 10 m above it [5]. Hence, there is an urgent need to take appropriate measures that assist in mitigating the risks related to climate change.

It is worth mentioning that there is an increased demand for construction materials in the development of infrastructure, such as buildings and roadway pavements, which form the backbone of any nation. Research studies have reported that concrete is the most widely used building material and the current consumption rates of concrete are almost three times higher than what they were about forty years ago [6]. Among the several concrete constituents, environmental impacts associated with the production of Portland cement concrete were the highest (70%–80%) followed by the large coarse aggregates, which accounted for about 10%–20% of the total carbon dioxide (CO_2) emissions [7]. The impacts due to the coarse aggregates were majorly attributed to the electricity consumption (typically about 80%) during their manufacture. In addition, the quarrying of natural aggregates is consequential of land transformation, loss of biodiversity and resource depletion [8], which necessitates the use of recycled, secondary and alternative materials in developing the infrastructure.

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One such sustainable and green construction material is pervious concrete (PC), which utilizes zero to limited fine aggregates during production, resulting in a characteristic interconnected pore network structure that allows the infiltration of storm water through it while lowering the demand for material resources as well [9–11]. However, the high infiltration ability comes at the cost of reduced strength. Thus PC pavement (PCP) systems have been utilized in the areas with low-to-medium traffic, sidewalks, pathways, parking lots, medians and highway shoulders [12–14]. Some other benefits associated with PCPs include reduced noise, water purification ability and resistance to skidding and hydroplaning [15–18].

Another challenge that restricts the development of sustainable built environment is the disposal of solid wastes generated in the urban habitats. For instance, it is estimated that more than one billion waste rubber tyres (WRT) will be discarded by the end of 2030, while currently a small portion of the wastes is being recycled [19]. Further, the economic and demographic growth across the globe have led to an increase in aircraft building and operations, whose parts are generally designed with fibre-reinforced polymer (FRP) composite materials. At the end-of-life, the disposal of glass FRP (GFRP) and carbon FRP (CFRP) composite wastes (CW) pose a serious environmental threat due to the nonavailability of the disposal strategies with the current technology [20]. Studies have indicated that 8500 commercial aircraft will be discarded by the end of 2025, which is estimated to result in the generation of over 170,000 t of CFRP-CW [21]. Due to high durability and nonbiodegradable nature, rubber and CW are difficult to handle and dispose. Additionally, stringent legislations exist globally that restrict landfilling as well as incineration of WRT and CW. Hence, there is a need to identify green and cost-effective technologies that promote upcycling of WRT and CW in the material supply chain and assist in transitioning from linear to circular economic practices.

Past research has shown that the incorporation of WRT and CW in cementitious materials is an emerging technology. Though multiple investigations are being conducted globally to assess the suitability of WRT and FRP-CW in conventional concrete, limited efforts have been made to identify their effect on the characteristics of specialty materials such as PC. In addition, only a few studies have tried to investigate the sustainability credentials of PC products with/without the waste materials. Therefore this chapter presents the effect of addition of WRT as well as CFRP- and GFRP-CW on the properties of PC, while also highlighting their lifecycle impacts. It is envisioned that this chapter will become an important repository capable of demonstrating the research and implementation strategies pertinent to the PCP products engineered with recycled waste materials, thus serving as a low-impact development strategy for green urban infrastructure.

16.2 Inclusion of waste products in pervious concrete

16.2.1 Crumb rubber

At the global level, continuous attempts are being made to engineer the special PC material with crumb rubber (CR), which is a commonly available recyclable material obtained by processing WRT. Mondal and Biligiri used three different contents (2.5%, 5% and 10%) of CR in the size range of 1.18–0.15 mm to replace coarse aggregates by weight in PC [19]. Three different coarse aggregate gradations designated as A (100% retaining on 4.75 mm), B (50% each of 4.75–9.5 mm) and C (100% retained on 9.5 mm) were used along with ordinary PC 53-grade [22] as a binding agent. The water-to-cement (w/c) ratio was kept as 0.40. Twenty-one PC mixes were investigated, and three replicate cylindrical specimens were prepared for each mix totalling 126 specimens.

The addition of CR increased density and reduced the porosity of PC mixes. The highest increment in density was observed for gradation B attributed to the ability of CR to occupy the large pores created using 9.5 mm aggregates. Further, the CR particles contributed to an increase in the pore surface area, thereby offering a rougher flow path and causing a reduction in permeability. In addition, the increased density was consequential of lower Cantabro mass loss, which reflected the ability of CR-modified PC (CR-PC) to better resist the abrasive and impact forces than the control mixes. Furthermore, the lower porosity of CR-PC resulted in improved compressive strength. In general, the compressive strength increased consistently for the different gradations within a range of 3–4 MPa at 10% CR replacement levels.

In another investigation, single-sized CR aggregates (4.75–2.36 mm) were added in dosages of 5% and 10% (by weight of the coarse aggregates) to the control PC mix [23]. The specific gravity and water absorption of CR were 0.89% and 5.42%, respectively, which were about 65% lower and 94% higher than the coarse aggregates (with a particle size of 6.3–4.75 mm). PC mixes were designed at a fixed aggregate-to-cement (a/c) ratio and cement content of 3.75 and 325 kg/m^3, respectively. Three levels of w/c ratios (0.27, 0.30 and 0.33) were adopted, and a polycarboxylic ether-based superplasticizer [24] was added at a dosage of 0.25% by dry mass of cement. The test results for the fundamental PC properties investigated in the study are presented in Table 16.1.

As observed from Table 16.1, with increasing CR content, the porosity and permeability increased, while the density and compressive strength reduced, which were contradictory to the results reported elsewhere [19]. The increase in porosity of the PC mix was due to the replacement of some proportion of coarse aggregates by CR inclusions in the matrix, as against what was found elsewhere [19,25]. Further, the permeability increased with increasing porosity, which corroborated with the findings reported for conventional PC mixes [26,27]. Additionally, the low compressive strength in CR-PC mixes was due to the poor bonding between cement and rubber [28,29], and the lower stiffness of CR compared to coarse aggregates [30]. The low compressive strength of PC mixes with CR as additive necessitates investigating alternative strategies (lower rubber sizes, rubber treatment, supplementary cementitious materials, CR as replacement of aggregates, etc.) in a comprehensive manner, which would assist in developing engineered and green rubber–modified PC composites suitable for varied field implementation.

Table 16.1 Test results for pervious concrete.

Crumb rubber dosage (%)	Properties							
	Porosity (%)	Percent increase	Density (kg/m^3)	Percent reduction	Permeability (cm/s)	Percent increase	Compressive strength (MPa)	Percent reduction
0	20.68	–	1927.45	–	0.29	–	21.37	–
5	22.11	7	1784.41	7	0.44	53	7.76	64
10	23.82	15	1687.07	12	0.47	63	4.76	78

16.2.2 Composite wastes

This section reports the suitability of utilizing mechanically shredded GFRP-CW and CFRP-CW in PC mixes (Fig. 16.1) without the extraction of fibres from the polymer matrix in conjunction with promoting sustainable practices for waste disposal in PC mixes [31,32]. The aggregate gradation (12.5−4.75 mm), w/c ratio (0.30) and c/a ratio (1:3.75) were fixed, and the effect of varying dosages of CW (0.33%, 0.65% and 1% by the volume of mix) on PC properties were investigated. Seven PC mixes were prepared including one control and six CW-PC, resulting in a total of 42 cylinders (100 mm diameter and 200 mm height) and 21 prisms ($100 \times 100 \times 500\ \text{mm}^3$). The test results for GFRP-CW- and CFRP-CW-modified PC (CW-PC) are presented in Table 16.2.

The addition of CW-to-PC mixes resulted in a minor reduction in porosity compared to the control PC. At first, the porosity decreased followed by an increase in the property with increasing CW content. However, the porosity for all CW-PC mixes was less than the control PC, except at 1% CFRP-CW. Note that the mean particle size (6.3−4.75 mm) of CW was lower than the coarse aggregates (10−6.3 mm), which formed an open-graded matrix. Hence, CW occupied some percentage of void volume during compaction, resulting in lower porosity (1.39%−6.82%). However, at increased dosages of CW, the porosity increased, which was attributed to the presence of a higher proportion of irregular coarse fraction (flaky and elongated) of CW (high angularity, nonuniform edges and larger surface area) in the mix matrix. Another study also reported that the use of higher proportions of CW of sizes similar to those of coarse aggregates increased the porosity [33]. However, a higher porosity corresponded to the mixes with lower density or higher permeability and vice versa, which has also been reported elsewhere [34−36]. Further, the dynamic modulus for CW-PC was higher compared to the control mix and other mixes [37,38] highlighting that CW-PC mixes were indeed capable of resisting deformations/distresses before failure.

The compressive strength of GFRP-CW-PC was higher than the control mix by about 10%−23%, while that of CFRP-CW-PC was lower than the control by about 6%. The variation in compressive strength corresponded to the variation of porosity, which were similar to the findings reported elsewhere [35,39,40]. Further, the splitting tensile strength of CFRP-CW mixes was higher than PC with GFRP-CW

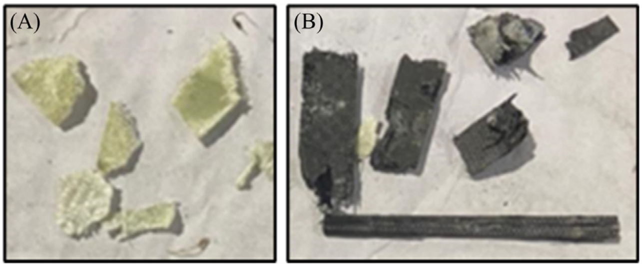

Figure 16.1 Schematics of (A) shredded GFRP-CW, (B) shredded CFRP-CW.

Table 16.2 Test results for composite waste−modified pervious concrete.

Property	**Specimen geometry**	**Control PC**	**GFRP-CW dosage (%)**			**CFRP-CW dosage (%)**		
			0.33	**0.65**	**1**	**0.33**	**0.65**	**1**
Porosity (%)	Cylinders	28.78	26.81	27.83	28.38	27.98	27.82	29.08
	Prisms	22.77	23.66	26.81	27.56	26.46	24.86	26.55
Density (kg/m^3)	Cylinders	1875	1907	1880	1861	1866	1871	1840
	Prisms	1969	1963	1926	1900	1932	1949	1918
Permeability (cm/s)	Cylinders	0.97	0.81	0.89	0.87	0.84	0.83	0.88
UPV (m/s)		3969	4129	4142	4143	4103	4055	3925
DME (GPa)		24.64	27.09	26.89	26.65	26.25	25.63	23.65
Compressive		17.75	21.85	20.53	19.46	16.71	18.05	16.64
Split tensile		2.39	1.87	1.87	1.89	2.16	2.03	2.01
Flexural	Prisms	2.34	2.38	2.25	2.15	2.33	2.36	2.46

CFRP-CW, Carbon fibre−reinforced polymer composite wastes; *DME*, dynamic modulus of elasticity; *GFRP-CW*, glass fibre−reinforced polymer composite wastes; *PC*, pervious concrete; *UPV*, ultrasonic pulse velocity.

ascribed to their higher tensile strength [41]. Additionally, the flexural strength of PC with CFRP-CW was higher than those with GFRP-CW due to the poor bond formation between GFRP-CW and cement [42] as well as the filament shaped CFRP-CW, which allowed the mixes to carry higher flexural loads before failure, as also reported in another study on FRP cement mortar [34,43]. Overall, it was understood that the addition of CW in PC ($>1\%$) did not alter the material's characteristics, instead allowed for recycling and disposal of CW in a sustainable manner.

16.3 Lifecycle assessment

Lifecycle assessment (LCA) is a modelling tool that is used to determine the environmental and economic impacts of products and processes. This tool helps identify the hotspots during the production of materials, which is useful for product development and strategic planning. Though past studies have extensively utilized LCA approach to study the environmental impacts of asphalt cement and/or cement concrete pavements, limited research is available in the domain of PCPs. Essentially, this section discusses the sustainability metrics associated with the novel PCP systems from their lifecycle perspective. Note that the research studies discussed herein were conducted in accordance with the international standards [44,45].

16.3.1 *Pervious concrete pavement parking lots*

This section reports the LCA results for PCP parking lots that were constructed in India [11−13]. The construction scenarios involved on-site mixing and transporting ready-mix material from the batch plants. In total, four pavement scenarios and configurations were investigated in this comparative LCA, as presented in Table 16.3. The system boundary considered in the study is shown in Fig. 16.2. Further, a simplified LCA framework was developed using Microsoft Excel to quantify the energy consumed and the emissions generated for the pavement systems. Due to the absence of end-of-life data, a cradle-to-gate approach was undertaken, where the functional unit was *a single-lane km pavement system with surface and base*

Table 16.3 Pavement scenarios and configurations.

Scenario	**A**	**B**	**C**	**D**
Surface course	Pervious concrete	Portland cement concrete	Pervious concrete	Portland cement concrete
Base layer	Granular			
Mixing method	Ready-mix		In situ	

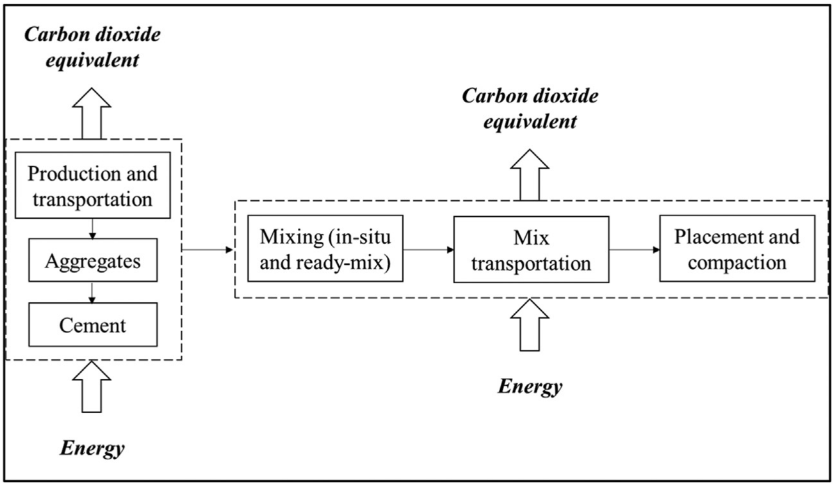

Figure 16.2 System boundary for the different pavement systems.

layer thicknesses of 0.15 and 0.20 m, respectively. The LCA models that were used to compute the energy, carbon-dioxide equivalent (kg CO_2-eq.) and capital cost per lane km are presented in Eqs. (16.1)–(16.3), respectively.

$$\text{Total embodied energy (MJ/km)} = \sum (1000 \times W \times (T \times D_n \times (P_e + M_e + (T_e \times D_i)) + C_e)) \qquad (16.1)$$

$$\text{Total kg } CO_2\text{-eq./km} = \sum (1000 \times W \times (T \times D_n \times (P_g + M_g + (T_g \times D_i)) + C_g)) \qquad (16.2)$$

$$\text{Total cost (USD/km)} = \sum (T \times W \times (M_c + T_c + C_c)) \qquad (16.3)$$

where T is the thickness of layer in m; W is the width of the road in m; D_n is the density of pavement material in kg/m^3; P_e is the material production value in MJ/kg; P_g is the material production value in kg CO_2-eq./kg; M_e is the material mixing value in MJ/kg; M_g is the material mixing value in kg CO_2-eq./kg; T_e is the ransport from production site to application site in MJ/kg-k; T_g is thet ransport from production site to application site, kg CO_2-eq./kg-km; D_i *is the* istance from material production site to application site in km*;* C_e is the material compaction value in MJ/m^2; C_g is the material compaction value in kg CO_2-eq./m^2; M_c is the material cost in USD/km/m^2*;* T_c is the material transportation cost in USD/km/m^2; C_c is the construction cost in Indian USD/km per m^2. The LCA results for the considered pavement systems are presented in Fig. 16.3. Note that the environmental impacts of the subgrade and base layers were similar with embodied energy for subgrade and base

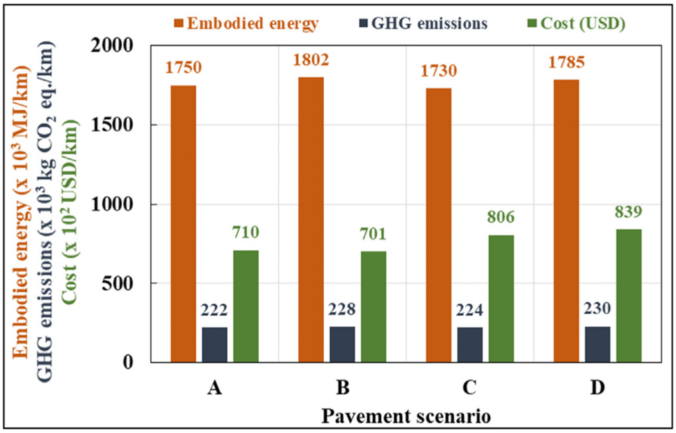

Figure 16.3 Results for embodied energy, CHGs and capital costs. *CHG*, Greenhouse gas.

course being 1.40×10^3 MJ/kg and 210.35×10^3 MJ/kg, respectively, and the corresponding GHG emissions being 5.52 kg CO_2-eq./km and 14.83×10^3 kg CO_2-eq./km. Irrespective of the mixing method, the embodied energy and kg CO_2-eq. of PCPs were lower than the Portland cement concrete pavement (PCCP) systems by about 3%. The lower environmental footprint of PCP was attributed to the reduced cement content than PCCPs. This observation agreed with the findings of other researchers who stated that cement was the major contributor to the environmental impacts compared to the other raw materials during concrete production [7,46,47]. Furthermore, the sensitivity test indicated that the environmental impacts associated with the production of a unit quantity of PC increased with increasing density of the materials, while the transportation-related impacts were not significant as the materials were procured from the local suppliers. In terms of capital cost, for the ready-mix method, the PCPs were slightly expensive alternatives than PCCPs, which corroborated with the findings of other studies [48,49]. Note that though the cradle-to-gate investments associated with PCPs were higher, their lifecycle costs were much lower than PCCPs attributed to their ability to infiltrate storm water [49,50]. On another account, PCP systems were found to be economical than PCCPs due to the absence of sand particles within their mix matrix.

16.3.2 Composite waste–modified pervious concrete

GFRP-CW and CFRP-CW that imparted higher flexural strength (Table 16.2) when used with PC were evaluated using the LCA approach [31]. It was found that all the CW-PC mixes prepared in a recent study qualified the target parametric criteria of having porosity >15% to be categorized as PC [9], so the mixes with only the highest flexural strength (major structural design parameter) were considered for designing the surface wearing course layers of the PCP systems. In the cradle-to-gate LCA study, the functional unit of the selected sidewalk was defined by 1 km length, 2.5 m width and 0.10 m thick section [51,52]. The concrete batch plant was located on-site to minimize the emissions due to transportation of the ready-mix PC, while the CW were shredded and transported from a facility that was 500 km from the site. The system boundary is presented in Fig. 16.4, and the lifecycle inventory (LCI) was a mix of primary and secondary data (Ecoinvent version 3.8) for the conditions suitable for India. Further, SimaPro 9.2 LCA software was used for modelling purposes and IMPACT World + method [53] was adopted to translate the LCI into meaningful environmental indicators.

No major variations in the impacts between the particular impact categories for the different PC mixes were observed, and the impact categories with highest environmental burdens are depicted in Fig. 16.5. It is important to mention that CW were added as reinforcement in the PC mixes, which led to increased environmental burdens. The damage to the ecosystem quality was about 72% higher than human health. Further, cement was quantified as the most energy-intensive material (> 70%) followed by aggregate production. The damage to human health and ecosystem quality due to aggregate production were 56 and 180 times higher than processing of GFRP-CW. However, the shredding of CFRP-CW produced 1–3 times higher environmental impacts attributed to the large proportions of CFRP-CW and higher stiffness than GFRP-CW. This finding necessitates the need to establish the cut-off/optimized dosage of CW to produce green CW-PC mixes. The material production phase was the major parameter responsible for damage to human health and also ecosystem, which was similar to the results reported elsewhere [11,27]. Overall, it was possible to recycle about 1.47 t of GFRP-CW and 3.9 t of CFRP-CW in a one-lane km PCP system that was 3.5 m wide and 0.15 m thick. Clearly, the recycling of CW in PC will assist in minimizing the landfill requirements and other energy-emission intensive processes (e.g. incineration) after the end-of-life, remarkably contributing to the formulation of sustainable waste management practices.

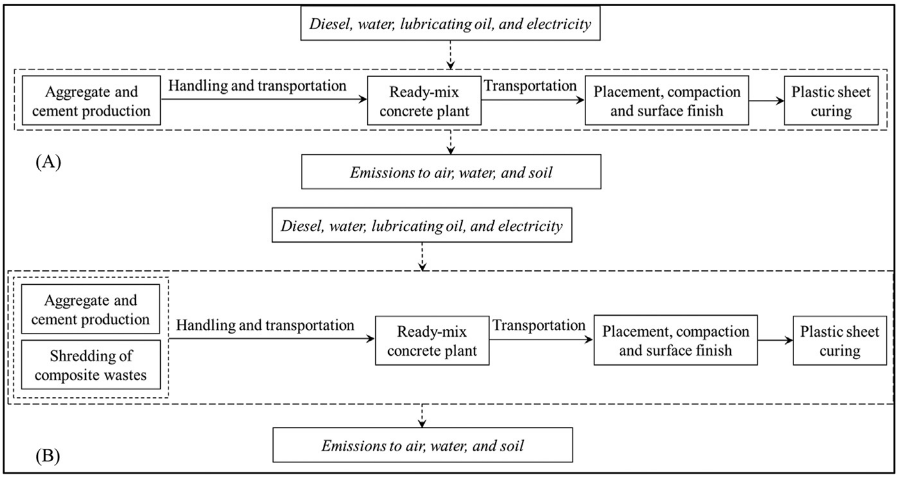

Figure 16.4 System boundary for (A) control mix, and (B) composite waste–modified mix.

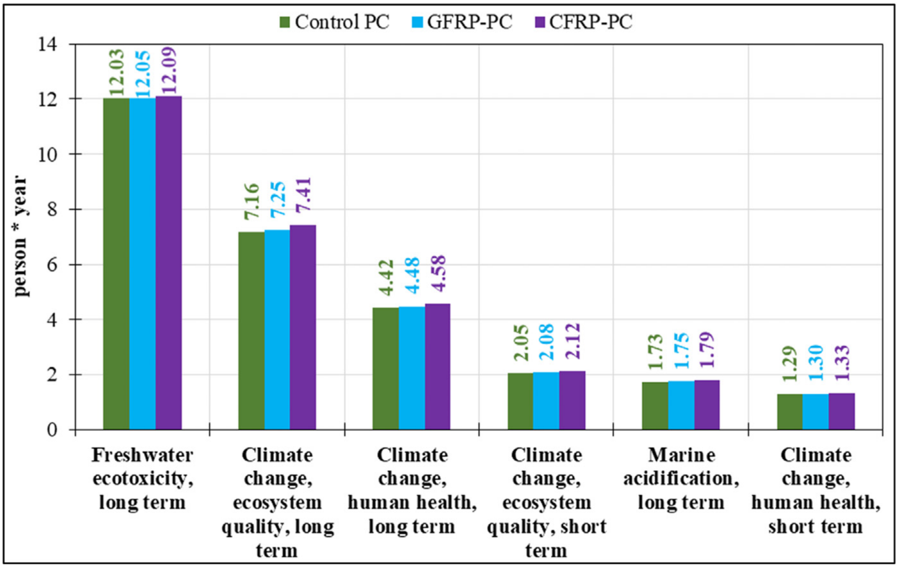

Figure 16.5 Impact categories with highest environmental impacts.

16.4 Conclusions and way forward

This chapter discussed the performance characteristics of PC products designed with two environmentally threatening waste products, namely CR and CW. The inclusion of fine CR was beneficial for the structural performance of PC, albeit coarse CR reduced the compressive strength significantly, rendering the special PC unfit for field implementation. Further, the addition of rubber did not alter the physiognomies of the PC significantly, thereby rendering it suitable to host CW in its matrix. In addition, the LCA results demonstrated that the incorporation of CW in PC (with a maximum dosage of 1%) caused insignificant damage to human health and the ecosystem quality when compared to the control mix. Further, the lifecycle performance of PC pavement system was superior than the conventional cement concrete pavements majorly attributed to the reduced cement requirement during the production.

As observed in this chapter, the research pertinent to the use of waste materials in PC is still emerging, and there exists significant room to investigate the effect of different sizes and proportions of rubber and CW on PC materials characteristics. Further, there is a definite need to establish the optimum or cut-off percentages for the utilization of waste materials in PC to harness maximum benefits of recycling. Furthermore, the simplified LCA framework presented in this work may be expanded by incorporating additional number of environmental indicators. Research must be conducted on the economic and social aspects of utilizing waste products in innovative pavement materials, such as PC. Overall, the scope of utilizing such waste products must also be explored in other concrete mixes and roadway materials from both performance and sustainability perspectives to assist rationally in the design of green urban infrastructure.

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