DATABASE STUDY ON THE SUSTAINABILITY ASSESSMENT OF PLASTIC WASTE UTILIZATION IN CONCRETE: TOWARDS THE DEVELOPMENT OF SUSTAINABLE WASTE MANAGEMENT ROUTE

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CHIMA DANIEL NWAOKETE

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Prof. Dr. Cumali Sabah
Chairperson

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science

Assoc. Prof. Dr. Ceren
İnce Derogar
Program Coordinator

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. Ceren
İnce Derogar
Supervisor

Examining Committee Members

Assoc. Prof. Dr. Ceren İnce Derogar	METU NCC/SEES	
Asst. Prof. Dr. Çanras Batunlu	METU NCC/EEE	
Asst. Prof. Dr. Ali Baştaş	EMU/IE	

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Name, Last name: Chima Daniel Nwaokete

Signature:

ABSTRACT

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Nwaokete, Chima Daniel
Master of Science, Sustainable Environment and Energy Systems Program
Supervisor: Assoc. Prof. Dr. Ceren Ince Derogar

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The non-biodegradable nature of most plastic waste has devastating impacts on ecosystems, the biophysical environment, and human health. The current waste management alternatives such as landfilling, incineration and recycling are often accompanied by adverse effects on the environment. Although concrete incorporating polypropylene and polyethylene terephthalate has been investigated in the literature, the diverse use of these plastics along with the variances in the mix concrete constituents has brought along contradicting research results in the literature. This study, therefore, aims to evaluate the life cycle performance of concrete incorporating polypropylene and polyethylene terephthalate using the database approach. 635 data points sourced from research studies, utilized to construct the database in this study, enabled a comprehensive establishment of the optimum use of the polypropylene, polyethylene terephthalate and pozzolans in concrete. Established concrete types were then used to perform the life cycle assessment of concrete incorporating polypropylene, polyethylene terephthalate and pozzolanic materials. The results reported herein suggest that the utilisation of waste plastics, particularly when accompanied by pozzolans could substantially reduce the global warming potential and the other associated indices such as ozone and water depletion potentials. It is also eminently exhibited in the study that the incorporation of waste plastic in concrete, the proposed waste management approach, could substantially reduce the life cycle indices and hence enables not only greener construction materials to be produced but also vitally contributes to environmental preservation and sustainable development of the ecosystems by offering waste plastics a cleaner disposal method.

Keywords: Plastic waste, recycling, database, life cycle analysis.

ÖZ

BETONDA PLASTİK ATIK KULLANIMININ SÜRDÜRÜLEBİLİRLİK DEĞERLENDİRMESİNE İLİŞKİN VERİTABANI ÇALIŞMASI: SÜRDÜRÜLEBİLİR ATIK YÖNETİMİ GÜZERGAHININ GELİŞTİRİLMESİNE DOĞRU

Nwaokete, Chima Daniel
Yüksek Lisans, Sürdürülebilir Çevre ve Enerji Sistemleri Programı
Tez Yöneticisi: Assoc. Prof. Dr. Ceren Ince Derogar

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Çoğu plastik atığın biyolojik olarak parçalanamayan doğası, ekosistemler, biyofiziksel çevre ve insan sağlığı üzerinde yıkıcı etkilere sahiptir. Düzenli depolama, yakma ve geri dönüşüm gibi mevcut atık yönetimi alternatiflerine genellikle çevre üzerinde olumsuz etkiler eşlik etmektedir. Polipropilen ve polietilen tereftalat içeren beton literatürde geniş çapta çalışılmış olmasına rağmen, bu plastiklerin farklı kullanımları ve karışım beton bileşenlerindeki farklılıklar, literatürdeki çelişkili araştırma sonuçlarını beraberinde getirmiştir. Bu nedenle bu çalışma, veri tabanı yaklaşımını kullanarak polipropilen ve polietilen tereftalat içeren betonun yaşam döngüsü performansını değerlendirmeyi amaçlamaktadır. Literatürden derlenen ve bu çalışmada veri tabanı oluşturmak için kullanılan 635 veri noktası, betonda polipropilen, polietilen tereftalat ve puzolanların optimum kullanımının kapsamlı bir şekilde kurulmasını sağlamıştır. Yerleşik beton türleri daha sonra polipropilen, polietilen tereftalat ve puzolanik malzemeler içeren betonun yaşam döngüsü değerlendirmesinde kullanıldı. Burada bildirilen sonuçlar, atık plastiklerin kullanımının, özellikle puzolanlarla birlikte kullanıldığında, küresel ısınma potansiyelini ve ozon ve su tüketme potansiyelleri gibi diğer ilişkili endeksleri önemli ölçüde azaltabileceğini göstermektedir. Önerilen atık yönetimi yaklaşımı olan atık plastiğin betona dahil edilmesinin yaşam döngüsü endekslerini önemli ölçüde azaltabileceği ve bu nedenle yalnızca daha çevreci inşaat malzemelerinin üretilmesini sağlamakla kalmayıp aynı zamanda atık plastikleri daha temiz bir şekilde bertaraf etme yöntemi sunarak çevrenin korunmasına ve ekosistemlerin sürdürülebilir gelişimine hayati bir şekilde katkıda bulunmaktadır.

Anahtar Kelimeler: Plastik atık, geri dönüşüm, veri tabanı, yaşam döngüsü analizi.

Dedicated to

Jude Nwaokete

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TABLE OF CONTENTS

CHAPTERS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ABBREVIATIONS

PP	Polypropylene
PET	Polyethylene terephthalate
RWP	Recycled waste plastic

CHAPTER 1

INTRODUCTION

1.1 Background

Today, a world without plastics seems unthinkable. Plastics are sophisticated, lightweight, and inexpensive making them ideal for a variety of applications [1 – 6]. The durability and versatility of plastics coupled with the growth of the plastic industry have led to a significant increase in the volume of plastic items manufactured each year [1, 3]. The issue with plastic does not arise from its use phase, but from the mode of disposal when its useful life is over. [4, 8]. Plastic wastes are seen to float on oceans, clog canals, litter cities, and destroy marine ecosystems [6, 9, 10]. They do not biodegrade, and thus, remain in the environment for a very long time [1, 8, 11]. Of the total number of plastics produced since 1950, only 9 percent of all plastics have been effectively recycled, with over 79 percent of these plastics disposed of in dumpsites and surrounding environment [12]. Every year, 4 to 12 million metric tons of waste plastic are estimated to find their way into the ocean [13], and by 2050, The World Economic Forum estimates that there would be more waste plastic than fish in the oceans. [14, 15, 16].

While landfills have been the conventional approach for handling plastic wastes, obtaining land for such purposes has grown increasingly difficult in recent times with an increasing amount of waste being generated [1, 3, 17]. 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 [1, 19, 20]. 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 [1, 3]. Incineration of plastic wastes, with or without energy recovery, is another approach for handling plastic wastes to reduce the waste load in landfills. However, the environment and human health are adversely imperilled by the discharge of hazardous compounds during the combustion of plastic waste. [1, 21 - 25]. Exhaust gases from an incinerator may contain potentially harmful substances such as carbon monoxide, oxides of sulphur, oxides of nitrogen, acid gases, metals (lead and mercury), dioxins, furans, polycyclic aromatic compounds, chlorinated volatile organic compounds as well as particulate matter [1, 21 - 26]. Recycling plastic waste, though 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 waste into another reusable form. In comparison to landfilling or incineration, recycling seems to be a more advanced method of disposal because it limits the production of new plastics. However, these plastics could only be reused just once or twice. [28]. This indicates that the majority of recycled plastic is eventually disposed of or incinerated. [8, 28]. Moreover, recycling could be considered inefficient as it consumes high amounts of energy and provides diminished reliability of the products formed when contrasted with the initial products [10].

A more viable approach for handling plastic wastes with minimized environmental harm is reported to be the incorporation of such wastes in mortars and concrete as complete or partial replacement of aggregates or as fibre additions [18, 29 - 37]. Cement, sand, crushed stone, and water commonly forms the mix constituents for concrete [38 - 40]. The most common building material used globally is concrete. [41 - 44]. 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 [43 - 45]. 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 [46 - 50]. Between 2017 and 2020, the amount of cement consumed worldwide surged by 23.7%, from 4,257 to 5,266 million tonnes [51]. Typically, 0.927 tonnes of CO_2 are released for every tonne of cement manufactured [52, 53], and cement production accounts for around 5% of global CO_2 emissions [52, 54]. On the other hand, in addition to making up 65 to 80 percent of the total volume of the concrete mix, aggregates also significantly influence its qualities in the fresh and hardened states. [55, 56]. This implies that substantial amounts of these aggregates are being consumed to meet the global demand for concrete manufacture [57]. Therefore, the energy consumed in processes to attain the right form 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 [58, 63]. According to estimates, the market for aggregates exceeded 51.7 billion tonnes in 2019.. This implies a 5.2 percent 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 [57]. The development of infrastructure and growing personal incomes also in developing countries further contributed to the increased demand for the mix constituents of concrete [57, 59]. Numerous research has been done to determine how incorporating waste plastic into concrete affects its fresh and hardened properties. However, there has not been sufficient consideration given to the environmental, sustainable, and ecological aspects of this research. Moreover, while some research reported improved mechanical properties of concrete when waste plastic are incorporated, several investigations showed a diminution of these properties. Establishing the optimum replacement limit for the effective incorporation of plastic waste in concrete is thus paramount.

1.2 Objective of the Study

While plastics can be recycled, it must be emphasized that not all plastics can be recycled via conventional means. This thesis, thus, will evaluate the performance of concrete incorporating 2 types of plastic wastes namely Polypropylene (PP) and, Polyethylene terephthalate (PET). Asides from PET, PP cannot be easily recycled using conventional mechanical or chemical recycling. The database comprised 635 data points sourced from research studies enabled the optimum replacement levels and types of these wastes to be determined together with the use of pozzolans. These boundary conditions established the possible concrete types to be considered for the environmental impact assessment, eco-strength and cost efficiency of concrete incorporating plastic waste.

1.3 Organization of the Thesis

This thesis is organized into nine chapters. Chapter one describes the background of the study, the research gap, and the aims and objectives of the thesis. In chapter two, a deeper look at previous research findings is provided. Chapter three details the approach utilized in developing the database of concrete containing plastic waste and pozzolans. Chapter four discusses how the database developed is analysed to obtain causal relationships between parameters. The chapter also discusses the life cycle assessment methodology, concrete CO_2 emissions, eco-strength, and cost efficiency calculations. Chapter five and six provides the results of the durability and mechanical properties of pozzolanic concrete containing polypropylene and polyethylene terephthalate plastic waste respectively. Chapter seven discusses the results of the life cycle and sustainability analysis of concrete incorporating polypropylene and polyethylene terephthalate, while chapter eight presents a detailed conclusion of the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Plastic Production and Waste Generation

Plastics are typical contemporary materials with a wide range of applications and uses. Plastic, in its broadest sense, refers to a material or substance that may be easily formed or moulded while soft and then allowed to set into a slightly elastic or solid form [64]. They are normally manufactured by polymerizing monomers obtained from oil or gas and then adding other chemical additives to achieve the desired plastic grade. Plastics are phenomenally durable, versatile, lightweight, cheap, strong, corrosion-resistant, and have excellent thermal and electrical insulating capabilities [1 – 6, 64]. The last five decades ushered in a tremendous increase in the demand and application for plastic products as shown in the figure below.

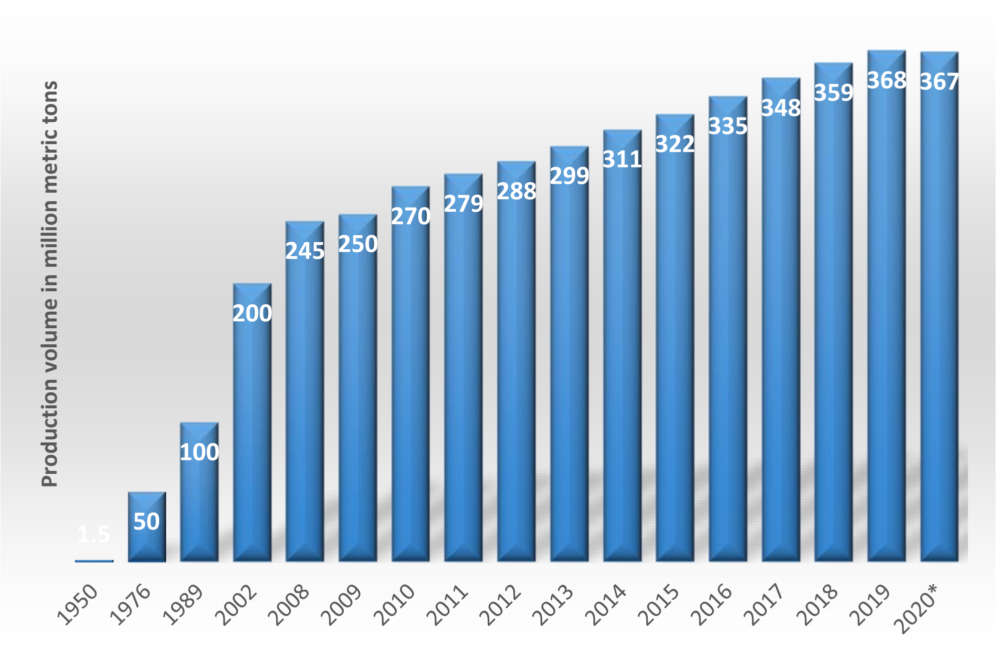


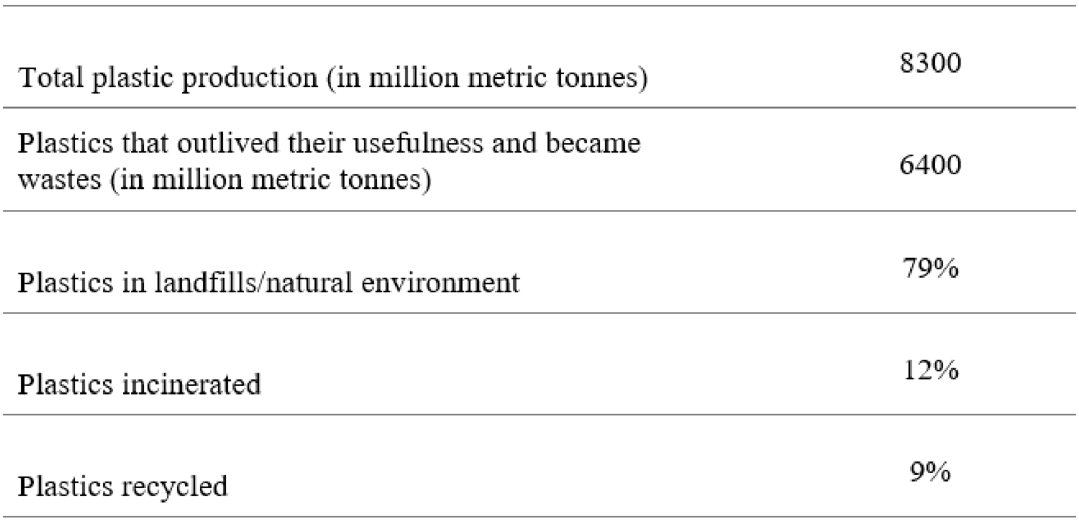
Figure 2.1 *Plastics produced globally from 1950 to 2020 [7]*

Global plastic production grew more than two hundredfold to 367 million metric tonnes in 2020, up from 1.5 million metric tonnes in 1950 [7]; approximately 4 percent of crude oil produced globally is used as feedstock for plastic production and about the same amount of oil is used as energy to drive plastic production processes [6]. Petroleum-based plastics' intrinsic non-biodegradability has created significant concern for the environment because of their relative amounts in waste streams. Plastic's durability and widespread use provide a considerable waste management issue, with plastics contributing to around 10% of all waste produced. While some of it is recycled, most of it is discarded in landfills [27]. Only 9% of all plastics made since 1950 have been efficiently recycled, with the remaining 79% disposed of in dumpsites or the surroundings [12]. These wastes have been found floating in the oceans, clogging waterways, littering cities, and degrading marine habitats. According to the World Economic Forum, the ocean will contain more plastic waste than fish by 2050 [14].

2.2 Existing Plastic Waste Management Approach

In general, plastic wastes have three distinct fates. First, they can be disposed of in regulated facilities such as in sanitary landfills or left unmanaged in open dumps or the natural environment [1, 8]. Second, plastic wastes can be thermally decomposed; although new methods are emerging, such as pyrolysis, which recovers fuel from the plastic waste, practically all thermal decomposition has been accomplished by incineration, with or without energy recovery options [8]. Finally, plastic waste may well be recycled or transformed into another item [8].

Table 2.1 Plastic produced and waste generated globally from 1950 to 2017 [7]



Total plastic production (in million metric tonnes)	8300
Plastics that outlived their usefulness and became wastes (in million metric tonnes)	6400
Plastics in landfills/natural environment	79%
Plastics incinerated	12%
Plastics recycled	9%

2.2.1 Landfills

Traditionally, landfills have been used for plastic and municipal waste management, but due to an increase in waste generation in some countries, it has become harder to find available land for landfills [1, 3 17]. Due to the degradation of plastic products and additives, plastic wastes at landfill sites can pose long-term risks of soil and groundwater contamination [1, 19, 20]. The inability to salvage any material resources used in the production of plastic continues to be a major drawback of landfills for the disposal of plastic waste [1, 3].

2.2.2 Incineration

Plastic waste can be incinerated either with or without energy recovery. The volume of waste in landfills is decreased via incineration. However, the emission of harmful compounds during the burning of plastic wastes raises serious issues for both the environment and human health [1, 21–25]. Carbon monoxide, sulfide and nitrogen oxides, acid gases, metals (lead and mercury), dioxins, furans, polycyclic aromatic hydrocarbons, chlorinated volatile organic compounds, and particulate matter are just a few of the potentially harmful substances that can be found in incinerator exhaust gases [1, 21–26].

2.2.3 Recycling

The recycling of plastic waste combines a variety of technologies to facilitate the production of secondary raw materials. In comparison to landfilling or incineration, recycling seems to be a more advanced method of disposal because it limits the production of new plastics. However, these plastics could only be reused just once or twice, as most plastic are either landfilled or combusted [28]. Instead of avoiding eventual disposal, recycling postpones it. Only if it replaces primary plastic manufacturing does it minimize future plastic waste generation; but, due to its retroactive form, this replacement is exceedingly difficult to show. Contamination and polymer mixing also produce secondary polymers with restricted or poor technical and commercial value [28]. Furthermore, recycling is largely inefficient, consuming high amounts of energy, with diminished reliability of the products formed when contrasted with the initial products [10].

2.2.3.1 Mechanical Recycling

The primary technique for recycling plastics nowadays is mechanical recycling [65]. Four processes are often involved in mechanical recycling; collection and sorting of the material, shredding the sorted material, washing, and drying, and finally melting and reprocessing to form pellets blended with virgin plastic [65]. Occasionally, clean streams of RWP are recovered. Thermoplastic polymers are usually the only materials that are mechanically recycled because after grinding and re-melting, the polymer chains formed are degraded, with diminished durability [66]. Depending on whether the waste is pre-consumer or post-consumer, mechanical recycling is often divided into primary and secondary types [67]. In most cases, pre-consumer waste is clean, single-type, and does not require further processing. In contrast, since it is heavily contaminated, post-consumer waste must undergo more complex treatment procedures such as collection, sorting, and cleaning [67].

2.2.3.2 Chemical Recycling

Thermoplastic or cross-linked polymers are recycled chemically if mechanical recycling cannot provide products of the appropriate grade [68]. Polymers can be chemically transformed into substances with less molecular weight or, occasionally, back to its initial form. Light weight molecules are employed as feed for petrochemical industries, while monomers can be re-polymerized into the original polymer once more [68]. Depolymerization, hydrolysis, and hydrocracking are often used processes for such a recycling approach [68]. Only a few polymers are economically and environmentally viable for chemical recycling, like polyether ether ketone and polymethyl methacrylate, owing to the substantial energy and chemical inputs required by these processes. Although recycling polyethylene terephthalate (PET) via chemical means has been established, the cost of processing prevents its widespread use [68].

2.3 Types of Plastics

Plastic are made based on their derived feedstock and desired applications. The following are plastics commonly found in waste streams:

2.3.1 Polyethylene terephthalate (PET)

Polyethylene terephthalate is a common plastic with a wide range of uses. It is a thermoplastic polyester, semi-crystalline with good strength, stiffness, translucency, heat and fire-resistant, and safety characteristics [69], formed from ethylene glycol and pure terephthalic acid intermediates derived from crude oil. PET is manufactured in large quantities because it is used in the textile sector as high-strength clothing fibres, packaging for food containers and beverage bottles, as well as in building and appliance industries [70].

2.3.2 Polypropylene (PP)

Polypropylene was developed in 1954 and immediately acquired widespread adoption due to its low density among common polymers. PP is derived catalytically from the monomer propylene, is chemically resistant, and may be produced using a variety of processes, including injection moulding and extrusion [71]. PP finds applications in making pipes, bottles, medical containers, household wares, electronics, and luggage boxes, among other things.

2.3.3 Polystyrene (PS)

Polystyrene is derived from the feedstock styrene and can be formed into brittle, hard, or foamed products. Polystyrene can possess characteristics of a glassy surface, stiff, transparent to opaque, high clarity, and is impacted by solvents and fats. Typical applications include disposable cups, dairy containers, switch plates, plugs, and electrical and communication equipment. Expanded or foamed types are used as insulation or packaging materials [70].

2.3.4 Polyvinyl Chloride (PVC)

It is made from the polymerization of vinyl chloride and is often used in the building sector for its weather-resistant and durability qualities, with uses including pipes, fittings, window profiles, and doors, roof gutters, ceiling tiles, electrical wire coatings, as well as for numerous furniture and upholstery purposes. PVC materials contain a variety of by-products and additives, most of which are toxic to humans, therefore the issue of whether the health dangers of PVC use exceed its many benefits persists [72].

2.3.5 High-Density Polyethylene (HDPE)

HDPE is the strongest polyethylene plastic possessing high corrosion and chemical resistance, good impact strength and rigidity, and a high melting point. Typical applications include pipes, blow moulded products such as water bottles and containers, as well as injection moulded products such as buckets and storage bins [70].

2.3.6 Low-Density Polyethylene (LDPE)

LDPE is a flexible, soft, and lightweight polyethylene plastic, with characteristic toughness and corrosion resistance. It is widely used to make carrier bags, nursery bags, heavy-duty bags, milk packaging, plastic wraps, and miniature squeeze bottles, among other things [70].

2.3.7 Polyurethane (PU)

Polyurethanes are a versatile family of materials with a wide range of possible uses, owing to their structure and characteristics. Their unique physical, mechanical, and chemical features have sparked a lot of interest in customizing PUs for various purposes, such as stiff foam for insulation in appliances, walls, and roofs, soft foam for upholstery and furniture, thermoplastic urethane in medical equipment, sealants, adhesives, coatings, footwear, and elastomers for flooring and car interiors [73].

2.3.8 Other Plastics

Other than these outlined types of plastics, which are often utilized in the engineering industry, there are many others. Nylon, polycarbonate (PC), and acrylonitrile butadiene styrene (ABS) are among the examples [73].

2.4 Plastic Waste Incorporation in Concrete

Plastic wastes are generally incorporated into concrete either as fibres or as natural aggregate replacement. Fibres find use as reinforcement in mortars and concrete, primarily to increase tensile strength and provide adequate ductility [103]. Among their advantages are high toughness, low weight, and high strength [103, 126]. These outstanding properties of fibres make them an excellent replacement for steel and asbestos frequently utilized in building airports and highway pavements [103]. On the other hand, plastic wastes are utilized in replacing natural aggregates because of their lightweight and low bulk density, and thus, find applications in making low-weight concrete. Additionally, numerous studies have noted that plastic fibres and aggregates greatly impact the mechanical and fresh properties of concrete [81, 102, 127 – 129].

2.4.1 Influence of Plastic Waste Incorporation on the Fresh Properties of Concrete

The fresh concrete mix remains in a fresh phase from the moment it is prepared until it hardens. As the consistency of the freshly mixed concrete slowly reduces after mixing is complete, the properties of hardened concrete are correlated to its fresh phase. Handling, compaction, and placement are of enormous importance for concrete in this state [35]. In addition, the quality and compaction of the mix greatly influence the durability and strength of the finished product. Thus, the workability and consistency of the fresh concrete mix are key important properties. Consequently, incorporating recycled waste plastic either as coarse or fine aggregate could considerably affect the fresh properties of concrete [35].

2.4.1.1 Workability

A key parameter for the fresh concrete mixture is its workability. It affects the ease of mixing and pouring concrete, as well as its homogeneity [75]. The workability of the fresh concrete is typically obtained using the concrete slump test. Factors that influence the workability of concrete include particle size, grading, shape, the roughness of aggregates, the amount of plasticizer used, and the water-binder ratio [75]. Thus, the workability and the amount of free water that is present in the mix are both impacted by the addition of recycled plastic waste [75]. Islam et al. [76] studied the durability properties of concrete using recycled polypropylene (PP) waste as partial replacement for up to 20% coarse aggregate. Their results showed adding recycled PP aggregate improved the workability of the concrete mix. Dhanani et al. [77] investigated the partial replacement of coarse and fine aggregates in concrete using recycled plastic waste. Their findings revealed as the amount of recycled plastic aggregates added rose to 40%, the workability of the obtained concrete was enhanced. Also, according to Tang et al. [79], up to a 40% swap of coarse aggregate with recycled plastic resulted in improved workability of the concrete mix. An improvement in workability was similarly observed for greater substitution values of 50% coarse aggregate with recycled plastic waste [80]. This is caused by the reduced water absorption of plastic aggregates, which possess a smoother exterior compared to natural aggregates and made more water available from the mixture [77, 78, 81, 82]. Conversely, it was shown that workability moderately declined at 60% and 80% recycled plastic aggregate levels [77].

However, Rahmani et al. [83] reported a reverse trend in workability when sand was replaced with recycled plastic waste. Research findings by Ismail et al. [84] showed a decreasing trend in workability and slump values as recycled waste plastic was used as sand replacement in the concrete mix. Comparable outcomes were published by Rai et al. [85] and Batayneh et al. [86]. The observed decreasing trends in workability are strongly influenced by the particle shape of recycled waste plastic [87]. Findings from several studies demonstrate that the roughness and size of the particles of recycled waste plastic impact how concrete slumps; when concrete mixtures are composed of finely shaped lamellar particles, their workability is increased, while coarse-shaped flaky particles reduce it [88, 89].

2.4.1.2 Dry and Fresh Density

For a concrete mix, the density is evaluated by its compactness and its specific gravity [82]. As recycled waste plastics tend to have lower densities than regular aggregates, both fresh and dry densities are expected to decline with increased substitution [80, 81, 90, 91]. Research has shown that concrete density decreases as the percentage of recycled plastic increases [92 – 94]. When larger and flakier RWP particles are added, it is discovered that the density loss becomes greater [90]. Osei et al. [95] reported a 42.3% reduction in dry density compared to the control concrete when normal aggregates were completely replaced by RWP. Similar findings were reported by Coppola et al. [93] as they observed a 57% drop in density when 50% natural sand was replaced with RWP. This decrease in density is associated with the low specific gravity of RWP ranging from 0.52 to 1.01 [96 - 98].

2.4.2 Influence of Plastic Waste Incorporation on the Mechanical Properties of Concrete

Waste plastic is often utilized as fine aggregate, coarse aggregate, or fibre additions in concrete. Despite being advantageous for the environment, using waste plastic in concrete is not without its drawbacks. Its engineering or mechanical properties are distinct from those of normal aggregates [35].

2.4.2.1 Porosity and Water Absorption

One significant characteristic of concrete is porosity and water absorption, which is correlated with its density in its hardened state [75]. Several literary works have examined the effect of RWP incorporation on the porosity of concrete. Chen et al. [99] studied the use of 4mm RWP as fine aggregate replacement in concrete. Their findings showed that the porosity of the various concrete mixtures incorporating RWP up to 20% of fine aggregates varied only slightly. However, when fine aggregate was used in place of 30%, 50%, and 100% RWP, porosity was found to be roughly 110%, 167%, and 387% greater than in the control mix (which did not include any RWP aggregates). This result demonstrates that the porosity of concrete is increased with the addition of RWP. Several other studies have reported similar results [79, 100]. The increased concrete porosity can be explained by the irregular shape of RWP aggregates. Immiscibility between RWP and natural sand aggregate could also explain this increase. Furthermore, bubbles may develop on the surface of RWP aggregates due to their hydrophobic properties [35]. To combat the increase in porosity, the geometry of the RWP aggregates might need to be adjusted. In this context, novel pre-processing techniques for RWP aggregates would be necessary rather than traditional mechanical processing. The aggregates' form can be altered when treated with chemicals, which can enhance its general grading [35].

2.4.2.2 Compressive Strength

In the simplest terms, compressive strength is the optimum load that a sample can withstand till it fractures divided by the cross-sectional area of the sample [75]. Various researchers have examined the compressive strength of concrete with different proportions of RWP as coarse and fine aggregates or as fibre additions in concrete. Rajawat et al. [74] replaced as much as 5% of fine aggregate (sand) with polyethylene terephthalate (PET). The 28-day compressive strength result showed a significant improvement up to 3% sand replacement in the concrete mix. By replacing sand in the concrete matrix with PET, the interfacial transition zone is reduced, resulting in an improvement in compressive strength. Though, a decrease in compressive strength was noticed beyond this point. Similar findings were also recorded by Azhdarpour et al. [98], who observed that PET plastic aggregate substitution levels of up to 10% enhanced the compressive strength of the mix. According to Yang et al. [101], the compressive strength of self-compacting lightweight concrete containing RWP aggregate was increased when the replacement level of aggregates was below 20%. However, several authors reported the opposite trend. Concrete compressive strength was observed by Islam et al. [76] to decrease up to 26.9% with recycled PP content and varied w/c ratios. Studies by Frigione et al [102] showed decreased compressive strength of concrete when as much as 5% of fine aggregate was replaced by an equal amount of recycled waste PET plastic. RWP has a chemically inert and hydrophobic nature, which explains why concrete exhibits strength reductions due to more porous microstructural development within the matrix [35, 75, 103].

2.4.2.3 Tensile and Flexural Strength

The tensile strength of concrete specimens is the stress developed when the concrete specimen cracks under compression when tensile loads are applied while the flexural strength, or modulus of rupture, is the peak bending stress that it can withstand before it fractures [75]. Incorporating RWP into concrete as a natural aggregate replacement will impact its tensile and flexural properties. Several studies have reported improved tensile and flexural properties with moderate use of RWP in concrete [78, 98, 101, 104]. According to Yang et al. [101], a moderate replacement of natural aggregates with RWP resulted in a 15% improvement in split tensile and a 20% improvement in flexural strength of test concrete. The performance of RWP fibres in concrete at various percentages (0.25 - 1.25) under direct tensile and flexural strength tests was examined by Mohammadhosseini et al. [104]. Their findings showed the strongest tensile and flexural tensile strengths were found in concrete mixtures with 0.5% RWP fibre content. There was no obvious distinction between the strengths of the concrete containing 1.25% RWP fibre content and the control concrete. Several other studies reported similar findings [78, 98, 105]. However, several studies have also reported a reverse trend in these properties with the incorporation of RWP aggregate [88, 91, 102]. Manjunath et al. [106] replaced fine and coarse aggregates in concrete with RWP at 10%, 20%, and 30% percentage compositions. The findings indicated that adding waste plastic to concrete mixes caused a notable drop in split tensile strength. A 5%, 10%, and 15% substitution of natural aggregates with PET plastic was the subject of an experimental study by Saikia et al. [107]. The results revealed that when PET plastic waste content increased, split tensile strength decreased. In this case, the smooth texture of plastic aggregates plus free water on the surface of the particle is responsible for a reduced bond between cement and plastic aggregates.

2.4.2.4 Elastic Modulus

When determining the stiffness of concrete, the elastic modulus, sometimes referred to as the modulus of elasticity or the coefficient of elasticity, reveals how resistant a material is to deform when under stress [75]. Just as for compressive strength, similar findings were obtained in the literature for the elastic modulus. Generally, the elastic modulus is reduced with increasing amounts of RWP as aggregate replacements in concrete [92, 98]. Azhdarpour et al. [98] investigated the use of PET on the strength and physical properties of concrete. Their findings revealed a decreasing trend in elastic modulus of concrete with increasing RWP addition. This decrease in the elastic modulus of concrete is a result of the elevated porosity of concrete when RWP aggregates are added [107]. Additionally, this can be linked to the weak elastic modulus of the RWP aggregates themselves compared to normal aggregates [88].

2.5 The Use of Pozzolans in Concrete

The use of pozzolans has often been utilized in mortars and concrete mainly to compensate for the adverse effects of waste utilization in the matrix, particularly in the long term [108 - 112]. Several studies have shown that silica from pozzolans reacts with calcium hydroxide, a key component of hydration. This pronounced reaction, known also as pozzolanic activity, results in the creation of supplementary calcium-silicate-hydrate gels that are essentially needed for the strength formation of the cementitious matrix [108 - 111, 113 - 116]. It is pertinent to note, however, that the actual effect of pozzolanic activity in cementitious media can only be observed over time. This is primarily because pozzolanic reaction relies solely on calcium hydroxide formation and occurs at a much slower rate than cement hydration. [46 - 49, 108, 110]. 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 in general [46 - 49]. It is also worth mentioning that the utilization of pozzolans, often used 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 natural materials for making concrete further contributes to the reduction of CO_2 emissions and the associated environmental impacts [46 - 48, 117 - 120]. It must also be emphasized that the use of pozzolans encourages waste incorporation in concrete and conjointly reduces the landfilling routes both for pozzolans and for the waste materials [121 - 125].

2.6 The Importance of a Database Methodology for The Comprehensive Assessment of RWP in Concrete

Over the last two decades, research has been conducted to better comprehend the behaviour of concrete incorporated with different plastic wastes. A major aspect being analysed is to what extent these substitutes can be incorporated into concrete and how their incorporation will alter the properties of concrete. While several studies of concrete incorporated with such wastes as plastics and pozzolans have reported improved mechanical properties of concrete as regards compressive strength, flexural strength, tensile strength, modulus of elasticity, shrinkage, and creep, there have been a significant number of contradictory results as well. These contradictory results are quite understandable as various raw materials and mix design principles could be used in concrete making. The different chemical and physical properties of the recycled waste plastic, either incorporated as fibres or as an aggregate replacement, also influences the properties of the concrete. Specific factors such as the water-cement ratio, cement type, and the type and amount of fine and coarse aggregate used are also responsible for these contradictory results. Consequently, there is a need for a more comprehensive assessment of the plastic waste in concrete that would enable sustainability analysis to be conducted more precisely. This necessitated the construction of a database comprised of 635 data points harvested from literature. The contradictory results are well expected, and the insight gained from studying these contradictions helped determine the boundary conditions for generating the concrete types (models) for further lifecycle and sustainability analysis.

CHAPTER 3

DATABASE DEVELOPMENT

3.1 Data Sourcing

The database constructed in this study addresses the incorporation of polypropylene and polyethylene terephthalate in concrete. In conducting a literature review, polypropylene and polyethylene terephthalate were found to be the most common types of plastic incorporated in concrete, providing sufficient data points for analysing the optimum boundary conditions. Having conducted a literature review, numerous published articles from reputable journals incorporating polypropylene and polyethylene terephthalate into concrete were collected and screened based on key set criteria to ensure data quality. Data from the journal articles which fulfilled these criteria were then collated into an excel worksheet and analysed to obtain the optimum boundary conditions for further life-cycle assessment.

3.2 Set Criteria

The data presented in this study were meticulously assessed in terms of test procedures, mix constituents, and relevant standards applied. In particular, the data set with absent information in the context of the mix constituents, replacement and/or additional levels of PP, PET and pozzolans were disregarded from the database. Also, the database did not include experimental data without appropriate testing and inspection standards. Figure 3.1 demonstrates a flowchart that exemplifies the approach used to construct this study’s database. It is worth noting that although a total of 433 data points on concrete incorporating polypropylene and 202 data points for concrete incorporating polyethylene terephthalate were initially attained, 5 experiments which did not satisfy the aforementioned set criteria were omitted from the database for further evaluation. Though there are numerous factors influencing the quality of concrete incorporating these plastic wastes, key factors like the replacement type and amount of plastic waste, water-cement ratio and the type of replacement and level of pozzolans, are determined to be the most prominent parameters and therefore were utilised to establish the boundary limits in this study. These factors significantly govern the boundary conditions and are essential in determining the concrete types used in this study. The boundary limits facilitated the evaluation of the optimal addition and replacement levels of polypropylene, polyethylene terephthalate and pozzolans and thus the definition of the concrete types. The meticulous establishment of concrete types was essential for the definitive life cycle assessment.

The database comprised concrete standard mix constituents, water-cement ratio, replacement type and level of plastic waste as well as the replacement type and level of pozzolans, as well as short and long-term mechanical properties of concrete incorporating these plastic wastes. The database utilised for the determination of optimum additional and replacement levels of polypropylene fibres and pozzolans is summarised in Table 3.1, while that of polyethylene terephthalate is summarised in Table 3.2. Table 3.1 and 3.2 encompasses the authors of the publications, the number of data points used in the assessment, water-cement ratio, the replacement and additional levels of polypropylene and polyethylene terephthalate, replacement type and level of pozzolanic materials, short and long-term mechanical properties of concrete comprising polypropylene and polyethylene terephthalate used in the analysis.

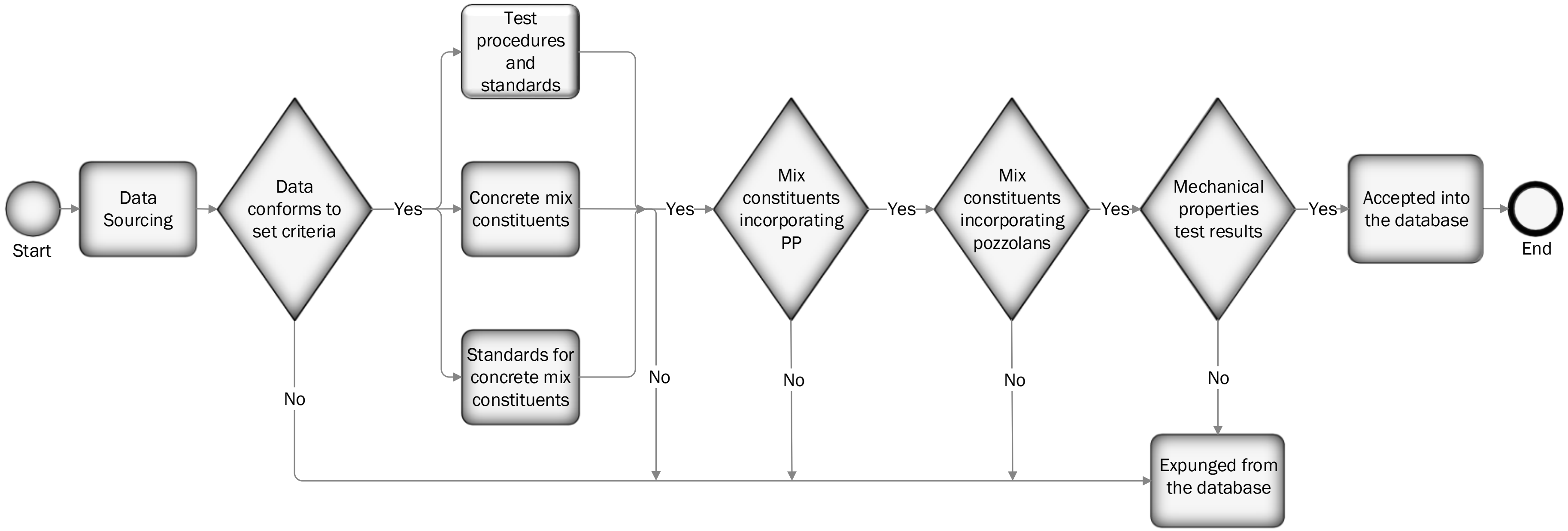


Figure 3.1 Database development flowchart

Table 3.1 Database of concrete incorporating polypropylene

#	**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

Table 3.2 Database of concrete incorporating polyethylene terephthalate

#	Author	Year of Publication	# of data points	Water: Cement Ratio (Range)	Compressive strength (MPa) (28 days)	Split tensile strength (MPa) (Range)	Flexural strength (MPa) (Range)	Aggregate Replacement /Fibre Addition	PET Replacement Range (%)	Pozzolan Type	Pozzolan Amount (Range) (%)
1	Dawood et al.	2021	7	0.41	33 - 50	2 - 3	4 - 6	FA	5 - 20	-	-
2	Alfahdawi et al.	2019	20	0.35	33 - 68		4 - 10	CA	0.25	Flyash	30 - 40
3	Sadrmomtazi et al.	2016	10	0.3 - 0.43	19 - 36	1 - 3	5 - 11	FA	5 - 15	Flyash/ Silica fume	10 - 30
4	Islam et al.	2016	15	0.42 - 0.57	3 - 31	-	-	CA	20 - 50	-	-
5	Rahmani et al.	2013	8	0.42 - 0.54	29 - 42	0 - 3	5 - 7	FA	5 - 15	-	-
6	Saikia et al.	2014	10	0.52 - 0.74	15 - 43	1 - 3	-	Aggregate	5 - 15	-	-
7	Saxena et al.	2018	10	0.45	5 - 27	-	-	Aggregate	5 - 20	-	-
8	Mohammed et al.	2019	20	0.38	40 - 73	-	-	FA	2 - 8	-	-
9	Al-Hadithi et al.	2019	9	0.33	50 - 72	-	4 - 7.5	Fibre	0.25 - 2	Silica fume	10
10	Hasan-Ghasemi et al	2021	4	0.47	40 - 55	4 - 5	-	FA	5 - 15	-	-
11	Nematzadeh et al	2020	9	0.3	36 - 68		-	FA	5 - 10	Silica fume	10
12	Bui et al	2018	9	0.45	29 - 48	3 - 5	-	Fibre	0.25 - 0.75	Silica fume	5
13	Borg et al.	2016	9	0.55	32 - 35	-	-	CA	0.5 - 1.5	-	-
14	Mousavimehr et al	2020	4	0.51	30 - 54	-	4 - 6	FA	7.5 - 15	-	-
15	Kim et al	2010	7	0.45	24 - 27	-	-	Fibre	0.5 - 1	Fly ash	10
16	Ochi et al	2007	12	0.55 - 0.65	31 - 48	-	-	Fibre	0.5 - 1.5	-	-
17	Fraternal et al	2014	3	0.3	40 - 44	-	-	Fibre	1	-	-
18	Frigione et al	2010	8	0.45 - 0.55	41 - 70	4 - 7	-	Fibre	5	-	-
19	Ferreira et al	2012	6	0.53 - 0.61	20 - 37	1 - 3	-	FA	7.5 - 15	-	-
20	Azhdarpour et al	2016	7	0.5	22 - 51	-	-	FA	5 - 30	-	-
21	Silva et al	2013	6	0.52 - 0.61	20 - 37	-	-	Aggregate	7.5 - 15		

CHAPTER 4

DATA ANALYSIS

4.1 Data Cleaning and Preparation

Following the construction of the database, the data were cleaned and reviewed for completeness, and if any missing values were discovered, they were thoroughly investigated. In a similar manner, duplicate observations were identified and removed from the database. As recommended by the American Concrete Institute (ACI), data points below the threshold of 17.2 MPa (megapascals) for structural applications were further expunged from the database. For this study, the standard was raised to 20 MPa. Also, data points with compressive strength value greater than 100MPa were discarded as these are often not feasible and applicable. To enable the use of statistical techniques, the data had to be well organized. The linear regression technique was then applied to obtain the causal relationships between the amount of plastic waste incorporated in concrete and its compressive strength, the water content, the split tensile and flexural strengths, and the optimum amount of pozzolans to be utilized. Although other regression techniques were applied, such as exponential, polynomial, and power regression, the linear regression technique provided the most accurate results for analysing causal relationships between parameters, with the coefficient of determination (R-squared) values closest to 1.

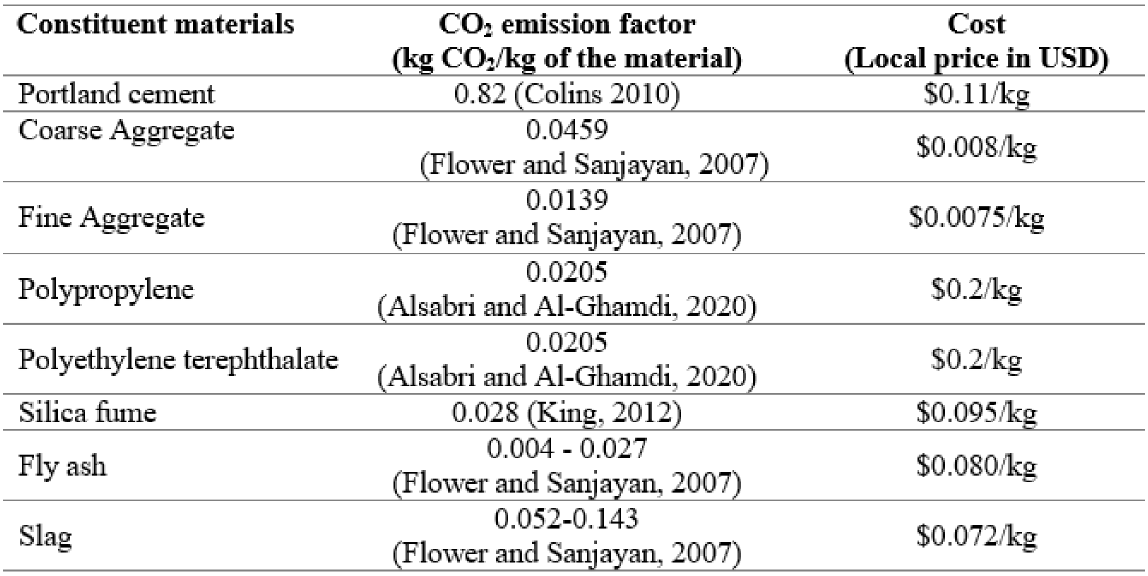
4.2 Development of the Concrete Models

A thorough analysis of the database, which was primarily harvested from the literature, and the application of the linear regression technique enabled the generation of potential concrete models by determining the optimal additional and replacement levels of polypropylene, polyethylene terephthalate and pozzolans. For a comprehensive life cycle analysis to be conducted, concrete models had to be developed.

4.3 CO_2 emissions, Cost Effectiveness and Eco-strength Efficiency

Calculating the total CO_2 emissions, cost-effectiveness, and eco-strength efficiency are well-established methods for sustainability evaluation. It is necessary to take into account that all steps involved in producing and preparing the core components of concrete, such as cement and aggregates, are taken into consideration in quantifying CO_2 emissions. In this research, for example, the CO_2 emission factor for cement considers emissions from fuel use, emissions from the manufacturing process, as well as emissions from mining and transportation of raw materials. Clinker manufacturing, and more specifically the fuel used for pyro-processing, is responsible for CO_2 emissions from combusting fuels in the cement industry. By contrast, process-related emissions result from chemical reactions which reduce limestone to calcium oxide and associated carbon dioxide. For fine and coarse aggregates, CO_2 emission factors also include excavation, grinding and trimming, sieving, and haulage to the site.

Table 4.1 The unit price of constituent materials and the carbon dioxide emission factors



Constituent materials	CO_2 emission factor (kg CO_2/kg of the material)	Cost (Local price in USD)
Portland cement	0.82 (Colins 2010)	\$0.11/kg
Coarse Aggregate	0.0459 (Flower and Sanjayan, 2007)	\$0.008/kg
Fine Aggregate	0.0139 (Flower and Sanjayan, 2007)	\$0.0075/kg
Polypropylene	0.0205 (Alsabri and Al-Ghamdi, 2020)	\$0.2/kg
Polyethylene terephthalate	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

The emission factor for plastic wastes in this study simply considers the emissions from the end-of-life assessment processes including transporting the waste plastic, washing, crushing/grinding, sieving, and chemical treatment applied.

4.3.1 Cost Efficiency Factor (CEF)

The CEF is calculated by dividing concrete compressive strength by the total material cost per cubic meter. This method is adapted from Ince et al. [48] and Agarwal & Gulati [130].

$$Cost\ efficiency\ factor\ (CEF) = \frac{\sigma}{C} \qquad 4.3.1$$

In Equation 4.3.1, σ represents the compressive strength, and C is the total cost of the concrete mix. The respective compressive strength values of each specimen are provided by the database. Accordingly, the CEF could be calculated by dividing concrete compressive strength by its total cost. The cost of concrete comprising waste plastic and pozzolans is estimated in dollars using the local pricing of the mix component, which is summarized in Table 4.1. Thus, the concrete cost was determined by multiplying each raw material in the database, by the associated carbon dioxide emissions factor, summarized in Table 4.1.

4.3.2 Eco-strength Efficiency Factor (ESEF)

The ESEF of concrete is calculated based on the ratio of its compressive strength to the CO_2 emissions per kilogram.

$$Eco - strength\ efficiency\ factor\ (ESEF) = \frac{\sigma}{kg\ CO_2} \qquad 4.3.2$$

The compressive strength values obtained from the database, including the associated CO_2 emissions for each specimen, summarized in 4.1 are used to calculate the eco-strength efficiency factor.

4.4 The Life Cycle Assessment Methodology

The life cycle assessment (LCA) approach is a great tool for determining the environmental impacts of products in addition to evaluating the attributes of competing items. It enables examination of a product's environmental effects over its life cycle and the possible effects these may have on the environment. A life cycle assessment (LCA) is primarily conducted in four phases: aim and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation [133].

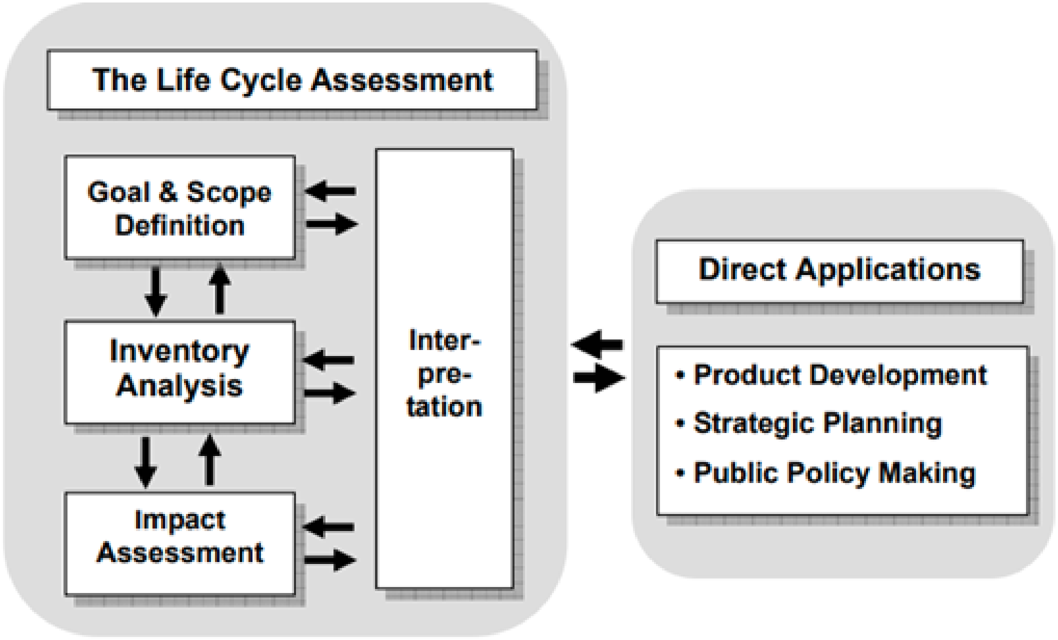


Figure 4.1 The Different LCA Phases [133]

To assess the incorporation of plastic waste in concrete, the goal and scope of the assessment must be first specified. The goal of this study is to evaluate the sustainability and environmental benefits of adding plastic waste to concrete. The scope entails obtaining the optimum incorporation levels of plastic waste and pozzolans in concrete for an assessment basis or functional unit of 1m^3 of concrete. The LCA inventory data utilised in this study is obtained from the ecoinvent 3.7 databases. Inventory data are transformed into an impact score indicator by the life cycle analysis [134]. In the literature, there are numerous evaluation methods for life cycle inventory analysis. ReCiPe is one of the most often employed impact assessment techniques. Several environmental impacts are assessed at the midpoint level by the technique, which then groups the midpoints into a set of three endpoint categories (ecosystems, human health, and resource availability) [135].

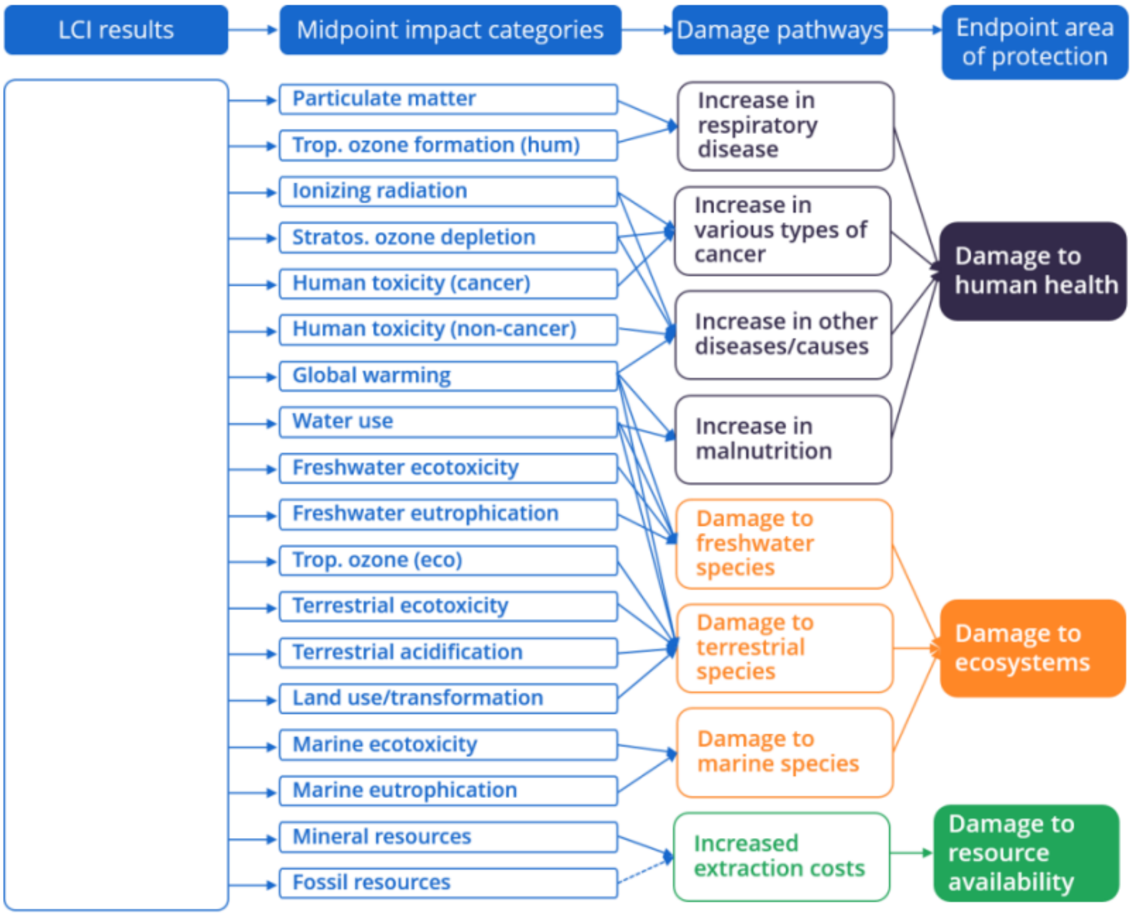


Figure 4.2 Summary of the impact categories contained in the ReCiPe 2016 technique [135]

Although there exist several evaluation methods in the openLCA software utilized for this study, the analysis is conducted using the ReCiPe method and the midpoint approach with hierarchies. Various concrete types incorporating plastic wastes and pozzolans are evaluated based on their contribution to human toxicity potential (HTP), marine ecotoxicity (METP), climate change (GWP100), water depletion (WDP), fossil depletion (FDP), and ozone depletion (ODP).

CHAPTER 5

ASSESSMENT OF MECHANICAL PROPERTIES OF CONCRETE CONTAINING POLYPROPYLENE PLASTIC WASTE

5.1 Determination of The Optimum Addition Level of Polypropylene in Concrete

The replacement type and level of polypropylene incorporated in concrete are examined in this section. When the 383 data points, harvested for the construction of the database, are 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 texture of polypropylene (61, 103, 136, 137, 138, 139) as well as the weak interfacial transition zone that develops within the matrix (103, 140) are the main barriers of the polypropylene utilisation as cement replacement in concrete. The common use of polypropylene in concrete is observed to be in the form of fibres. The crack-bridging ability of these fibers improves the microstructural properties of the matrix substantially and hence enhances the mechanical properties of the hardened concrete (103, 141).

28-day compressive strength of concrete incorporating polypropylene was plotted versus the additional levels of polypropylene in Figure 5.1. It must be reported that Figure 5.1 comprises 362 data points. The majority of the data points (more than 92%) embody the additional level of polypropylene to be less than 5%. It is exhibited in Figure 5.1 that the rise in the additional level of polypropylene substantially reduces the compressive strength of concrete. The reduction in compressive strength of concrete is more markedly seen with specimens comprising more than 10%

polypropylene used as an addition. The poor interfacial properties of polypropylene as well as the non-polar nature of these fibers are largely responsible for the results demonstrated in Figure 5.1 (103). On the other hand, polypropylene fibres do not contribute to hydration reactions 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 yields a greater reduction in compressive strength.

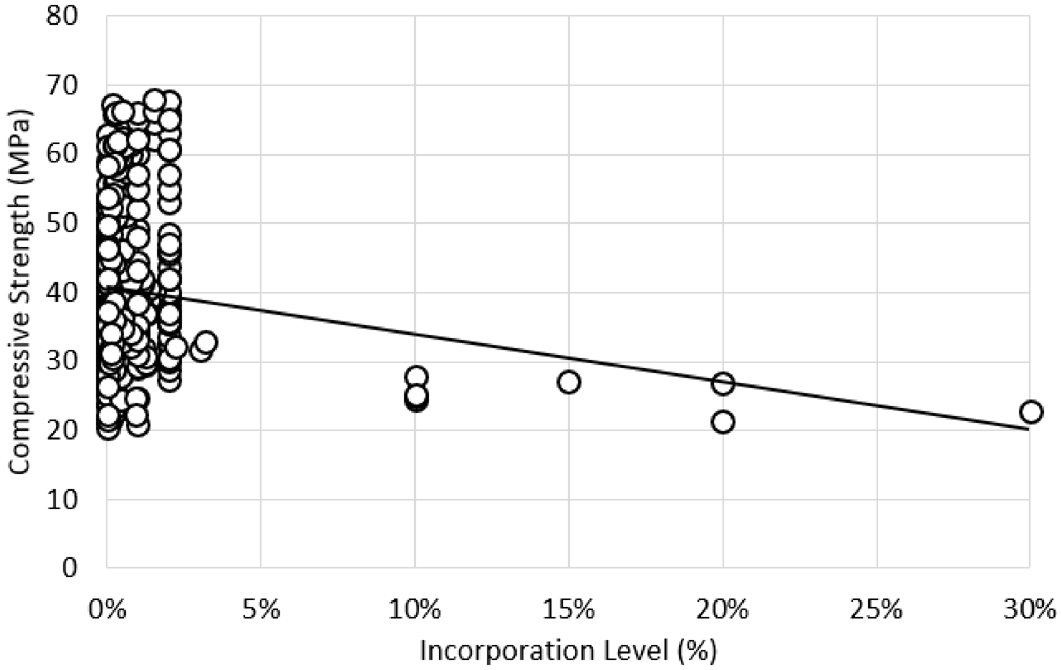


Figure 5.1: *Compressive strength of concrete incorporating polypropylene fibers as addition up to 30% (362 data points)*

28-day compressive strength of concrete incorporating polypropylene was plotted against the additional levels of polypropylene in Figure 5.2. It must be reported the additional level of polypropylene was limited to 3% in Figure 5.2. Figure 5.2 comprises 353 data points. The results in Figure 5.2 exhibit that the increase in the additional level of polypropylene considerably increases the compressive strength of concrete. When the results are studied closely, it can be observed that the utilisation of polypropylene up to 3% of bridges across the crack effectively results in a denser microstructure with reduced fissures and fractures and hence improves the compressive strength of concrete. The results demonstrated in Figure 5.2 indicate that the optimum additional level of polypropylene can be determined to be 3%.

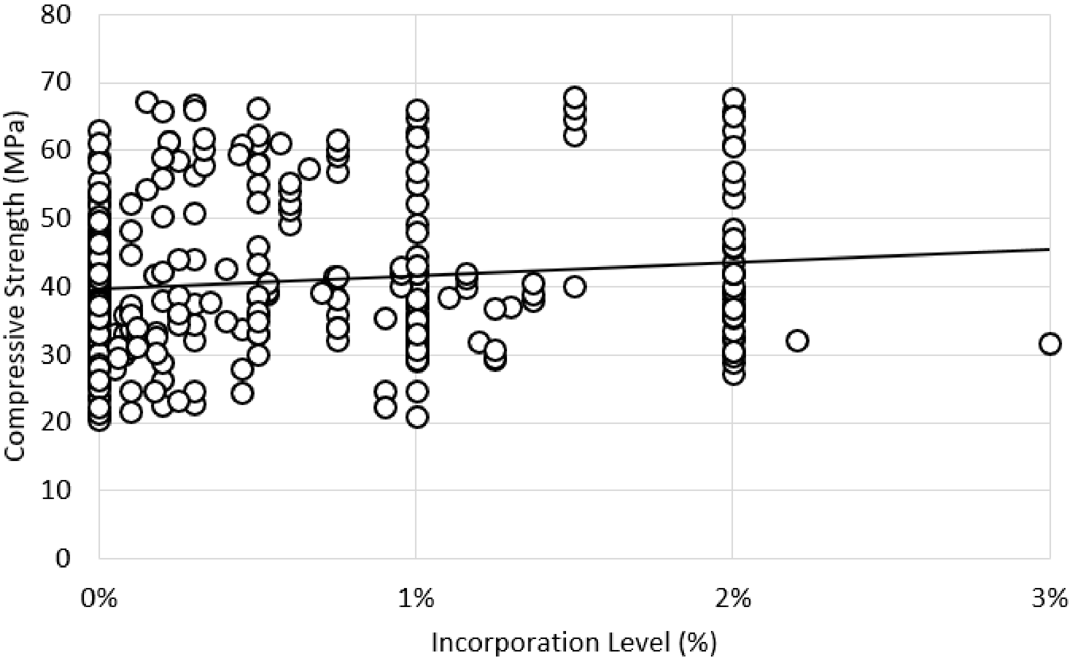


Figure 5.2: *Compressive strength of concrete incorporating polypropylene fibers as addition up to 3% (353 data points)*

Split tensile strength of concrete incorporating polypropylene was plotted versus the additional levels of polypropylene in Figure 5.3. It must be reported that Figure 5.3 comprises 131 data points. The split tensile strength was employed to re-examine the optimum additional level of polypropylene incorporated in concrete. The majority of the data points (more than 95%) encompass the additional level of polypropylene that are up to 3% and this is consistent with the results shown in Figure 5.1. It is exhibited in Figure 5.3 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 more than 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 essentially responsible for the reduction in the mechanical properties of concrete incorporating large additional levels of polypropylene. The additional level of polypropylene fibers is reduced to 2% in purpose in Figure 5.4. It must be noted that an additional level of 3% polypropylene was not detected in the database. The split tensile strength of concrete incorporating polypropylene was also plotted versus the additional levels of polypropylene in Figure 5.4. The results shown in Figure 5.4 attribute once again that when the additional levels of polypropylene fibres are limited by 2-3%, their crack bridging characteristics become more governing in densifying the matrix and hence yield a considerable increase in the split tensile strength of concrete.

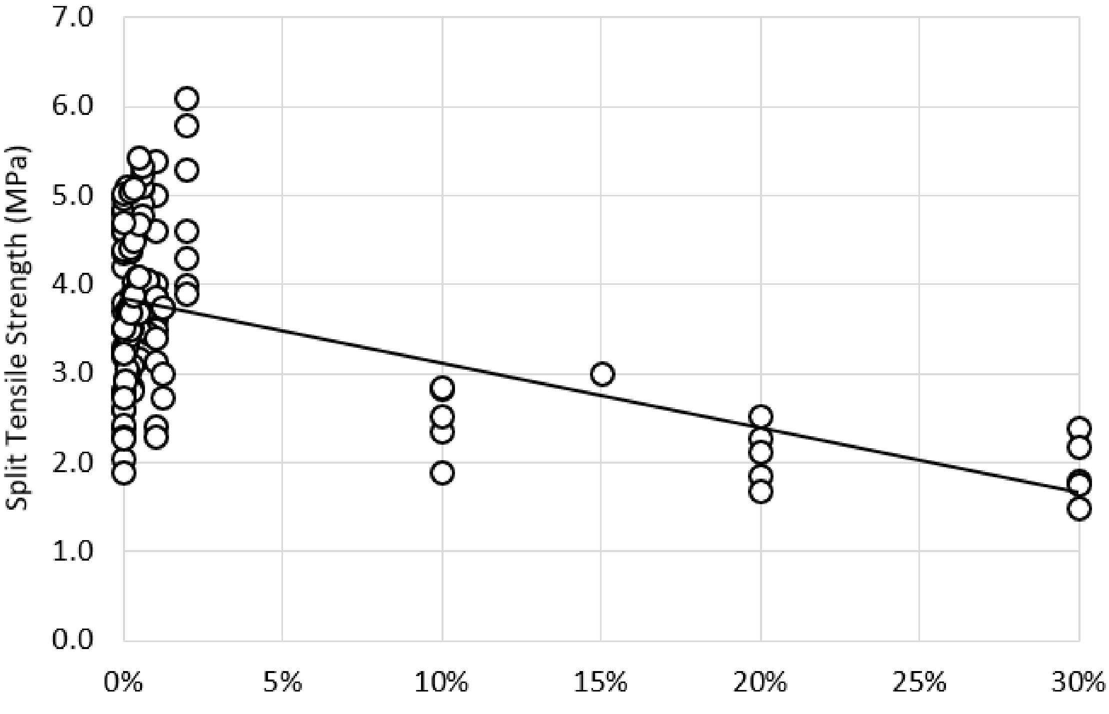


Figure 5.3: *Split Tensile strength of concrete incorporating polypropylene fibers as addition up to 30% (131 data points)*

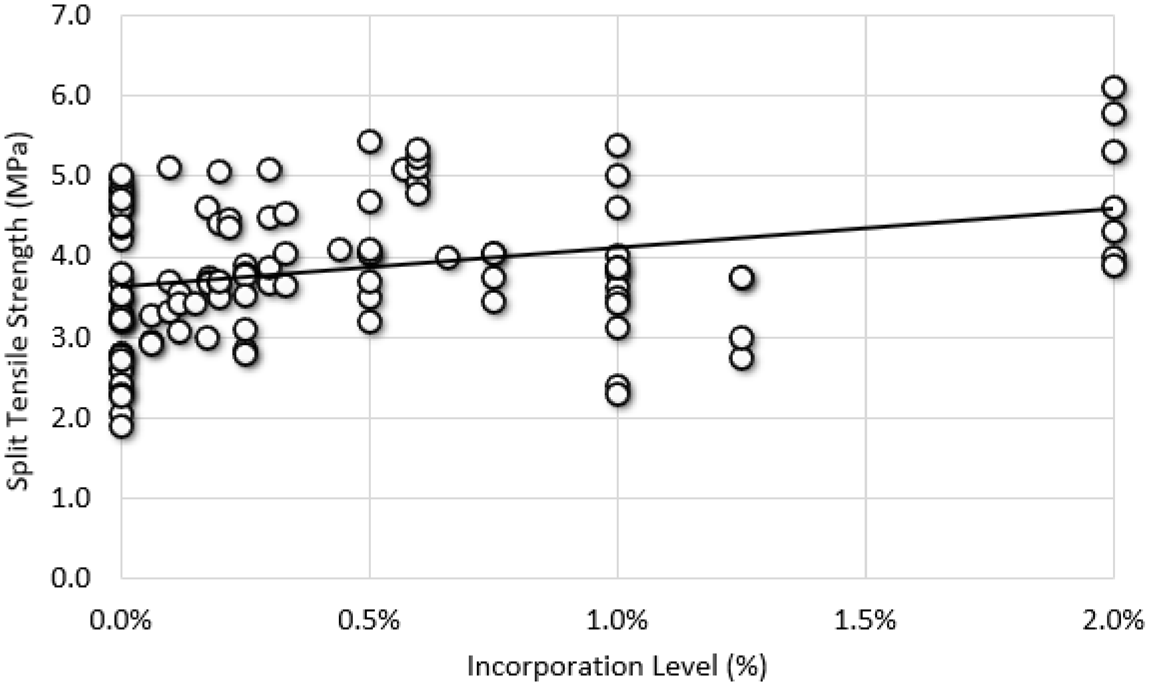


Figure 5.4: *Split tensile strength of concrete incorporating polypropylene fibers as addition up to 2% (115 data points)*

5.2 The influence of the water: binder ratio on the Polypropylene addition

The influence of the water: binder ratio on the compressive strength of concrete comprising increased additional levels of polypropylene fibres is studied. The water: binder ratios are divided into two categories; 0.2<water: cement<0.45 and 0.45<water: cement<0.8. The compressive strength of concrete comprising polypropylene fibres is plotted versus the additional levels of polypropylene in Figure 5.5. The results demonstrated in Figure 5.5 indicate that the use of high additional 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 lesser reduction in the compressive strength of concrete comprising polypropylene fibers, this contradicting observation is accredited to the diverse variations of the mixtures as well as the non-homogeneous data points, particularly at high additional levels of polypropylene fibers. Another conceivable reason for attaining the lower compressive strength of concrete comprising high additional levels of polypropylene with lower water: binder class is mainly because of the insufficient water accessible for hydrating the cement due to the substantial increase in the surface area of polypropylene fibers in the matrix.

The compressive strength of concrete comprising polypropylene fibres is plotted against the additional levels of polypropylene in Figure 5.6. It must be noted that the additional levels of polypropylene fibres were limited to 3% as this was determined to be the optimum use of these fibres formerly. It must also be noted that Figure 5.6 comprises 353 data points where 72% represents water: cement ratios betwixt 0.2 to 0.45 and 27% represents water: cement ratios between 0.45 to 0.80. The results shown in Figure 5.6 clearly state that the increased additions of polypropylene fibres have yielded to enhance the compressive strength of concrete and that this feature is valid at both water: cement ratio intervals utilized to examine the quality of concrete in this study. More importantly, the results exhibited in Figure 5.6 demonstrated that concrete comprising polypropylene fibres with lower water: cement ratio class (0.2<water: cement<0.45) resulted in greater compressive strength. The correct reflection of this well-known feature in this figure, compared to Figure 5.5 above, re-validates once again that 3% is the right optimum additional level of polypropylene fibres to be used in concrete.

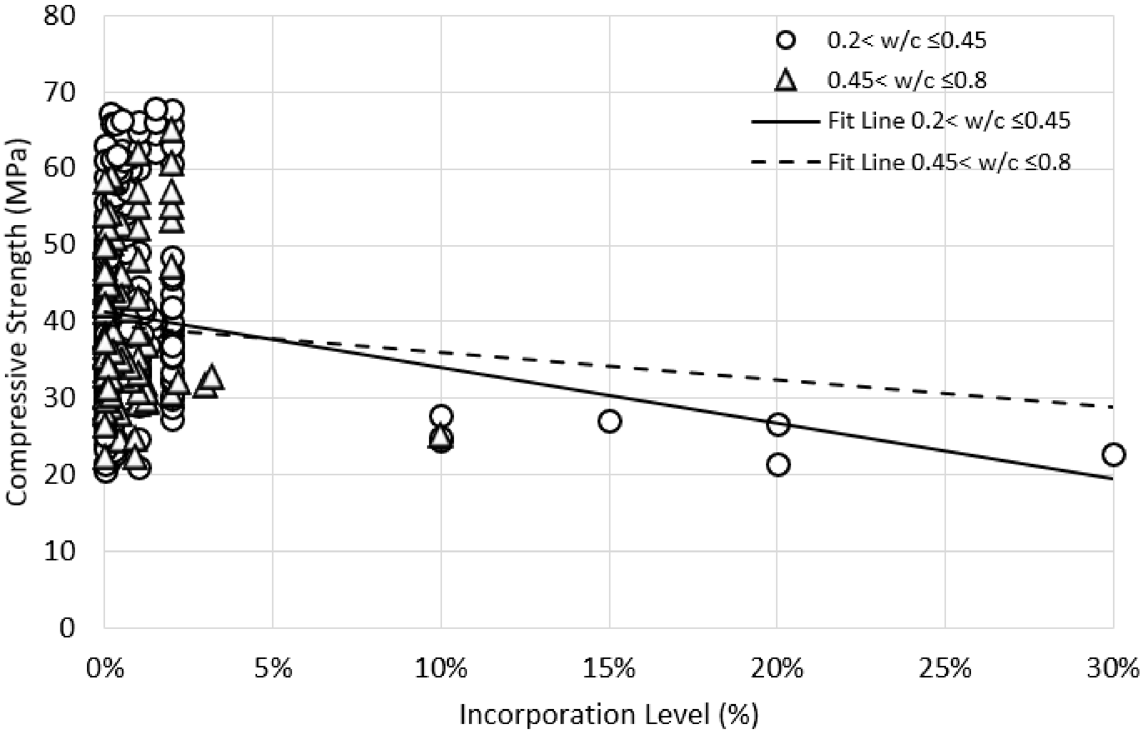


Figure 5.5: Compressive strength of concrete incorporating polypropylene fibers as addition up to 30%; 0.2< w/c ≤ 0.45 (263 data points); 0.45< w/c ≤ 0.8 (99 data points)

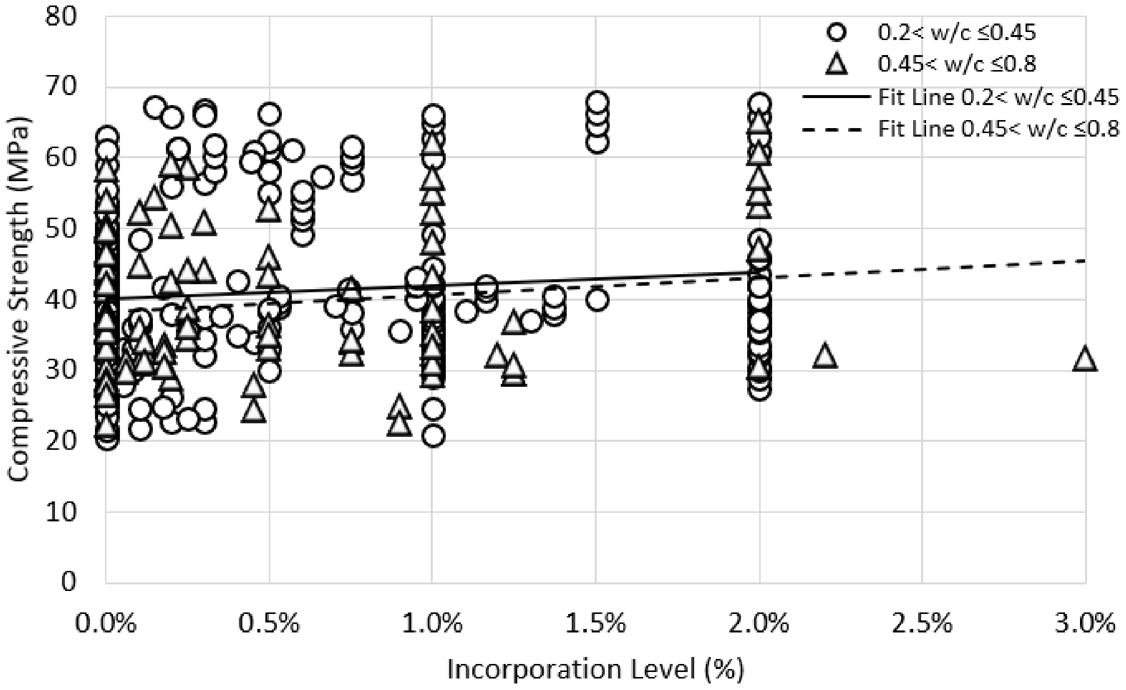


Figure 5.6: Compressive strength of concrete incorporating polypropylene fibers up to 3%; 0.2< w/c ≤0.45 (256 data points); 0.45< w/c ≤0.8 (97 data points)

5.3 The influence of the use of pozzolans on the PP addition

The essential role of pozzolans in concrete comprising polypropylene fibres is well addressed formerly in the paper. The compressive strength of concrete containing polypropylene fibres with and without pozzolans is plotted against the additional levels of polypropylene in Figure 5.7. It must also be noted that Figure 5.7 comprises 128 data points of concrete compressive strength comprising pozzolans and 265 data points showing the compressive strength of concrete without the use of pozzolans. It is not surprising at this stage of the study that both concrete groups yielded a reduction in compressive strength with increased additional levels of polypropylene fibres. It should also be noted that concrete comprising polypropylene fibres with pozzolans provided greater compressive strength in comparison to that of the specimens without pozzolans even at 28 days.

The additional levels of polypropylene fibres were particularly limited to 3% in Figure 5.8 as this was determined to be the optimum utilisation of these fibres previously. The substantial increase in the compressive strength of concrete comprising pozzolans is prominently shown in Figure 5.8 compared to that of concrete without pozzolans. The high fineness of pozzolans and thus the increased surface area of the solid volume fraction of fines often are 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 Figure 5.8 therefore support the previously determined supposition that pozzolans enhance the concrete’s mechanical properties which contain polypropylene fibres even at the early strength development stage.

The compressive strength of concrete at 28 days containing polypropylene fibres is plotted versus the replacement levels of pozzolans used as cement substitutes in Figure 5.9. The most utilised pozzolans are detected to be silica fume, slag and fly ash. The results shown in Figure 5.9 indicate that the increased replacement levels of pozzolans yield a considerable decline in concrete’s compressive strength at first sight. The decrease attained in concrete’s compressive strength due to the increased replacement level of pozzolans in the short term is mainly because of the substitution of the very hydraulic cement with pozzolans. The pozzolanic reaction is not only depending on the presence of calcium hydroxide and therefore the cement hydration but also is a much slower process than that of the hydration. The replacement of the hydraulic binder with pozzolans, therefore, results in a gradual decrease in the compressive strength of concrete in the short term. Moreover, a good pozzolan's strength activity index can be determined using the ASTM C 618. Utilizing the short-term compressive strength results, the optimum replacement levels of fly ash, slag and silica fume are determined to be 30%, 15% and 7.5% respectively. These determinations also were used to define the independent concrete types essential for the life cycle assessment of the study.

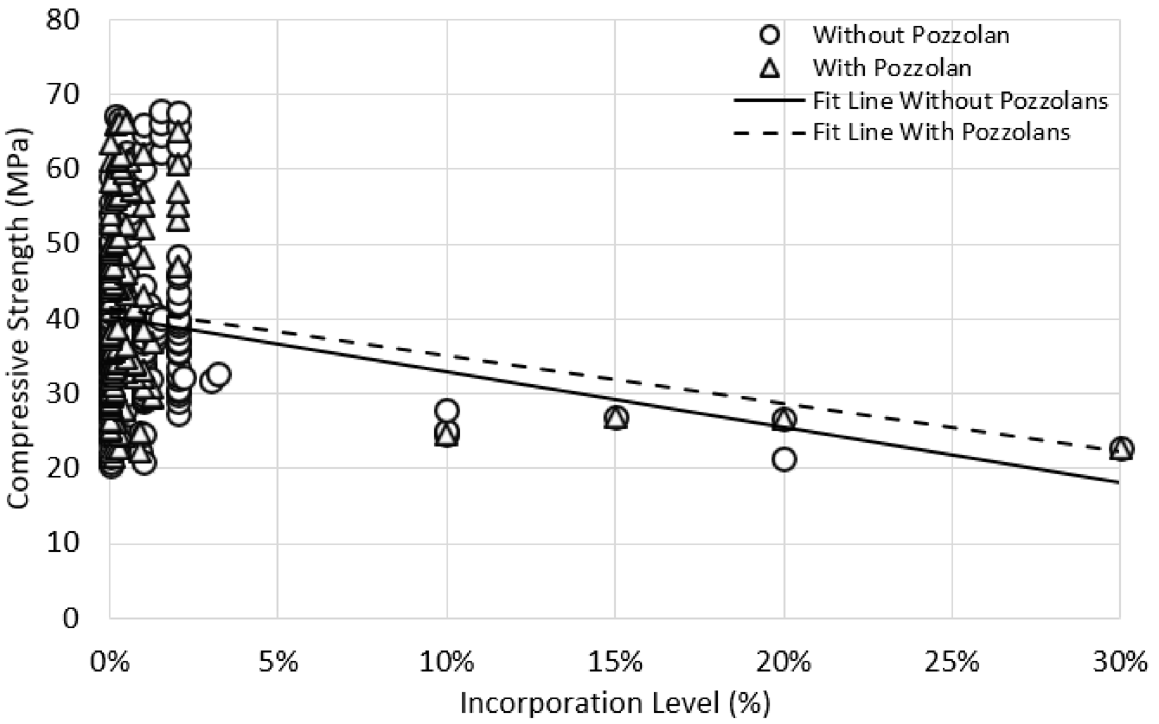


Figure 5.7: Compressive strength of concrete incorporating polypropylene fibers as addition up to 30%; with pozzolans (128 data points); without pozzolans (256 data points)

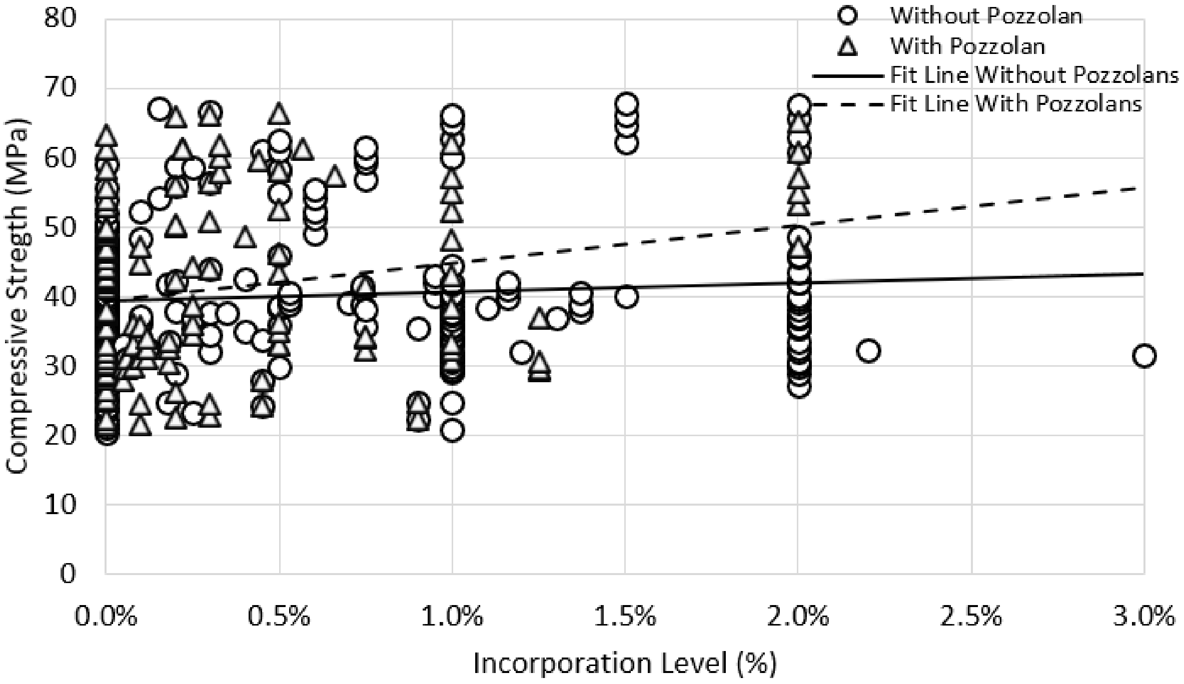


Figure 5.8: Compressive strength of concrete incorporating polypropylene fibers as addition up to 3%; with pozzolans (124 data points); without pozzolans (256 data points)

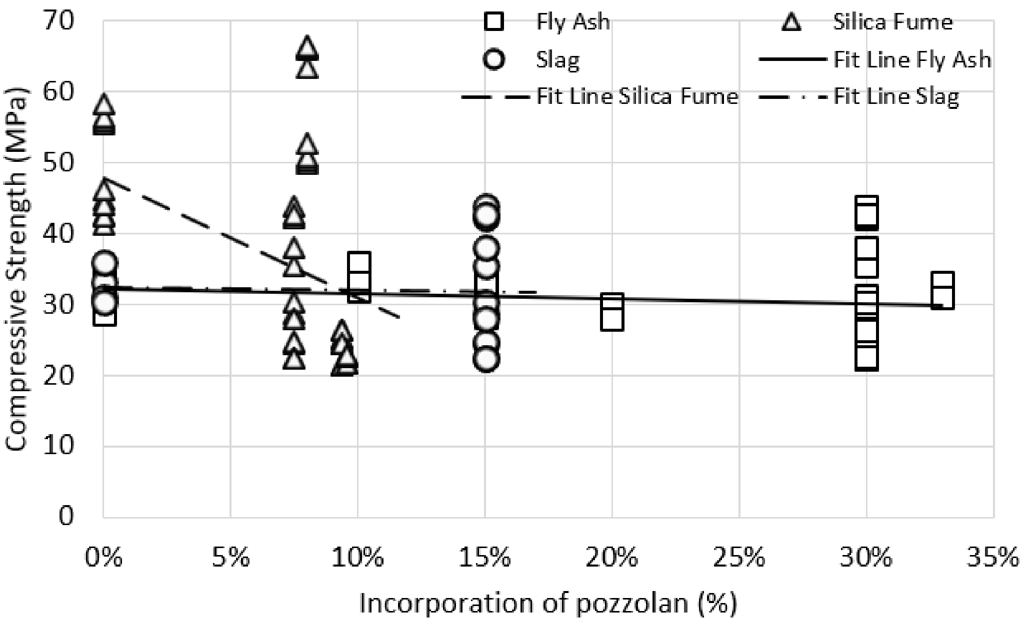


Figure 5.9: Compressive strength of concrete incorporating polypropylene fibres with varying pozzolans; Fly Ash (40 data points), Silica fume (48 data points) and Slag (16 data points)

5.4 Short- and Long-Term Compressive Strength

Short-term and long-term compressive strength of concrete containing polypropylene fibres is plotted against the replacement levels of pozzolans used as cement substitutes in Figure 5.10. It must also be noted that Figure 5.10 comprises 521 data points in total where 362 data points represent short-term compressive strength and 159 data points represent long-term compressive strength of concrete comprising polypropylene. The results shown in Figure 5.10 attribute that the long-term authentic performance of pozzolans is hindered due to the high additional levels of polypropylene fibres utilised in concrete. For instance, compared to the short-term strength results, concrete comprising pozzolans as an alternative for cement resulted in greater compressive strength in the long term when the polypropylene levels were limited to 15%. The long-term compressive strength of pozzolanic concrete comprising more than 15% polypropylene fibers is smaller than that of the short-term.

This incident is formerly discussed in Section 5.1. Utilizing greater additional levels of polypropylene fibers results in a substantial increase in the surface area of the solid fractions in the mixture. This may cause some of the mixing water to be used to wet the fibers in the mixture and hence may result in drier mixes to be attained. The reduction in the consistency of concrete incorporating polypropylene fibers is well noted in the literature (103). The increase in the water demand both for consistency and for the hydration reaction, therefore, is essential for concrete comprising polypropylene fibers. The use of polypropylene fibers often yields a reduced amount of water remaining in the mix which may not be sufficient for complete hydration to be performed. This may further delay or diminish the creation of hydration reactions such as the formation calcium silicate hydrate and calcium hydroxide which would also adversely affect the rate of the pozzolanic reaction. The utilisation of high additional levels of polypropylene fibers, therefore, is not suggested once again even though the use of pozzolans could partially compensate for this adverse effect to a great extent in the long term.

Short-term and long-term concrete compressive strength containing polypropylene fibres is plotted against the incorporation levels of pozzolans used as cement substitutes in Figure 5.11. The additional level of polypropylene was limited to 3% in Figure 5.11. The results demonstrated in Figure 5.11 show that the long-term influence of the pozzolans on the compressive strength of concrete is more prominently distinguished. The authentic influence of the pozzolanic reaction can only be seen in the long term (109, 110, 142) due to the slow nature of the reactions that take place between the calcium hydroxide and silica. The results shown in Figure 5.11 also re-validates the assertion that when the additional level of polypropylene fibres is limited to 2-3%, the veritable influence of the pozzolanic reaction on the compressive strength of concrete could be detected at both terms investigated herein. These results also re-validate the correctness of the optimum additional level of polypropylene fibres.

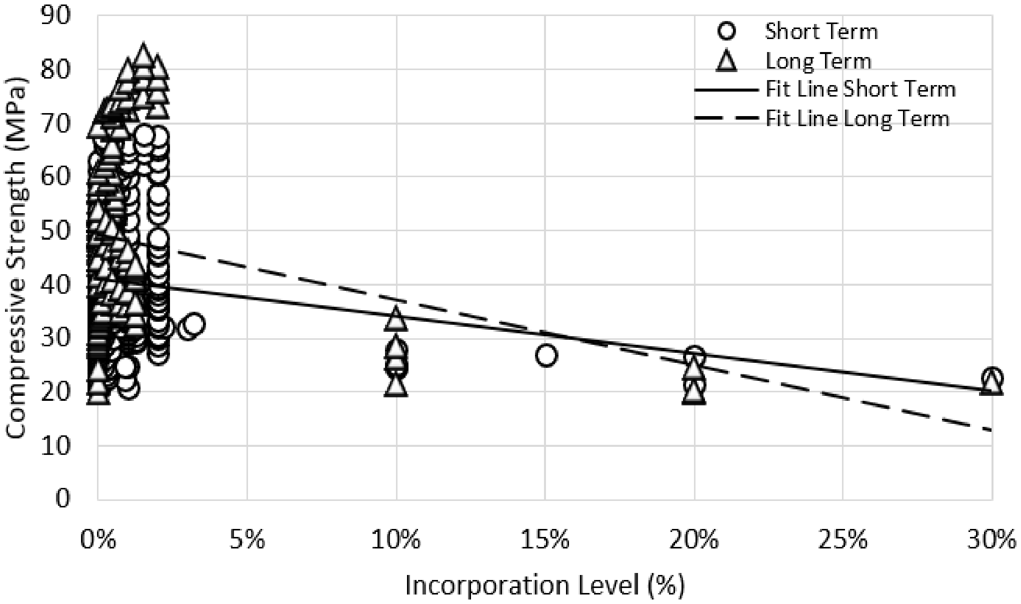


Figure 5.10: Compressive strength of concrete incorporating polypropylene fibers up to 30%; Short-term (362 data points) and long-term (159 data points)

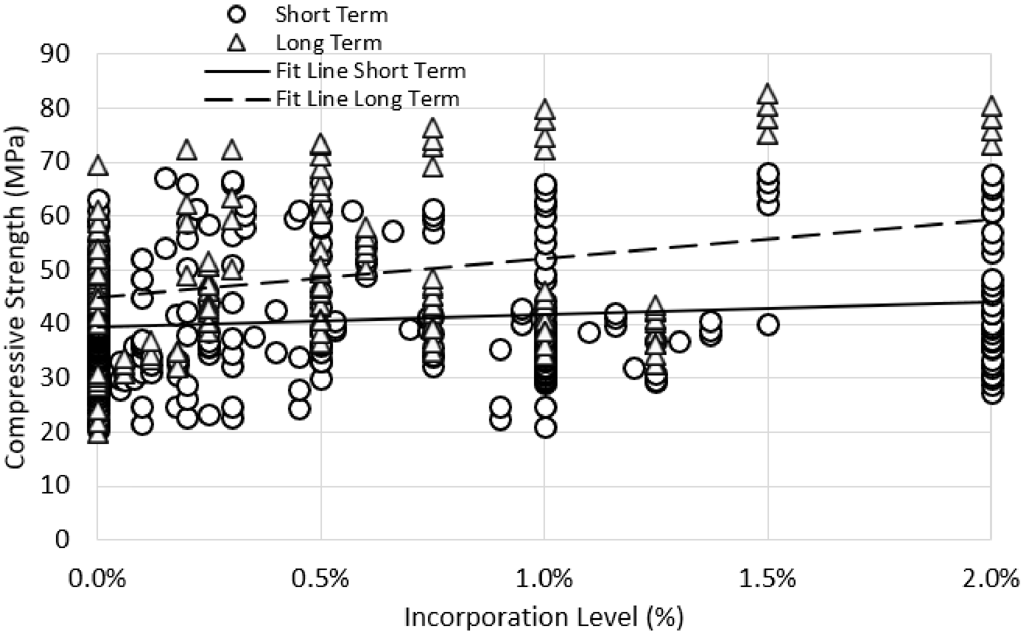


Figure 5.11: Compressive strength of concrete incorporating polypropylene fibre up to 2%; Short term (354 data points) and long-term (151 data points)

5.5 The Boundary Limits and Concrete Types Containing Polypropylene

Meticulous analysis of the database, principally harvested from the literature for the establishment of the optimum additional and/or replacement levels of polypropylene fibers and pozzolans, enabled potential concrete types to be generated. The establishment of concrete types were essential in order to perform a comprehensive life cycle analysis. These concrete types can be divided into three (3) groups. Type 1 represents the control concrete. This reference concrete specimen does not comprise polypropylene fibers nor pozzolans. Average mix constituent values of the control concrete containing no polypropylene fibers nor pozzolans were thus calculated from the control data points in the database. Type 2 comprises concrete specimens that incorporate the optimum additional levels of polypropylene fibres without pozzolans. Type 3 comprises concrete specimens incorporating optimum additional levels of polypropylene fibers with three commonly used pozzolans. For instance, Model 3a, 3b, and 3c were established using the previously determined optimum replacement levels of fly ash, slag and silica fume respectively. To obtain these mix constituents for the different sub-types of type 3 concrete, the percentage replacement amount of cement for the different pozzolans was calculated using the mix constituents obtained from the control concrete. Table 5.1 summarises the concrete types, the key constituents, the replacement type, and the amount of polypropylene fibres and pozzolans incorporated in concrete.

Table 5.1 Established polypropylene concrete types

Concrete Type	**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)**
Type 1 (Control concrete)							
Type 1 (Control)	184.7	425.4	784.4	936.9	NA	NA	
Type 2 (Concrete incorporating 3% PP only)							
Type 2 (3%PP)	184.7	425.4	784.4	936.9	27.3	NA	
Type 3 (Concrete incorporating 3% PP and various types of pozzolans)							
Type 3a (3%PP + 30%FA)	184.7	299	784.4	936.9	27.3	Fly ash (FA)	127
Type 3b (3%PP + 15%S)	184.7	362	784.4	936.9	27.3	Slag (S)	63
Type 3c (3%PP + 7.5%SF)	184.7	394	784.4	936.9	27.3	Silica fume (SF)	31

CHAPTER 6

ASSESSMENT OF MECHANICAL PROPERTIES OF CONCRETE CONTAINING POLYETHYLENE TEREPHTHALATE PLASTIC WASTE

This study employs a database approach to assess important aspects such as the water: binder ratio, replacement type, as well as incorporation levels of polyethylene terephthalate and pozzolans. The results obtained in this section made it possible to independently determine the boundary conditions, which were necessary for the implementation of the comprehensive assessment of the sustainability analysis.

6.1 The influence of the water: binder ratio on Concrete Containing Polyethylene Terephthalate

Concrete compressive strength containing polyethylene terephthalate, and the effect of the water-binder ratio are investigated. The water-binder ratios are divided into two categories; 0.3 - 0.45 and 0.45 - 0.8. Figure 6.1 demonstrates the link between the compressive strength of concrete containing polyethylene terephthalate. The results demonstrated in Figure 6.1 indicate that the use of high additional levels of polyethylene terephthalate yields a substantial decrease in the compressive strength of concrete irrespective of the water-binder ratio. However, the higher water-binder ratios resulted in a greater decline in the compressive strength of concrete containing polyethylene terephthalate.

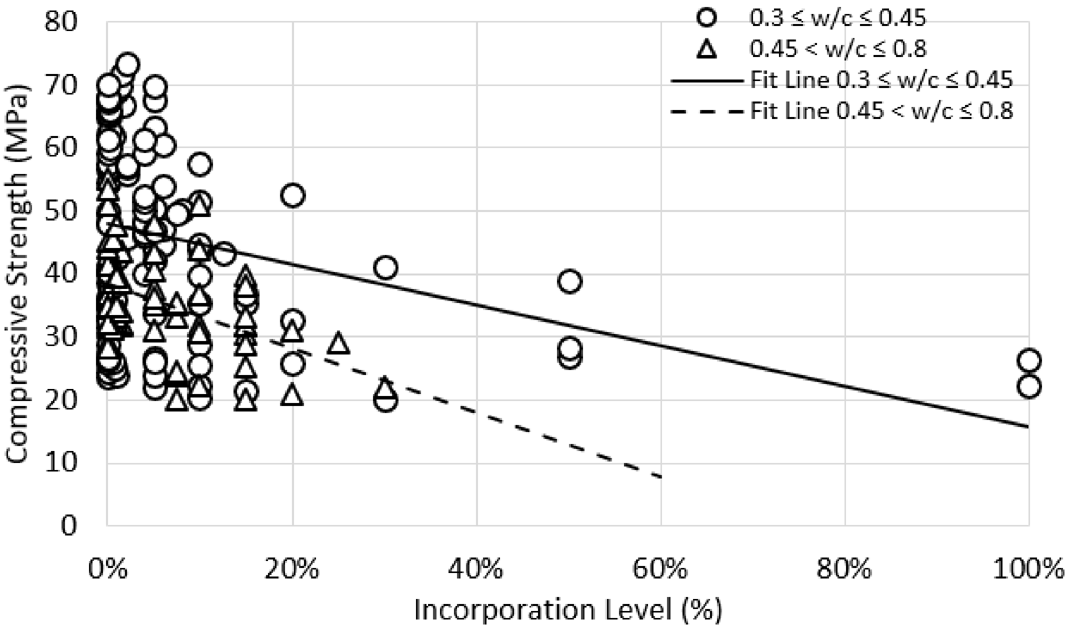


Figure 6.1: *Compressive strength of concrete incorporated with Polyethylene Terephthalate (PET) up to 100% replacement level and different water-to-cement ratios: 0.3 < w/c ≤ 0.45 (117 data points), 0.45 < w/c ≤ 0.8 (66 data points)*

In Figure 6.2 concrete compressive strength comprising polyethylene terephthalate is plotted versus the incorporation levels of polyethylene terephthalate. It must be noted that the incorporating levels of polyethylene terephthalate were limited to 20% to best assess its optimal use. It must also be noted that Figure 6.2 comprises 174 data points where 63% represents water-cement ratios ranging from 0.3 to 0.45 and 37% represents water: cement ratios between 0.45 to 0.80. More significantly, the results exhibited in Figure 6.2 demonstrated that concrete comprising polyethylene terephthalate with lower water: cement ratio class (0.3<water: cement<0.45) resulted in greater compressive strength.

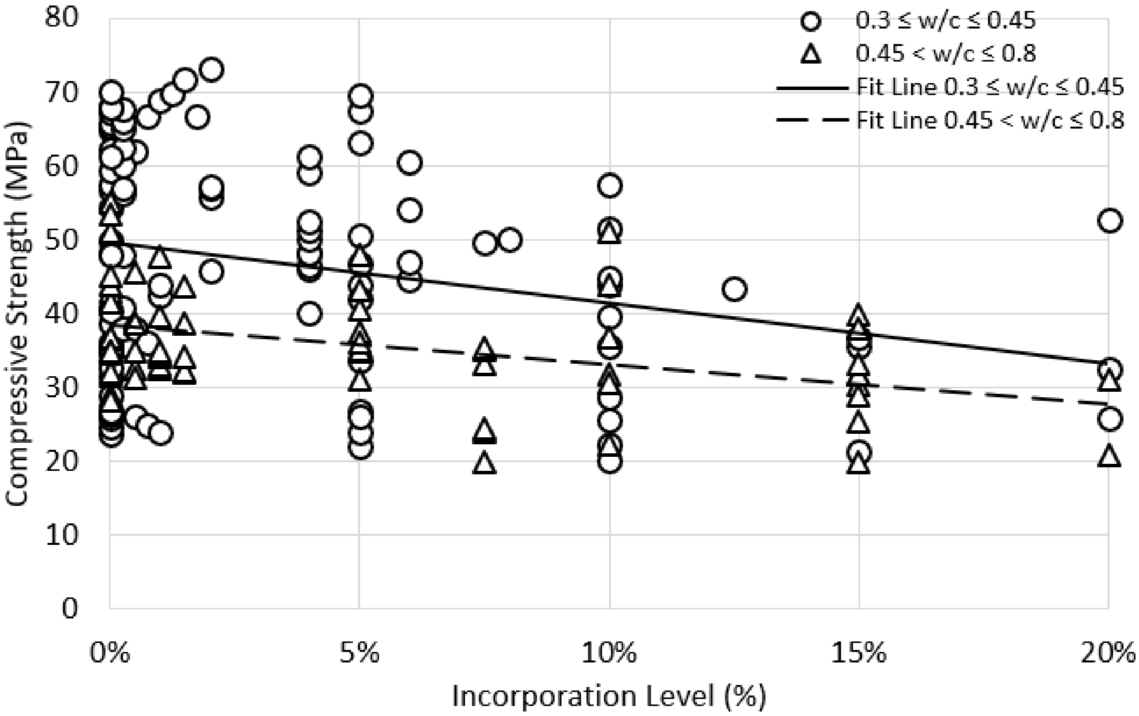


Figure 6.2: Compressive strength of concrete incorporated with Polyethylene Terephthalate (PET) up to 20% replacement level and different water-to-cement ratios: 0.3 < w/c ≤ 0.45 (110 data points), 0.45 < w/c ≤ 0.8 (64 data points)

6.2 The influence of pozzolans on Concrete Containing Polyethylene Terephthalate

The relationship between concrete compressive strength containing polyethylene terephthalate with and without the use of pozzolans is illustrated in figure 6.3. While both concrete groups yielded a decline in compressive strength with increased levels of polyethylene terephthalate, it should be noted that concrete comprising polyethylene terephthalate with pozzolans provided greater compressive strength in comparison to those of the specimens without pozzolans even at 28 days.

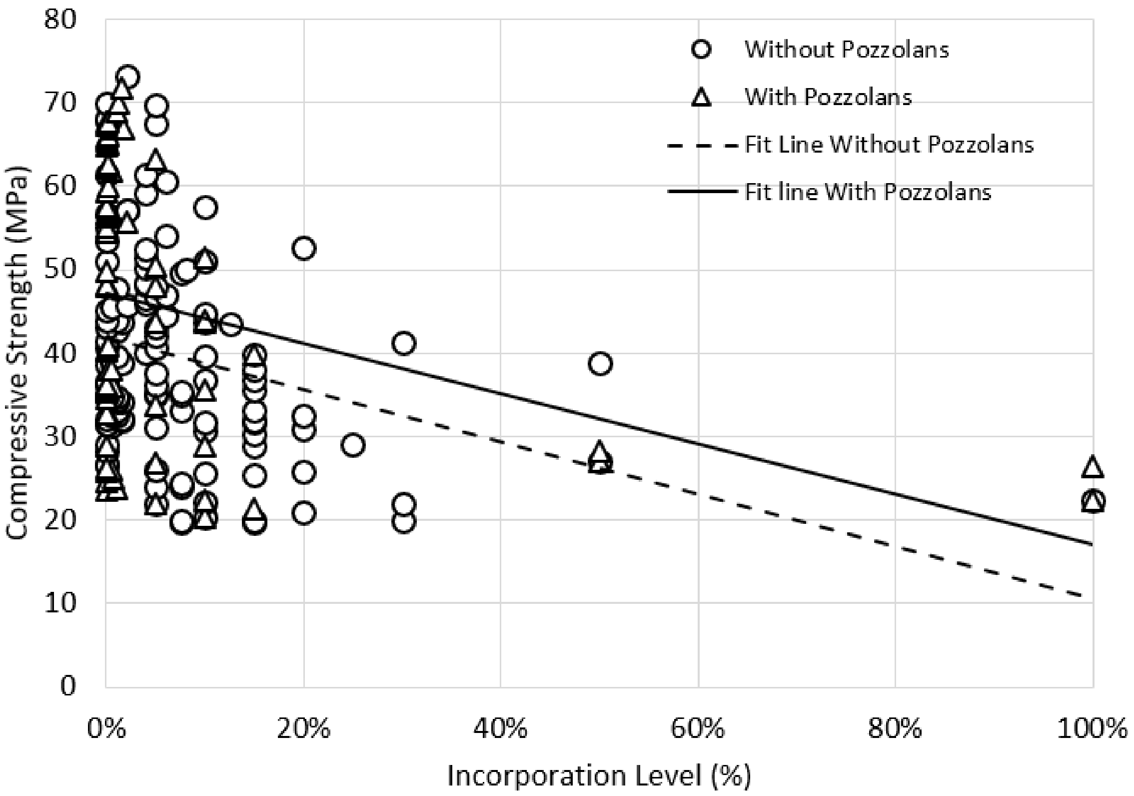


Figure 6.3: Compressive strength of concrete incorporated with Polyethylene Terephthalate (PET) up to 100% replacement level with (70 data points) and without (126 data points) the use of pozzolans

Figure 6.4 illustrates the relationship between the compressive strength of concrete comprising polyethylene terephthalate with and without the use of pozzolans. It is worth mentioning that the polyethylene terephthalate incorporation levels were restricted to 20% to best assess its optimal use. It is important to note that concrete comprising polyethylene terephthalate with pozzolans provided greater compressive strength compared to that of the specimens without pozzolans. However, beyond the 10% incorporation level of polyethylene terephthalate, the compressive strength of concrete containing pozzolans is seen to decrease when compared to those of concrete without the use of pozzolans. The use of polyethylene terephthalate often results in

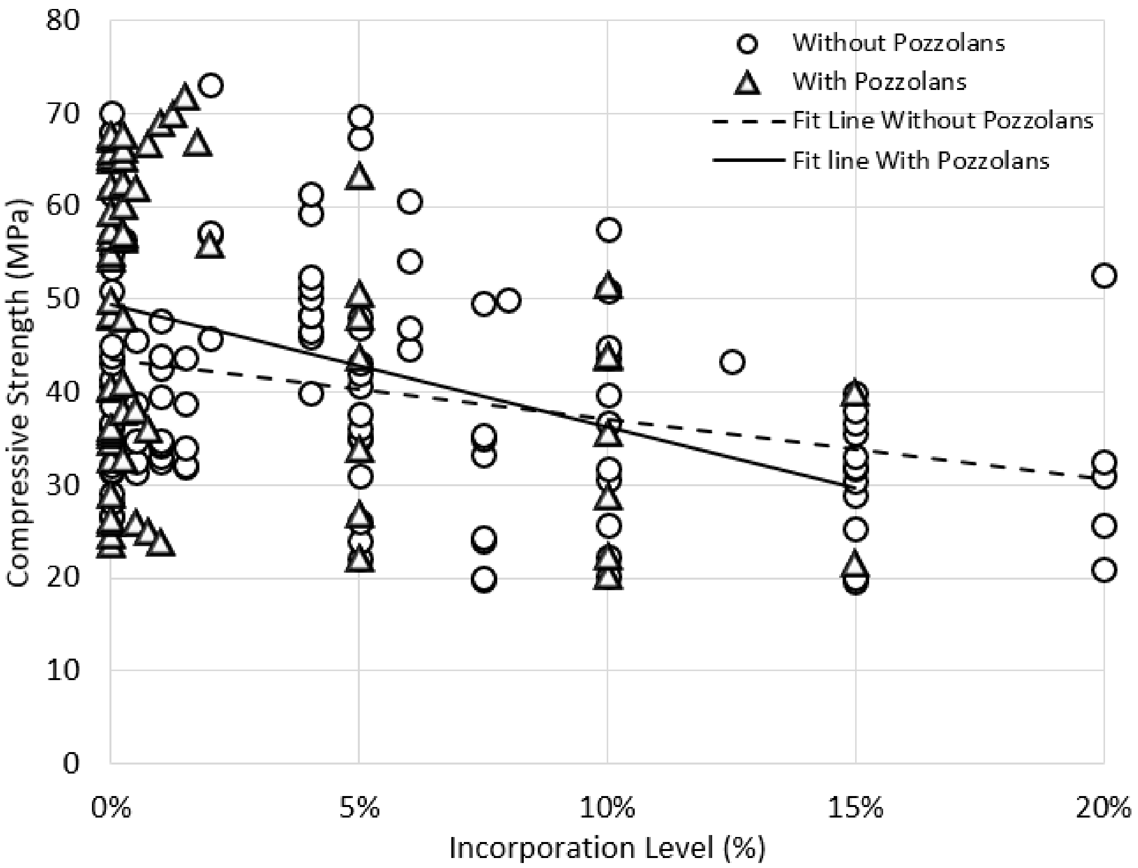


Figure 6.4: Compressive strength of concrete incorporated with Polyethylene Terephthalate (PET) up to 20% replacement level with (66 data points) and without (119 data points) the use of pozzolans

reduced amount of water remaining in the mix which may not be sufficient for complete hydration to be performed. This may further delay or diminish the formation of hydration products including calcium hydroxide and calcium silicate hydrate which would also adversely affect the rate of the pozzolanic reaction.

The 28-day concrete compressive strength comprising polyethylene terephthalate is plotted versus the replacement levels of pozzolans used as cement substitutes in Figure 6.5. The most utilised pozzolans are detected to be fly ash and silica fume. The results shown in Figure 6.5 indicate a considerable rise in compressive strength with increased cement substitution with silica fume up to 10% and fly ash up to 30%.

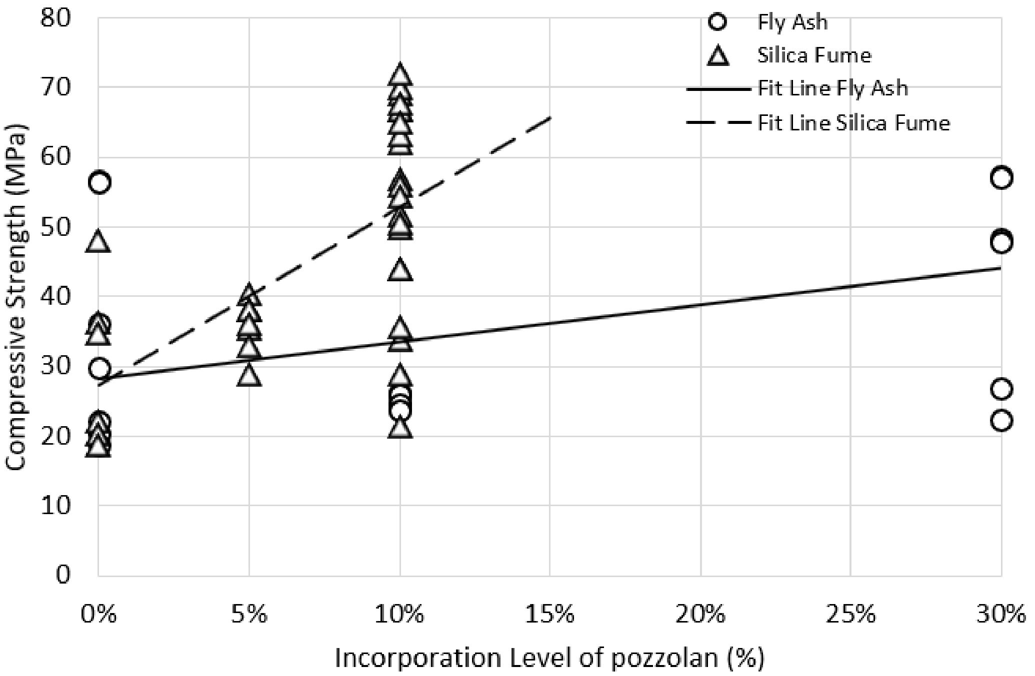


Figure 6.5: Compressive strength of concrete incorporated with PET and Fly Ash as cement replacement up to 30% replacement level (28 data points) as well as Silica Fume as cement replacement up to 10% replacement level (34 data points)

6.3 Types of Concrete Incorporating Polyethylene Terephthalate

The various concrete types incorporating polyethylene terephthalate are assessed in this section. A detailed analysis of the database shows polyethylene terephthalate can be incorporated into concrete as fibre additions, or as aggregate replacement for coarse or fine aggregates. This agrees with the findings obtained from the literature. Figure 6.6 illustrates the relationship between the 28-day concrete compressive strength and the incorporation levels of polyethylene terephthalate as fibre additions, fine aggregate, and coarse aggregate replacements. Figure 6.6 comprises 177 data points where 48 data points represent fibre additions, 46 data points represent coarse aggregate replacement, and 83 data points represent fine aggregate replacement.

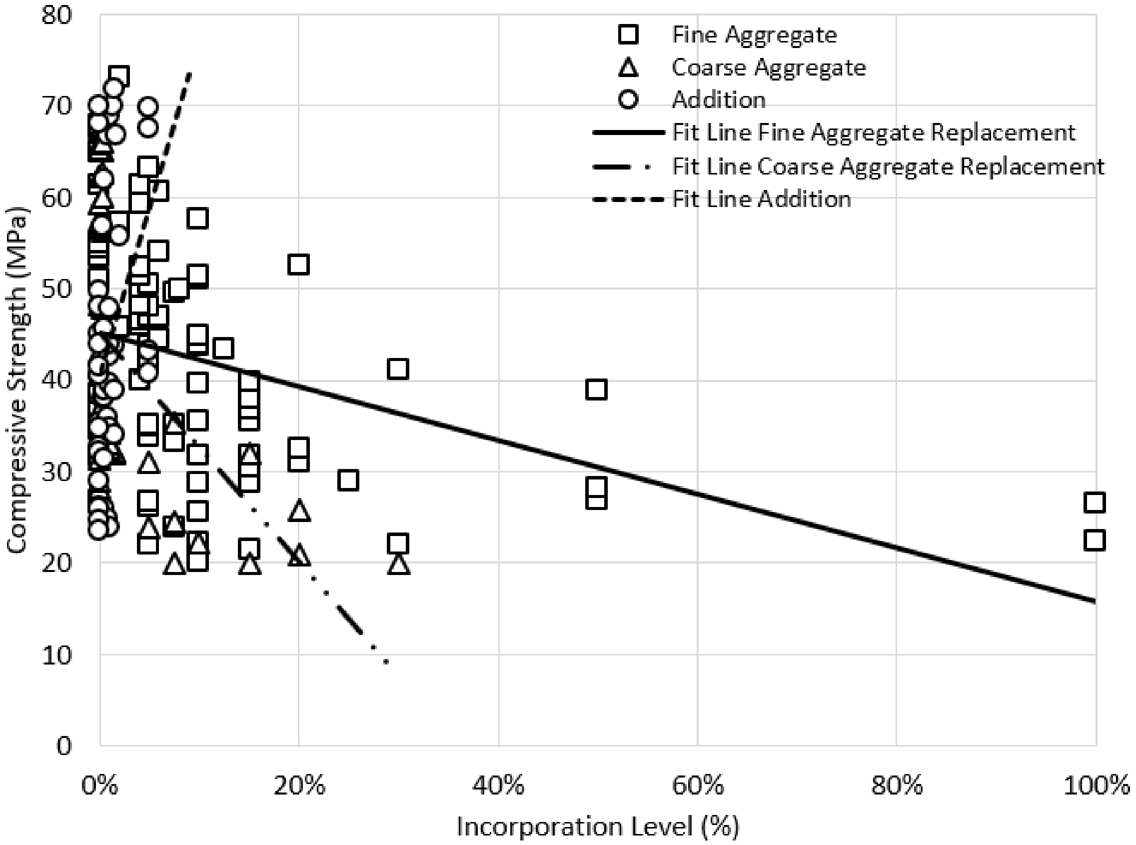


Figure 6.6: Compressive strength of concrete incorporated with PET up to 100% replacement level as fine aggregate (83 data points), coarse aggregate (46 data points) and as an addition (48 data points)

Figure 6.6 clearly demonstrates that the compressive strength of concrete containing polyethylene terephthalate used as coarse aggregate replacement is most significantly reduced when compared to concrete containing polyethylene terephthalate as fine aggregate replacement. The replacement of high-strength mix constituents such as coarse aggregate in concrete with low-strength plastic aggregate results in a greater decrease in compressive strength and correlates with findings obtained from the literature.

Figure 6.7 depicts the relationship between the 28-day concrete compressive strength and the incorporation levels of polyethylene terephthalate as fibre additions, fine aggregate, and coarse aggregate replacements. The incorporation levels of polyethylene terephthalate were limited to 20% in figure 6.7 to best assess the optimum boundary conditions for the different concrete types. It is pertinent to note the data points have been reduced to 168, with 48 data points representing fibre additions, 45 data points as coarse aggregate replacements and 75 data points as fine aggregate replacements. Figure 6.7 shows increased concrete compressive strength with increased incorporation of polyethylene terephthalate as fibre additions. It is important to mention that in conducting the database analysis, the maximum incorporation levels of polyethylene terephthalate as fibre additions obtained from the database did not exceed 5%. To obtain the optimum replacement levels of polyethylene terephthalate as coarse and fine aggregates, a reference standard of

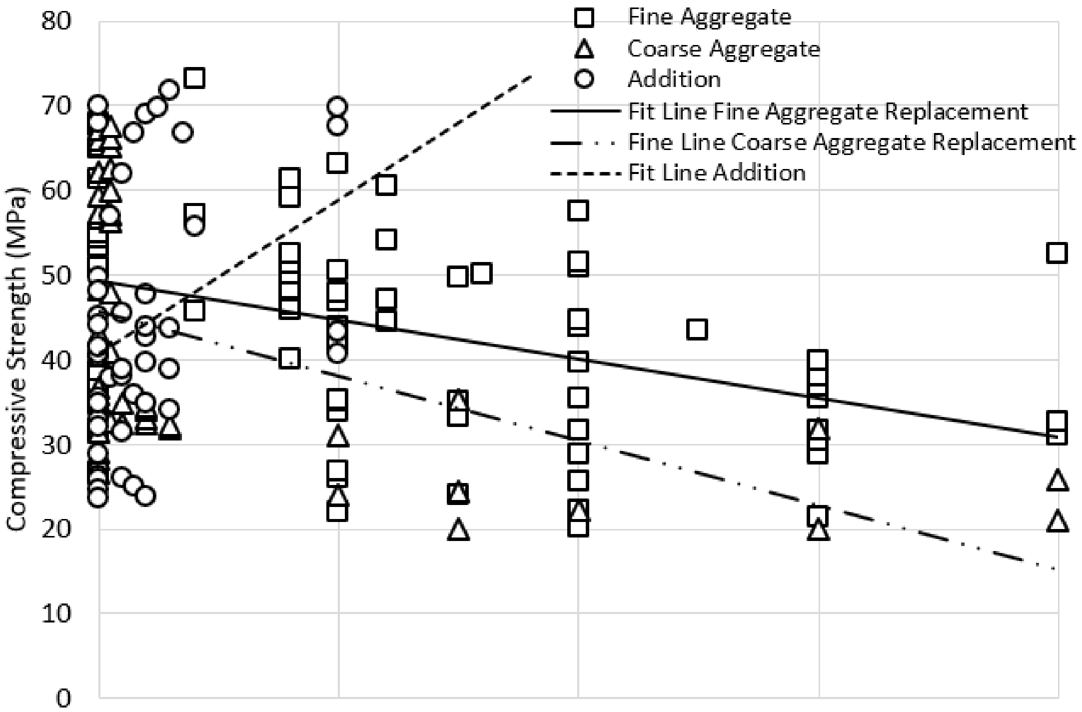


Figure 6.7: Compressive strength of concrete incorporated with PET up to 20% replacement level as fine aggregate (75 data points), coarse aggregate (45 data points) and up to 5% as an addition (48 data points)

30MPa was employed. At this reference point, the optimum replacement level for coarse aggregate is obtained to be 10%, while the optimum replacement level for fine aggregate is obtained to be 20%. This is in correlation with similar findings obtained from the literature.

Figure 6.8 illustrates the 28-day concrete compressive strength comprising up to 5% polyethylene terephthalate as fibre additions plotted against the replacement levels of pozzolans used as cement substitutes. The most utilised pozzolans are detected to be fly ash and silica fume. The findings presented in Figure 6.8 indicate that the increased replacement levels of cement with pozzolans yield a considerable increase in the compressive strength of concrete for silica fume, but a considerable decrease for fly ash, even while both are utilized up to a replacement of 10% as cement substitutes. The chemical and physical effects of silica fume are attributed to the greater increase in compressive strength [143]. The silica fume particles can infuse the micro-voids in the bulk mix and the transition zone since they are much smaller than the cement grains. As a result, the physical packing is enhanced, which causes the microstructure to become denser. Also, silica fume is extremely reactive and readily participates in pozzolanic reactions. When free water and calcium hydroxide created during cement hydration interact in a process known as the pozzolanic reaction, more calcium silicate hydrate (C-S-H) is produced, helping to increase the compressive strength [144]. Silica fume can also reduce the amount of water. The flocculated cement grains can be dispersed in fresh mixes. As a result, the water that was trapped in the flocculated cement grains is released and is now usable for hydration. Additionally, a stronger link between the mix and aggregate forms as a result of the efficient micro-filling action of silica fume and the hastened pozzolanic reaction.

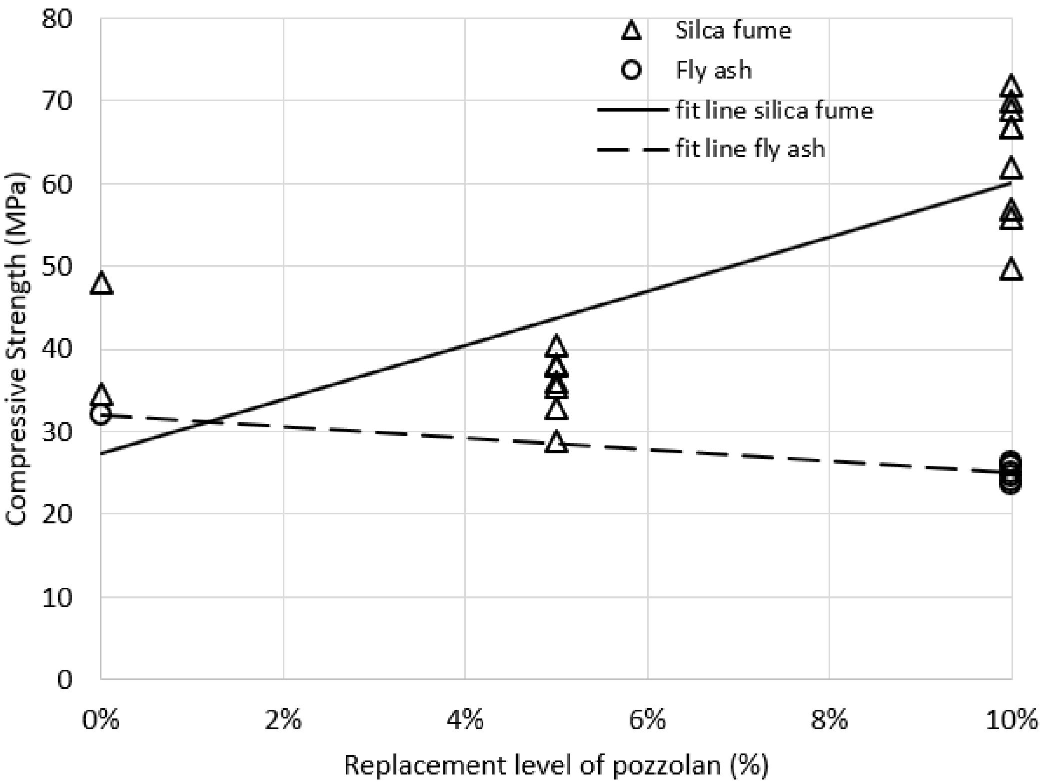


Figure 6.8: Compressive strength of concrete incorporated with Polyethylene Terephthalate (PET) as an addition up to 5% replacement, silica fume up to 10%, and fly ash up to 10%

Figure 6.9 illustrates the 28-day concrete compressive strength comprising up to 10% polyethylene terephthalate as coarse aggregate replacement plotted against the substitution levels of pozzolans used as cement substitutes. The most utilised pozzolans are detected to be fly ash, applied up to 30% cement substitute. The findings ploted in Figure 6.9 indicate that the increased replacement levels of cement with fly ash yield a considerable decrease in the compressive strength of concrete. This demonstrates that micro filling of the bulk concrete mix with fly ash was inefficient. Fly ash typically has particles that are virtually the same size as cement, the micro-voids are therefore not filled, which does not improve the physical packing. Additionally, fly ash also does not exhibit significant pozzolanic activity at an early stage. The non-reactive component of fly ash is responsible for this. Fly ash, however, displays pozzolanic activity in later stages, which increases its compressive strength.

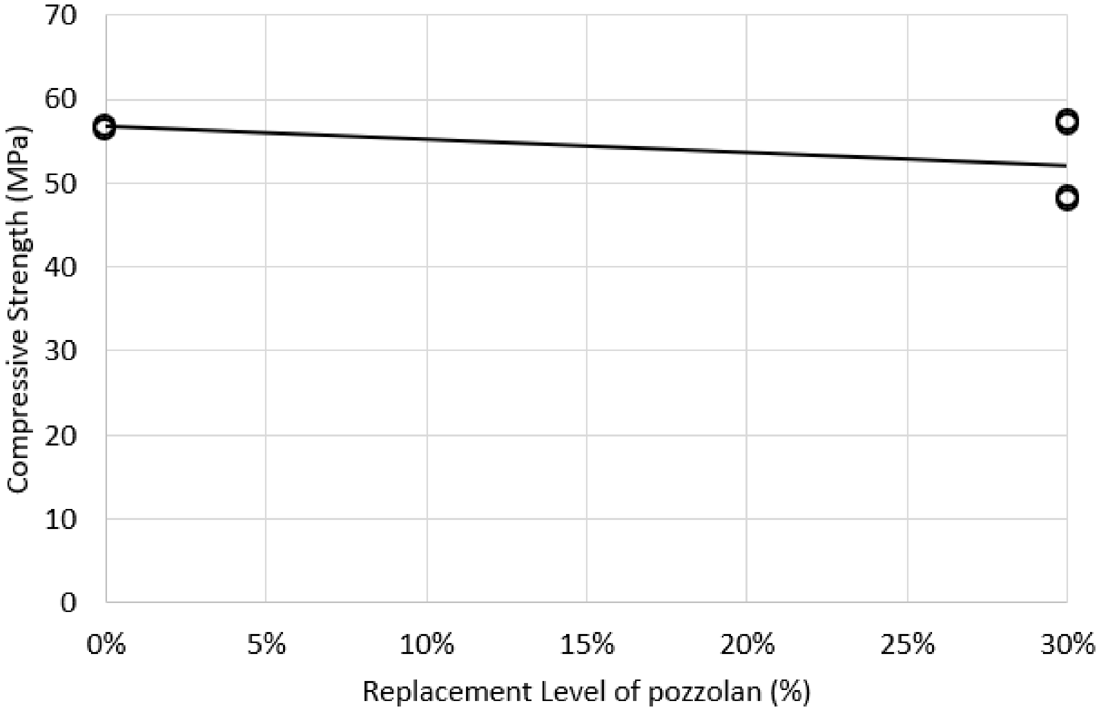


Figure 6.9: Compressive strength of concrete containing up to 10% of PET as coarse aggregate replacement, and fly ash up to 30% as cement replacement

The 28-day compressive strength of concrete comprising up to 20% polyethylene terephthalate is plotted against the replacement levels of pozzolans used as cement substitutes in Figure 6.10. The most utilised pozzolans are detected to be fly ash and silica fume. Silica fume is assessed to be utilized as cement replacement up to 10% and fly ash up to 30%. The results shown in Figure 6.10 indicate that the increased replacement levels of cement with pozzolans yield a considerable increase in the compressive strength of concrete for silica fume, but a considerable decrease for fly ash. Due to its high level of reactivity, silica fume readily takes part in the pozzolanic reaction, while fly ash does not exhibit significant pozzolanic activity at the onset stage.

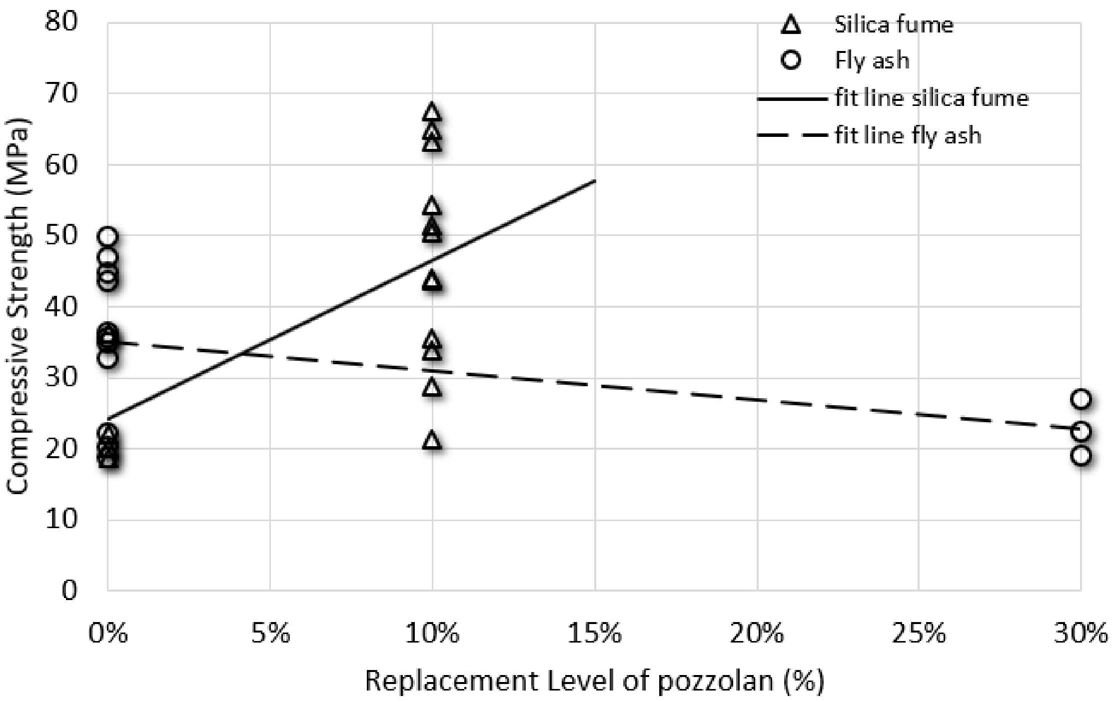


Figure 6.10: Compressive strength of concrete containing up to 20% of PET as fine aggregate, 10% silica fume and 30% fly ash as cement replacement

6.4 The Boundary Limits and Concrete Types Containing Polyethylene Terephthalate

The boundary limits are assessed and employed in evaluating the sustainability indicators in this thesis. Critical parameters that greatly impact the durability of concrete incorporating polyethylene terephthalate were identified. The most effective concrete strength values were found to be those with water: cement ratios between 0.3 and 0.45. From the database analysis, the optimum incorporation levels of polyethylene terephthalate in concrete were obtained to be 5% as fibre additions, 10% as coarse aggregate replacement and 20% as fine aggregate replacement. Also, 5% polyethylene terephthalate incorporation as fibre additions can be utilized with a 10% silica fume and 10% fly ash as cement replacement; 10% polyethylene terephthalate incorporation as coarse aggregate replacement can be utilized with 30% fly ash as cement replacement, silica fume was not detected from the database in this instance; 20% polyethylene terephthalate incorporation as fine aggregate replacement can be utilized with a 10% silica fume and 30% fly ash as cement replacement.

The establishment of the concrete types was essential in order to perform a comprehensive life cycle analysis. These concrete types can be divided into four (4) groups. Type 1 represents the control concrete. This is the reference concrete specimen which does not comprise polyethylene terephthalate or pozzolans. Average mix constituent values of the control concrete containing no polyethylene terephthalate nor pozzolans were thus calculated from the control data points in the database. Type 2a comprises concrete specimens that incorporate 5% polyethylene terephthalate as fibre additions without pozzolans. Type 2b and 2c comprise concrete specimens incorporating 5% polyethylene terephthalate as fibre additions and two commonly used pozzolans: 10% silica fume and 10% fly ash respectively. Type 3a comprises concrete specimens that incorporate 10% polyethylene terephthalate as coarse aggregate replacement without pozzolans. Type 3b comprises concrete specimen incorporating 10% polyethylene terephthalate as coarse aggregate replacement and 30% fly ash. Type 4a comprises concrete specimens that incorporate 20% polyethylene terephthalate as fine aggregate replacement without pozzolans. Type 4b and 4c comprise concrete specimens incorporating 20% polyethylene terephthalate as fine aggregate replacement and two commonly used pozzolans: 10% silica fume and 30% fly ash respectively. Table 6.1 summarises the concrete types, the key constituents as well as the type and the amount of polyethylene terephthalate and pozzolans incorporated in concrete. It should be emphasized again that these concrete types obtained are used for the life cycle analysis detailed in chapter 7.

Table 6.1 Established polyethylene terephthalate concrete types

Concrete Type	Water (kg/m^3)	Cement (kg/m^3)	Fine Aggregates (kg/m^3)	Coarse Aggregates (kg/m^3)	The use of PET (kg/m^3)	Type of pozzolan	The use of pozzolan (kg/m^3)
Type 1 (Control concrete)							
Type 1 (Control)	196.7	439.7	760.8	886.4	NA	NA	
Type 2 (Concrete incorporating 5% PET as an Addition)							
Type 2a (5% PET)	196.7	439.7	760.8	886.4	41.2	NA	
Type 2b (5% PET) + 10% SF	196.7	395.7	760.8	886.4	41.2	Silica fume (SF)	44
Type 2c (5% PET) + 10% FA	196.7	395.7	760.8	886.4	41.2	Fly ash (FA)	44
Type 3 (Concrete incorporating 10% PET as Coarse Aggregate)							
Type 3a (10% PET)	196.7	439.7	760.8	797.76	88.6	NA	
Type 3b (10% PET) + 30% FA	196.7	307.8	760.8	797.76	88.6	Fly ash FA	132
Type 4 (Concrete incorporating 20% PET as Fine Aggregate)							
Type 4a (20% PET)	196.7	439.7	608.6	886.4	136	NA	
Type 4b (20% PET) + 10% SF	196.7	395.7	608.6	886.4	136	Silica fume (SF)	44
Type 4c (20% PET) + 30% FA	196.7	307.8	608.6	886.4	136	Fly ash FA	132

CHAPTER 7

LIFE CYCLE AND SUSTAINABILITY ASSESSMENT OF CONCRETE INCORPORATING POLYPROPYLENE, POLYETHYLENE TEREPHTHALATE AND POZZOLANS

Life cycle assessment of concrete containing polypropylene, polyethylene terephthalate and pozzolans was performed using openLCA software. The concrete types, precisely determined in chapters 5 and 6, enabled the integrated life cycle analysis to be conducted. The indices used in the analysis comprised climate change, ozone depletion potential, fossil depletion potential, metal depletion potential, freshwater ecotoxicity, human toxicity, marine ecotoxicity, terrestrial ecotoxicity potential, agricultural land occupation and urban land occupation.

The main aspect of the study is to evaluate the environmental and sustainable impacts of the incorporation of polypropylene, polyethylene terephthalate and pozzolans in concrete. The concrete types encompassing the incorporation levels of polypropylene fibres, polyethylene terephthalate and replacement levels of pozzolans, established through the database analysis, are employed in the life cycle assessment herein. The functional unit in this study was determined to be 1 m3 of concrete. It should be emphasized that this approach is consistent with Marinkovic et al. (2010) [145].

It must also be noted that the production phase of the concrete models studied here encompasses system boundaries. It is well documented in the literature that the manufacturing phase constitutes the most relevant process in terms of environmental impacts [102-104] as this stage comprises the processing of raw materials, transportation, and manufacture of concrete. Energy consumed for the processing and transportation of the raw materials along swith the mixing processes were included in the system boundaries. Figure 7(a) exhibits the schematic flow of the system boundaries adopted in this study.

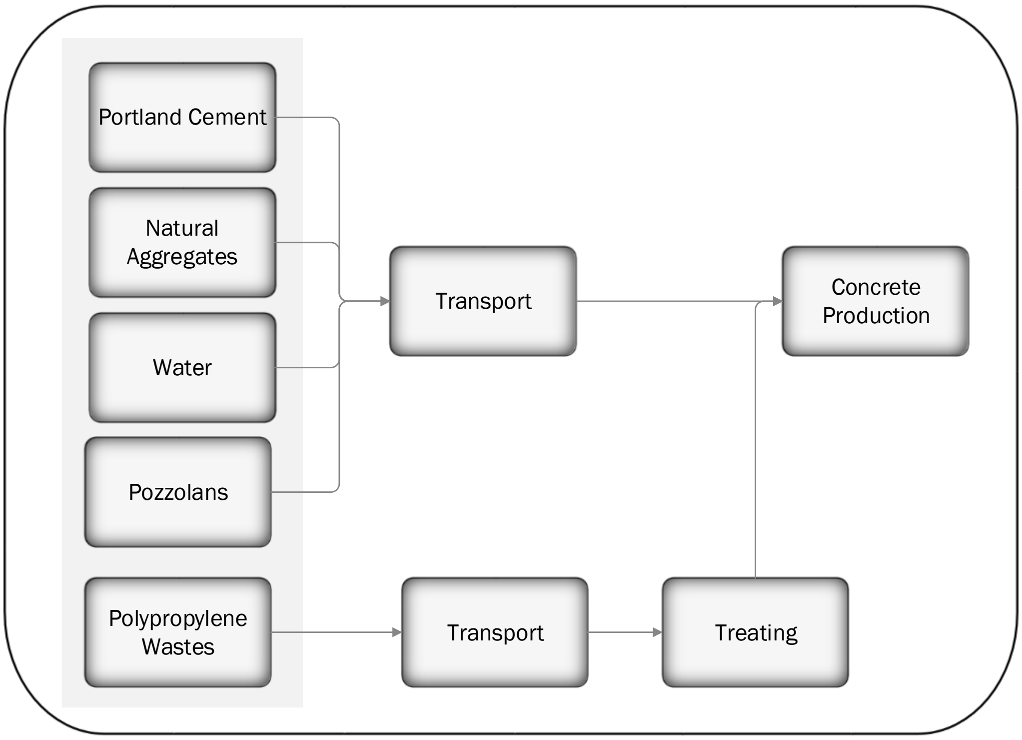


Figure 7.1: System boundaries

Relevant data such as transportation and production data were obtained from the ecoinvent database. ReCiPe impact assessment method, the midpoint approach concerning the hierarchies is utilized to transform the inventory data into an indicator to determine the impact scores [135, 146]. Although the life cycle inventory (LCI) is established for most of the mix constituents, a meticulous literature survey is conducted to supply the absent inputs [147].

7.1 Life Cycle Assessment of Polypropylene Incorporation in Pozzolanic Concrete

Figures 7.2 – 7.5 demonstrate the indicators used to assess the life cycle analysis of pozzolanic concrete incorporating polypropylene fibres. Although the polypropylene inclusion in concrete does not seem to make a discernible development in climate change and ozone depletion, type 3a, b, and c, concrete comprising both the polypropylene fibres and pozzolans appear to significantly decrease these indices. Type 3a, concrete incorporating 3% polypropylene fibres and 30% fly ash provided the greatest reduction in climate change and ozone depletion. It must be emphasised that the utilisation of pozzolans as cement replacement was essential to support the successful incorporation of polypropylene fibres in the matrix which is reported to improve the mechanical properties of such materials in long term. It is substantially satisfying to document that the utilisation of pozzolans also played a key role in decreasing climate change and ozone depletion. The considerable decrease attained in ozone depletion is an indication of the decreased adverse effects of certain types of skin cancers and immune deficiency disorders (146). It is also vastly reported in the literature that the decrease in climate change has a considerable effect in mitigating extreme droughts and floods, sea-level rise, and biodiversity loss (146, 148).

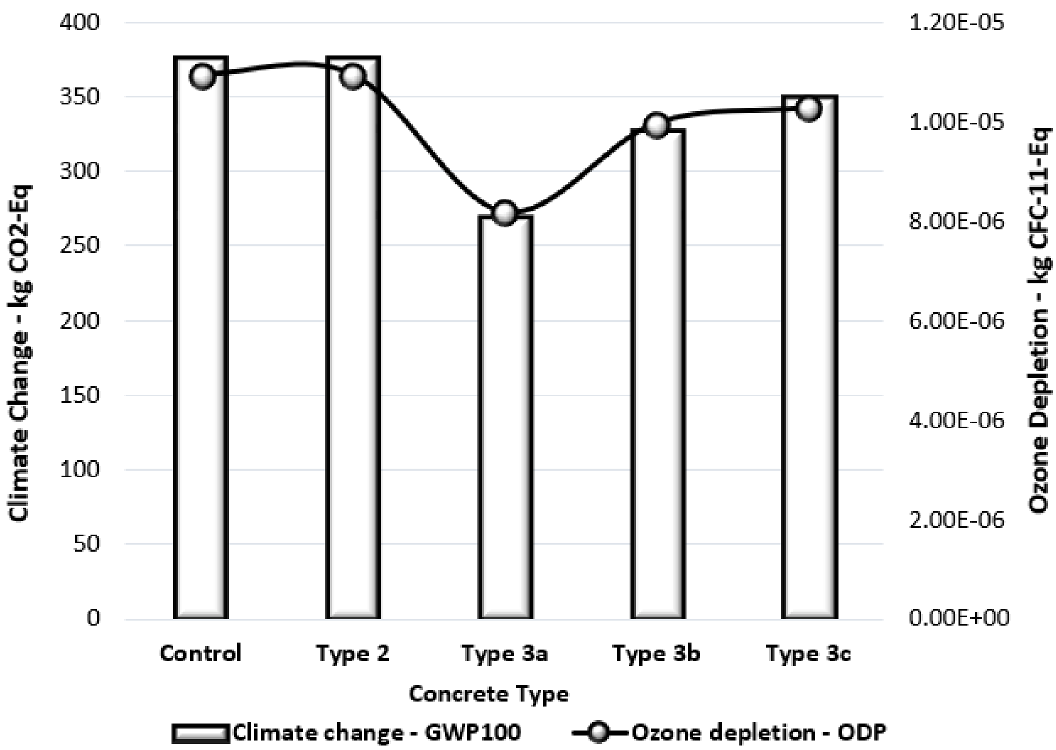


Figure 7.2: Climate change and ozone depletion potentials of concrete incorporating polypropylene

The results exhibited in Figure 7.3 demonstrate the inclusion of polypropylene fibres along with the utilisation of pozzolans as binder replacement plays a great role in decreasing fossil, metal, and water depletion. Like the results shown in Figure 7.2, the greatest decrease in the depletions attained in types 3a, 3b and 3c is mainly due to the considerable contribution of pozzolans used as binder replacements herein. The reduction in fossil fuel depletion is evidently associated with the decrease attained in climate change as the reduction in fossil fuel consumption led to a considerable decrease in the greenhouse gases like carbon dioxide that can entrap the heat in the earth’s atmosphere and substantially reduce the effect of climate change (146). The reduction in fossil fuel depletion also significantly contributes to the mitigation of hazardous air pollutants (involving sulphur dioxide, nitrogen oxide and particulate matter etc.) which can assist in the establishment of environmental integrity and improved human health (146). The decrease in water depletion is also attributed to the reduction in the discharge of industrial wastewater into the water sources and hence consequently reduction in the pollutants and contaminants in the water resources (149).

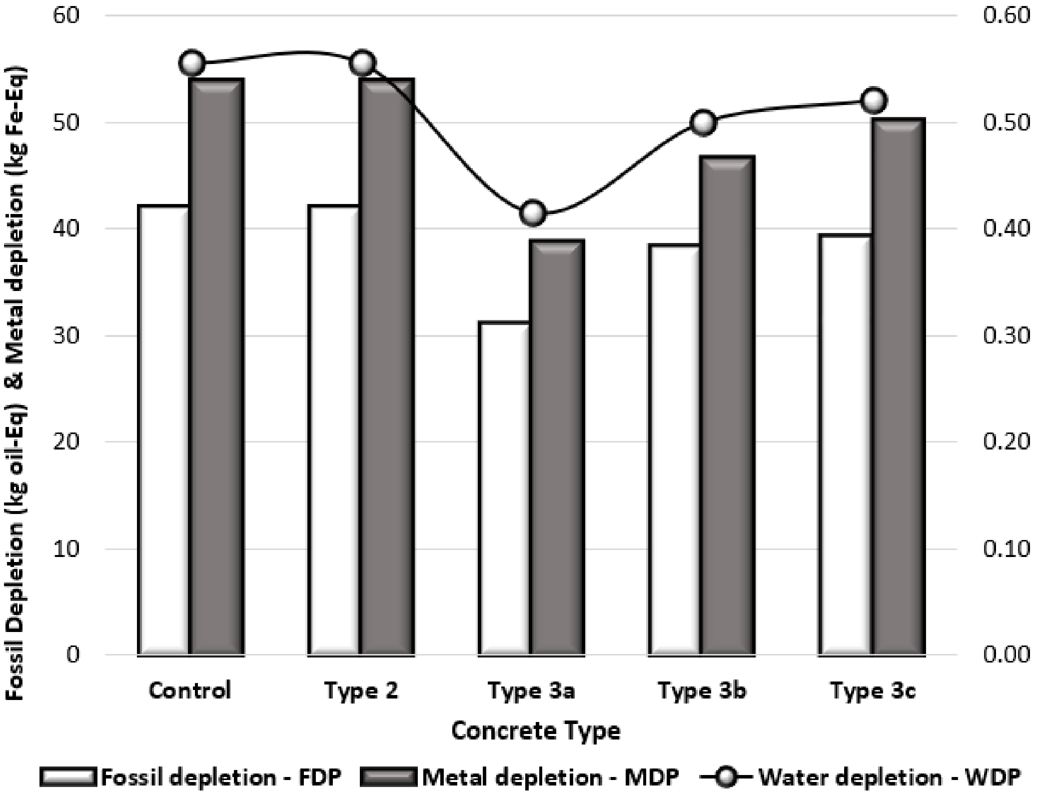


Figure 7.3: Fossil, metal, and water depletion of concrete types

The decrease attained in freshwater ecotoxicity, marine ecotoxicity human toxicity, and terrestrial ecotoxicity versus the particulate matter formation of concrete models examined in this paper are shown in Figure 7.4. The results exhibited in Figure 7.4 demonstrate that all sub-types of type 3 performed a remarkable decrease in the aforementioned indices. The greatest decrease in these indices is observed in Type 3a mainly due to the highest replacement level of pozzolans utilisation compared to that of Models 3b and 3c. This feature also provided the lowest particulate matter formation and hence supported the Environmental Protection Agency of the United States' national and regional regulation in relation to mitigating the emissions of pollutants that generates particulate matter. The diminution in the particulate matter will markedly contribute to the state and local governments in meeting the agency's air quality standards (150). The substantial decrease observed in these toxicity indices also is an indication of the reduced transformation of chemicals in the ecology and hence improved environmental sustainability and preserved ecosystem (151).

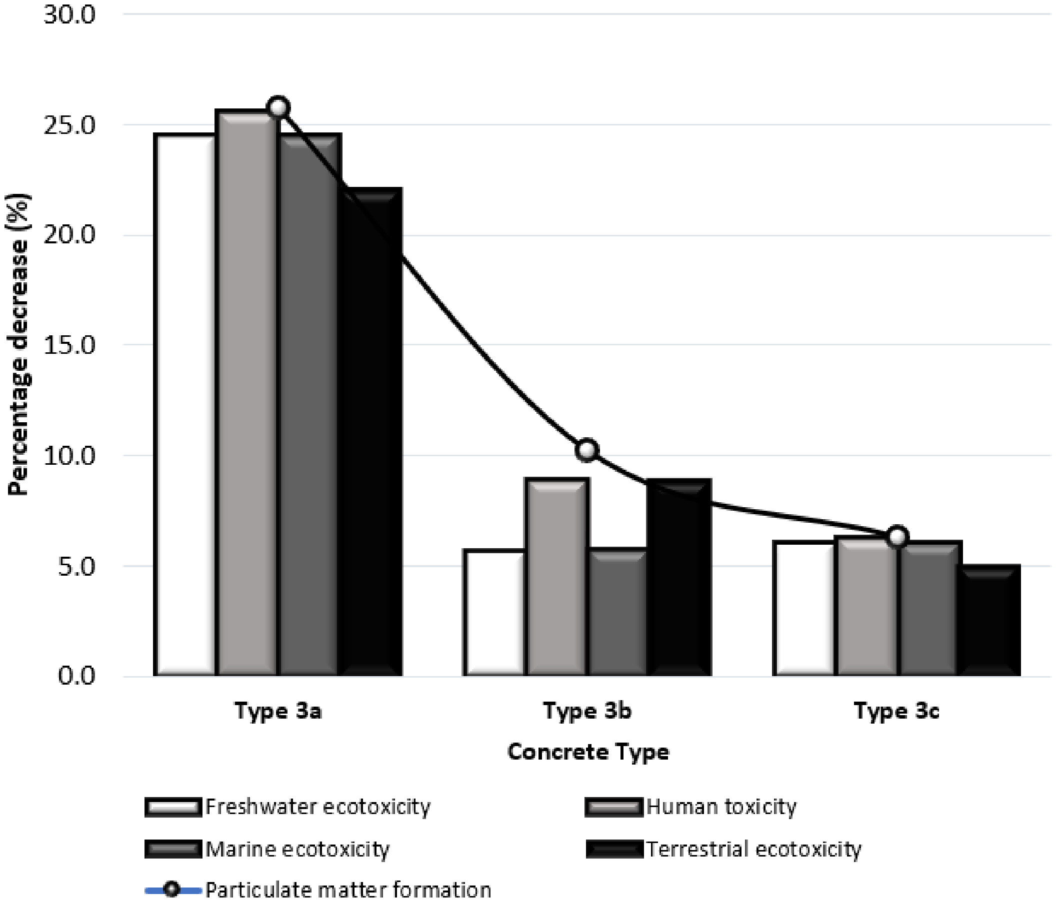


Figure 7.4: Freshwater ecotoxicity, human toxicity, marine ecotoxicity, terrestrial ecotoxicity and the particulate matter formation of PP concrete types

Agricultural and urban land occupation versus the concrete types examined in the study is plotted in Figure 7.5. As anticipated, a considerable decrease in both agricultural and urban land occupation is detected in all sub-types of Type 3.

The reduction attained in agricultural and urban land occupation is encouraging to raise awareness for the appropriate determination of land usage as well as the land recyclability that requires significant adaptation to climate change (146, 152). It is well documented in the literature that inappropriate land usage can raise the risks of climate change such as increased endanger of floods and water scarcity (153). The results shown in Figure 7.5 also elicit the fact concerning land ethics which is defined by Leopold as the 'community' that comprises not only humans but also all the other parts of the Earth, soils, waters, plants, animals, and lands (154).

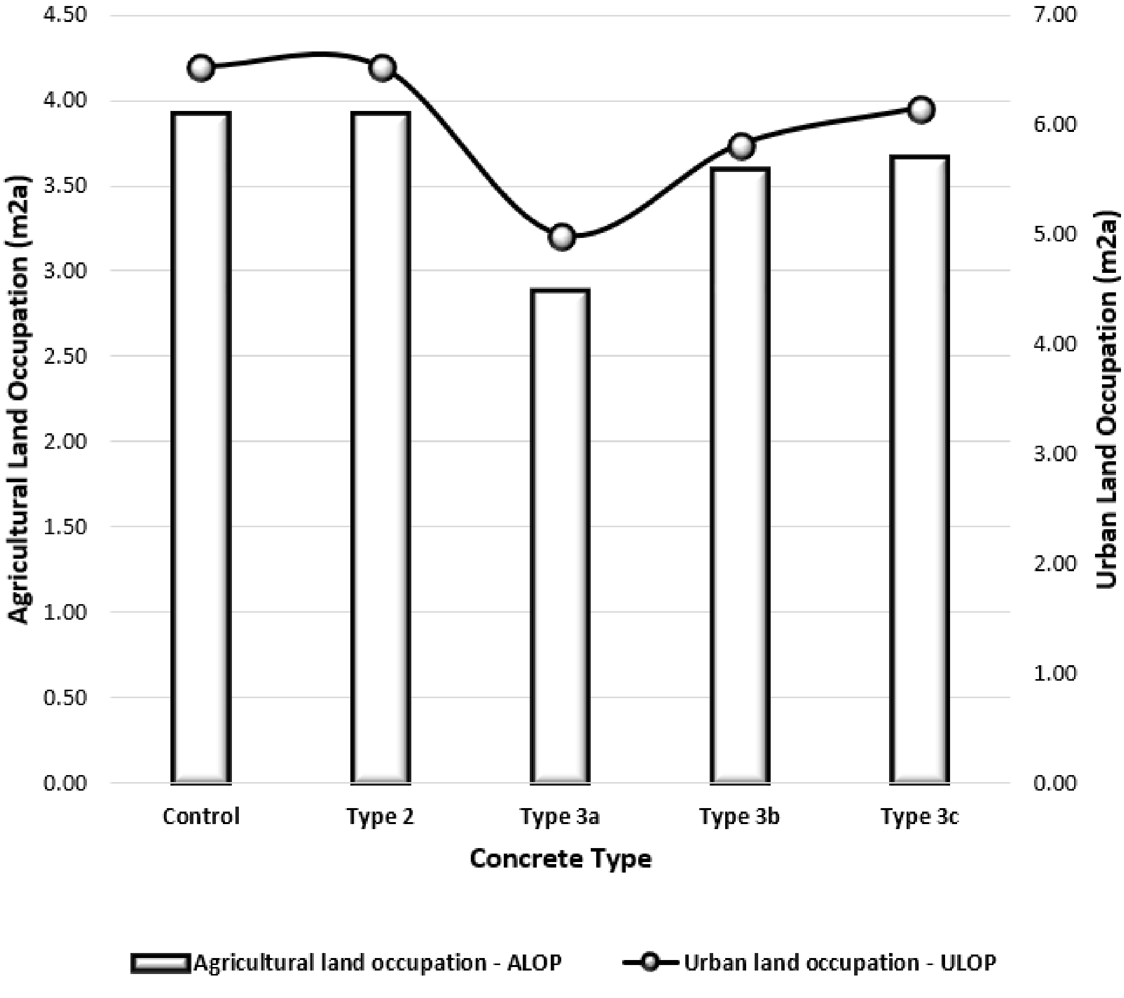


Figure 7.5: Agricultural and urban land occupation of concrete types

7.2 Cost Efficiency and Eco-Strength Efficiency of Concrete Incorporating Polypropylene

The cost efficiency and eco-strength efficiency of concrete comprising polypropylene fibres are shown in Figure 7.6. The results shown in Figure 7.6 demonstrate that Type 2, concrete incorporating polypropylene fibres alone, provided enhanced cost and eco-strength efficiencies considerably. It must be emphasised that the analysis shown in Figure 7.6 comprises both the sustainability indices and the engineering performances of concrete incorporating polypropylene fibres and hence the significance of such fibre integration in concrete is more comprehensively perceived. The higher compressive strength, attained through the formation of the additional calcium-silicate-hydrate gels because of the pozzolanic reaction, eminently provided improved cost and eco-strength efficiencies in all sub-types of Type 3. The results illustrated in this section inset an additional standpoint to the findings reported in the former section as they further emphasised the practicability and feasibility of polypropylene incorporation in concrete through the engineering performance of the end product. It must be noted that the increase attained in the cost and eco-strength efficiencies of concrete incorporating polypropylene fibres are in great agreement with Ozturk et al. (2022) [46] and Ince et al. (2022) [47].

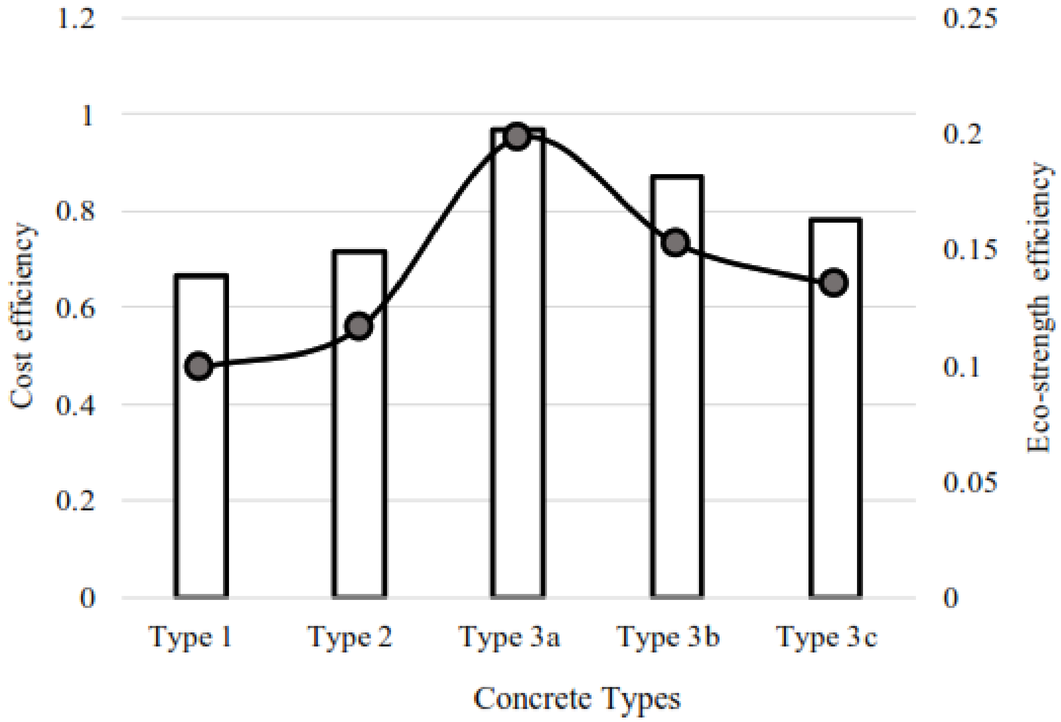


Figure 7.6: Cost and eco-strength efficiency of PP concrete types

7.3 Life Cycle Assessment of Polyethylene Terephthalate Incorporation in Pozzolanic Concrete

Figures 7.7 – 7.10 shows the parameters used to evaluate the life cycle assessment of pozzolanic concrete containing polyethylene terephthalate. Whilst the incorporation of polyethylene terephthalate into concrete does not appear to have a discernible impact on climate change and ozone depletion, types 3b, and 4c, concrete containing both pozzolans and polyethylene terephthalate appears to dramatically lower these indices. The most significant reduction in ozone depletion and climate change was achieved by Type 3b concrete (which contains 10% polyethylene terephthalate as coarse aggregate replacement and 30% fly ash as cement replacement) and Type 4c concrete (containing 20% polyethylene terephthalate as fine aggregate replacement and 30% fly ash). The use of pozzolans as cement replacement is essential for the successful incorporation of polyethylene terephthalate into the matrix, which is reported to improve the mechanical properties in the long term.

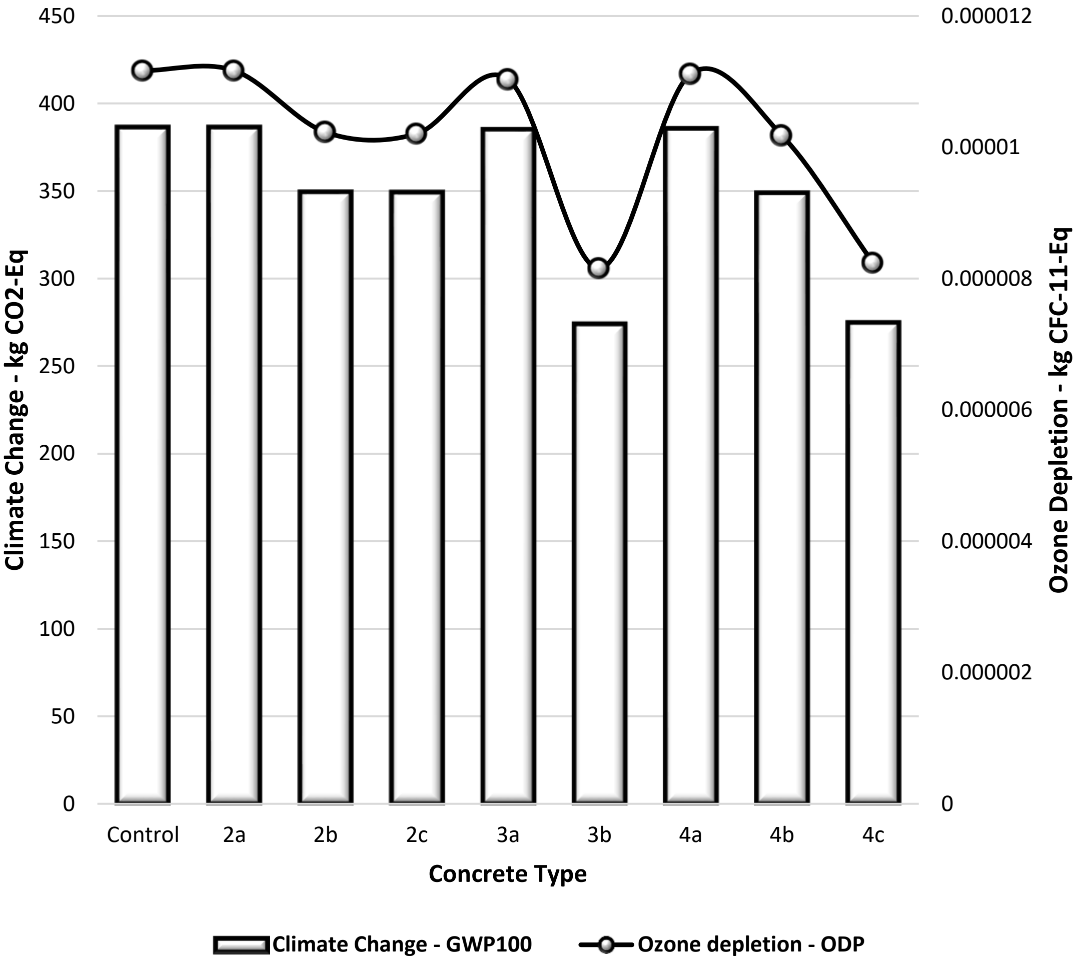


Figure 7.7: Climate change and ozone depletion potentials of PET concrete types

In figure 7.8, the inclusion of polyethylene terephthalate as well as the use of pozzolans as a binder replacement contributes significantly to a decrease in fossil fuel, metal, and water depletion potentials. Comparable to the results shown in Figure 7.6, the most significant decrease in the depletions attained in types 3b and 4c is mainly due to the considerable contribution of pozzolans used as binder replacements.

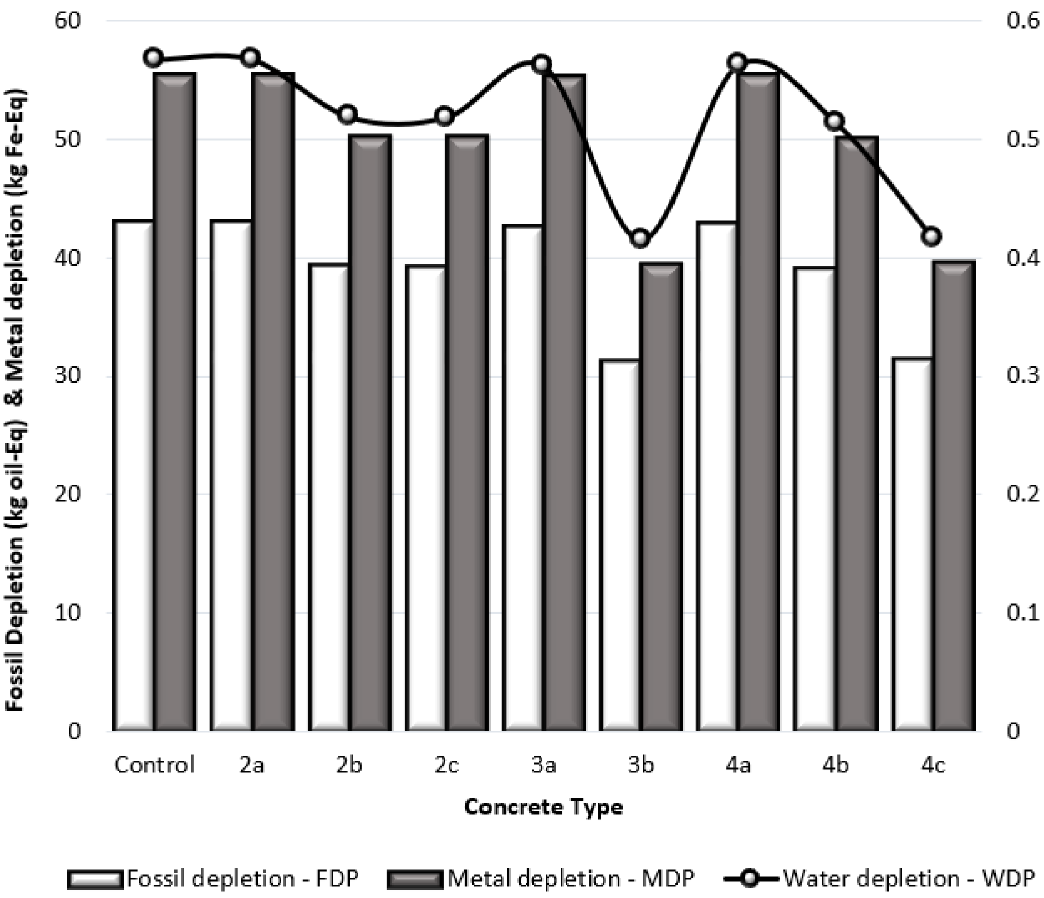


Figure 7.8: Fossil, metal, and water depletion of PET concrete types

The decrease in fossil fuel consumption results in a significant decrease in greenhouse gases like carbon dioxide, which can entrap heat in earth's atmosphere and significantly lessen the effects of climate change, so it is obvious that the decrease in fossil fuel depletion is linked to the decrease in climate change (146). Reduced industrial wastewater discharge into water sources, and subsequently lower levels of pollutants and toxins in water resources, are also credited with a decrease in water depletion (149).

Figure 7.9 illustrates the reduction in freshwater ecotoxicity, marine ecotoxicity human toxicity, terrestrial ecotoxicity and particulate matter formation for concrete types incorporating polyethylene terephthalate and pozzolans. Figure 7.9 shows a remarkable decrease in the indices for concrete types 3b and 4c. A significant reduction in human toxicity to freshwater, marine toxicity to humans, and terrestrial toxicity is observed in Type 3b and 4c, primarily due to the high replacement level of pozzolans.

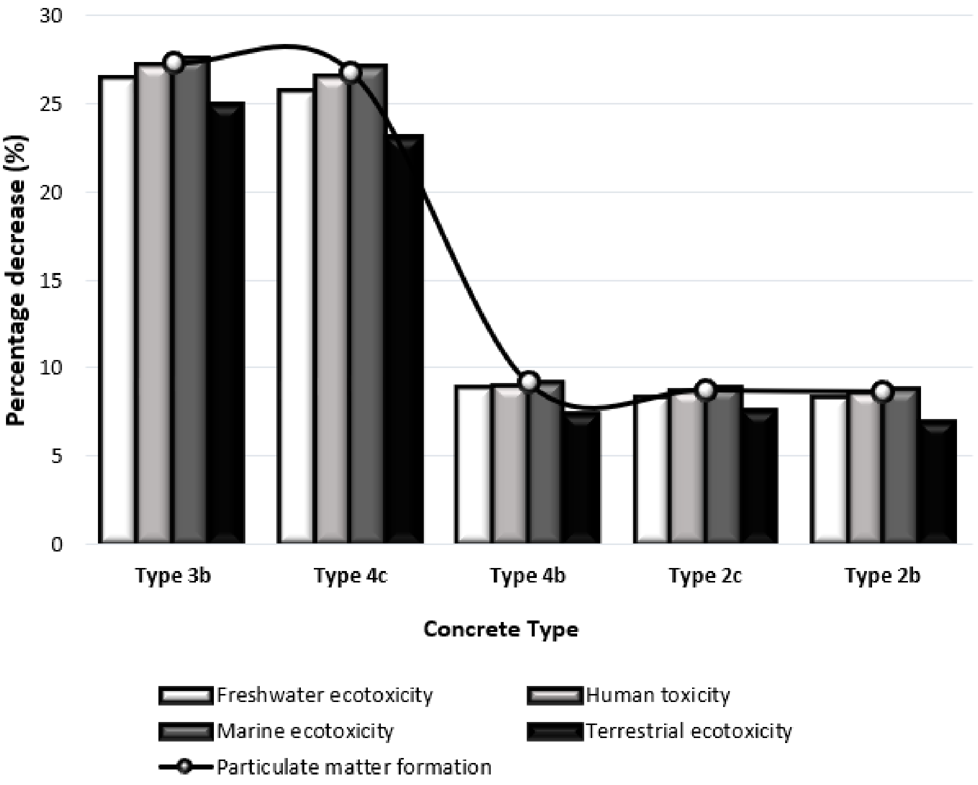


Figure 7.9: Freshwater ecotoxicity, human toxicity, marine ecotoxicity, terrestrial ecotoxicity and the particulate matter formation of PET concrete types

Figure 7.10 plots agricultural and urban land occupation versus the concrete types examined in the study. As expected, concrete types 3b and 4c show a considerable decline in both agricultural and urban land occupation. Consequently, more land area is made available for urban use and agricultural crop production as against the need for such land for landfilling waste plastic and pozzolans.

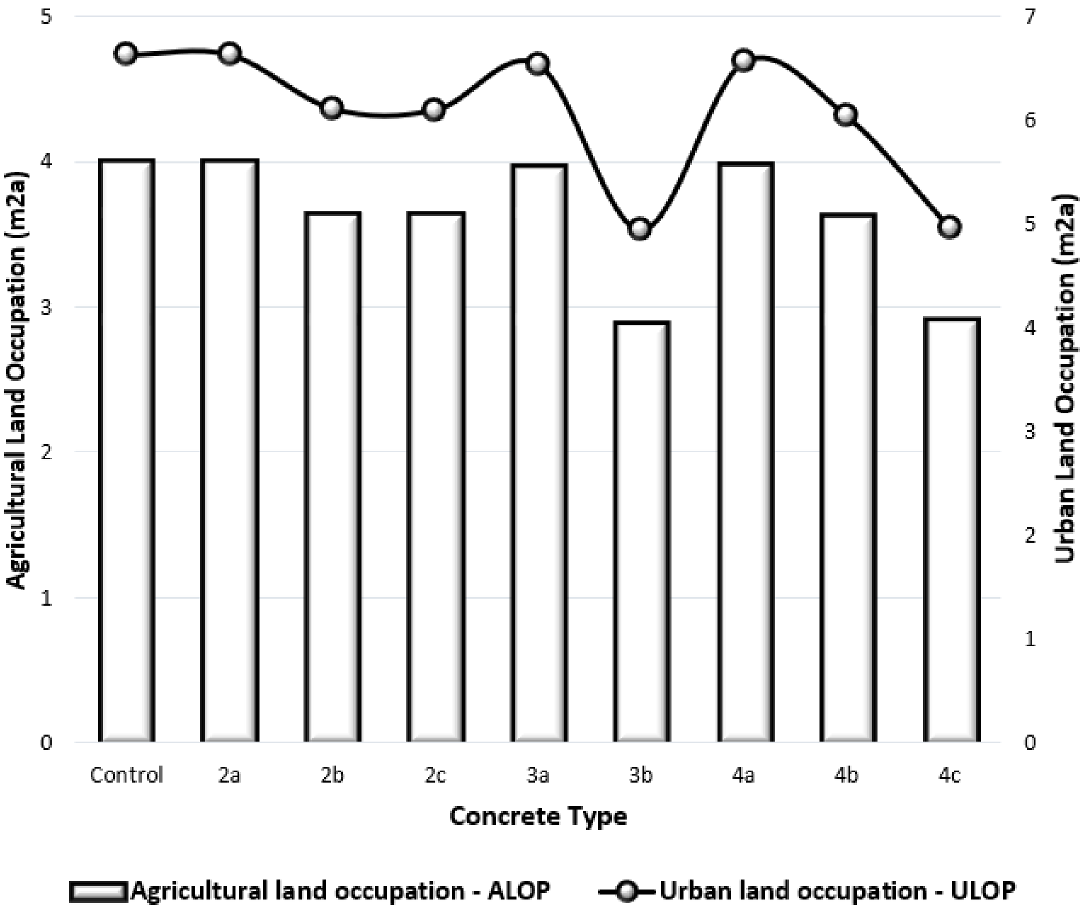


Figure 7.10: Agricultural and urban land occupation of PET concrete types

7.4 Cost Efficiency and Eco-Strength Efficiency of Concrete Incorporating Polyethylene Terephthalate

Figure 7.11 illustrates the cost-effectiveness and eco-strength efficiency of concrete containing polyethylene terephthalate. The results shown in Figure 7.11 demonstrate that Type 2b, concrete incorporating 5% polyethylene terephthalate as fibres and a 10% silica fume as cement replacement, provided the greatest cost efficiency, while Type 3b, concrete containing 10% polyethylene terephthalate as coarse aggregate replacement and 30% fly ash as cement replacement, provided the most significant eco-strength efficiency. The decrease in cost efficiency for the other concrete types incorporating polyethylene terephthalate can be attributed to the increasing cost of recycled PET waste in the European market as a result of increased demand driven by legislation changes such as the European union single plastic directive and other forms of plastic tax. This significantly increases the cost of PET relative to the cost of other concrete mix constituents. On the other hand, the increased compressive strength in Type 3b due to additional calcium-silicate-hydrate gels resulting from the pozzolanic reaction, provides improved eco-strength efficiency. The remarkable increase in strength and the corresponding decrease in the CO_2 emissions of the concrete mix both contributed significantly to the improved concrete eco-strength efficiency.

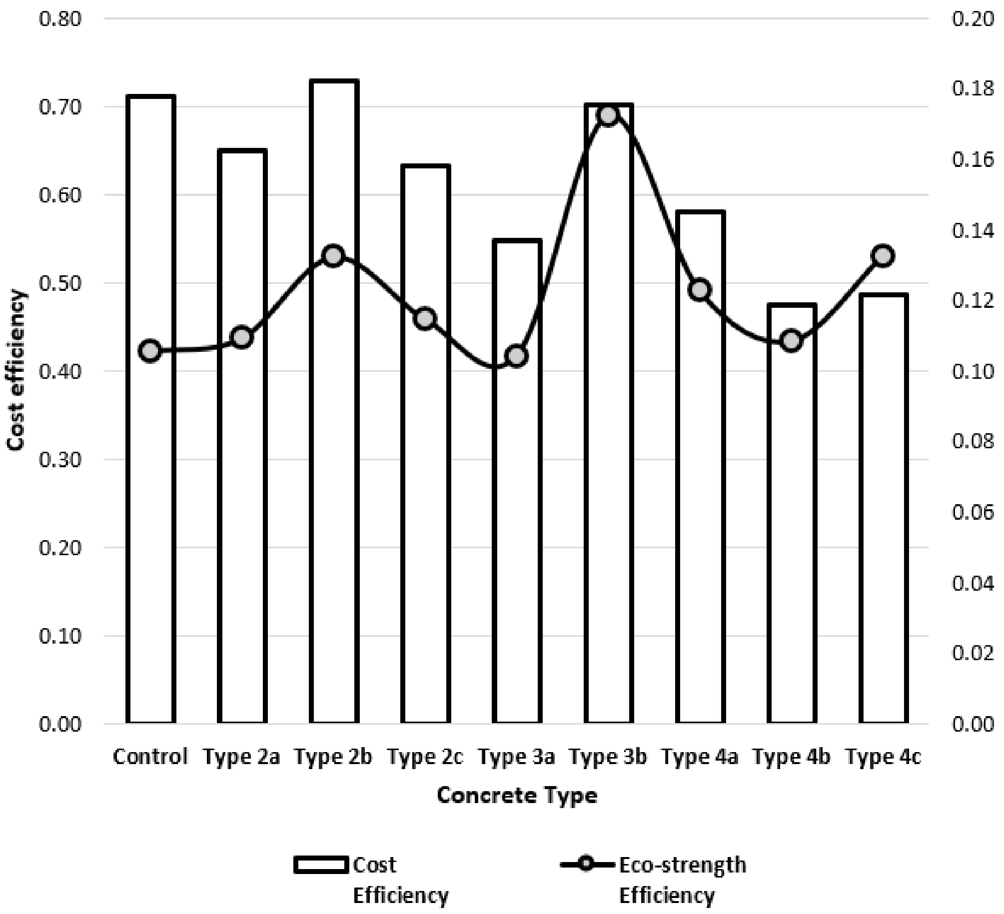


Figure 7.11: Cost and eco-strength efficiency of PP concrete types

CHAPTER 8

CONCLUSION

The study investigates the life cycle performance of concrete incorporating polypropylene and polyethylene terephthalate using the database approach. The database contained 635 data points carefully collected from the literature enabled concrete types incorporating polypropylene and polyethylene terephthalate to be established. The optimum use of polypropylene and polyethylene terephthalate along with the replacement type and levels of pozzolans are determined for the construction of concrete types. Defining the boundary limits played a key role in the establishment of the concrete types which was also critical for the life cycle assessment of concrete incorporating these plastic wastes.

The results reported in this study indicated that the optimum addition of polypropylene fibre in concrete was found to be 3%. The higher usage of such fiber additions in matrix found to be incompatible within the cement matrix. This is mainly due to the chemically inert nature and hydrophobic texture of the fibers that yields a more porous microstructural development of the cement matrix and consequently decreased strength of the hardened concrete. It is also recognised that the utilisation of pozzolans in concrete incorporating polypropylene was essential to compensate the possible adverse effects of this implementation and further improve the mechanical properties and durability characteristics of concrete comprising such fibers. The replacement types and levels of the most used pozzolans, also designated through the database analysis, were 30% fly ash, 15% slag and 7.5% silica fume all used as binder replacement in this study.

For concrete comprising polyethylene terephthalate, the optimum incorporation levels were found to be 5% as fibre additions, 10% as coarse aggregate replacement and 20% as fine aggregate replacement. Additionally, the database analysis outlined the replacement types and percentages of the two most used pozzolans that were used in this study as binder replacements when polyethylene terephthalate is incorporated into concrete: 30% fly ash, and 10% silica fume.

The life cycle assessment of the precisely determined models demonstrated that all sub-types of Type 3, concrete incorporating polypropylene fibres and pozzolans, provided the greatest reduction in most of the indices used in the assessment. Similarly, concrete type 3b — which contains 10% polyethylene terephthalate as coarse aggregate replacement and 30% fly ash as cement replacement — and concrete Type 4c — containing 20% polyethylene terephthalate as fine aggregate replacement and 30% fly ash — provided the most significant reduction in the indices employed in the assessment. The utilisation of pozzolans along with polypropylene and polyethylene terephthalate in concrete enabled a considerable reduction in climate change, ozone depletion, 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 shown to improve substantially human health, mitigate extreme droughts and floods, alleviate hazardous air pollutants, enhance environmental sustainability and preserved the ecosystem. The considerable reduction attained in the agricultural and urban land occupation also raises awareness of land recyclability and land ethics.

The increased cost and eco-strength efficiency of concrete incorporated with polypropylene and polyethylene terephthalate adds an additional standpoint to the findings reported in the study with respect to the practicability and feasibility of polypropylene and polyethylene terephthalate incorporation in concrete through the engineering performance of the end product. Life cycle performance of polypropylene and polyethylene terephthalate incorporation in concrete, proposed as a new waste management approach herein, is examined in comparison with incineration and landfilling. The results have eminently demonstrated that polypropylene and polyethylene terephthalate incorporation in concrete provided the lowest climate change and lowest freshwater and marine ecotoxicity and that improved land preservation and water resources conservation for enhanced ecosystems. The results reported in this study suggest that the utilisation of these plastic wastes particularly when accompanied with pozzolans could substantially reduce the global warming potential and the other associated indices such as ozone and water depletion potentials and hence enables not only greener construction materials to be produced but also vitally contributes in the environmental preservation and sustainable development of the ecosystems by offering waste plastic a cleaner disposal method.

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