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Full length article

Environmental impact and sustainable development of pozzolanic concrete incorporating polypropylene fibers: A database study

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ABSTRACT

The study evaluates the life cycle performance of concrete incorporating polypropylene fibres using a database approach. Linear regression analysis identified 2 % to be optimum polypropylene fiber content, while 30 % fly ash, 15 % slag and 7.5 % silica fume were detected to be the optimum pozzolanic replacement that is demonstrated to play an essential role in mitigating the adverse effect of polypropylene fibres use on the engineering properties of concrete. The established models attained through the database analysis were consequently subjected to the life cycle assessment based on a cradle-to-gate approach. The inventory analysis has shown that the utilisation of polypropylene fibers, particularly when accompanied with pozzolans, could considerably reduce the life cycle associated indices. Model 3a, for instance, yielded over 25 % reduction in climate change potential and in ozone depletion. The study highlights the significances of greener production of construction materials and embraces environmental preservation through a cleaner waste disposal approach.

1. Introduction

Plastics have been used in a wide variety of applications mainly because they possess high durability and are lightweight and inexpensive (Hopewell et al., 2009; Agarwal and Gupta, 2017; Siddique et al., 2008; d'Ambrières, 2019; Patil et al., 2017; Thompson et al., 2009). Global plastic production grew more than two hundredfold from 1.5 million metric tonnes in 1950 to 367 million metric tonnes in 2020 (Statista, 2020), with approximately 4 % of crude oil produced globally used as feedstock for plastic production, and roughly the same amount of oil used as energy to drive plastic production processes (Hopewell et al., 2009; Thompson et al., 2009). The concern regarding plastics does not entirely emerge from their use phase, but from the mode of disposal at the end of their useful life (d'Ambrières, 2019; Geyer et al., 2017). Due to the non-biodegradable nature of the plastics, they remain in nature for several decades (Hopewell et al., 2009; Geyer et al., 2017). Plastic wastes, float on oceans, clog canals, litter cities, and destroy marine ecosystems (Thompson et al., 2009; Dussud et al., 2018; Gopinath et al., 2020). Microplastics, generated as a result of the degradation of plastics, are an emerging environmental concern due to their increasing prevalence and risks to health and the ecosystem (Galloway and Lewis, 2016; Eerkes-Medrano et al., 2015; Abel et al., 2018). Additionally, Sussarellu et al. (2016) reported that microplastics can diminish generative productivity and physical fitness in marine organisms by modifying their ability to ingest food and energy distribution (Sussarellu et al., 2016). Only 9 % of all plastics produced since 1950 have been adequately recycled, with the remaining 79 % disposed of in landfills and the natural environment (Geyer et al., 2017; de Souza Machado et al., 2018; Statista 2017). While thermal decomposition of plastic wastes could be challenging, innovative methods such as pyrolysis can lead to useful products (Geyer et al., 2017). Comprehensive evaluation of the environmental aging of polymers can be found

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inKrauklis et al. (2022). It is estimated that 4 to 12 million metric tons of plastic waste end up in the ocean every year (Jambeck et al., 2015), and by 2050, The World Economic Forum estimates that there will be more plastic waste in the world's ocean than fish (Shen et al., 2020; Getor et al., 2020; Farady, 2019).

While landfills have been the conventional approach for handling plastic wastes, locating suitable land has become increasingly challenging in recent times due to the substantial increase in the amount of waste generation (Hopewell et al., 2009; Siddique et al., 2008; Leao et al., 2001). Plastic wastes are known to pose persistent risks of contamination in soil and groundwater at landfill sites due to the decomposition of some plastic additives (Hopewell et al., 2009; Mohammadhosseini et al., 2017; Oehlmann et al., 2009; Teuten et al., 2009). Also, a key limitation of landfills for plastic waste disposal from a sustainability viewpoint remains the inability to recover any material resource utilized in the plastic production process (Hopewell et al., 2009; Siddique et al., 2008). Incineration of plastic wastes, with or without energy recovery, is another approach for handling plastic wastes with the advantage of reducing the waste load in landfills. However, the release of toxic substances during the combustion of plastic wastes poses severe concerns to human health and the environment (Hopewell et al., 2009; Verma et al., 2016; Velis and Cook, 2021; Rajmohan et al., 2019; Ágnes and Rajmund, 2016; Ashworth et al., 2014). Exhaust gases from an incinerator may contain potentially harmful substances such as carbon monoxide, oxides of sulfur, oxides of nitrogen, acid gases, metals (lead and mercury), dioxins, and furans, polycyclic aromatic hydrocarbons, chlorinated volatile organic compounds as well as particulate matter (Hopewell et al., 2009; Verma et al., 2016; Velis and Cook, 2021; Rajmohan et al., 2019; Statista 2000; Barnes et al., 2009). Recycling of plastic wastes, nevertheless termed a more environmentally friendly approach, generates a tangible loss of mass, as the process remains impracticable to completely convert the total mass of plastic wastes into another reusable form. Despite the fact that recycling appears to be a more advanced route of disposal as it prevents further plastic manufacturing when compared to incineration or landfilling, most plastics can only be recycled once or twice (Ritchie and Roser, 2018). This implies that the majority of recycled plastic winds up in a landfill or is incinerated (Geyer et al., 2017; Ritchie and Roser, 2018). Moreover, recycling could be considered an inefficient process as it consumes high amounts of energy and provides diminished reliability of the products formed when contrasted with the initial products (Gopinath et al., 2020).

A more viable approach for handling plastic wastes with reduced impact on the environment is reported to be the incorporation of such wastes in mortars and concrete as complete or partial replacement of aggregates or as fibre additions (Leao et al., 2001; Saikia and De Brito, 2012; Ismail and Al-Hashmi, 2008; Yin et al., 2015; Sharma and Bansal, 2016; Liu et al., 2015; Basha et al., 2020; Babafemi et al., 2018; Mercante et al., 2018; Soloaga et al., 2014; Thorneycroft et al., 2018). Concrete, basically constitute from cement, sand, crushed stone, and water, is the most widely utilised building material worldwide (Babor et al., 2009; Surahyo and Surahyo, 2019; Mundra et al., 2016; Naik, 2008; Meyer, 2002; Leung, 2011; Macdonald, 2008; Sabir et al., 2001). This is mainly because cement, a key component in concrete, can be made from a wide variety of raw materials at a modest relative cost, and that concrete is flexible and adaptable enough to be used to build a variety of structural forms (Leung, 2011; Macdonald, 2008; Sabir et al., 2001). Considering the progressive demand for construction materials such as cement and aggregates and more pronouncedly their deleterious effect on the environment, there remains a great need to establish sustainable substitutes for these construction materials (Ozturk et al., 2022; Ince et al., 2022; Ince et al., 2020; Ayasgil et al., 2022; Ince et al., 2021). Global cement demand increased by 23.7 % from 4257 million metric tonnes to 5266 million metric tonnes between 2017 and 2020 (Statista, 2020). Although on average, 0.927 tonnes of CO_2 are emitted for every tonne of cement produced (Marceau et al., 2006; Benhelal et al., 2013), cement production nevertheless remains to account for around 5 % of global CO_2 emissions (Marceau et al., 2006; Collins, 2010). On the other hand, aggregates do not only constitute 65 – 80 % of the overall volume of the concrete mix alone but also have governing impacts on the fresh and hardened properties of the end product (Faraj et al., 2019; Almeshal et al., 2020). This implies that vast quantities of both fine and coarse aggregates are being consumed to meet the global demand for concrete manufacture (Spiesz et al., 2016). Therefore, the energy consumed in processes to attain suitable forms of aggregates for concrete making, for instance, mining, crushing, screening, washing, and transportation operation, should not be underestimated nor the deleterious negative impacts on the natural ecosystem and consequently human health (Mehta, 2001). The global market for building aggregates is estimated to reach 51.7 billion tonnes in 2019. This implies a 5.2 % annual growth rate which is driven primarily by the demand to construct more contemporary homes and developments in the housing markets, particularly in industrialized nations (Spiesz et al., 2016). The development of infrastructure and growing personal incomes also in developing countries further contributed to the increased demand for the mix constituents of concrete (Spiesz et al., 2016; Green, 2016).

It should be elucidated that the plastic waste compositions are conspicuously diverse, embracing not only polypropylene but also a spectrum of other polymers including low-density polyethylene, high-density polyethylene, polyethylene terephthalate, and high-impact polystyrene in varying and often complex proportions. Polypropylene, constitutes a subclass within the broader set of plastics, stands as a thermoplastic polymer and emerges as a focal point within the ambit of this investigation. Over the last two decades, studies have been carried out to provide an insight into the behaviour of concrete incorporating polypropylene plastic waste (Hsie et al., 2008; Kakooei et al., 2012; Bayasi and Zeng, 1993; Flower and Sanjayan, 2007). The majority of these studies investigated the optimum additional and/or replacement levels of polypropylene fibres which are closely related to their compatibility within the matrix itself along with the influences of such incorporation on the fresh and hardened state properties of mortars and concrete (Afroughsabet and Ozbakkaloglu, 2015; Ahmed et al., 2020; Behnood and Ghandehari, 2009). Most of the studies reported in the literature demonstrated improved mechanical properties of concrete incorporating polypropylene fibres (Ahmed et al., 2020; Islam and Shahjalal, 2021; Karimipour et al., 2020; Kilmartin-Lynch et al., 2021; Shi et al., 2020; Yuan and Jia, 2021; Eidan et al., 2019; Altalabani et al., 2020; Hussain et al., 2020). For instance, Islam et al. (2021) studied the effect of polypropylene as a partial replacement for coarse aggregate on the properties of concrete. It was reported that the use of polypropylene fibres up to 10 % replacement to coarse aggregate in concrete resulted in significantly higher compressive strength, split tensile strength and modulus of rupture than the control concrete (Islam and Shahjalal, 2021). Kilmartin-Lynch et al. (2021) investigated the use of polypropylene fibres harvested from waste face masks to improve the mechanical properties of concrete. The fibres were introduced into concrete at 0.10 %, 0.15 %, 0.20 % and 0.25 % by volume. The research results have shown that the increased strength and enhanced quality of concrete are established when polypropylene fibres are used up to 0.2 % in concrete (Kilmartin-Lynch et al., 2021). The mechanical properties of self-compacting concrete incorporating polypropylene fibres were also investigated by Karimipour et al. (2020). It was observed that the use of 0.1 % of polypropylene fibres enhanced the compressive strength of concrete, and up to 0.3 % of polypropylene fibres exhibited a remarkable increase in split tensile strength and impact resistance of concrete due to the crack bridging ability of such fibres (Karimipour et al., 2020).

Nevertheless, it is also largely reported in the literature that polypropylene fibres do not directly contribute the cement hydration due to the non-polar nature of these fibres. The chemically inert and hydrophobic nature of such fibres does explain the main causes of the strength reductions attained in concrete which is essentially the result of the more porous microstructural development within the matrix. The use of pozzolans, on the other hand, have often been utilised in mortars and concrete mainly to compensate for the adverse effects of waste utilisation in the matrix, particularly in the long term (Colak, 2002; Navrátilová and Rovnaníková, 2016; Bui et al., 2018; Rodrıguez-Camacho and Uribe-Afif, 2002; Sata et al., 2007). The reaction of pozzolans with calcium hydroxide, one of the main end products of hydration, results in the formation of additional calcium-silicate-hydrate gels that contribute to the strength development of the cementitious matrix (Colak, 2002; Navrátilová and Rovnaníková, 2016; Bui et al., 2018; Hemalatha et al., 2016; Dembovska et al., 2017; Lin and Lin, 2006; Carette and Malhotra, 1983). However, compared to the hydration of clinker phases and the reliance of pozzolanic activity on the formation of calcium hydroxide, the reaction is much slower (Ozturk et al., 2022; Ince et al., 2022; Ince et al., 2020; Ayasgil et al., 2022; Colak, 2002; Bui et al., 2018). The use of pozzolans also improves the mechanical properties and durability of concrete to a great extent due to the increased fineness in the matrix that provides consolidated and denser microstructural properties (Ozturk et al., 2022; Ince et al., 2022; Ince et al., 2020; Ayasgil et al., 2022). It must also be noted that the utilisation of pozzolans often performed as binder or aggregate replacement provides cost-effective solutions for the manufacture of the end products due to the decrease in the mix constituents. The reduced demand for the raw materials for the manufacture of concrete further contributes to the reduction of CO_2 emissions and the associated environmental impacts (Ozturk et al., 2022; Ince et al., 2022; Ince et al., 2020; Pekmezci and Akyüz, 2004; Ince et al., 2015; Altwair and Kabir, 2010; Uzal et al., 2007). The utilisation of waste materials with pozzolanic properties can enable the incorporation of additional wastes into concrete and provide an alternative for landfill as a disposal route (Rukzon and Chindaprasirt, 2009; Tangchirapat et al., 2007; Cheerarot and Jaturapitakkul, 2004; AlBiajawi et al., 2021; Meyer, 2009).

Despite the fact that the studies on the utilisation of polypropylene fibres coupled with pozzolans convey a significant degree of understanding on the development of concrete comprising such fibres, it must be emphasised that the research results reported in this context demonstrate inevitable discrepancies (Garg and Garg, 2021; Topcu and Canbaz, 2007; Nili and Afroughsabet, 2010; Islam et al., 2022; Zhong and Zhang, 2020; Ahmed et al., 2022; Jun Li et al., 2016). This is mainly because of the physical and chemical properties of polypropylene fibers involving fibre length, surface texture, fibre characteristics, and the treatment method adopted along with properties of constituent materials, comprising the water: binder ratio, the mix design principles used, and the replacement type and amount of pozzolans utilised in the cementitious mixture. Nevertheless, it is also largely reported in the literature that polypropylene fibres do not contribute the cement hydration due to the non-polar nature of these fibres. The chemically inert and hydrophobic nature of such fibres does explain the main causes of the strength reductions attained in concrete which is essentially the result of the more porous microstructural development within the matrix (Ince, 2019; Marinković et al., 2010; Khasreen et al., 2009; Borghi et al., 2018; Junnila et al., 2006; Goedkoop et al., 2009; Hauschild and Huijbregts, 2015; Goedkoop et al., 2009; Bagherzadeh et al., 2012; Ramujee, 2013; Khan et al., 2015; Jhatial et al., 2018; Mohod, 2015; Sun and Xu, 2009). It was therefore essential to conduct a more comprehensive assessment on the performance of concrete incorporating polypropylene fibres. Also, the majority of the studies reported in the literature address the material properties and durability characteristics of polypropylene fibre incorporation in concrete and that the environmental, sustainable, and ecological aspects of their implementation often is neglected to a large extent. There are only few studies in the literature that address the environmental and sustainable aspects of the polypropylene fibre utilisation in concrete. For instance, Yin et al. (2015) discussed the cost and environmental benefits of plastic fibers in concrete whereas Soloaga et al. (2014) reported the ecological footprint of recycled plastics in concrete.

This paper therefore aims to evaluate the performance of concrete incorporating polypropylene fibres using a database approach at the first phase of the study. The database, comprised 383 data points harvested from the recent literature, enabled a comprehensive assessment to be established through the linear regression analysis to determine the optimum use of polypropylene fibres and pozzolans in concrete. Defining the boundary conditions through the regression analysis along with the use of the designated factors influencing the engineering performance of concrete incorporating polypropylene fibers was essential to determine the optimum concrete models. Established optimum models based on the set criterion were then used in the life cycle assessment of concrete incorporating both polypropylene and pozzolanic materials in the subsequent phase of the work. The life cycle assessment, based on the well-established IS0 14040, comprised climate change, ozone depletion, freshwater and marine ecotoxicity, human toxicity, fossil fuel, metal and water depletion and well as the agricultural and urban land occupation. The cost and eco-strength efficiency of concrete incorporating polypropylene fibers were also adopted to further evaluate the life cycle performance of such implementation. Finally, the proposed pathway for a waste management approach in the paper; polypropylene recycling in concrete, is compared to the existing conventional methods namely; incineration and landfilling.

The methodology consists of two foremost sections: database development of concrete incorporating polypropylene fibers and life cycle analysis of this utilisation using the optimum models established through the database approach. In the first phase of the study, a comprehensive database was constructed to elaborate the properties of mix constituents of concrete making materials and polypropylene fibres, along with the physical and mechanical properties of concrete incorporating polypropylene fibres. Key parameters influencing concrete performance, including the utilisation type and amount of polypropylene fibers, water-to-binder ratio, and replacement types and levels of pozzolans, were identified and used to establish boundary conditions. The boundary conditions, determined through linear regression analysis using the database approach, facilitated the designation of optimal additional and replacement levels for polypropylene fibers and pozzolans in concrete. This method is essential particularly because it allows decisions to be made on optimum replacement levels by encapsulating different variations in the analysis in conjunction with the critical engineering judgement in decision making providing insight understanding of the context and not solely depending on the linear regression analysis. This was also essential for defining optimum concrete models for the subsequent life cycle analysis which is conducted using the openLCA software. The LCA methodology, followed a cradle-to-gate approach, comprised climate change potential (GWP 100), ozone depletion potential (ODP), freshwater eco-toxicity (FETP), human toxicity potential (HTP), marine eco-toxicity potential (METP), water depletion potential (WDP), fossil depletion potential (FDP), particulate matter formation (PMFP), agricultural land occupation (ALOP) and urban land occupation (ULOP) for the evaluation of the polypropylene incorporation in concrete.

It must be emphasised that the majority of the focus relied on achieving better performance of concrete in terms of attaining higher strength (compressive strength in particular) when determining the optimum additional levels of polypropylene fibers in the study. Compressive strength of concrete was the most widely reported property in the database and hence frequently used in the analysis. We must report however that this fact forms one of the limitations of the study as the analysis heavily relied on the availability and extractability of the data despite some inconsistencies and omissions in the literature. It should also be summarised herein that investigating the variations in environmental conditions, material sources, origin, composition and the manufacturing or recycling processes were beyond the scope of the study and hence are generalised for simplicity when needed for the life cycle analysis. Also, the scope of the study is limited to the life cycle assessment of concrete incorporating polypropylene fibers and pozzolans therefore, the environmental circumstances, geographical locations, and constituents related to changing costs as well as the social factors related to the production, utilisation and disposal are not addressed in the study.

The study introduces a novel and comprehensive approach for the assessment of the environmental and engineering performance of concrete incorporating polypropylene fibers, harnessing an expansive database methodology for a rigorous evaluation. The database approach, encompassing a wide range of mix constituent properties and different incorporation types and levels of polypropylene fibers, provides a thorough and detailed evaluation of their use in concrete. The variation within the dataset, primarily arising from the inherent divergences in mix properties and conditions, is crucial for accurately determining the optimum concrete models incorporating polypropylene fibers. This comprehensive analysis, which accounts for a wide spectrum of mix properties, is central to ensuring that all relevant factors are considered when deciding on the optimal replacement levels. The ability to integrate this diverse range of conditions represents a key aspect of the study's novelty, enabling a more robust assessment of polypropylene fiber use in concrete. The study's originality also lies in the integration of life cycle assessment (LCA) with the optimized concrete models derived from the comprehensive database analysis. Unlike studies that rely on narrow datasets with specific mix designs and replacement levels, which are often tailored to individual scenarios, this approach ensures that the models designated for the life cycle assessment represent a broader spectrum of mix properties and conditions. Using data that captures the full range of possible variations, the study provides a more holistic understanding of the environmental implications of incorporating polypropylene fibers into concrete, making it possible to assess their life cycle impacts across different concrete formulations and conditions. This comprehensive evaluation offers a more robust and generalized framework for understanding the sustainability of polypropylene fiber utilization in concrete.

Table 1
The database.

#	Author	Year of Publication	# of data points	Water: Cement Ratio	Compressive strength (MPa) (28 days)	Split tensile strength (MPa)	Flexural strength (MPa)	Aggregate Replacement /Fibre Addition	PP Incorporation (%)	Type of Pozzolan	Amount of Pozzolan (%)
1	Islam et al	2021	16	0.45 - 0.55	15 - 28	1.5 - 2.85	–	Replacement	10 - 30	–	–
2	Hussain et al	2020	8	0.32 - 0.55	33 - 53		3.5 - 7.1	Replacement	1	–	–
3	Ahmed et al	2022	6	0.69	21 - 33		–	Replacement	8 - 40	–	–
4	Ramana et al	2021	8	0.4	30 - 38		3.55 - 6.70	Addition	0.25 - 0.5	–	–
5	Alaskar et al	2021	12	0.48 - 0.61	–			Addition	0.25 - 1.25	–	–
6	Yuan et al	2021	14	0.46 - 0.54	22 - 43	3.6 - 5.58	–	Addition	0.45 - 1.35	Slag	7.5 - 30
7	Karimipour et al	2020	69	0.32	29 - 46	3.19 - 6.10	–	Addition	1 - 2	–	–
8	Ahmadi et al	2021	3	0.44 - 0.49	33 - 38		–	Addition	0.4	–	–
9	Altalabani et al	2020	9	0.44	57 - 62	3.63 - 5.09	–	Addition	0.2 - 0.6		
10	Mohammadhosseini et al	2020	12	0.61	30 - 36	2.38 - 5.59	–	Addition	0.25 - 1.25		
11	Alwesabi et al	2020	6	0.45	21 - 48	2.3 - 5.1		Addition	0.1 - 1		
12	Mohammadhosseini et al	2020	12	0.47 - 0.59	29 - 47	2.95 - 4.4		Addition	0.25 - 1.25		
13	Mohebi et al	2019	4	0.33	59 - 67			Addition	0.15 - 0.45		
14	Karimipour et al	2020	3		32 - 36			Addition	0.1 −0.3		
15	Yang et al	2015	5	0.36	23 - 27	2.13 - 3.0	2.97 - 4.26	Addition	10 - 30	Fly ash	30
16	Akid et al	2021	12	0.56 - 0.8	26 - 34	2.33 - 4.39		Addition	0.06 - 0.18	Fly ash	15 - 30
17	Ren et al	2021	9	0.4	45 - 53			Addition	0.1 - 0.4		
18	Kilmartin-Lynch et al	2021	5	0.5	50 - 59	3.32 - 3.37		Addition	0.1 - 0.25		
19	Orouji et al	2021	24	0.28	41 - 68			Addition	0.5 - 2		
20	Reshma et al	2021	11	0.34	47 - 55	2.63 - 5.61	2.12 - 4.67	Addition	0.6		
21	Alhozaimy et al	1996	7	0.40 - 0.45	33 - 38						
22	Das et al	2018	8	0.45	33 - 39			Addition	0.5 - 1		
23	Li et al	2017	6	0.45	36 - 39			Addition	0.5 - 1.25		
24	Hsie et al	2008	8	0.6	28 - 33			Addition	0.2 - 3		
25	Li et al	2016	18	0.44	38 - 43			Addition	0.5 - 1.3		
26	Nili et al	2010	16	0.36 - 0.46	41 - 66	2.67 - 5.86	4.45 - 7.83	Addition	0.2 - 0.5	Silica fume	8
27	Islam et al	2022	12	0.35 −0.50	27 - 45			Replacement	10 - 20	–	–
28	Mazaheripour et al	2011	8	0.32	22 - 26			Addition	0.1 - 0.3	Silica fume	9.4 - 9.6
29	Zhong et al	2020	7	0.4	38 - 62	2.8 - 7.4	2.5 - 5.7	Addition	0.1 - 0.5	–	–
30	Haq et al	2022	9	0.5 - 0.63	12 - 23	1.7 - 2.8	3 - 5	Addition	0.25 - 1.25	Silica fume	10
31	Topcu et al	2007	9	0.45	28 - 36		–	Addition	0.05 - 0.08	Fly ash	10 - 20

2. Methods

2.1. Database development

The database constructed in this study describes the properties of mix constituents of polypropylene incorporation in concrete along with the physical and mechanical properties of the end product. Despite there are numerous parameters affecting the performance of concrete incorporating polypropylene fibres such as the origin and aspect ratio of the fibres as well as the degree of amorphousness and the fineness of pozzolans, the key factors involving the replacement type and amount of polypropylene fibres, water: binder ratio along with the replacement type and level of pozzolans and the short- and long-term performance of this implementations, were identified to be the most prominent parameters and therefore used to establish the boundary conditions in this study. The boundary conditions, attained through the linear regression analysis using the database approach, enabled the optimal addition and replacement levels of both the polypropylene fibres and pozzolans to be designated and hence the optimum concrete models to be defined. Development of representative concrete models was also essential for the life cycle assessment and are utilised in openLCA in the latter phase of the work.

The database contained information on the concrete mix constituents, water: binder ratio, replacement type and level of polypropylene fibres as well as the replacement type and level of pozzolans, along with the short- and long-term mechanical properties of the resulting polypropylene fibre concrete. The database utilised for the determination of optimum additional and replacement levels of polypropylene fibres and pozzolans is summarised in Table 1. Table 1 encompasses the authors of the publications, the number of data points used in the assessment, water: binder ratio, additional levels of polypropylene fibres, replacement type and level of pozzolanic materials, and the short- and long-term mechanical properties of concrete comprising polypropylene fibres used in the analysis. The polypropylene fibers reported in the studies comprising the database were all hydrophobic and did not receive any physical and chemical treatments prior to utilisation. Their length ranged from 1 mm to 2 mm, diameter from 24 μm to 40 μm, and tensile strength between 400 MPa to 550 MPa. The pozzolans referenced in the database were all complied with BS 8615–1:2019 (BS 8615-1, 2019).

The test data extracted from the literature was meticulously assessed with respect to the test procedure, mix constituents, and standards used at the first phase of the evaluation. In particular, the data set with absent information in the context of the mix constituents, replacement and/or additional levels of polypropylene fibres and pozzolans were disregarded from the database. Experimental data omitted to provide the appropriate standards for testing and inspecting were also not included in the database. Fig. 1 presents a flowchart that exemplifies the approach utilised to construct the database in this paper. It is worth noting that although a total of 433 data points on concrete incorporating polypropylene fibres were initially attained, 5 experiments which did not satisfy the aforementioned set criteria were omitted from the database for further evaluation. Establishing the assigned criteria was crucial in attaining a data set that was consistent and reliable for further analysis. Therefore, the criteria comprising the utilisation of standard mix constituent materials, standard experimentation, polypropylene properties, used types and levels of polypropylene fibers, type of pozzolans as well as the replacement type and levels of pozzolans were examined in detail before a data set or a test result was included in the database.

The database approach, comprising varying properties of mix constituents and varying incorporation types and levels of polypropylene fibers, offers a comprehensive evaluation of the utilisation of such fibers in concrete. The variation in the data, envisaged mainly due to the aforementioned divergences, is essential to be taken into account when determining the optimum concrete models comprising polypropylene fibers to encapsulate wide spectrum of conditions of this utilisation. The database approach, also comprising diverse parameters on the determination of performance of concrete incorporating polypropylene fibers, enhances robust analysis to be conducted taking into account the trends and patterns as well as the correlations between these parameters.

2.2. Life cycle analysis

Life cycle assessment (LCA), conducted in the current study, offers a methodology to assess the environmental impacts of a product or system over its complete life cycle from the extraction of raw materials to its disposal or recycling (Manjunatha et al., 2021; Muralikrishna and Manickam, 2017). The LCA comprises the energy consumption and emissions linked to a product from inception through its entire life cycle, encompassing raw material extraction, production, utilization, transportation, operation, recycling, and eventual disposal for the raw materials of all concrete constituents. Therefore, LCA is employed to evaluate the energy and material fluxes as well as environmental consequences at each phase of the product's life cycle and this process is also known as "cradle-to-grave," approach that entails assessing all stages. The LCA of the polypropylene fibers and the pozzolans, used either as an addition or as a partial replacement in concrete making in the study, however have comprised the energy consumption and emissions related to the recycling and/or treatments, preparations and operations such as washing, drying, grinding, cutting as well as the transportation of the products. The 'general category' for all types of pozzolans designated to be in the defined concrete models of the study were chosen as the specific chemical composition or performance characteristics of the pozzolans were not necessarily critical for the analysis.

The concrete models developed employ system boundaries. It is well

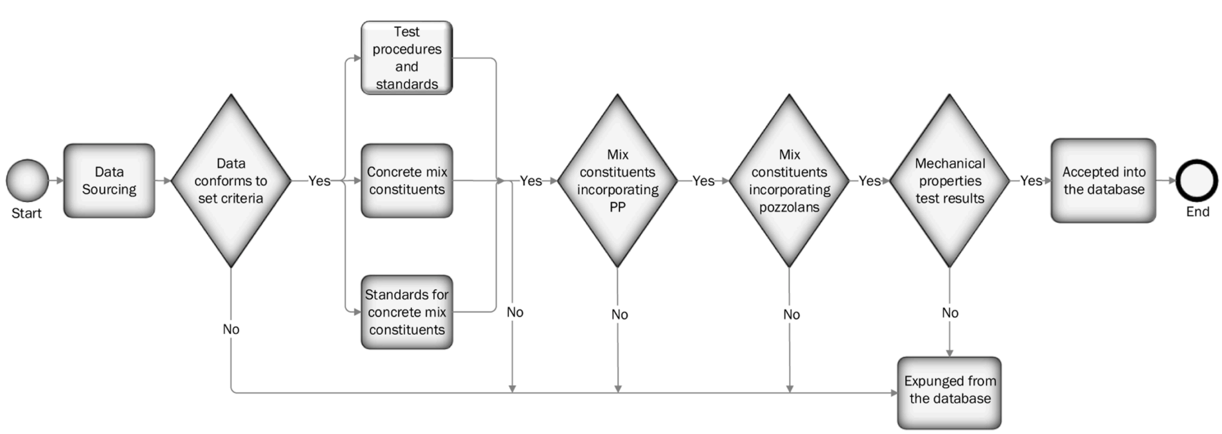

Fig. 1. Database development.

documented in the literature that the production phase constitutes the most relevant process in terms of environmental impacts (Khasreen et al., 2009; Borghi et al., 2018; Junnila et al., 2006). In this case they comprise the processing of raw materials, transportation, and manufacture of concrete. Energy consumed for the processing and transportation of the raw materials along with the mixing processes were included in the system boundaries. Fig. 2 shows the schematic flow of the system boundaries adopted.

Life cycle assessment of concrete incorporating polypropylene fibres and pozzolans, was performed using the openLCA software which is defined by the International Organization for Standardization ISO 14040 and ISO 14044 (ISO 2006a and 2006b). Goal and scope definition, life cycle inventory, impact assessment and the interpretation of the results constitute the four major phases of life cycle assessment. Climate change potential (GWP 100), ozone depletion potential (ODP), freshwater eco-toxicity (FETP), human toxicity potential (HTP), marine eco-toxicity potential (METP), water depletion potential (WDP), fossil depletion potential (FDP), particulate matter formation (PMFP), agricultural land occupation (ALOP) and urban land occupation (ULOP) are used in the life cycle assessment of concrete incorporating polypropylene fibres and pozzolans.

The main aim of the study is to evaluate the environmental and sustainable impacts of the polypropylene fibres incorporated into concrete. The concrete models encompassing the additional levels of polypropylene fibres and replacement levels of pozzolans, established through the database analysis, were employed in the life cycle assessment herein. The functional unit in the database was 1 m^3 of concrete which is consistent with Marinković et al. (2010).

Relevant data relating to transportation and production were obtained from the ecoinvent database. The methodology considered for the life cycle assessment comprised a cradle-to-gate approach for the mix constituents of concrete. ReCiPe impact assessment method, midpoint approach concerning the hierarchies is utilized to transform the inventory data into an indicator to determine the impact scores (Goedkoop et al., 2009; Hauschild and Huijbregts, 2015; Goedkoop et al., 2009). The energy consumption and emissions related activities of mix constituents of concrete, polypropylene fibers and pozzolans, used in the openLCA analysis, were defined from the 'global parameters' that represent the average global values of such activities and were kept constant throughout the models. Although the life cycle inventory (LCI) is established for most of the mix constituents, a meticulous literature survey was conducted to supply the absent inputs (Borghi et al., 2018). Foreground and background processes of concrete incorporating polypropylene fibers and pozzolans are summarised in Tables 2 and 3 respectively. It should be noted that the data sourced was obtained from ecoinvent v3.8 and that Tables 2 and 3 are comprising unit processes as the basis for each environmental step in lifecycle analysis of concrete. However, they aggregate the unit processes to demonstrate a cradle-to-gate approach, and eventually compiled in openLCA as a system process. Also, the data quality mostly fell at class 4 indicating high quality with a very few cases that fell at class 3 indicating medium quality demonstrating strong reliability of the data in each process.

Cost efficiency and eco-strength efficiency of concrete incorporating polypropylene fibers were determined. CO_2 emissions comprises the manufacturing and preparation processes of the basic constituents of concrete. The CO_2 emission factors of polypropylene and the pozzolans consider the grinding, preparation and sieving operations, the essential processes employed prior to the replacement of such materials in concrete. It must be noted that polypropylene representing the polypropylene resin recycled from used polypropylene and not a manufactured virgin polypropylene fiber in Table 4. The CO_2 emission factors and the unit local prices at the date of the study (2022) of the raw materials used in concrete making, summarised in Table 4, are used for the cost efficiency and eco-strength efficiency computations in the study.

Cost efficiency is conducted by means of the ratio of concrete compressive strength to the total cost of material per m^3 (Ince et al., 2021; 2022; 2020). The local prices of mix constituents, summarised in Table 4

4, are used to determine the total cost of concrete and concrete containing polypropylene fibers and pozzolans in dollars. Eco-strength efficiency is then determined using the ratio of concrete compressive strength to CO_2 emissions of the materials per kg (Ozturk et al., 2022).

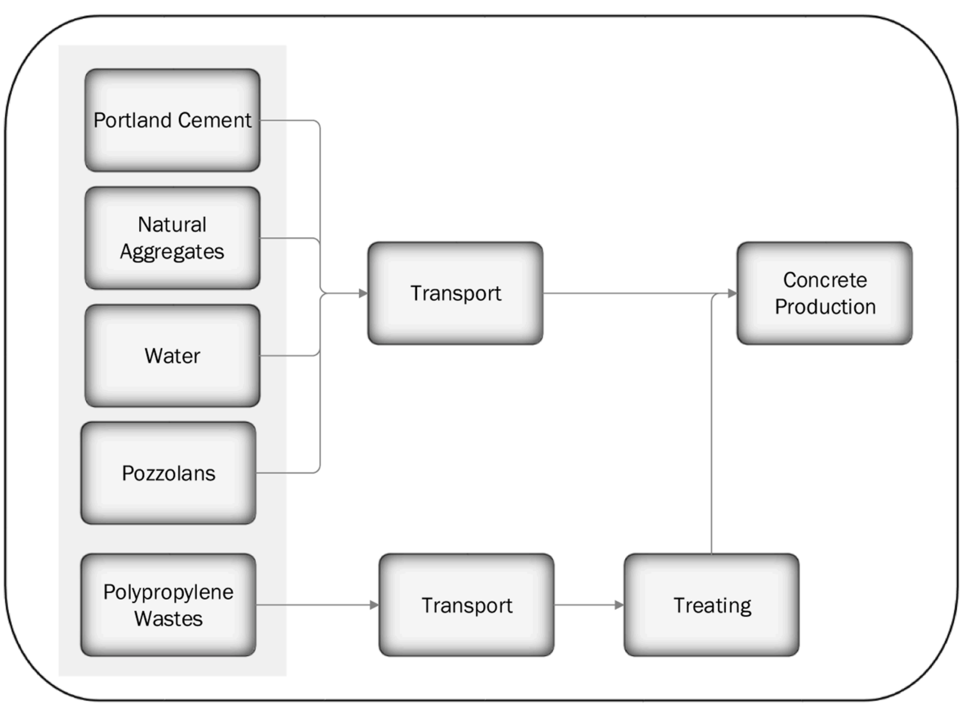

Fig. 2. System boundaries.

Table 2
Foreground processes of concrete incorporating polypropylene fibers and pozzolans.

Processes	Ecoinvent process	Input (Material / Energy)	Output (Emissions / Waste)	Unit	Impact category
Cement production	Natural Gas: 3.215280, Electricity: 0.023574	Cement, Energy (Natural Gas)	CO_2: 821.8145, CO: 4.054856, NO_x: 2.132541, SO_x: 3.368744	kg CO_2, kg SO_x kg NO_x	Global Warming Potential (GWP 100), Ozone Depletion Potential (ODP), Freshwater Eco-toxicity (FETP), Human Toxicity Potential (HTP), Marine Eco-toxicity Potential (METP), Terrestrial Eco-toxicity Potential (TETP), Water Depletion Potential (WDP), Fossil Depletion Potential (FDP), Metal Depletion Potential (MDP), Particulate Matter Formation (PMFP)
Fine aggregate production	Electricity: 0.012584	Fine Aggregate, Energy (Electricity)	CO_2: 13.8547, CO: 0.003154, NO_x: 0.014632, SO_x: 0.004872	kg CO_2, MJ	Resource Depletion, Energy Use, Global Warming Potential (GWP 100), Water Depletion Potential (WDP), Fossil Depletion Potential (FDP)
Coarse aggregate production	Electricity: 0.014052	Coarse Aggregate, Energy (Electricity)	CO_2: 45.9057, CO: 0.003847, NO_x: 0.015124, SO_x: 0.004968	kg CO_2, MJ	Resource Depletion, Energy Use, Global Warming Potential (GWP 100), Particulate Matter Formation (PMFP)
Polypropylene fiber production (from resin)	Electricity: 0.003245	Polypropylene, Energy (Electricity)	CO_2: 20.5052, CO: 0.0019055, NO_x: 0.007498, SO_x: 0.002395	kg CO_2, MJ	Energy Use, CO_2 Emissions, Global Warming Potential (GWP 100), Human Toxicity Potential (HTP), Fossil Depletion Potential (FDP)
Fly ash production	NA (Energy from transport)	Fly Ash, Transport Energy	CO_2: 15.5878, CO: 0.001307, NO_x: 0.005071, SO_x: 0.0016021	kg CO_2, MJ	Energy Use, CO_2 Emissions, Global Warming Potential (GWP 100), Marine Eco-toxicity Potential (METP)
Slag production	NA (Energy from transport)	Slag, Transport Energy	CO_2: 25.8515, CO: 0.002098, NO_x: 0.008405, SO_x: 0.0027983	kg CO_2, MJ	Energy Use, CO_2 Emissions, Global Warming Potential (GWP 100), Water Depletion Potential (WDP)
Silica fume production	NA (Energy from transport)	Silica Fume, Transport Energy	CO_2: 28.4521, CO: 0.002385, NO_x: 0.009375, SO_x: 0.003125	kg CO_2, MJ	Energy Use, CO_2 Emissions, Global Warming Potential (GWP 100), Human Toxicity Potential (HTP)
Concrete mixing	Electricity: 3.12565	Cement, Aggregates, Water, Polypropylene Fibers	CO_2: 231.54, CO: 0.88526, NO_x: 1.78502, SO_x: 0.92564	kg CO_2, kWh	Energy Consumption, CO_2 Emissions, Global Warming Potential (GWP 100), Fossil Depletion Potential (FDP), Particulate Matter Formation (PMFP), Water Depletion Potential (WDP)
Transportation (to the concrete production facility)	Diesel: 0.078625 per km	Diesel, Materials (Aggregates, Cement, etc.)	CO_2: 5752.45, NO_x: 12.5369, SO_x: 94.6651	kg CO_2, L Diesel	Transport Emissions, Resource Use, Global Warming Potential (GWP 100), Fossil Depletion Potential (FDP), Particulate Matter Formation (PMFP)

3. Results and discussions

3.1. The database approach

The database approach investigated the critical factors affecting the optimum incorporation types and levels of polypropylene in concrete. These factors, determined based on the data harvested from the literature, comprised the water: binder ratio, the replacement type and levels of pozzolans, and the short- and long-term properties on the performance of concrete incorporating polypropylene. The results generated in this section allowed independent concrete models to be determined which were crucial for the implementation of the comprehensive life cycle assessment latter in the study.

3.1.1. Determination of the optimum addition level of polypropylene

The replacement type and level of polypropylene incorporated in concrete is examined in this section. When the 383 data points, harvested for the construction of the database, were studied, it was observed that only 30 number data points indicated the utilisation of polypropylene as binder and aggregate replacement. The majority of the data points (92 %) indicated the use of polypropylene as an addition in concrete. The hydrophobic surface of polypropylene (Kakooei et al., 2012; Ince, 2019; Ramujee, 2013; Khan et al., 2015; Mohod, 2015) as well as the weak interfacial transition zone that develops within the matrix (Ahmed et al., 2020; Ince, 2019) are the main barriers to polypropylene utilisation. The common use of polypropylene in concrete is observed to be in the form of fibres. The crack bridging ability of these fibers improve the microstructural properties of the matrix substantially and hence enhances the mechanical properties of the hardened concrete (Ince, 2019; Bagherzadeh et al., 2012).

28-day compressive strength of concrete incorporating polypropylene was plotted in Fig. 3(a) which comprises 362 data points. The majority of the data points (>92 %) embodies the additional level of polypropylene to be <5 %. Fig. 3(a) shows that the rise in the additional level of polypropylene substantially reduces the compressive strength of concrete. The reduction in compressive strength of concrete is greater in specimens containing >10 % polypropylene addition. The poor interfacial properties of polypropylene as well as the non-polar nature of these fibers are largely responsible from the reduced strength (Ince, 2019). On the other hand, polypropylene fibres do not contribute to hydration reaction due to their chemically inert nature. The hydrophobic character of these fibers forms a more porous matrix particularly at the interfaces between the fibers and the paste which yield a greater reduction in compressive strength.

28-day compressive strength of concrete incorporating polypropylene was plotted versus the additional levels of polypropylene in Fig. 3(b). The additional level of polypropylene was limited to 3 % in Fig. 3(b) and contains 353 data points. The results show that the increase up to 2 % in polypropylene fiber addition results in an increase in the compressive strength of concrete. There was no significant increase in strength observed at 3 % polypropylene fiber addition. Polypropylene contents up to 2 % can act as bridges across the cracks effectively resulting in a denser microstructure with reduced fissures and fractures which improve the compressive strength of the concrete. The results demonstrated in Fig. 3(b) indicates that the optimum additional level of polypropylene can be determined to be 2 %.

Table 3
Background processes of concrete incorporating polypropylene fibers and pozzolans.

Processes	Input (Material / Energy)	Output (Emissions / Waste)	Unit	Impact category
Electricity production (grid mix)	Energy mix (coal, natural gas, renewables)	CO_2, NO_x, SO_x, PM10, CH_4	kWh, kg CO_2, MJ	Global Warming Potential (GWP 100), Particulate Matter Formation (PMFP), Fossil Depletion Potential (FDP), Water Depletion Potential (WDP)
Extraction of limestone	Limestone, Energy (Diesel, Electricity)	CO_2, NO_x, Particulate Matter	kg CO_2, MJ	Resource Depletion, Global Warming Potential (GWP 100), Water Depletion Potential (WDP), Particulate Matter Formation (PMFP),
Extraction of clay	Clay, Energy (Diesel, Electricity)	CO_2, NO_x	kg CO_2, MJ	Global Warming Potential (GWP 100), Particulate Matter Formation (PMFP), Ozone Depletion Potential (ODP), Resource Depletion
Extraction of aggregates	Sand, Energy	CO_2, NO_x, SO_x	kg CO_2, MJ	Resource Depletion, Global Warming Potential (GWP 100)
Water production (for concrete)	Water	CO_2, NO_x	m^3 Water	Fossil Depletion Potential (FDP), Global Warming Potential (GWP 100), Particulate Matter Formation (PMFP)

Table 4
CO_2 emission factors and the unit prices of constituent materials.

Constituent materials	CO_2 emission factor (kg CO_2/kg of the material)	Cost (local price in $)
Portland cement	0.82 (Collins et al. 2010)	$0.11/kg
Coarse aggregates	0.0459 (Flower and Sanjayan, 2007)	$0.008/kg
Fine aggregates	0.0139 (Flower and Sanjayan, 2007)	$0.0075/kg
Polypropylene	0.0205 (Alsabri and Al-Ghamdi, 2020)	$0.2/kg
Silica fume	0.028 King (2012)	$0.095/kg
Fly ash	0.004–0.027 (Flower and Sanjayan, 2007)	$0.080/kg
Slag	0.052–0.143 (Flower and Sanjayan, 2007)	$0.072/kg

Split tensile strength of concrete incorporating polypropylene was plotted versus the additional levels of polypropylene in Fig. 3(c) which comprises 131 data points. The spilt tensile strength was employed to re-examine the optimum additional level of polypropylene incorporation. The majority of the data points (more than >95 %) encompass the additional level of polypropylene that are up to 2 % and this is consistent with the results shown in Fig. 3(a). It is exhibited in Fig. 3(c) that the increase in the additional level of polypropylene, once again, noticeably decreases the compressive strength of concrete. The reduction attained in split tensile strength of concrete is more evidently seen with specimens containing >10 % of polypropylene used as an addition. As aforementioned, the poor interfacial transition zone as well as the non-polar nature of these fibers are responsible for the reduction in mechanical properties of concrete. The additional level of polypropylene fibers up to 2 % is shown in Fig. 3(d). It must be noted that data harvested from the literature did not include data from split tensile tests on concrete with >2 % fibre incorporation. Split tensile strength of concrete incorporating polypropylene was also plotted versus the additional levels of polypropylene in Fig. 3(d). The results shown in Fig. 3(d) illustrate that when the additional levels of polypropylene fibres are limited 2 %, their crack bridging characteristics become more influential in governing matrix densification and hence yield a considerable increase in the split tensile strength of the concrete. It must be emphasised that utilising both the compressive and split tensile strength for the determination of optimum additional levels of polypropylene fibers provided high confidence due to the very similar patterns and data distributions attained in both cases. Although much less number of data points were available for the split tensile strength of concrete, both evaluations have culminated with almost identical optimum additional levels of polypropylene fibers. It should be noted however that, the aforementioned comparative evaluation could not be followed in the later parts of the study due to the great decrease in data points available for the split tensile strength of concrete which is associated with the relevant parameters evaluated in the study.

3.1.2. *The influence of the water: binder ratio on the polypropylene addition*

The influence of water: binder ratio on the compressive strength of concrete comprising increased levels of polypropylene fibres was studied. The water: binder ratios were divided in two categories; 0.2<water: cement<0.45 and 0.45<water: cement<0.8. Compressive strength of concrete comprising polypropylene fibres was plotted versus the additional levels of polypropylene in Fig. 4(a). The results indicate that the use of high levels of polypropylene fibres yields a substantial decrease in the compressive strength of concrete regardless of the water: binder ratio. Although the use of greater water: binder ratios attributed to a smaller reduction in the compressive strength, this contradicting observation is attributed to the diverse variations of mixtures as well as the non-homogeneous data points particularly at high additional levels of polypropylene fibers. Another conceivable reason for the lower compressive strength of concrete in the lower water: binder class, is mainly because of the insufficient water available to hydrate all the cement particles due to the substantial increase in the surface area of polypropylene fibers within the matrix.

Compressive strength of concrete comprising polypropylene fibres is plotted versus the additional levels of polypropylene in Fig. 4(a). The additional levels of polypropylene fibres were limited to 3 % but the majority of the additional levels were 2 % as this was also previously determined to be the optimum use of these fibres. It is also noteworthy that Fig. 4(b) comprises 353 data points in total where 72 % of the data represents water: cement ratios between 0.2 to 0.45 and that 27 % of the data represents water: cement ratios between 0.45 to 0.80. The results shown in Fig. 4(b) clearly indicate that additions of polypropylene fibres yielded an increased compressive strength of the concrete and that this feature is valid at both water: cement ratios. More importantly, the results exhibited in Fig. 4(b) demonstrated that concrete comprising polypropylene fibres with lower water: cement ratio class (0.2<water: cement<0.45) resulted in a greater compressive strength. Comparison of this feature in Figs. 4(a) and 4(b), re-validates once again that 2 % is an optimum level of polypropylene fibres in concrete.

3.1.3. *The influence of the use of pozzolans on the polypropylene addition*

The essential role of pozzolans in concrete containing polypropylene fibres has been addressed in the previous sections of this paper. Compressive strength of concrete comprising polypropylene fibres with and without pozzolans is plotted versus the additional levels of polypropylene in Fig. 4(c). It must also be noted that Fig. 4(c) comprises 128 number of data points representing the compressive strength of concrete comprising pozzolans and 265 data points representing the compressive strength of concrete without the use of pozzolans. It is not surprising at

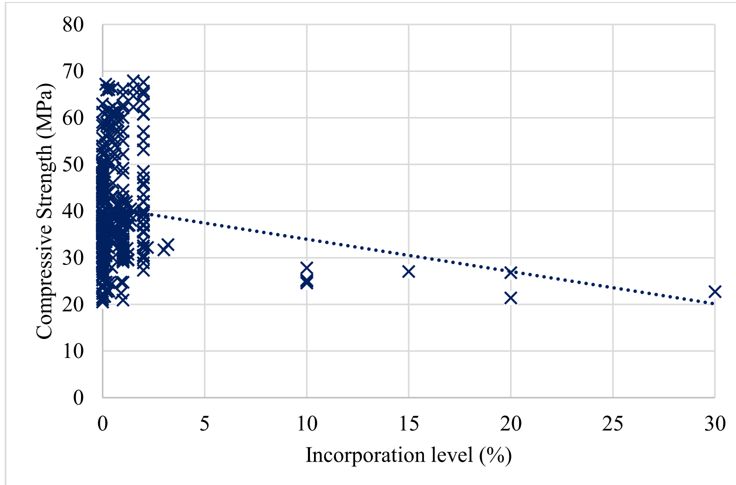

Fig. 3a. Compressive strength of concrete incorporating polypropylene fibers as addition (362 data points).

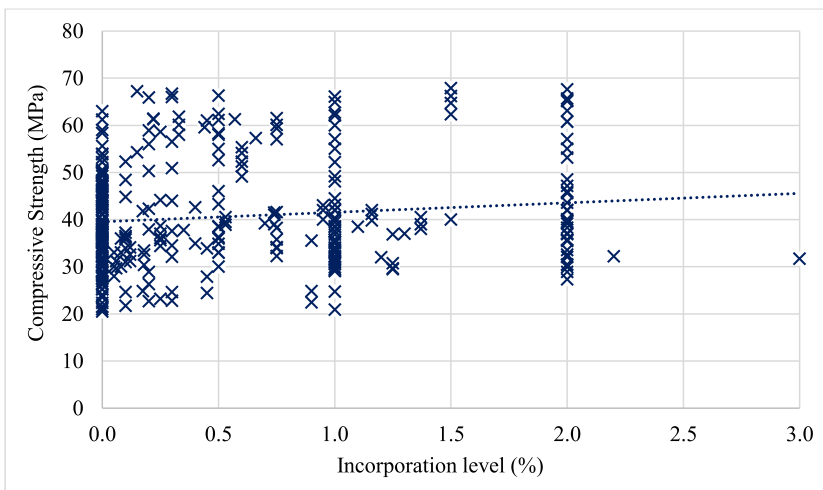

Fig. 3b. Compressive strength of concrete incorporating polypropylene fibers as addition up to 2 % (353 data points).

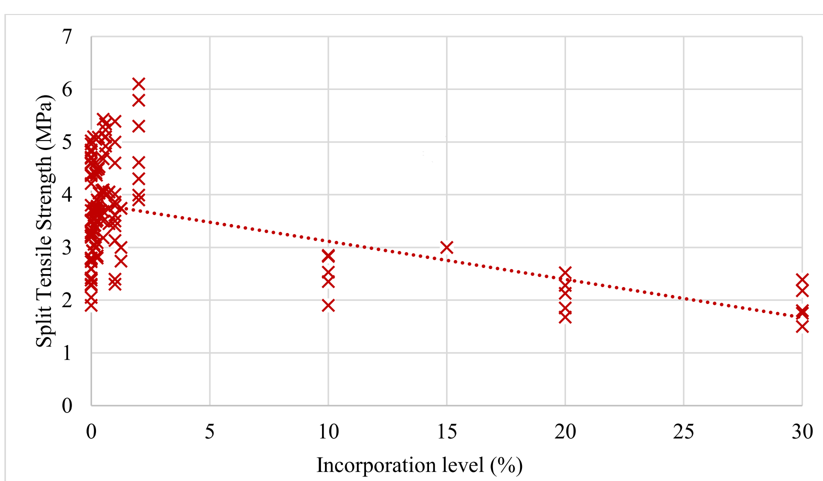

Fig. 3c. Split Tensile strength of concrete incorporating polypropylene fibers as addition up to 30 % (131 data points).

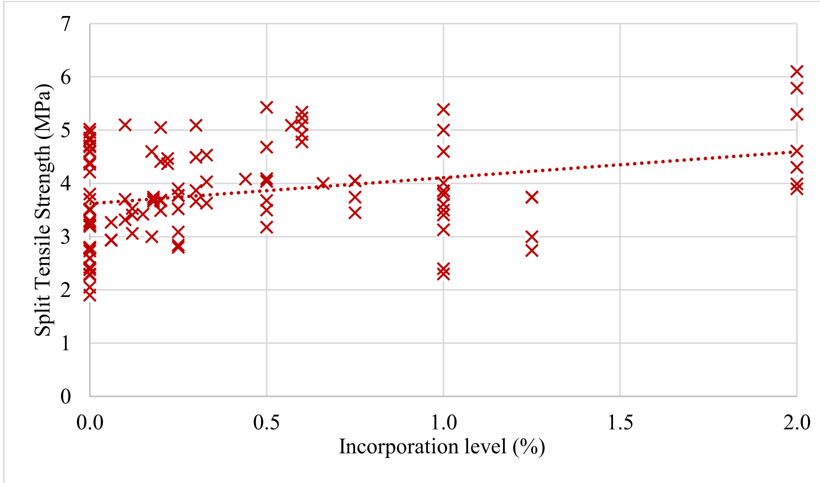

Fig. 3d. Split tensile strength of concrete incorporating polypropylene fibers as addition up to 2 % (115 data points).

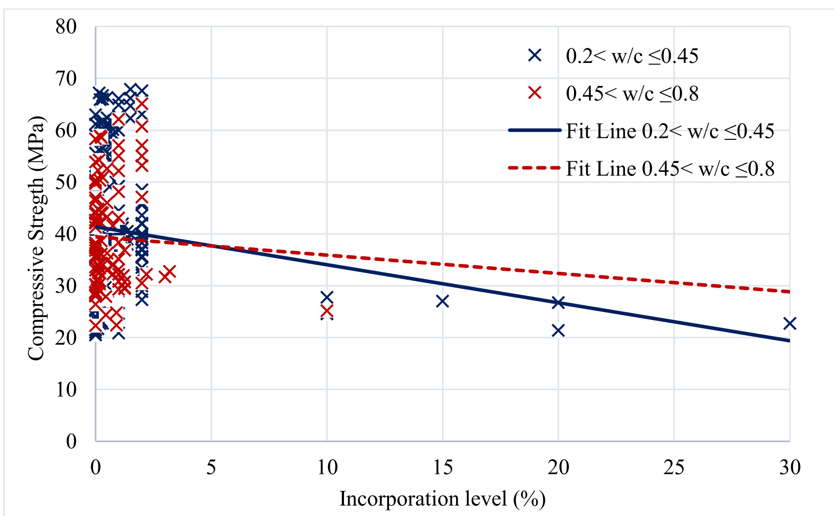

Fig. 4a. Compressive strength of concrete incorporating polypropylene fibers as addition up to 30 %;°, 0.2 < $w/c \leq 0.45$ (263 data points); □, 0.45< $w/c \leq 0.8$ (99 data points).

this stage of the study that both concrete groups yielded a reduction in compressive strength as levels of polypropylene fibres increased. It should also be noted that concrete comprising polypropylene fibres with pozzolans provided greater compressive strength compared to that of the specimens without pozzolans even at 28-days.

The levels of polypropylene fibres were limited to 3 % in Fig. 4(d). However, the majority of the data displayed up to 2 % polypropylene fibers addition as this was also determined to be the optimum amount. The substantial increase in the compressive strength of concrete comprising pozzolans is shown in Fig. 4(d) compared to concrete without pozzolans. The high fineness of pozzolans and thus the increased surface area of the solid volume fraction of fines is often responsible for densifying the matrix and therefore enabling greater mechanical properties of concrete to be attained even at early time scales. The results shown in Fig. 4(d) therefore supports the supposition proposed, that pozzolans enhance the mechanical properties of concrete comprising polypropylene fibres even during the stage of early strength development.

3.1.4. *The influence of the type of pozzolans utilized on the polypropylene addition*

28-day compressive strength of concrete comprising polypropylene fibres is plotted versus the replacement levels of pozzolans used as cement substitutes in Fig. 5(a). The most commonly used pozzolans were fly ash, palm oil fuel ash, slag and silica fume. The results shown in Fig. 5 (a) indicate that the increased replacement levels of pozzolans yield a considerable decrease in the early compressive strength development of concrete. This is attributed to the replacement of fast reacting clinker phases, such as tri calcium silicate (C_3S), with slower reacting pozzolans. Pozzolanic reaction is not only dependent on the formation of calcium hydroxide and therefore the cement hydration but is also inherently a much slower process. However, the strength activity index of a pozzolan can be determined using the ASTM C 618. Based on the short-term compressive strength results, the optimum replacement levels of fly ash, palm oil fuel ash, slag and silica fume are determined to be 30 %, 20 %, 15 % and 7.5 % respectively. These determinations also were used to define the independent concrete models essential for the life cycle assessment of the study.

3.1.5. *Short and long term compressive strength*

Short- and long-term compressive strength of concrete comprising polypropylene fibres was plotted versus the replacement levels of pozzolans used as cement substitutes in Figs. 5(b) and 5(c). Fig. 5(b) comprises 521 number of data points in total where 362 data points

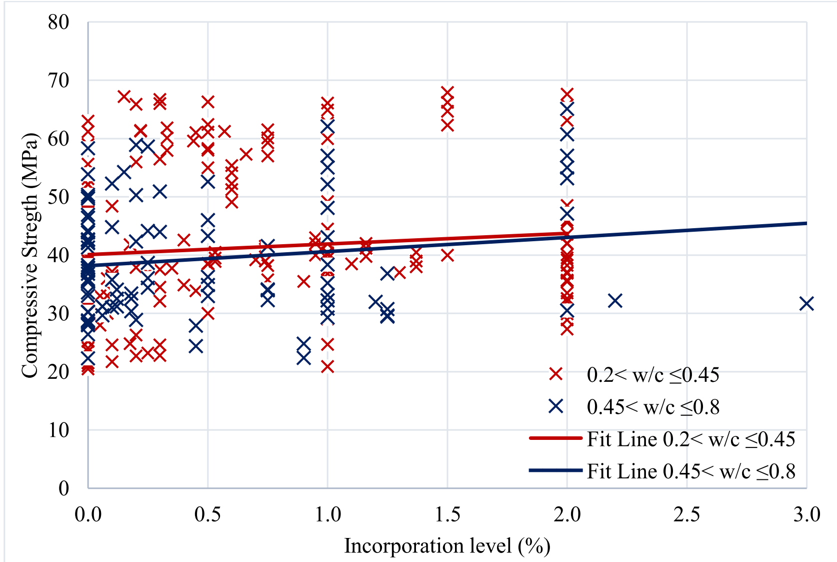

Fig. 4b. Compressive strength of concrete incorporating polypropylene fibers up to 2 %;°,0.2 < *w/c* ≤ 0.45 (256 data points); □, 0.45< *w/c* ≤ 0.8 (97 data points).

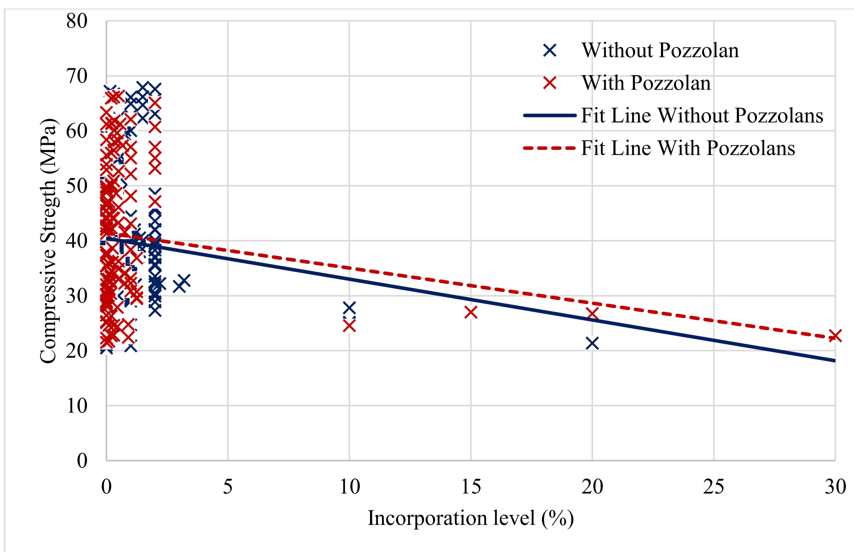

Fig. 4c. Compressive strength of concrete incorporating polypropylene fibers as addition up to 30 %; □, with pozzolans (128 data points); °, without pozzolans (256 data points).

represent short-term compressive strength and 159 data points represent long-term compressive strength. The results shown in Fig. 5(c) indicate the long-term performance of pozzolans is hindered by addition of high levels of polypropylene fibres. For instance, compared to the short-term strength results, concrete comprising pozzolans as a cement substitute resulted in a greater compressive strength over the long-term when the polypropylene levels were limited to 15 %. The long-term compressive strength of pozzolanic concrete comprising >15 % polypropylene fibers is smaller than that of the short-term. This observation is discussed in Section 3.1.2. The addition of high levels of polypropylene fibers results in a substantial increase in the surface area of the solid fractions in the mixture. This may result in a proportion of the mixing water to adsorb onto the fiber surfaces, thus resulting in a drier mix. The reduction in the consistency of concrete incorporating polypropylene fibers is well documented in the literature (Ince, 2019). Accommodating for this by increasing the water demand it important to maintain a usable consistency and progression of hydration reactions. The reduced water availability attributed to the presence of polypropylene fibers often results in incomplete hydration. This may further delay or diminish the formation of hydration products such as calcium silicate hydrate gels and calcium hydroxide which can directly reduce the rate of the pozzolanic reaction.

Short- and long-term compressive strength of concrete comprising polypropylene fibres is plotted versus the replacement levels of pozzolans used as cement substitutes in Fig. 5(b). The additional level of polypropylene was limited to 2 % in Fig. 5(c) to emphasis change up to this level. The strength increase associated with the pozzolanic reactions are most prominent over the long-term (Colak, 2002; Navrátilová and Rovnaníková, 2016; Bui et al., 2018) due to their slow nature of the reactions. The results shown in Fig. 5(c) also corroborate the assertion that when the additional level of polypropylene fibres is limited to 2 %, the influence of the pozzolanic reaction on the compressive strength of concrete could be detected. These results also support the optimum additional level of polypropylene fibres proposed.

3.1.6. *The models*

Analysis of the database compiled from the literature enabled

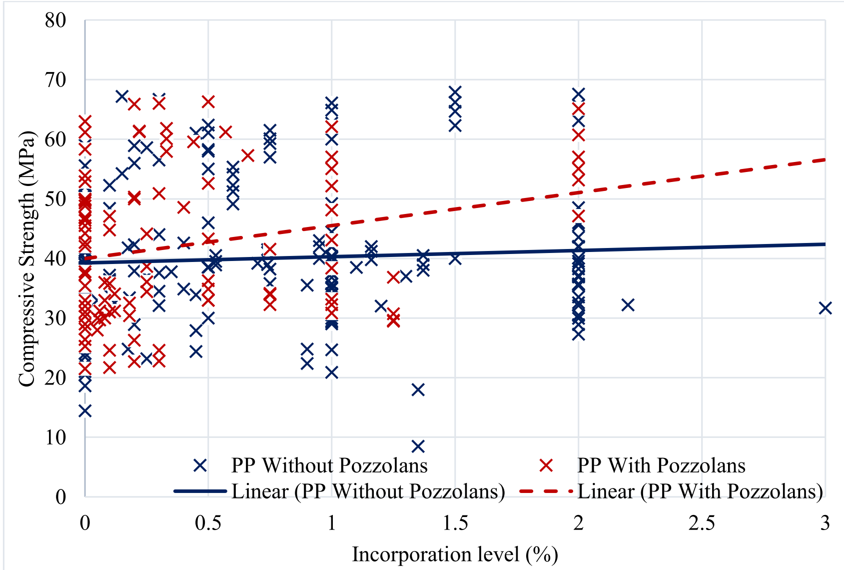

Fig. 4d. Compressive strength of concrete incorporating polypropylene fibers as addition up to 2 %; □, with pozzolans (124 data points); °, without pozzolans (256 data points).

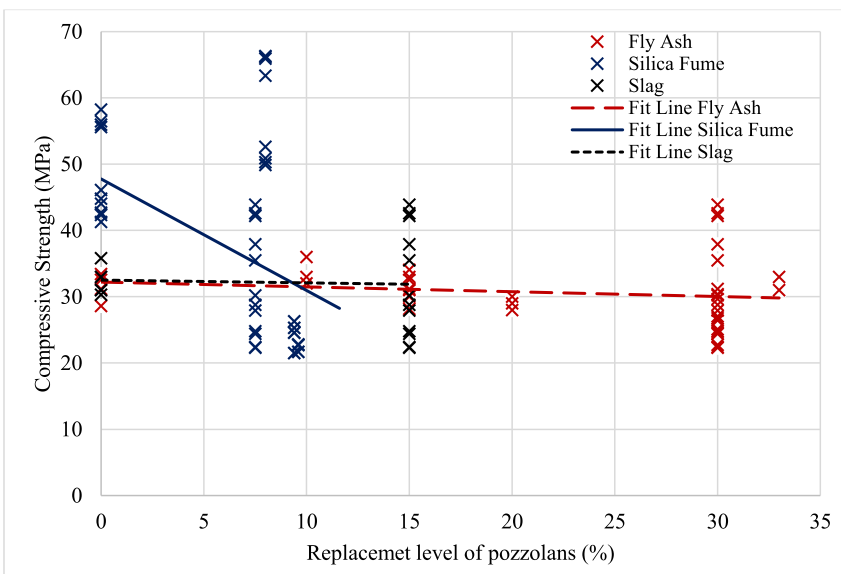

Fig. 5a. Compressive strength of concrete incorporating polypropylene fibers with varying pozzolans; °; Fly Ash (40 data points), ●; Silica fume (48 data points), □; POFA (24 data points), and ■; Slag (16 data points.

potential concrete models to be generated. Establishing concrete models was essential to perform a comprehensive life cycle analysis. These models can be divided in 3 groups. The first model represents the control concrete and is used as reference for concrete specimens with no polypropylene fiber or pozzolanic additions. The second model comprises concrete specimens that incorporate polypropylene fibers without pozzolans. The third model comprises concrete specimens incorporating polypropylene fibers with commonly used pozzolans. Models 3a, 3b, 3c and 3d were established using previously determined optimum replacement levels of fly ash, palm oil fuel ash, slag and silica fume respectively. Table 5 summarises the Models, the main constituent as well as the replacement type, and amount of polypropylene fibers and pozzolans incorporated. It should be emphasized that these models are used for the life cycle analysis detailed in Section 3.2.

3.2. Life cycle assessment

Life cycle assessment of concrete incorporating both the polypropylene fibers and pozzolans was performed using openLCA. The concrete models, precisely determined in Section 3.1, enabled the integrated life cycle analysis to be conducted. The indices used in the analysis comprised climate change, ozone depletion, fossil depletion, metal depletion, water depletion, freshwater ecotoxicity, human toxicity, marine ecotoxicity, terrestrial ecotoxicity, agricultural land occupation and urban land occupation. Cost and eco-strength efficiency, including both the sustainability indices and the engineering performance was then carried out. The sustainability indices enabled comparison of the life cycle performance to existing waste management methods such as incineration and landfilling. The life cycle inventory data for the concrete mix constituents as well as the polypropylene and pozzolans utilised in concrete for the life cycle analysis conducted using

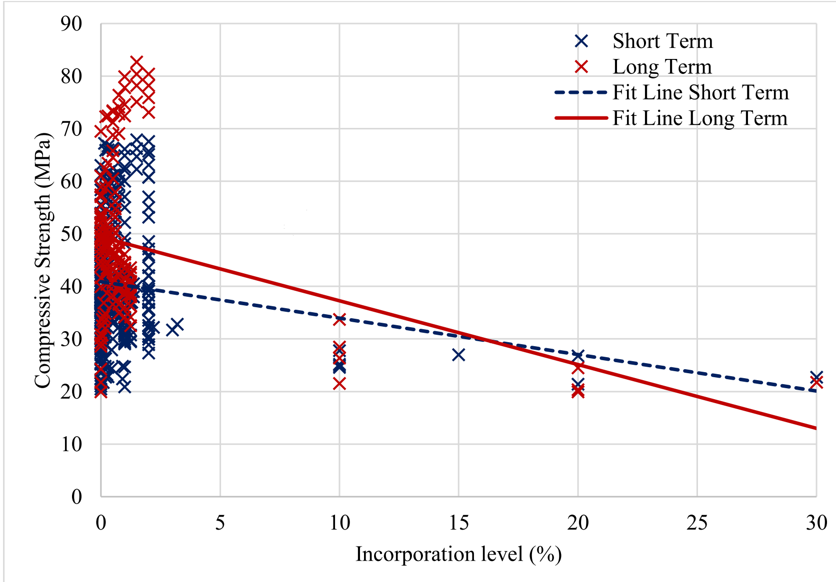

Fig. 5b. Compressive strength of concrete incorporating polypropylene fibers up to 30 %;°; Short-term (362 data points) and ●; long-term (159 data points).

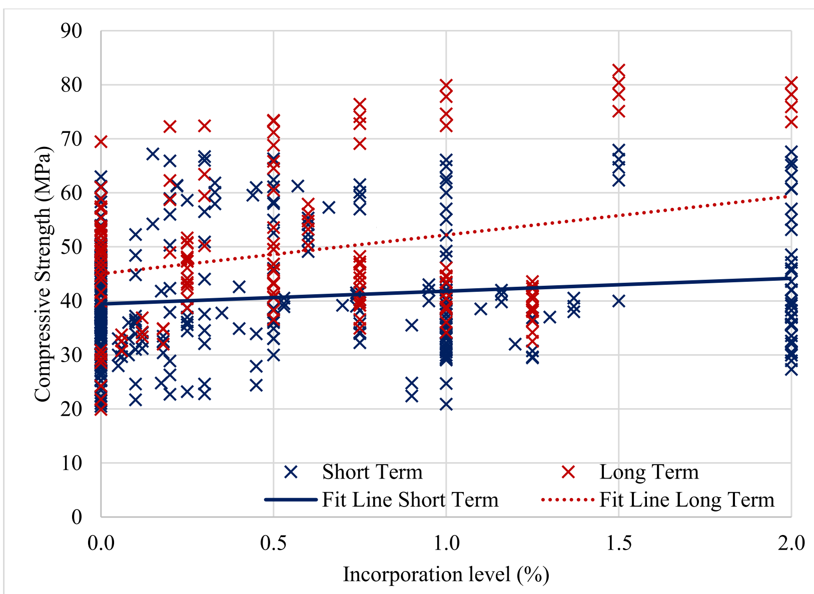

Fig. 5c. Compressive strength of concrete incorporating polypropylene fiber up to 2 %;°; Short term (351 data points) and ●; long term (151 data points).

Table 5
Established concrete models.

Model	Water (kg/m^3)	Cement (kg/m^3)	Fine Aggregates (kg/m^3)	Coarse Aggregates (kg/m^3)	The use of PP (kg/m^3)	Type of pozzolan	The use of pozzolan (kg/m^3)
Model 1 (Control concrete)							
Model 1 (Control)	184.7	425.4	784.4	936.9	NA	NA	
Model 2 (Concrete incorporating 3 % PP only)							
Model 2 (2 %PP)	184.7	425.4	784.4	936.9	18.2	NA	
Model 3 (Concrete incorporating 3 % PP and various types of pozzolans)							
Model 3a (2 %PP + 30 %FA)	184.7	299	784.4	936.9	18.2	Fly ash (FA)	127
Model 3b (2 %PP + 15 %S)	184.7	362	784.4	936.9	18.2	Slag (S)	63
Model 3c (2 %PP + 7.5 %SF)	184.7	394	784.4	936.9	18.2	Silica fume (SF)	31

Table 6
Life cycle inventory data.

	Production of Cement (kg)	Production of fine aggregate (kg)	Production of coarse aggregate (kg)	Production of concrete (1 m^3)	Production of Polypropylene (1 kg)	Production of fly ash (1 kg)	Production of slag (1 kg)	Production of silica fume (1 kg)	Transport (Medium-heavy truck) (tkm)
Energy (MJ)									
Coal									
Natural gas	3.215280								
Diesel	0.078625								
Electricity	0.023574	0.012584	0.014052		0.003245				3.12565
Emissions to air (g)									
CO	4.054856	0.003154	0.003847	0.71355	0.0019055	0.001307	0.002098	0.002385	0.88526
NO_x	2.132541	0.014632	0.015124	12.5369	0.007498	0.005071	0.008405	0.009375	1.78502
SO_x	3.368744	0.004872	0.004968	94.6651	0.002395	0.0016021	0.0027983	0.003125	0.92564
CH_4	1.001987	0.001147	0.001235	0.42586	0.000609	0.000407	0.000681	0.000759	0.241
CO_2	821.8145	13.8547	45.9057	5752.45	20.5052	15.5878	25.8515	28.4521	231.54
N_2O	0.000662	0.000052	0.000054	0.0285	0.000026	0.000017	0.0000289	0.0000335	0.006478
HCI	0.060700			2.54872					
HC	0.000576			0.02285					
NMVOC	0.033571	0.000374	0.000392	0.06954	0.000192	0.000131	0.000214	0.000243	0.47524
Particles	0.705892	0.001346	0.001395	10.8562	0.000691	0.000451	0.000751	0.000849	0.19025

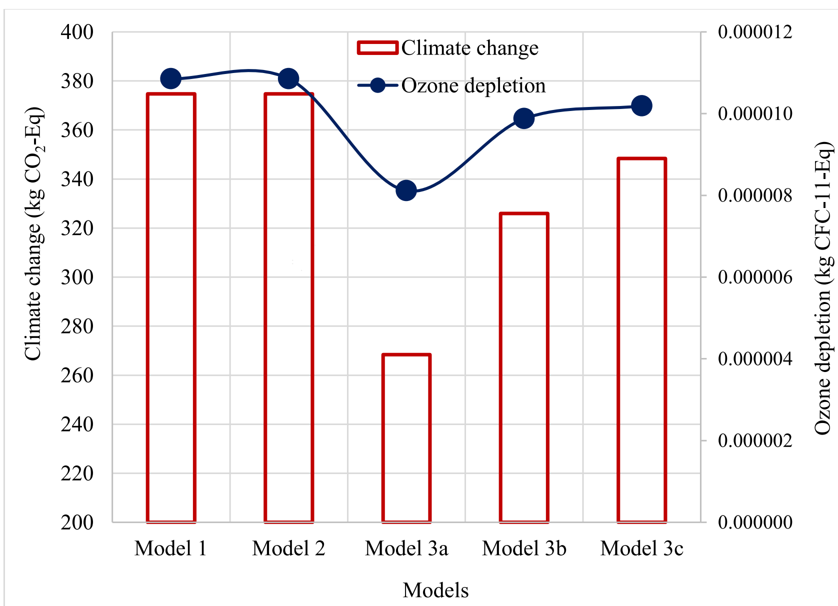

Fig. 6a. Climate change and ozone depletion potentials of concrete models.

openLCA, are summarised in Table 6.

3.2.1. Life cycle assessment of the polypropylene incorporation in pozzolanic concrete

Figs. 6(a–d) demonstrated the indicators used to assess the life cycle analysis of pozzolanic concrete incorporating polypropylene fibers. Although the inclusion of polypropylene in concrete does not make a discernible improvement in the climate change and ozone depletion, Models 3a, b, and c, of concrete containing both polypropylene fibers and pozzolans significantly decrease these indices. Model 3a, for concrete incorporating 2 % polypropylene fibers and 30 % fly ash provided the greatest reduction in the climate change and ozone depletion. While the decrease in the climate change reached 28 %, the decrease in the ozone depletion yielded >26 percent in Model 3a compared to the control Model 1 shown in Fig. 6(a). These observations are in a great agreement with the reductions in climate change and ozone depletion reported in Manjunatha et al. (2021) (Alsabri and Al-Ghamdi, 2020). The utilisation of pozzolans as a cement replacement is essential to support the successful incorporation of polypropylene fibers within the matrix which is reported to improve the mechanical properties of such materials over the long-term. It is noteworthy that the utilisation of pozzolans also played a key role in decreasing the climate change and ozone depletion. The considerable decrease attained in the ozone depletion is an indication of the decreased adverse effects of certain types of skin cancers and immune deficiency disorders (Hauschild and Huijbregts, 2015). It is also widely reported in the literature that decreasing climate change can have a considerable mitigating effect on extreme droughts and floods, sea-level rise, and biodiversity loss (Hauschild and Huijbregts, 2015; Alsabri and Al-Ghamdi, 2020; Nema et al., 2012).

The results presented in Fig. 6(b) demonstrate that including polypropylene fibers with a pozzolan binder replacement plays a significant role in decreasing the fossil, metal and water depletion. Like the results shown in Fig. 6(a), the greatest decrease attained in Models 3a, 3b and 3c can be attributed to the considerable contribution of pozzolans. It should also be emphasised that the greatest reduction attained in the

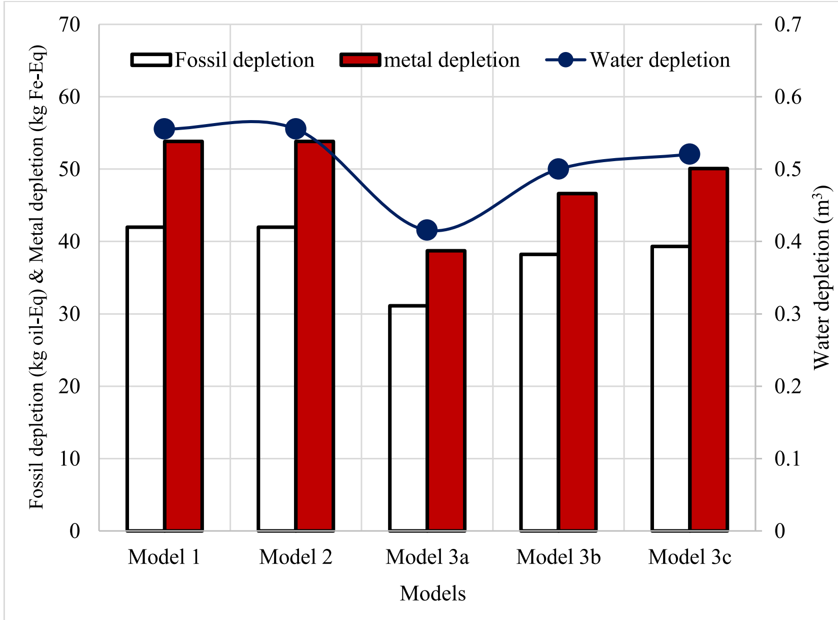

Fig. 6b. Fossil, metal and water depletion of concrete models.

fossil, metal and water depletions are in the range of 25 % to 28 % when Model 3a is compared to the control Model 1 and that these reductions are consistent with the decrease observed in climate change and ozone depletion shown in Fig. 6(a). The reduction in the fossil fuel depletion is evidently associated with the decrease attained in climate change as the reduction in the fossil fuel consumption led to a considerable decrease in greenhouse gases such as carbon (Hauschild and Huijbregts, 2015). The reduction in the fossil fuel depletion also significantly contributes to the mitigation of the hazardous air pollutants (involving the sulphur dioxide, nitrogen oxide and particulate matter etc.) which can establish environmental integrity and improved human health (Hauschild and Huijbregts, 2015). The decrease in the water depletion is also attributed to the reduction in the discharge of industrial waste water into the water sources and hence consequently reduce the pollutants and contaminants in the water resources (O'Connor et al., 2014).

Decrease in freshwater ecotoxicity, human toxicity, marine ecotoxicity, terrestrial ecotoxicity versus the particulate matter formation of concrete models are shown in Fig. 6(c). The results demonstrate that all sub-types of Model 3 performed a remarkable decrease in the aforementioned indices. The greatest decrease in the freshwater ecotoxicity, human toxicity, marine ecotoxicity, terrestrial ecotoxicity was observed in Model 3a mainly because it has the highest replacement level of pozzolans compared to Models 3b and 3c. This feature also provided the lowest particulate matter formation and hence supported the United States Environmental Protection Agency' national and regional regulation in relation to mitigate the emissions of pollutants that generates particulate matter. The diminution in particulate matter will markedly contribute the state and local governments in meeting the Agency' air quality standards (Azarmi et al., 2014). Substantial decreases observed in these toxicity indices is also an indication of reduced transformation of chemicals in the ecology and hence improved environmental sustainability and preserved ecosystem (Pradhan et al.,

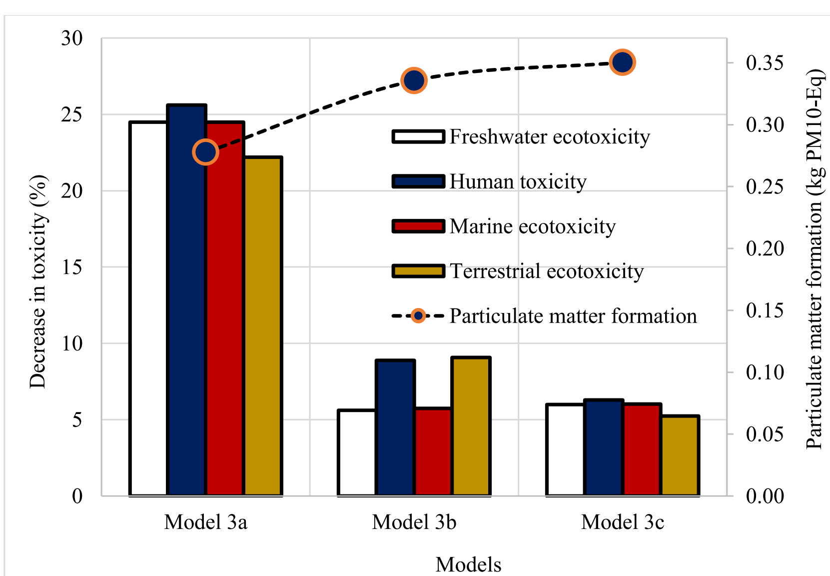

Fig. 6c. Freshwater ecotoxicity, human toxicity, marine ecotoxicity, terrestrial ecotoxicity and the particulate matter formation of concrete models.

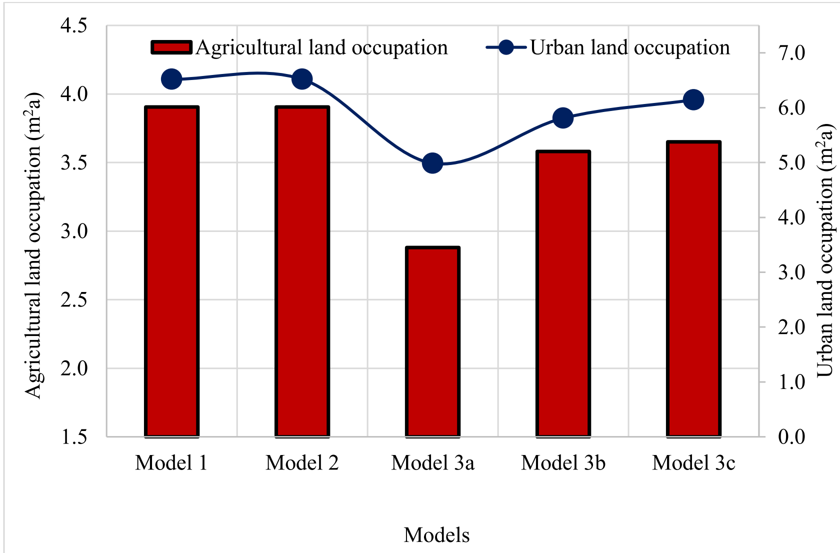

Fig. 6d. Agricultural and urban land occupation of concrete models.

2022).

Agricultural and urban land occupation versus the models examined in the study are plotted in Fig. 6(d). As anticipated, up to 26 % decrease in both the agricultural and urban land occupation is detected in all subtypes of Model 3 as a result of reduced demand on binder due to the utilisation of pozzolanic replacements. The reduction in agricultural and urban land occupation raises awareness for the appropriate determination of land usage as well as the land recyclability that requires significant adaptation to climate change (Hauschild and Huijbregts, 2015; Antón et al., 2007). It is well documented in the literature that inappropriate land usage can increase the risks associated with climate change such as increased flooding and water scarcity (Dale et al., 2011). The results shown in Fig. 6(d) also highlights the importance of land ethics as defined by Leopold which considers the 'community' as comprising not only humans, but also all the other parts of the earth including, soils, water, plants, animals and land (Leopold, 2017). The standard error for all the sustainability indices analysed in this section was computed to be <3 %. This therefore provides a high confidence on the life cycle analysis. It should also be noted that the major cause of the error is initiated from the precise determination of the raw materials used to produce concrete in this study.

3.2.2. *Cost efficiency and eco-strength efficiency*

Cost efficiency and eco-strength efficiency of concrete comprising polypropylene fibers are presented in Fig. 7(a). The results demonstrate that Model 2, concrete incorporating polypropylene fibers alone, provided considerable enhancement of these efficiencies. The analysis shown comprises both the sustainability indices and the engineering performances of concrete incorporating polypropylene fibers and hence the significance of such fiber integration in concrete comprehensively perceived. The higher compressive strength, attained through the formation of additional calcium-silicate-hydrate gels as a consequence of the pozzolanic reaction, provided improved cost and eco-strength efficiencies in all sub-types of Model 3. It is noteworthy that the greatest enhancement in cost efficiency reached up to 50 %, while the highest eco-strength efficiency yielded nearly 100 % in Model 3a, when compared to the control represented in Model 1. The results presented in this section support those in the former section by emphasising the practicability and feasibility of incorporating polypropylene into concrete to enhance the engineering performance of the end product.

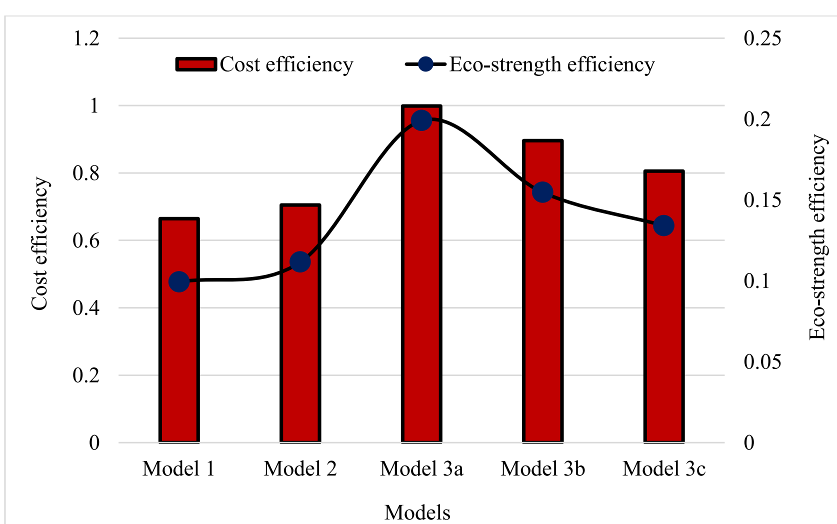

Fig. 7a. Cost and eco-strength efficiency of concrete models.

Increases in cost and eco-strength efficiencies are also in agreement with previous research by Ozturk et al. (2022_ and Ince et al. (2022).

3.2.3. Life cycle assessment of alternative waste management routes

In this section the existing waste management methods such as incineration and landfilling are addressed. Climate change, freshwater ecotoxicity and marine ecotoxicity versus waste management methods are presented in Fig. 7(b). The results show that incorporation of polypropylene into concrete provides the lowest climate change and lowest freshwater and marine ecotoxicity. While incineration was the biggest contributor for the climate change, landfilling caused the greatest freshwater and marine ecotoxicity among the waste management options examined.

Agricultural land occupation and water depletion of waste management methods are shown in Fig. 7(c). Fig. 7(c) showed that the utilisation of landfilling and incineration provides positive values for agricultural land occupation and hence demonstrates the adverse effects of such practises. The negative values of agricultural land occupation attained for incorporation of concrete is an indication of the land preservation. Correspondingly, negative values observed for water depletion through the incorporation of polypropylene in concrete, compared to incineration and landfilling, suggest the conservation of water resources for improved ecosystems. The results reported in this section reinforce the fact that polypropylene incorporation in concrete suggests a greener and cleaner waste disposal method for materials with improved engineering properties for applications in construction.

The research results reported in this study are in a great agreement with the previously published findings. For instance, the studies conducted by Yin et al., 2016, Tuladhar and Yin (2019), and Yin (2017) demonstrated that the use of polypropylene fibers exhibit over 90 % decrease in carbon emissions and up to 99 % decrease in water usage compared to the use of steel wire mesh. Similarly, the results reported in Jhatial et al. (2021) also demonstrated that the use of polypropylene fibers, along with Palm Oil Fuel Ash (POFA), and Eggshell Powder (ESP) as supplementary cementitious materials offer eco-efficient and cost-effective concrete solutions, thereby helping to mitigate environmental risks and emissions stemming from agro-industrial waste. The investigation carried out by Ozturk and Ozyurt (2022) furthermore indicated that the increase in the polypropylene fibers resulted in a reduction up to 15 % of CO_2 emissions. Although the method of adding polypropylene powders compared to that of the polypropylene fibers can be very different, the positive influence of the utilisation of polypropylene powders as a fine aggregate replacement in concrete with respect to the environmental and sustainability perspectives are also well documented in Javadabadi (2019) and Ersan et al. (2020). It is evidently shown in the current study that the incorporation of polypropylene fibers coupled with the use of pozzolans enabled resource efficiency and waste reduction that lead to a reduced environmental impact and therefore the mitigation of climate change with enhanced ecosystem preservation and sustainable construction practices.

4. Conclusions

The study evaluated the performance of concrete incorporating polypropylene fibres using a database approach comprising 383 data points harvested from the recent literature. The database analysis, through the linear regression, used to investigate the critical factors affecting the optimum incorporation types and levels of polypropylene and pozzolans in concrete. These factors, determined based on the data harvested from the literature, comprised the water: binder ratio, the replacement type and levels of pozzolans, and the short- and long-term properties on the performance of concrete incorporating polypropylene. This comprehensive assessment was essential in obtaining the independent concrete models for the implementation of the systematic life cycle assessment latter in the study.

The results reported evidently showed that the optimum addition of polypropylene fiber in concrete should be 2 % when compressive and split tensile strength particularly were used to define the boundary conditions in the study. Higher levels of fiber additions to the matrix were found to be incompatible within the cement matrix. This was mainly due to the chemically inert nature and hydrophobic texture of the fibers that yielded development of a microstructure with higher porosity and decreased strength of the hardened concrete. It is also recognised that the utilisation of pozzolans in concrete incorporating polypropylene was essential to compensate the adverse effects of the mechanical properties attributed to the inclusions of fibers. The designated types and optimum replacement levels of pozzolans, used as a substitute to cement in the study through the database analysis, found were 30 % fly ash, 15 % slag and 7.5 % silica fume.

The life cycle assessment of the precisely determined models demonstrated that all sub-types of Model 3, concrete incorporating polypropylene fibers and pozzolans, provided the greatest reduction in the majority of indices used in the assessment. The results reported in the paper has shown that the utilisation of 30 % fly ash with the use of 2 % polypropylene fibers (shown in Model 3a) yielded up to 28 % decrease in the climate change and a subsequent 26 % decrease in the ozone

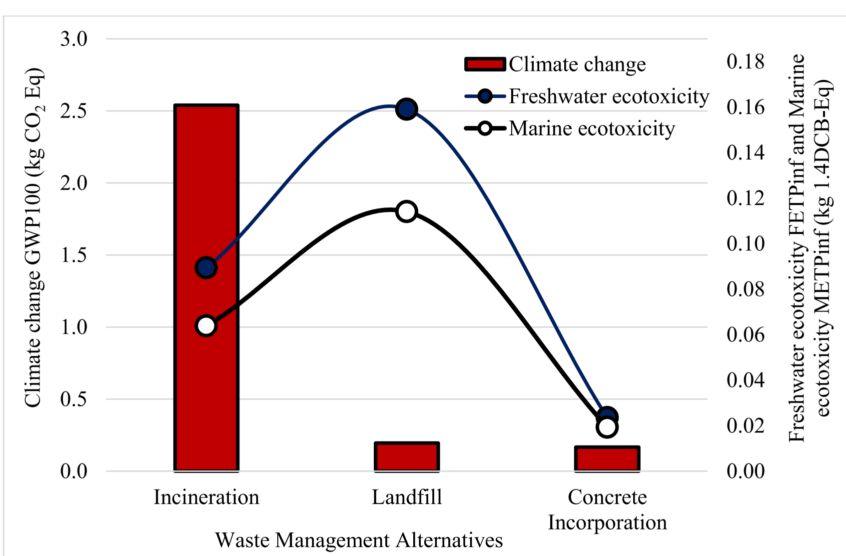

Fig. 7b. Climate change, freshwater ecotoxicity, and marine ecotoxicity of waste management alternatives.

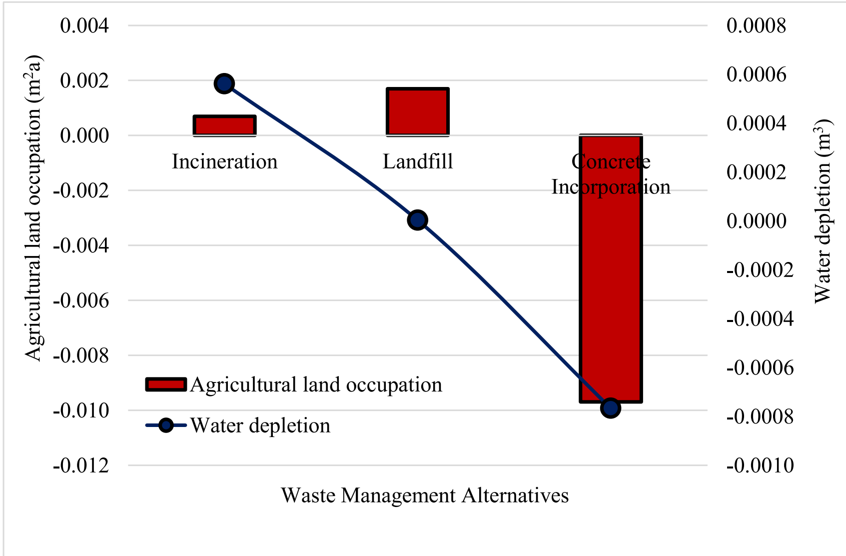

Fig. 7c. Agricultural land occupation and water depletion of waste management alternatives.

depletion compared to the control Model 1. It was evidently shown in the study that the utilisation of pozzolans along with the polypropylene fibers in concrete enabled a considerable reduction also in the fossil, metal and water depletion, freshwater and marine ecotoxicity and particulate matter formation, along with the agricultural land occupation. The aforementioned reduction of these indices, employed in the life cycle assessment, have been shown to improve human health, mitigate against extreme droughts and floods, alleviate hazardous air pollutants, enhance environmental sustainability and preserve the ecosystem. Considerable reductions attained in the agricultural and urban land occupation also raises awareness of land recyclability and ethics.

The increased cost and eco-strength efficiency of concrete incorporating polypropylene alone set an additional consideration with respect to the practicability and feasibility of incorporating polypropylene fibres in concrete through the engineering performance of the end product. It is remarkable to note that the greatest enhancement in cost efficiency reached up to 50 %, while the highest eco-strength efficiency yielded nearly 100 % in Model 3a (concrete comprising 30 % fly ash and 2 % polypropylene fibers), when compared to the control represented in Model 1. Life cycle performance of polypropylene incorporated in concrete, proposed as a new pathway, is then compared to incineration and landfilling. Results demonstrated that incorporation of polypropylene in concrete provided the lowest climate change and lowest freshwater and marine ecotoxicity, along with improved land preservation, water resources conservation and ecosystems. The results reported in this study suggest that the utilisation of polypropylene fibers, particularly when accompanied with pozzolans could reduce the global warming potential and other associated indices such as ozone and water depletion potentials. This would enable not only production of greener construction materials, but also contribute to the environmental preservation and sustainable development of ecosystems by offering a cleaner disposal method for waste polypropylene.

The study offers a robust database methodology that can be adopted as a model in similar context. The statistical analysis further enhanced the credibility of the study's findings and that enlighten the optimised models to be determined. The integration of LCA into the work adds a holistic perspective in evaluating the environmental and sustainable impact of such implementations. The authors suggest further investigations on optimising the content of polypropylene fibers in concrete taking into account more specific scenarios such as maximising the mechanical properties including tensile strength and spilt tensile strength, including the origin, composition recycling process of polypropylene fibers, fiber lengths, surface texture as well as treatment methods of fibers used to enhance the compatibility of fibers within the cementitious matrix. It is also suggested that the future research could also explore the incorporation of other types of plastic wastes such as recycle plastics from different sources or industrial by-products in concrete. The long-term durability characteristics of such implementations should also be comprehensively studied through an extensive experimental work.

CRediT authorship contribution statement

Daniel Nwaokete: Writing – original draft, Formal analysis, Data curation. **Ceren Ince:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Shahram Derogar:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Demetris Nicolaides:** Writing – original draft, Data curation, Conceptualization. **Richard James Ball:** Writing – review & editing, Writing – original draft, Formal analysis, 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.

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Data availability

No data was used for the research described in the article.

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