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Thermal performance and life cycle analysis of 3D printed concrete wall building

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ABSTRACT

Automated construction process with extrusion-based 3D concrete printing (3DCP) is widely recognised due to its ability to construct complex freeform geometrical shapes. Furthermore, the automation process reduces labour and minimises material wastage, thus improving productivity. The structural performance of printed structures has been widely discussed; however, addressing the knowledge gap in energy performance and their environmental impact needs further investigation. Thus, this study investigated and compared the insulation characteristics, life cycle cost and environmental impact assessment of 3DCP structures with traditional reinforced concrete members. The evaluation of the insulation properties of 3D printable concrete allows the characterisation of operational costs and greenhouse gas emissions incurred from the additional heating and cooling systems. Furthermore, this study also suggested a method to enhance the thermal resistance of 3DCP with recycled fibre recovered from face mask waste. A comparison between face mask fibre-reinforced 3D-printed wall element and conventional reinforced concrete wall is also performed across the thermal, life cycle cost and environmental impact parameters. The results showed that the insulation properties of 3DCP walls were increased by 49.5% with the addition of face mask fibres compared to RC walls. This results in reduced energy consumption from additional heating and cooling systems along with a reduction in greenhouse gas emissions, thereby improving the energy performance of the building. Further, face mask fibre-reinforced printed walls showed a reduction in the life cycle cost, mainly in the operation stage, due to the low labour requirement and elimination of formwork. Moreover, a significant reduction in the depletion of resources and ozone depletion was observed for 3DCP face mask fibre-reinforced walls, along with the reduced impact on human health and ecosystem damage. Consequently, the incorporation of face mask fibres into the 3DCP process paves the way for its potential in constructing energy-efficient and environmentally sustainable buildings.

1. Introduction

Economically viable and environmentally sustainable construction practices are becoming important in reducing greenhouse gas emissions and improving buildings' energy efficiency [1]. Owing to the drastic changes in climatic conditions, the overall energy consumption of buildings rises, resulting in more greenhouse gas emissions, which adversely affect the environment [2,3]. Consequently, improving the thermal characteristics of building envelopes will reduce operational energy consumption [4]. The use of insulation materials to improve the thermal performance of the building and thereby minimise the energy demand, especially under hot climates, is a vastly adopted method [5]. Providing vacuum insulation panels was observed to enhance the thermal resistivity and thereby reduce energy consumption [6]. Furthermore, the degradation of insulation materials can lead to an underestimation of the energy performance of buildings [7]. However, it is to be noted that one-fourth of the total heat transfer depends on the external wall characteristics and its thermal properties [8]. Therefore, evaluating the thermal properties of the external wall can be adopted as a tool to characterise the overall thermal performance of the building envelope.

Measuring the thermal conductivity and thermal resistance of the wall using various in-situ steady state and transient methods was observed to be an efficient method, thereby evaluating the overall

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thermal performance [9–11]. Installation of insulation layers to the walls is one of the common methods to improve thermal performance. However, improper installation, use of damaged materials, and defects in workmanship result in a reduction in the thermal insulation capacity of the building [12]. Adopting proper quality management programmes and improving the workmanship during the operational phase results in improving the construction work and thus eliminates these installation defects [13]. Furthermore, incorporating fly ash and rice husk ash as a sustainable material for the replacement of cement was observed to reduce the thermal conductivity of the mortar significantly, thereby improving the thermal performance and reducing the energy consumption of the building [14,15]. However, along with improving the thermal performance of the building envelope, it is important to reduce the life cycle cost and environmental impact. The optimisation of both cost and environmental impact, considering the different stages (construction, operation, maintenance and disposal) during the life cycle of the building, is important [16]. The effect of life cycle cost and carbon emission on the structural design of buildings shows that adopting lightweight construction methods and normal concrete reduces the cost of material and CO_2 emission [17]. Furthermore, optimising the life cycle cost and environmental impacts to improve the building star rating and greenhouse gas emissions were evaluated for different residential buildings [16,18–20]. However, no approved methods are suggested for analysing the life cycle of environmental impact assessment [21]. In addition, while considering the environmental impact assessment, greenhouse gas emissions, ecosystem toxicity, and climate change on the life cycle of the building needs to be considered. However, owing to the rapid increase in the requirement for dwellings, an increase in construction time and a reduced labour force have become a prime necessity. 3D concrete printing (3DCP) technology is an automated construction method that provides freeform construction and builds aesthetically pleasing complex geometries.

The 3DCP method builds structures by depositing concrete in a layered fashion through extrusion from the nozzle [22]. The 3D printable concrete mix needs its rheological characteristics tailored to suit the printability requirements along with the required mechanical strength [23,24]. Furthermore, the automated construction method results in a significant reduction in the labour and material costs associated with formwork, along with an increased rate of construction, resulting in improved building quality [25,26]. Moreover, comparing the 3DCP process with conventional concrete construction showed a significant reduction in the material cost and environmental impact [27]. Even though the 3DCP process shows potential advantages in construction, improving the mechanical properties with reinforcement still poses one of the major challenges [28]. Recent studies in adopting short steel fibres, face mask fibres and textile reinforcement for 3DCP structures were observed to improve the overall mechanical properties of the structures [24,29–31]. 3DCP technology has the potential to transform the potential developments in the construction industry. However, raising concerns on the environmental impacts and energy efficiency improvement of buildings, the life cycle cost, environmental impacts and energy performance of 3DCP buildings need to be evaluated.

Life cycle assessments of 3DCP elements were evaluated in previous studies, along with a comparison to the conventional construction practice. It was observed that 3DCP elements had the potential to reduce the global warming potential and eutrophication potential significantly when compared to conventional construction elements [32]. However, the incorporation of conventional reinforcement methods with 3DCP technology increased the overall environmental impact, suggesting adopting new and sustainable reinforcement strategies. Further, impact assessment of large scale 3DCP structures revealed that a reduction in the overall environmental impact was observed. However, the high cement content in printable materials is a major concern in increasing the overall environmental impact [33]. Replacement of cement with sustainable earth based material for printing was observed to reduce the overall environmental impact of printed structures [34]. Even though studies reveal the environmental benefits of 3DCP technology and the cost and time saving achieved during construction, the energy performance of 3DCP elements is important in characterising the building's energy consumption with the associated operation costs and greenhouse gas emissions. Therefore, evaluating the thermal performance of building components constructed using 3DCP technology needs to be evaluated to characterise energy efficiency. Evaluating the thermal transmittance of 3D-printed walls with and without cavities showed that the thermal performance was lower than the standard for printed walls without cavities. However, incorporating a cavity into the printed walls resulted in reducing the thermal transmittance and thus enhanced the overall performance [35]. Further, in order to improve the thermal performance of 3DCP walls, voids in the walls and the modification of the mix proportion to incorporate more sustainable and low-conductive materials can be adopted [2]. Due to the high cement content in 3DCP elements, the overall thermal performance of solid wall elements is higher, and thus, cavities were incorporated into the walls to improve the thermal performance [36]. However, the 3D printable mix with high cement content often results in low thermal performance and thus, alternative ways to improve the thermal performance and environmental impact of 3DCP building elements along with enhanced mechanical properties need to be discussed.

Thus, in this study, the thermal performance and life cycle assessment of 3D-printed walls reinforced with short face mask fibres and polypropylene (PP) fibres were performed and compared with conventional reinforced concrete walls. The author's previous study showed that the incorporation of 1 % face mask fibre and 1 % PP fibre (by volume) into the printable mix improves the mechanical strength and durability aspects [24]. Thus, the strength optimised mix was adopted in this study to evaluate the thermal performance and life cycle assessment. In addition, the effect of face mask fibres on the thermal performance of the 3D printable mix was compared by measuring the thermal properties of unreinforced and reinforced printed elements. Further, the life cycle cost for the three different walls (face mask fibre reinforced printed wall, PP fibre reinforced printed wall and conventional reinforced concrete wall) were calculated and compared. In addition, a detailed environmental impact assessment considering the potential impact factors over the life cycle period of the wall element was performed using SimaPro v9.4 software. The comparison of the thermal performance, life cycle cost and environmental impact of 3DCP walls with face masks and traditional reinforced concrete walls are discussed in detail, and the potential of adopting face mask fibre-reinforced printed building components is reported.

2. Materials and methods

2.1. Material properties

This study compares the thermal performance, life cycle cost and environmental impact of three different types of exterior load bearing wall systems, namely (a) 3D concrete printed wall with recycled fibre recovered from face mask (FM) as reinforcement (3DCP-FM), (b) 3D concrete printed wall with polypropylene (PP) fibres as reinforcement (3DCP-PP) and (c) traditional reinforced concrete wall (RC-32). All three solid walls considered in this study have the dimension of $3 \times 3 \times 0.22$ m (length $\times$ height $\times$ thickness).

The 3D printable concrete mix consists of Ordinary Portland Cement (OPC) confirming to AS 3972 [37] and silica fume confirming to AS 3582.3 [38] as binders and three different sieve-graded silica sands as aggregates. The details of the particle size distribution and mix proportion are similar to the author's previous study [24]. Furthermore, based on the previous investigation, a 1 % face mask fibre dosage (by volume) was observed to have enhanced mechanical properties with good printability. Hence, the printable mix adopted for the life cycle analysis and thermal performance of the external load bearing wall consists of 1 % face mask fibre dosage and 1 % PP fibre dosage mix with a compressive strength of 58.1 MPa and 61.5 MPa, respectively and a flexural strength of 13.1 MPa and 12.8 MPa respectively.

The traditional reinforced concrete adopted for the external load bearing walls was chosen to give similar structural strength to that of 3DCP walls with fibres. The reinforced concrete wall consists of cement, coarse aggregate and fine aggregate with a compressive strength of 32 MPa. Further, a minimum reinforcement to provide crack control and robustness was adopted in the study, and details are N16 @ 150 mm for vertical rebars and N12 @ 200 mm for horizontal rebars. The flexural capacity of the reinforced concrete wall was approximately 14.6 MPa, which is similar to the flexural strength of 3DCP-FM and 3DCP-PP mixes. It is to be noted that the material properties of the RC-32 wall were adopted only to assess the life cycle cost and environmental impact.

The mix proportion adopted for the three different wall elements are provided in Table 1. It is to be noted that the mix proportion adopted for the concrete wall is a general mix design for an approximate compressive strength of 32 MPa.

2.2. Thermal performance evaluation

The insulation properties of the mixes are evaluated by determining the thermal resistance of the material and will give us insight into the thermal performance of the wall and thus predict the overall operational energy requirement for the structure [10,39,40]. The thermal resistance (R) of the wall element depends on the thermal conductivity (k) and the thickness of the wall (t) and can be represented in Eq. (1).

$$\boldsymbol{R} = \frac{\boldsymbol{t}}{\boldsymbol{k}} \tag{1}$$

where, R is the thermal resistance in m^2K/W, k is the thermal conductivity in W/mK and t is the thickness of the wall in m. It can be observed that the lower the thermal conductivity of the material, the higher the thermal resistance, thus reducing the operational energy requirement. Hence, the thermal conductivity of the materials used in the construction of the wall element was measured to predict thermal performance.

The thermal conductivity of the 3D printable concrete mix without fibres and with 1 % face mask fibres and 1 % PP fibres was measured using a transient line source TLS-100 instrument confirming to ASTM D5334 [41]. The specimens were printed using a gantry type 3D printer as described in the author's previous work [24]. Rectangular blocks of size 200 mm long and 60 mm wide were printed, and a total of 12 layers were printed, forming a total height of 120 mm (each printed layer 10 mm height). The schematic of the printed specimens and the gantry printer with extruder are shown in Fig. 1. The printed blocks were cured for 28 days before conducting the test. The curing procedure adopted was also similar to the previous study [24].

The printed blocks were saw cut to prisms of 40 × 40 × 120 mm, and three specimens were cut from each printed block and tested for each of the mixes (unreinforced printable mix, face mask fibre reinforced mix, and PP fibre reinforced printable mix). In order to insert the TLS-100 probe into the specimen, after printing, a thin metallic road of 2.5 mm diameter was used to create a hole to ensure the proper insertion of the thermal conductivity probe. During the testing, a thermal paste was applied to the probe to ensure the proper contact between the probe and the concrete surface. The probe was inserted into the specimen and kept for 15 min to ensure thermal equilibrium. The display device shows the thermal conductivity reading, and the values are recorded. Three readings were taken for each specimen to avoid any anomalies. The same procedure was adopted for all the specimens, and the thermal conductivity results were recorded. However, it is to be noted that the thermal conductivity of the concrete mix was adopted from previous literature. The test specimen and the thermal conductivity test setup are shown in Fig. 2.

Table 1
Mix proportion of three walls.

Materials	3DCP-FM	3DCP-PP	RC-32
OPC	0.8	0.8	1
Silica Fume	0.2	0.2	
Fine sand	0.5	0.5	
Medium Sand			
Coarse Sand			
Fine aggregate			2
Coarse aggregate			3
Reinforcement ratio*	0.021	0.021	0.21
Water	0.28	0.28	0.4
Superplasticiser	0.004	0.004	
Retarder	0.0035	0.0035	

Note: All the proportions are in the weight ratio of binders
*FM fibres and PP fibres are used for 3DCP-FM and 3DCP-PP wall respectively and for RC-32 wall minimum steel reinforcement is used.

2.3. Life cycle cost analysis

The cost involved in the analysis of a building element consists of different categories, namely the construction phase, operational phase, maintenance phase, and disposal phase. Further, the life cycle period for the building element was considered to be 50 years. The cost involved during the construction phase consists of the individual cost of different construction materials used for each type of wall element. The operational cost consists of labour, machinery, and transportation costs. Finally, the maintenance and disposal costs pertaining to the different wall elements were assumed to be similar. All the costs were calculated based on the Rawlinsons Australian Construction Handbook [42], and the costs are reported in Australian dollars (AUD). Initially, all the costs were estimated based on the present values (P) and were then projected to incorporate the future cost (F) with respect to an inflation rate of 4 % based on the general trend observed in Australia over the past years [43]. However, the projected future costs do not account for any reduction in the costs, and thus, an appropriate discount rate of 6 % was adopted to re-estimate the future cost [44,45]. The future cost and the discounted cost (DC) were calculated based on Equation (2) and Equation (3) given below.

$$\boldsymbol{F} = \boldsymbol{P} \times (1+\boldsymbol{f})^{\boldsymbol{n}} \tag{2}$$

$$\boldsymbol{DC} = \frac{\boldsymbol{F}}{(1+\boldsymbol{d})^{\boldsymbol{n}}} \tag{3}$$

where, f is the inflation rate, d is the discount rate and n is the life cycle period in years.

2.4. Environmental impact assessment

A thorough and systematic evaluation of environmental impacts was undertaken through the employment of SimaPro v9.4 [16,46] in an environmental impact assessment (EIA) for the three types of walls, namely (a) 3DCP-FM, (b) 3DCP-PP, and (c) RC-32. Within each of these scenarios, the associated environmental effects were meticulously analysed. The EIA procedure strictly adhered to the directives outlined in ISO 14040 [47] and ISO 14044 [48], which lay out the requisites and specific guidelines for delineating the scope and objectives, facilitating the interpretation of the results.

The principal objective of this EIA endeavour is to establish both the technical viability and the ecological sustainability of integrating fibre generated from facemask waste in 3D-printed concrete technology. The analysis employs two distinct methodologies, namely consequential and attributional EIA, to gauge the environmental ramifications of wall construction. This approach delves into the ripple effects that this process has on alternate practices within the waste management supply chain. Conversely, the current study adopts an attributional EIA approach, focusing on quantifying the associated impacts of facemask fibre and processing 3D-printing concrete. This approach centres on a

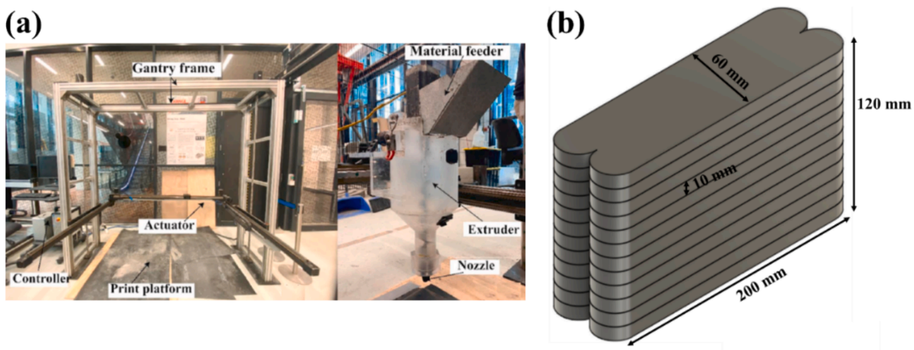

Fig. 1. (a) Gantry type 3D printer (b) Schematic of a printed specimen.

Fig. 2. Thermal conductivity test setup and specimen details.

"cradle-to-gate" perspective, scrutinising these materials' collection, transportation, processing, and integration into road construction activities. The assessment meticulously evaluates pertinent material processing procedures to ascertain the direct carbon emissions and indirect resource conservation linked to employing 3D-printed concrete with PP and face mask fibre.

2.4.1. Functional units and system boundaries

The functional unit in an EIA pertains to the quantity of materials involved within a single production system or process. This unit serves as the foundation for quantifying the environmental repercussions of products, enabling meaningful comparisons. Therefore, the choice of an appropriate functional unit holds paramount importance in accurately reflecting the study's objectives and scope. In this context, adopting a functional unit representative of the potential impact of the wall (3 m × 3 m × 0.22 m) becomes essential. This choice enables the examination of whether the utilisation of face mask fibre from waste in the 3D-printed concrete presents an environmentally viable solution. The assessment of performance has been conducted based on experimental data and impact categories related to the materials employed in constructing walls with 3D printing and traditional concrete.

In this EIA, the system boundaries delineate the specific processes that encompass input and output considerations and those excluded from the assessment. This study adopts a "Cradle to Gate" boundary, which encompasses the entire lifecycle of activities related to the production of materials. These activities encompass factors such as the consumption of diesel, fuel oil, electricity, and other resources during manufacturing. Additionally, the transportation of materials to the construction site is recognised as a significant factor in conducting this EIA. The research employs the Australian Life Cycle Inventory (AusLCI) standard unit (SD U) to assess potential impacts. The mass of the required materials, measured in tons, serves as the basis for conducting the EIA, ensuring the generation of meaningful results. Furthermore, the pertinent activities of the life cycle analysis are comprehensively detailed in the life cycle inventory (LCI), providing a holistic understanding of the inputs involved in manufacturing. The collected LCI data accurately mirrors the specific practices and technologies employed within the assessment system, as delineated in Table 2. This comprehensive database contains all the requisite input information associated with the production system. It serves as the basis for calculating midpoint environmental impacts, including but not limited to climate change, acidification, eutrophication, and other relevant parameters.

2.4.2. Impact assessment

In this study, ReCiPe 2016 is employed as the chosen methodology for evaluating emissions and their implications when incorporating 3D printing concrete with PP and face mask fibres in wall construction. This approach encompasses eighteen midpoint impact categories and three endpoint indicators. The emission factors are categorised as characterisation factors, where they translate the consequential activities of various processes into emissions. These emissions are then transformed into impacts within three conservative areas of protection: disability-adjusted life years (DALYs), ecosystem damage, and resource scarcity. Fig. 3 provides an overarching view of the interconnected mechanism between midpoint and endpoint impacts.

The EIA framework offers an insight into the impact trajectory at the midpoint level, where environmental flows such as emissions and factors align. These resource extractions and emissions are interpreted into

Table 2
LCI used in the EIA.

Life Cycle Inventory Components	Unit
Portland cement production per kg	
Water, drinking, Australia/AU U	12.5 L
Limestone, milled, at plant/AU U	1.4 kg
Sand, river, at mine/AU U	0.363 kg
Iron ore, at mine/AU U	0.0077 kg
Bauxite, at mine/AU U	0.0294 kg
Gypsum, mineral, at mine /AU U	0.055 kg
Electricity, low voltage, Australian/AU U	0.351 MJ
Transport, lorry 3.5–20 t, fleet average/AusSD U	0.0000172 tkm
Coarse aggregate production per kg	
Lubricating oil, at plant/AusSD U	0.0000025 kg
Diesel, burned in building machine/AusSD U	0.0143 MJ
Industrial machine, heavy, unspecified, at plant /AusSD U	0.0000951 kg
Electricity, medium voltage, at grid /AusSD U/Link U	0.00906 kWh
Heat, light fuel oil, at boiler 10 kW, non-modulating /AusSD U	0.00491 MJ
Synthetic rubber, at plant /AusSD U	0.000004 kg
Transport, lorry 3.5–20 t, fleet average /AusSD U/Link U	0.00000292 tkm
Sand production per kg	
Diesel, burned in building machine /AusSD U	0.0147 MJ
Electricity, medium voltage, at grid /AusSD U/Link U	0.00272 kWh
Heat, light fuel oil, at boiler 10 kW, non-modulating /AusSD U	0.00244 MJ
Industrial machine, heavy, unspecified, at plant /AusSD U	0.0000112 kg
Lubricating oil, at plant /AusSD U	0.00000185 kg
Transport, lorry 3.5–20 t, fleet average /AusSD U/Link U	0.000000879 tkm
Silica fume production per kg	
Transport, freight train /Alloc Rec, U	0.0112 tkm
Transport, freight, lorry, unspecified/Alloc Rec, U	0.01932 tkm
Silica fume, densified,/silica fume, densified, Recycled Content cut-off /Alloc Rec, U	1 kg
Polypropylene fibre production per kg	
Hydrogen, gaseous	9.80471E-7 kg
Chemicals (unspecified)	0.00191269 kg
Mineral waste	0.000205438 kg
Overburden (deposited)	0.0162911 kg
Plastic (unspecified)	0.000340307 kg
Waste paper	2.35282E-9 kg
Wooden pallet	5.89215E-10 kg
Face mask fibre production per kg	
Hydrogen, gaseous	0.00636927 kg
Chemicals (unspecified)	0.0079249 kg
Mineral waste	0.00101884 kg
Overburden (deposited)	0.0433841 kg
Plastic (polypropylene, polyester)	0.0021083 kg
Waste paper	0.000237901 kg
Wooden pallet	5.65122E-5 kg
Superplasticizer production per kg	
Transport, freight, lorry, unspecified /Alloc Def, U	0.2088 tkm
Transport, freight, sea, transoceanic ship /Alloc Def, U	0.599 tkm
Transport, freight train market group /Alloc Def, U	0.3091 tkm
Plasticiser, for concrete, based on sulfonated melamine formaldehyde/AU U	1 kg
Retarder Borax production per kg	
Sodium borates, at plant /AusSD U	1.71 kg
Electricity, medium voltage, production /AusSD U/Link U	0.944 kWh
Heat, natural gas, at industrial furnace > 100 kW /AusSD U	13.6 MJ
Glass production site /AusSD U	1.25E-10 kg
Transport, lorry > 16 t, fleet average /AusSD U/Link U	0.0853 tkm

specific impact categories known as midpoint characterisation factors (CFM). These CFM's are further translated into three conservative protection areas at the endpoint level: human health, ecosystem damage, and resource scarcity. It's important to note that the midpoint and endpoint impacts are closely linked to input systems, and the midpoint bears a stronger connection to the input systems and low levels of uncertainty. In contrast, the endpoint characterisation factors (CFE) offer a more holistic understanding of relevant emissions and resource extraction flows, albeit with a higher degree of uncertainty than the midpoint. Equation (4) is used to derive the CFE.

$$\boldsymbol{CFE} = \boldsymbol{CFM}_{X,c} \times \boldsymbol{F}_{M\rightarrow E,c,a} \tag{4}$$

Where the cultural variations are represented by c and a indicates the conservative protection areas (human health, ecosystem, and resource), X is the implications density and $F_{M\rightarrow E,c,a}$ conversion factor midpoint to endpoint. These factors are constant along the impact categories as per variable impacts.

3. Results and discussion

3.1. Insulation properties

The insulation characteristics of the construction material are crucial in evaluating the building's energy performance and can be related to the material's thermal resistance and thermal conductivity. The thermal conductivity of the 3D printable mixes was calculated using the TLS-100 instrument, and the results are shown in Fig. 4(a). However, the thermal conductivity of a concrete mix was taken as an average value from previous studies for comparison purposes [6,39,49].

From Fig. 4(a), it can be inferred that the thermal conductivity of a normal 3D printable mix is about 39.4 % higher than traditional reinforced concrete. This increase in thermal conductivity is due to the higher cement paste content in the 3D printable mix. Hence, adopting a normal 3D printable concrete mix for wall elements will result in reduced insulation properties which is depicted by the thermal resistance values, as shown in Fig. 4(b). Furthermore, due to the low insulation characteristics of 3D printable mixes, during extreme climatic conditions, additional heating and cooling systems need to be installed in the building. This not only results in increased operational energy consumption but also adversely affects the environmental impact due to the generation of additional greenhouse gasses from these heating and cooling systems. However, incorporating recycled face mask fibres and PP fibres into a 3D printable mix reduced the thermal conductivity, thereby improving the thermal resistance. The addition of face mask fibres reduced the thermal conductivity of 3D printable mixes by 30 % and thus showed similar thermal performance to that of traditional concrete mix. The reduced thermal conductivity of mixes with PP or face mask fibres can be attributed to the lower thermal conductivity of individual PP and face mask fibres. The thermal conductivity of a composite material is characterised by the individual thermal conductivity of its materials. Furthermore, when compared to cement paste, the thermal conductivity of PP and face mask fibres are much lower, resulting in reduced thermal conductivity of the overall composite mix [50]. A similar reduction in thermal conductivity was observed for normal and lightweight concrete mixes with the addition of fibres [51–53]. Furthermore, incorporating PP fibres was observed to increase the voids in the printed specimens, resulting in reduced thermal conductivity. Hence, incorporating face mask and PP fibres into the 3D printable mix results in a similar thermal performance to that of conventional concrete. Further, the improvement in the thermal performance of 3DCP-FM walls results in reducing the requirement of additional heating and cooling systems, which incur additional costs and environmental impact. The additional operational energy consumed can be approximately proportional to the improvement of thermal insulation. It can be observed that about 49.5 % improvement in the thermal resistance was achieved with the incorporation of face mask fibres into the printable mix. Along with the improved thermal insulation, adopting an optimised print pattern for the external wall reduces the thermal mass of the building and thus can provide year-round thermal comfort and reduce the energy costs for the heating and cooling system [54,55]. It indicates that the thermal resistance improved by face mask fibre-reinforced 3D printable wall elements can contribute significantly to reducing the heating and cooling operational energy consumption of buildings.

Furthermore, previous studies indicate that external walls and ceilings mostly influence the energy consumption of the building, and improving the thermal insulation significantly reduces operational energy [56,57]. Thus, adopting face mask fibres improves energy

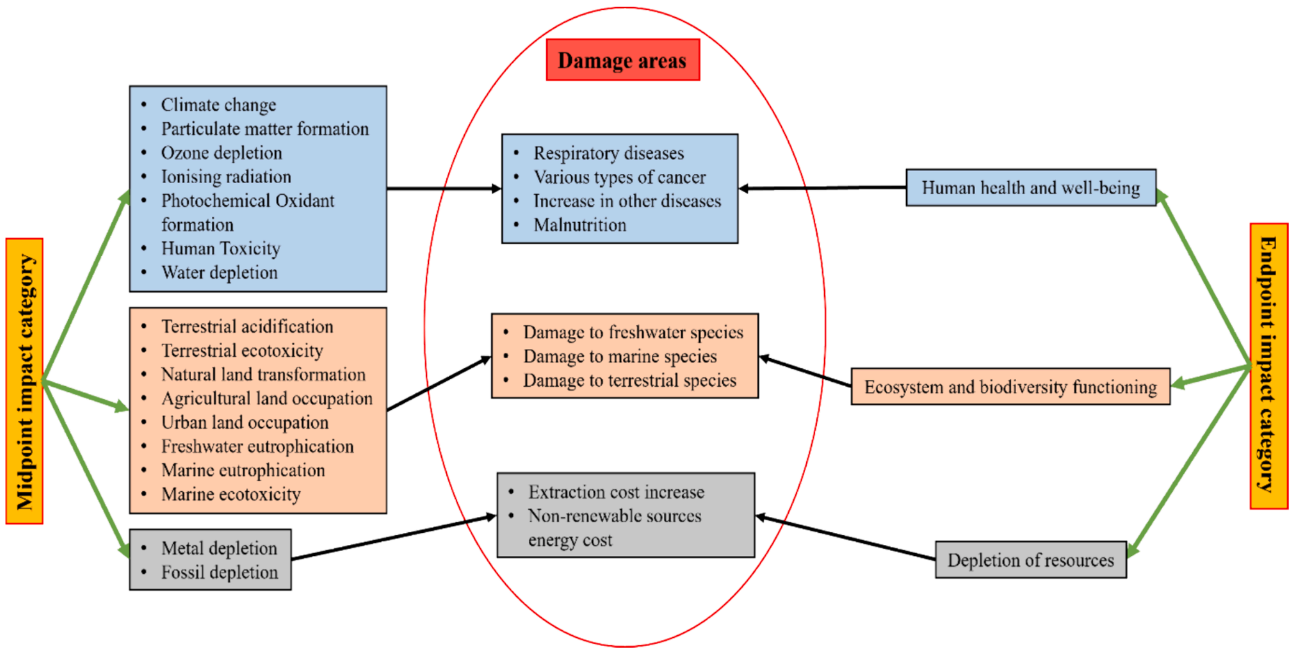

Fig. 3. Linkage mechanism between midpoints and endpoint impact categories covered in the ReCiPe 2016 methodology.

efficiency and results in better sustainability and lower life cycle costs. Furthermore, the construction of aesthetically pleasing complex geometries can be achieved by adopting the 3D printing method when compared to traditional construction. Moreover, adopting different printing patterns enhances the thermal insulation properties of the face mask fibre-reinforced 3D printed walls and thus can further improve the energy performance of the building [58].

3.2. Life cycle cost analysis

The life cycle cost of all three different types of walls for different phases is given below in Table 3. The construction and operational costs of the wall summed up to about 80 % to 85 % of the total cost for all the wall types. However, the maintenance and disposal costs were only 3.5 % and 12.5 % to 14 %, respectively. The life cycle costs are considered based on the life cycle period of 50 years, and the costs are presented in Australian dollars ($).

The material costs associated with the construction phase for the 3DCP-FM and 3DCP-PP walls are nearly three times higher than the traditional RC-32 wall. The higher material cost for the 3D printable mix is mainly associated with the higher cement content used. However, with the use of face mask fibres and PP fibres as reinforcement for printed walls, improved compression and flexural strength properties [24] are achieved, resulting in the construction of slender cross sections, which can reduce the material costs. In addition, the potential of constructing cavity wall structures easily with 3D printing further results in reduced material usage with better energy performance and improved structural behaviour [35,36].

However, a 35 % reduction was observed in the operation phase for the 3DCP-FM wall and 3DCP-PP wall when compared to the traditional RC-32 wall. The reduction in the operational phase is mainly from the 50 % reduction in the labour cost for 3D printable walls [25–27]. Even though the 3DCP process involves costs related to the printer's electricity usage and transportation, the total cost of the wall can be reduced from the low labour cost and removal of formwork. Furthermore, the construction time can be saved by more than 50 % with 3D printing when compared to traditional construction, which aids in the overall performance of 3D concrete printed buildings [26]. Moreover, in the current cost estimation, the operation costs of heating and cooling systems are not accounted. However, the thermal resistance of 3DCP-FM walls and traditional RC-32 walls are similar, which results in similar operational costs. However, when compared to normal 3D-printed walls, face mask fibre reinforced 3D-printed walls will result in more than 49 % reduction in the heating and cooling systems operational costs due to the improved insulation properties of 3DCP-FM walls. In addition, with the geometrical freedom from the 3DCP method, the thermal insulation of the external walls can be improved, and an additional reduction in the operational cost of heating and cooling systems can be achieved without compromising the structural performance [59,60].

3.3. Environmental impact assessment

Table 4 provides the midpoint environmental impacts for different impact categories for the three wall systems considered. EIA reveals that the wall constructed with 3DCP-PP results in higher carbon dioxide emissions, amounting to 1360 kg CO_2 eq, as shown in Table 4. In contrast, using 3DCP-FM for the wall construction reduces carbon emissions by about 23 kg CO_2 eq compared to the wall made with 3DCP-PP. Further, the wall constructed with traditional concrete (i.e. RC-32) has shown less carbon dioxide emissions than the other walls. This is mainly due to the higher cement content in the printable mix. However, sustainable cement replacement materials and reduced material usage for constructing slender wall elements using 3DCP would reduce the CO2 eq of 3DCP walls significantly [32]. Furthermore, additional greenhouse gas emissions from the heating and cooling systems can be reduced significantly when 3DCP-FM walls are used when compared to normal 3D-printed walls. The reduction in greenhouse gas emissions can be characterised by the improved insulation properties of the 3DCP-FM walls. The most significant environmental benefit arises from the use of facemask fibre, which helps prevent landfilling and promotes its integration with 3D-printed concrete to improve structural performance. This approach also minimises landfill overburden and contributes to a more sustainable circular economy.

The EIA results exhibit a 37.2 % and 31 % decrease in ozone depletion potential when facemask fibre is used to replace the PP fibre in the 3DCP wall and traditional RC-32 wall, respectively. Further, in the case of metal depletion (kg Fe eq), a wall constructed with 3D printed concrete with PP and face mask fibres has significantly less (i.e. around

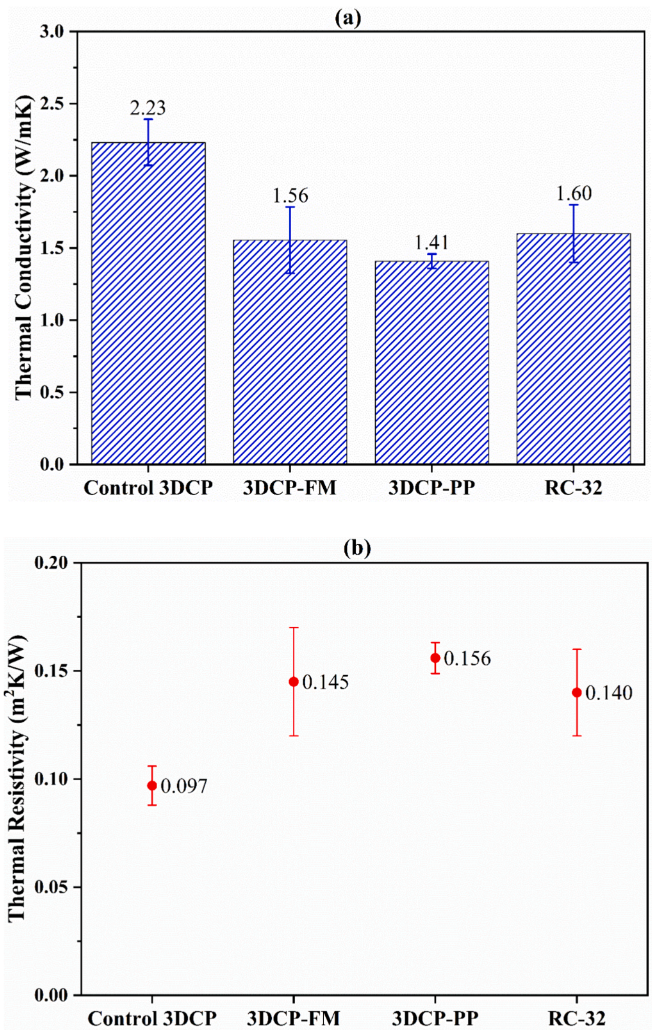

Fig. 4. (a) Thermal conductivity of different wall materials (b) Thermal resistance of the different walls.

Table 3
Life cycle cost for all walls in Australian dollars ($).

Wall type	Life cycle phase				Total
	Construction	Operation	Maintenance	Disposal	
3DCP-FM	1204.52 $	1641.68 $	126.04 $	486.61 $	3458.86 $
3DCP-PP	1378.33 $	1625.16 $			3616.14 $
RC-32	474.97 $	2700.59 $			3788.21 $

82 %) negative environmental impact than the traditional concrete wall. Moreover, adopting face mask fibre reinforced 3D concrete printed walls in construction could reduce the ecotoxicity by 37.2 % when compared to traditional concrete. This can be attributed to the reduction in landfill waste from the recycling of facemasks. Consequently, the midpoint impact categories affirm the comprehensive examination of potential indicators and offer valuable insights into the environmental advantages of utilising 3D printing concrete with face mask fibres.

The broader perspective of environmental sustainability, such as the impact on human well-being and health, ecosystem and biodiversity functioning, and depletion of resources, have been assessed through Endpoint impact categories. The impact on human health has been identified as DALYs (Disability-adjusted life years), signifying the number of persons affected by disability, disease, or accident due to emissions. The loss of species over a year is implied as species-year, which evaluates the ecosystem and biodiversity impact, and savings of the cost due to depletion of resources are identified as the US dollar ($). The endpoint environmental impacts on these categories for three types of walls are presented in Fig. 5.

Table 4
Midpoint environmental impacts.

Impact category	Unit	3DCP-FM	3DCP-PP	RC-32
Climate change	kg CO_2 eq	1337.67	1360.20	945.53
Ozone depletion	kg CFC-11 eq	9.80E-06	1.56E-05	1.42E-05
Terrestrial acidification	kg SO_2 eq	5.84	4.47	3.47
Freshwater eutrophication	kg P eq	4.43E-03	5.13E-03	1.00E-02
Marine eutrophication	kg N eq	1.78E-01	1.52E-01	1.39E-01
Human toxicity	kg 1,4-DB eq	30.16	31.57	46.49
Photochemical oxidant formation	kg NMVOC	4.88	4.16	2.84
Particulate matter formation	kg PM10 eq	1.95	1.61	1.29
Terrestrial ecotoxicity	kg 1,4-DB eq	1.15E-02	1.26E-02	2.83E-02
Freshwater ecotoxicity	kg 1,4-DB eq	0.17	0.18	0.20
Marine ecotoxicity	kg 1,4-DB eq	2.45E-01	2.84E-01	4.51E-01
Ionising radiation	kBq U235 eq	4.71E-01	7.51E + 00	4.92E-01
Agricultural land occupation	m^2a	6.86	6.86	18.83
Urban land occupation	m^2a	12.38	12.38	19.58
Natural land transformation	m^2	3.28E-02	3.28E-02	8.83E-02
Water depletion	m^3	30.47	30.37	20.31
Metal depletion	kg Fe eq	17.46	17.54	110.70
Fossil depletion	kg oil eq	265.29	290.44	199.49

The endpoint impact on the human health and well-being of the 3DCP-FM wall was observed to be low for all the categories when compared to the traditional RC-32 wall, as shown in Fig. 5(a). A reduction of about 77 % in DALYs was observed when face mask fibre reinforced walls were used compared to traditional concrete walls. However, the difference between face mask fibre and PP fibre in terms of the impact on human health and well-being was not significant. Similarly, when compared to traditional concrete walls, using 3DCP-FM walls would lead to up to 78.8 % savings in the loss of species per year, which results in a significant impact on the ecosystem. Furthermore, out of all the endpoint impact factors, resource depletion was the category most affected by the use of face mask fibres. It can be observed that about 81.2 % reduction in the total depletion of mineral and fossil resources can be achieved with the use of 3DCP-FM walls in construction when compared to traditional RC-32 wall. Hence, based on the endpoint impact assessment, adopting face mask fibre reinforced 3DCP walls can provide a significant reduction in the overall environmental impact when compared to traditional concrete walls.

4. Conclusions

This paper evaluates the thermal performance and environmental impact assessment of 3DCP walls reinforced with recycled fibre recovered from face masks and PP fibres and compares them with conventional reinforced concrete walls. The improved thermal performance of 3DCP walls with face mask fibres, along with reduced life cycle cost and

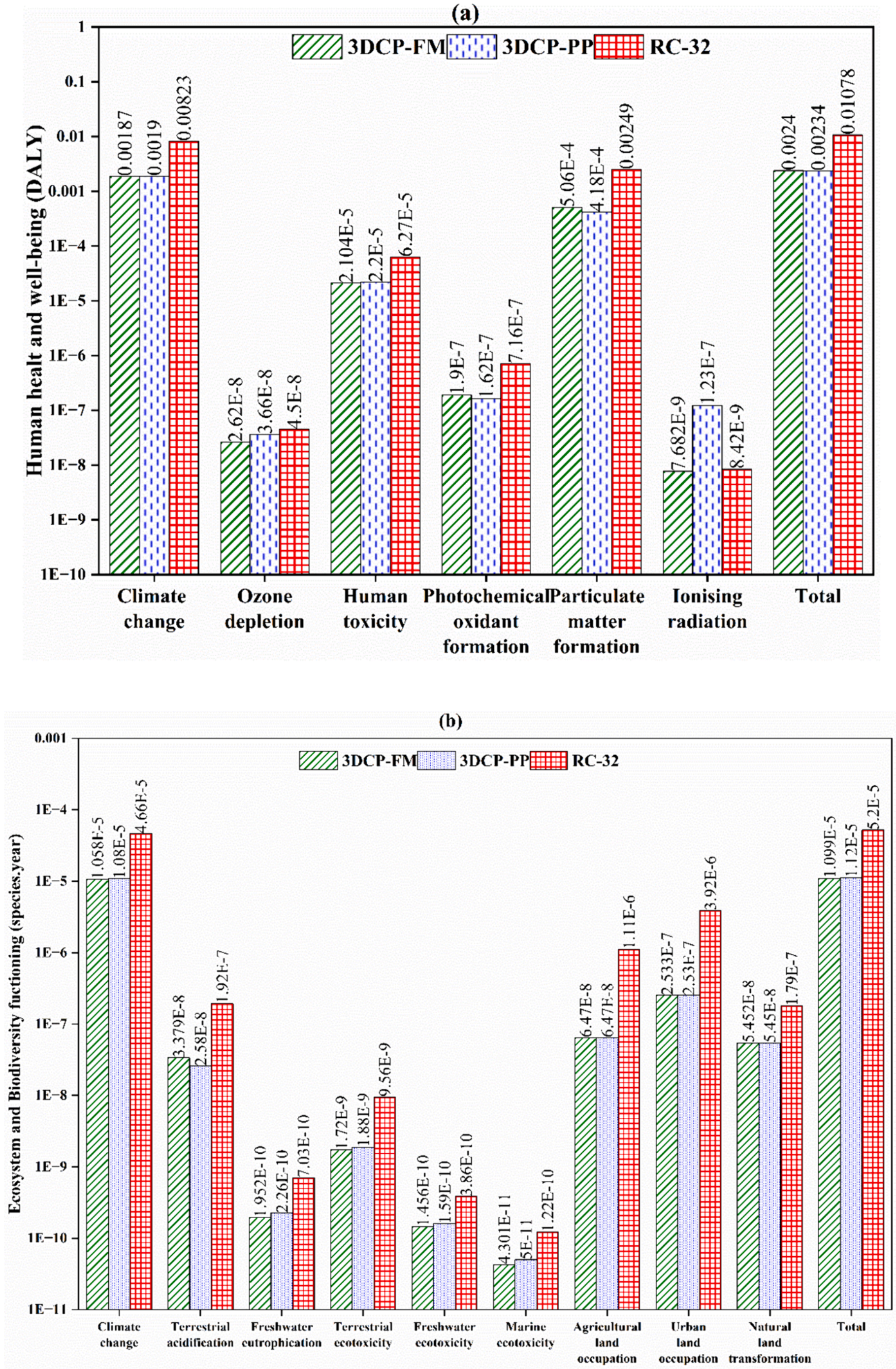

Fig. 5. Endpoint environmental impacts on (a) Human health and well-being, (b) Ecosystem and biodiversity functioning, (c) Depletion of resources.

environmental impact, suggests the potential to adopt face mask fibre reinforced 3DCP elements in building components. Based on the study, the following main conclusions were derived:

- The thermal resistance of 3D printable mix is low due to the high cement content. However, the addition of face mask fibres significantly increases the thermal resistance of 3D printable mix and are comparable to traditional reinforced concrete.
- The increased insulation characteristics of 3DCP-FM walls significantly reduce the heating and cooling operational requirements, thereby reducing greenhouse gas emissions, energy consumption and operational costs. Thus, using face mask fibre reinforced 3D printed walls can improve the energy efficiency of buildings.
- An overall reduction of about 9 % in the life cycle cost was observed for 3DCP-FM walls when compared to traditional RC-32 walls. The cost reduction can be further improved by replacing the cement with more sustainable building materials and construction of slender wall sections with good strength due to the enhancement from the face mask fibres.
- A substantial reduction in the labour and formwork material cost during the operation phase was observed for 3DCP-FM walls. Adopting the 3DCP process reduces the requirement of the labour force and material wastage.

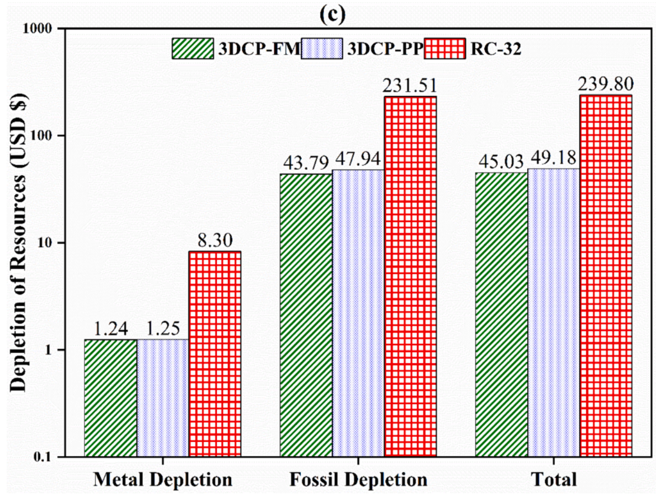

Fig. 5. (*continued*).

- Even though the midpoint impact assessment shows a higher carbon emission for 3DCP-FM walls than traditional RC-32 walls, the metal depletion and ozone depletion were reduced by about 82 % and 31 % for 3DCP-FM walls when compared to traditional RC-32 walls.
- The endpoint impact assessment showed that adopting face mask fibre reinforced 3D-printed walls significantly reduces the impact on human health, ecosystem and resource depletion when compared to conventional concrete.

Adopting 3DCP technology in construction paves the way for building architecturally complex geometries with reduced cost and in a time efficient manner. Further, incorporating face mask fibres as reinforcement for 3DCP building elements, results in improving the thermal performance and energy efficiency along with improved sustainability and cost saving. However, to quantify the energy performance more accurately, a detailed investigation focusing on evaluating the thermal and durability performance of a full-scale 3D-printed wall reinforced with face mask fibres over the long term needs to be conducted. Additionally, a life cycle impact analysis that considers the recycling process during the demolition stage can provide more in-depth understanding.

CRediT authorship contribution statement

Akilesh Ramesh: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Satheeskumar Navaratnam:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Pathmanathan Rajeev:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Jay Sanjayan:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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