Quantifying the environmental impacts of a sustainable concrete mix for a block paving system

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Abstract

A sustainable concrete mix design, incorporating industrial by-products: fly ash and recycled plastic pellets, was developed, and optimized through laboratory performance-based testing trials. The primary objective of this investigation was to offer environmentally sustainable alternatives to conventional concrete mixes that can be used for concrete block paving and aligns with circular economy principles and fosters enhanced employment opportunities and poverty reduction.

Following a laboratory investigation to optimise the quantities of fly ash and plastic pellets in the concrete mix, paving blocks were produced in the laboratory using the optimised mix. The blocks were also tested to ensure compliance with performance criteria stipulated in national specifications for concrete block paving. This chapter focusses on the comprehensive life cycle assessment (LCA) conducted to investigate the environmental impacts associated with the production of the optimised concrete mix design in comparison with two references mixes. All three mixes comprised varying quantities of cement, fly ash as a partial cement replacement, and plastic pellets as a partial substitute for sand. The analysis included concrete with 100% Portland limestone cement, concrete with 50% Portland limestone cement and 50% fly ash, and concrete with 50% Portland limestone cement, 50% fly ash, and plastic pellets.

The study, limited to a cradle-to-gate analysis, utilized the life cycle assessment software tool SimaPro 8.1 with the Ecoinvent Database version 3. The life cycle inventory dataset for each material was compiled, and the CML-IA Baseline World 2000 method was employed to generate and report the results.

The LCA study results demonstrated that adding fly ash as a cement substitution significantly reduced the environmental impacts of concrete mixes. However, the extent of this reduction depended on the type of allocation method used. Under no allocation and economic allocation scenarios, concrete mixes with fly ash exhibited lower environmental impacts than those without fly ash. Conversely, mass allocation scenarios indicated higher environmental impacts for concrete with added fly ash more than 35%. Additionally, it was noted that environmental impacts for fly ash concrete mixes with plastic pellets as a partial substitute for sand were marginally higher than those with fly ash concrete mixes using only sand.

1. Introduction

Concrete is the second most consumed substance on Earth, surpassed only by water, making it the world's most widely used material (Chen et al., 2010). Comprising cement, aggregate, and water, plain concrete's essential constituents include cement, which accounts for approximately 10 to 15% of the concrete volume, serving as the binding component (ACMP, 2011; Muigai et al., 2013). Aggregate, constituting gravel, sand, crushed stone, and recycled materials, is the primary structural filler, comprising about 65% to 80% of concrete volume (Muigai et al., 2013).

Concrete production significantly contributes to environmental burdens, particularly in carbon dioxide (CO_2) emissions (Wang et al., 2017). Ordinary Portland cement (OPC) is a key contributor to these high impacts (Celik et al., 2015; Marinković et al., 2016; Kurad et al., 2017). Studies indicate OPC's responsibility for 74-81% of emissions in typical commercially produced concrete mixes (Flower and Sanjayan, 2007). This production process, highly energy-intensive, contributes 5-7% of global CO_2 emissions, with approximately one ton of OPC production leading to roughly one ton of CO_2 emissions (Rashad and Zeedan, 2011).

Efforts to reduce concrete's environmental impact involve minimizing OPC use through supplementary cementitious materials (SCMs) like fly ash, ground granulated blast furnace slag (GGBS), and silica fume. In South Africa coal-fired power plants already produced approximately 34.4 million tons of fly ash in 2015 (Reynolds-Cluasen and Singh, 2019). Various studies have demonstrated that incorporating fly ash to partial replace OPC in concrete significantly reduces CO_2 emissions and energy consumption (Chen et al., 2010; Van den Heede and De Belie, 2012; Marinković et al., 2016; Wang et al., 2017; Kuda, et al., 2018).

Research on utilising industrial by-products as partial aggregate replacement or partial cement replacement in concrete has been ongoing for many years. Additionally, there has been substantial interest in using recycled waste plastic as a partial substitute for aggregate in the concrete industry. This approach addresses the feasible reuse of plastic, providing a solution to the plastic disposal issue (AbdelMoti and Mustafa, 2019; Sharma and Bansal, 2016; Kumar and Kumar, 2016; Saikia and de Brito, 2012).

Several studies have explored the use of plastic waste as aggregate replacements and demonstrated significant environmental benefits, particularly when combined with supplementary cementitious materials like fly ash (Betita, 2013; Mello et al., 2016; da Silva et al., 2021; Gravina et al., 2021; Ersan et al., 2022; Nikbin et al., 2022; Goyal et al., 2023). In the study by Goyal et al. (2023), the environmental impacts of manufacturing different types of paver blocks were compared. The results indicated that paver blocks with plastic as filler material (PFPB) and conventional concrete paver blocks (CCPB) processes had higher environmental impacts due to the use of cement, unlike paver blocks with plastic as a binder (PBPB). The study concluded that PBPB, manufactured by completely replacing cement, is more environmentally friendly than PFPB and CCPB. Furthermore, Ersan et al. (2022) investigated and compared the environmental impact of conventional lightweight concrete (LWC) and green LWC made by partially replacing coarse natural aggregates with 30% recycled plastic waste and replacing 20% of Portland cement with class F fly ash. The study reported that green LWC had lower environmental impacts than conventional LWC, except for eutrophication.

This chapter aims to explore the environmental impact of incorporating recycled plastic waste as partial replacement of fine aggregate in concrete, particularly when combined with fly ash while maintaining the strength and durability requirements for concrete block paving products.

2. Life cycle assessment methodology

A life cycle assessment (LCA) study was conducted to investigate the environmental impacts associated with the production of different concrete mix designs. Life cycle assessment (LCA) is a systematic approach that quantifies and evaluates the environmental impacts of a product or process throughout its entire life cycle, from the extraction and processing of raw materials, manufacturing, transportation and distribution, to use, maintenance, reuse, recycling, and final disposal (ISO/SANS 14040, 2006 and ISO/SANS 14044, 2006). Figure 2.1 illustrates the generic life cycle stages of a product for LCA.

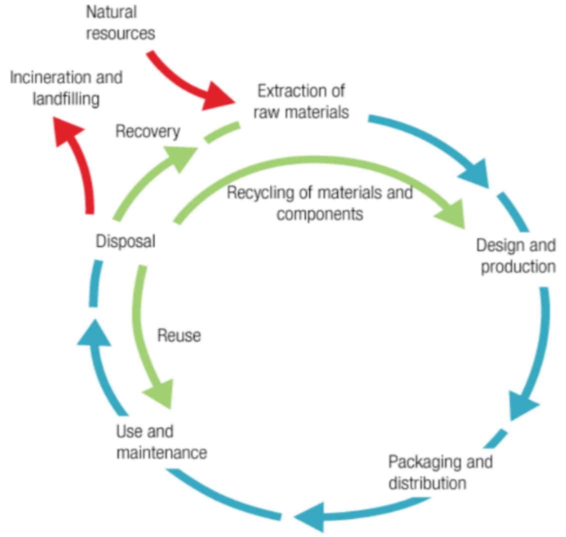

Figure 2.1: A typical product life cycle (UNEP/SETAC Life Cycle Initiative, 2023)

An LCA takes into account various environmental impact categories in the assessment, including energy, land, water, materials, and other resources, as well as various types of emissions to air, water, and soil. LCA identifies opportunities to improve product performance with the identification of environmental "hotspots' along the product life cycle, thereby revealing potential trade-offs.

The methodology used in this study follows the approach outlined by the International Organization for Standardization (ISO) 14040:2006 and ISO 14044:2006. ISO standards provide general principles, a methodological framework, guidelines, and requirements for performing the LCA of any system and should always be complied with. There are four mandatory stages (see Figure 2.2) in an LCA study, namely:

- Goal and scope definition which states the key objective of the study, defines the system boundaries, functional unit to be used in the investigation, the limitations and assumptions
- Life cycle inventory (LCI) analysis which involves data collection and calculation of an inventory of materials, energy and emissions related to the system being studied
- Life cycle impact assessment (LCIA) which involves analysis of the LCI results to evaluate contributions to environmental impact categories
- Life cycle interpretation which entails evaluation of the LCI and LCIA results in consideration of the initial intended goal and scope in order to reach conclusions and make recommendations.

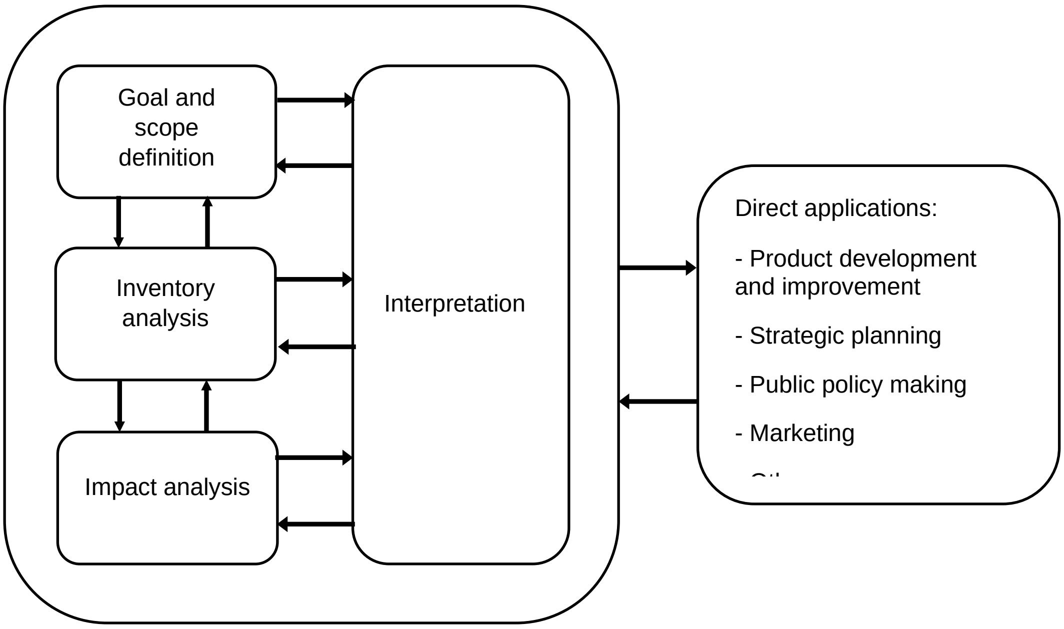

Figure 2.2: Life cycle assessment framework (ISO/SANS 14040, 2006,)

2.1. Goal and scope definition

2.1.1. Goal

The objective of this study is to assess and compare the environmental impacts associated with different concrete mixes, which incorporate fly ash as a cement partial replacement and plastic pellets as a partial substitution for sand. A description of the materials used in this study the proportion of mix ingredients are provided in Table 2.1 and Table 2.2, respectively.

Table 2.1: Materials description used in this study

Material	Description
Cement	42.5N Portland limestone cement
Fly Ash	Class F fly ash
Fine aggregates (Sand)	Crusher dust
Fine aggregates (Plastic pellets)	Pelletized recycled milk carton plastic
Coarse aggregates (Stones)	Meta-quartzite crushed aggregate

Three different concrete mixtures are analysed in this LCA study and are as follows:

- Mix 1: Concrete with 100% Portland limestone cement (control mixture)
- Mix 2: Concrete with 50% Portland limestone cement and 50% fly ash
- Mix 3: Concrete with 50% Portland limestone cement, 50% fly ash, plastic pellets as partial substitution for sand

Table 2.2: Mix proportions of concrete mixtures (kg/m^3) and compressive strength at 28 days (MPa)

Mix	Water/ binder	Cement	Fly ash	Water	Stone	Sand	Plastic pellets	Compressive strength (MPa)
Mix 1	0.36	583	-	210	1062	546	-	53
Mix 2	0.35	286	286	200	963	568	-	38
Mix 3	0.35	286	286	200	963	549	10	36

2.1.2. Scope

The functional unit of the study was chosen as one cubic meter (1 m^3) of concrete. The system boundary of the study was limited to cradle-to-gate analysis as shown in Figure 2.3. This will cover the environmental impacts resulting from the extraction, processing and production of raw materials required to produce the concrete mixes, transportation of raw materials to the concrete plant and concrete production at the plant as shown in Figure 2.4.

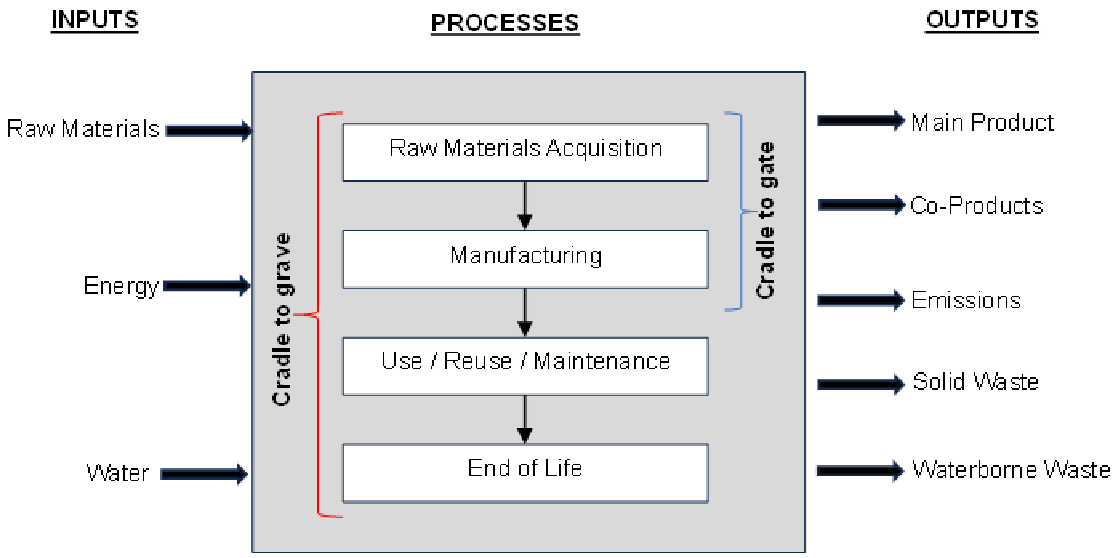

Figure 2.3: System boundaries (Environmental Protection Agency (EPA), 1993)

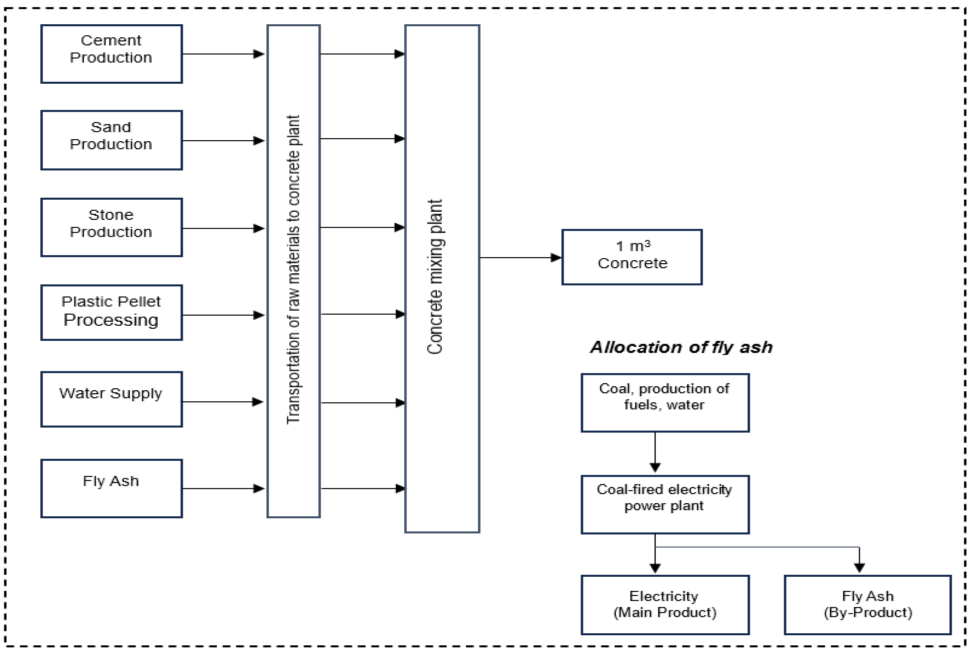

Figure 2.4: System boundary of concrete in the study

2.2. Life cycle inventory analysis

The life cycle inventory (LCI) phase of the study involves the data collection and calculation procedures. The inventory analysis gathers relevant inputs (e.g. energy, materials) and outputs (e.g. emissions and wastes) of the product system being studied, which is then scaled to relate to the functional unit. The inventory was prepared first qualitatively, then quantitatively for all the processes involved in the cradle-to-gate life cycle of the concrete mix designs. This is a very critical step as the data quality determines the success of the study. It is very important in the inventory phase to collect data from high quality resources.

2.2.1. Data sources

The LCA software tool SimaPro 8.1 with Ecoinvent database 3 was used to compile LCI dataset for each material of this study. Table 3.2 presents the inventory of the materials and transportation considered for each material. South African datasets were used whenever available in this study. In cases where no South African dataset was available for a particular material, the Rest of the World (RoW) dataset was selected as a proxy and adapted to suit the local context. For plastic pellets, only the energy used for shredding the plastic with a granulator and the energy used in the extrusion process, which pelletizes the plastic, were taken into account (refer to Table 3.2) (Mello et al., 2016).

Table 2.1: Life cycle inventory data sources and assumptions used in the study for the concrete mix designs.

Unit process	Sub-process	Assumptions	Sources
Portland limestone cement (CEM II/A)	Production	Cement, alternative constituents 6-20% {RoW}| Production | Alloc Def, U (CEM II/A) used as proxy	Ecoinvent 3 database
	Transporting	Road distance, PPC Jupiter to Pretoria = 65 km	
		Transport = lorry, > 16-32t	Ecoinvent 3 database
Fly ash	Allocation	Electricity, high voltage {ZA} electricity production, hard coal | Alloc Def, U	Ecoinvent 3 database
	Transporting	Road distance, Lethabo Power Station, Vereeniging to Pretoria = 140 km	
		Transport = lorry, > 16-32t	Ecoinvent 3 database
Stone	Production	Gravel, round {RoW}| gravel and sand quarry operation| Alloc Def, U used as proxy	Ecoinvent 3 database
	Transporting	Road distance, AfriSam Ferro Quarry to Pretoria = 10 km	
		Transport = lorry, > 16-32t	Ecoinvent 3 database
Sand	Production	Sand {RoW}| gravel and quarry operation| Alloc Def, U used as proxy	Ecoinvent 3 database
	Transporting	Road distance, AfriSam Ferro Quarry to Pretoria = 10 km	
		Transport = lorry, > 16-32t	Ecoinvent 3 database
Water	Production	Tap water, at user {RoW}| market for | Alloc Def, U	Ecoinvent 3 database
Plastic pellets	Processing	Granulator (shredding the plastic) = 0.000733 kWh/kg (capacity 50*150 kg/h)	Granulator Blade Man (GBMAN)

	Extruder (pelletise the plastic) = 0.2475 kWh/kg (capacity 200-250 kg/h)	Hume Machinery
Transporting	Road distance, Boksburg to Pretoria = 60 km Transport = lorry, > 16-32t	Ecoinvent 3 database

2.2.2. Allocation methodology

When collecting the inventory data, attention must be given to allocation. In processes yielding multiple products, environmental impacts must be distributed among the different end products. Allocation can be done either on a mass basis or an economic basis. Traditionally, fly ash was viewed as a waste product from coal-fired power plants. However, it is now recognized as a useful by-product, carrying a portion of the environmental burden of electricity production in coal-fired power plants. Therefore, for this study, three allocation scenarios were considered: no allocation, mass allocation, and economic allocation.

2.2.2.1. No allocation scenario

In this scenario, no allocation was applied, fly ash was considered as waste and only the environmental impact from transport was included.

2.2.2.2. Mass allocation scenario

In this scenario, the environmental impacts of electricity production in the coal-fired power plant were allocated between fly ash (by-product) and electricity (main product) based on Equation (1). The mass allocation coefficient Cm can be calculated as the mass ratio between the main product and by-product (Chen et al., 2010):

$$C_m = \frac{m_{by-product}}{m_{main\ product} + m_{by-product}} \quad \text{...Equation (1)}$$

where $m_{by\text{-}product}$ is fly ash mass and $m_{main\ product}$ is electricity mass.

Mass quantities were calculated based on LCI data from Ecoinvent Database 3. In the database, a South African dataset for electricity production from hard coal is available (Treyer and Bauer, 2016). To produce 1 kWh of electricity, 0.475 kg of hard coal is consumed, generating 0.0811 kg of hard coal ash. According to Siddique (2010), the ashes collected from pulverised coal-fired furnaces consist of fly ash and bottom ash, with fly ash constituting a major component ranging from 70-90%, while bottom ash accounts for 10-30%. For this study, it was assumed that fly ash constitutes 80% of hard coal ash, with the remaining 20% being bottom ash, resulting in the generation of 0.0645 kg of fly ash and 0.0166 kg of bottom ash.

A mass equivalent of 0.394 kg for electricity was calculated by applying the principle of the conservation of mass, as reported by Chen et al., 2010. Applying the mass allocation coefficient equation, Cm was calculated as 0.141. This means approximately 14.1% of the environmental impact of electricity production was attributed to fly ash production.

2.2.2.3. Economic allocation scenario

In this scenario, environmental impacts of electricity production in the coal-fired power plant were allocated between fly ash and electricity based on Equation (2) which gives the formula for the economic allocation coefficient (Ce) (Chen et al., 2010). The economic allocation coefficient C_e was calculated as follows (Chen et al., 2010):

$$C_e = \frac{(\varepsilon . m)_{by-product}}{(\varepsilon . m)_{main\ product} + (\varepsilon . m)_{by-product}} \quad \text{……………………………………Equation (2)}$$

where ε is the price per unit of material, $m_{by\text{-}product}$ is fly ash mass and $m_{main\ product}$ is electricity mass.

The mass quantities needed to calculate economic coefficient were determined using the same method as described for the calculation of the mass coefficient, Cm. Electricity rates in South Africa vary based on consumption and time of use. For industrial use during the summer season, an on-peak rate of R1.56/kWh was applied in the calculations (Joburg, 2019). The cost of fly ash in South Africa was found to be approximately R80/ton for unclassified fly ash (information obtained via phone call with Ulula Fly Ash). Utilizing the economic allocation coefficient equation, Ce was calculated as 0.0033. This implies that roughly 0.33% of the environmental impact of electricity production was attributed to fly ash production.

2.3. Life cycle impact assessment

In this phase, the potential environmental impacts are calculated based on the inventory. This study considered eight environmental impact categories for the environmental performance assessment, including global warming, acidification, eutrophication, human toxicity, abiotic depletion, abiotic depletion fossil, and photochemical oxidation. The CML-IA Baseline World 2000 method (Sleeswijk et al., 2008) which is included with the LCA software was used to generate and report the results.

2.4. Sensitivity analysis

A sensitivity analysis was conducted to assess the impact of fly ash prices when implementing economic allocation. The cost of fly ash in South Africa was found to be approximately R80/ton for unclassified fly ash and R150/ton for classified fly ash (information obtained via phone call with Ulula Fly Ash). As a result, economic allocation coefficients were calculated as 0.33% and 0.62%, respectively. Additionally, the ReCiPe midpoint hierarchist (H) method was employed for the sensitivity analysis, enabling a comparison of LCA results using these two methods.

3. Results and discussion

3.1. Environmental impacts: No allocation scenario

The environmental impact results of the cradle-to-gate LCA analysis, where no allocation of fly ash is applied, are presented in Table 3.1 and Figure 3.1. As shown in Table 3.1 and Figure

3.1, mix 1 exhibited higher environmental impacts than the concrete mixes incorporating fly ash (mix 2 and mix 3) in each of the investigated impact categories. It is evident that the inclusion of fly ash in concrete significantly reduces environmental impacts for mix 2 and mix 3. Specifically, mix 2 demonstrated the lowest impact, while mix 1 exhibited the highest across all environmental impact categories.

Table 3.1: Quantification of environmental impact categories when no allocation scenario is applied based on CML-IA baseline.

Impact category	**Units**	**Mix 1**	**Mix 2**	**Mix 3**
Global warming	kg CO_2 eq	488	253	256
Acidification	kg SO_2 eq	1.33	0.727	0.754
Eutrophication	kg PO_4^{3-} eq	0.221	0.129	0.136
Ozone layer depletion	kg CFC-11 eq	7.27×10^{-6}	4.42×10^{-6}	4.45×10^{-6}
Human Toxicity	kg 1,4-DB eq	36.9	24.5	25.4
Abiotic depletion	kg Sb eq	4.18×10^{-4}	3.34×10^{-4}	3.34×10^{-4}
Abiotic depletion fossil	MJ	1.73×10^{3}	1.05×10^{3}	1.09×10^{3}
Photochemical oxidation	kg C_2H_4 eq	0.0502	0.0284	0.0293

However, the results for mix 3, presented in Table 3.1 and Figure 3.1, indicate that incorporating plastic pellets into concrete as a partial substitution for sand does not enhance the environmental performance of concrete. These findings contradict what has been reported in the literature (Betita, 2013; Mello et al., 2016). Previous studies suggested that utilising waste PET/plastic as a partial substitution for sand could significantly improve the environmental performance of concrete, especially when combined with supplementary cementitious materials. This discrepancy was attributed to the high energy demand for shredding and pelletizing the plastic in this study compared to the values reported by Mello et al. (2016). The energy consumption estimates were based on South African company information for granulators and extruders. It's important to note that energy consumption data for shredding and pelletizing the plastic should ideally be obtained directly from the producers of the plastic pellets used in this study.

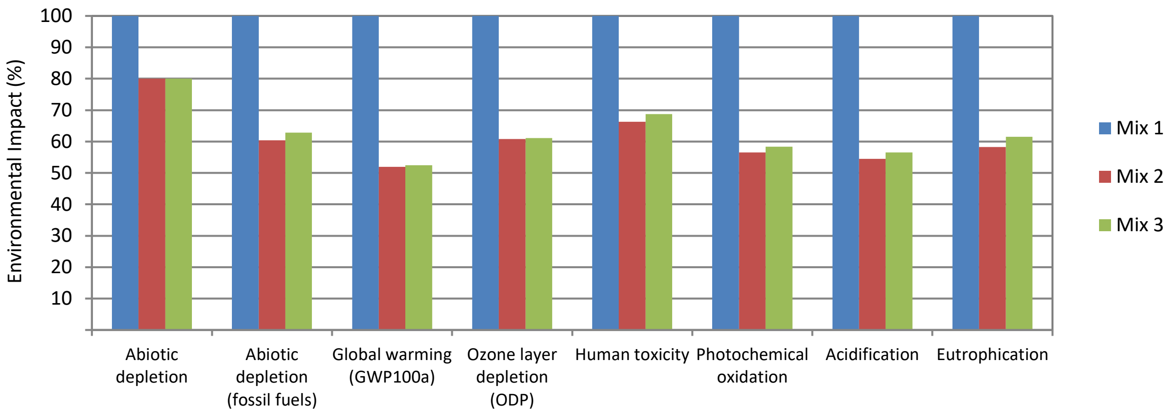

Figure 3.1: Environmental Impact Assessment – no allocation scenario

Additionally, Figure 3.2 illustrates the contribution of each stage to the manufacturing of concrete. According to the results, cement production emerges as the major contributor to the global warming potential in concrete production. This is primarily due to the clinker production stage, which is the most energy-intensive step in cement production. Portland limestone cement (CEM II/A) typically contains 80-94% clinker, 6-20% limestone, and 0-5% minor additional constituents (SANS 50197-1). These findings align with the results reported by Flower and Sanjan (2007), who reported that Ordinary Portland Cement (OPC) was responsible for 74-81% of CO_2 emissions from typical commercially produced concrete mixes.

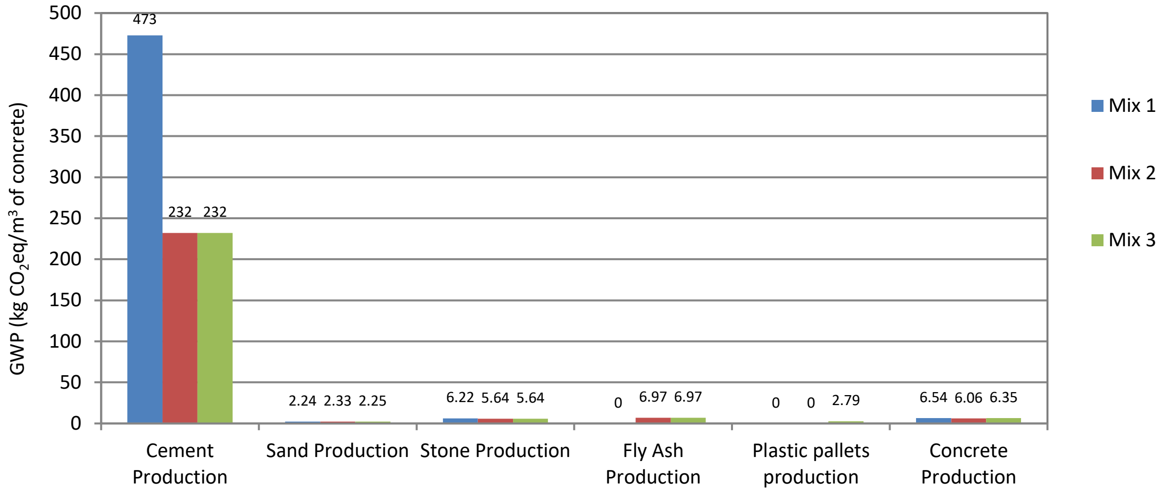

Figure 3.2: Global warming potential for each stage for the production of concrete for no allocation scenario

3.2. Environmental impacts: Economic allocation scenario

The environmental impact indicators, when economic allocation is adopted, are presented in Table 4.2 and Figure 4.3. Unlike the no allocation scenario, economic allocation results differ significantly. The process of electricity production from a coal power plant yields high environmental impacts; thus, even a small allocation coefficient can strongly influence fly ash impact indicators (Marinković et al., 2016).

In the economic allocation scenario, it was observed that mix 2 and mix 3 with fly ash, have lower impacts than mix 1 due to the relatively low price of fly ash in South Africa. Similar findings have been reported in several studies analysing the environmental impacts of concrete with economic allocation of fly ash (Chen et al., 2010; Van den Heede and De Belie, 2012; Marinković et al., 2016; Seto et al., 2017). However, there is a drawback to using economic allocation: the instability of prices, which can lead to significant fluctuations in LCA results (Van den Heede and De Belie, 2012). This is not the case with mass allocation, where the environmental burden of fly ash remains constant over a long period (Van den Heede and De Belie, 2012).

Table 3.2: Environmental impacts when economic allocation scenario is applied based on CML-1A baseline.

Impact category	Units	Mix 1	Mix 2	Mix 3
Global warming	kg CO_2 eq	488	263	266
Acidification	kg SO_2 eq	1.33	0.877	0.905
Eutrophication	kg PO_4^{3-} eq	0.221	0.169	0.176
Ozone layer depletion	kg CFC-11 eq	7.27×10^{-6}	3.98×10^{-6}	4×10^{-6}
Human Toxicity	kg 1,4-DB eq	36.9	29.2	30.1
Abiotic depletion	kg Sb eq	4.18×10^{-4}	3.18×10^{-4}	3.18×10^{-4}
Abiotic depletion fossil	MJ	1.73×10^{3}	1.21×10^{3}	1.25×10^{3}
Photochemical oxidation	kg C_2H_4 eq	0.0502	0.0333	0.0342

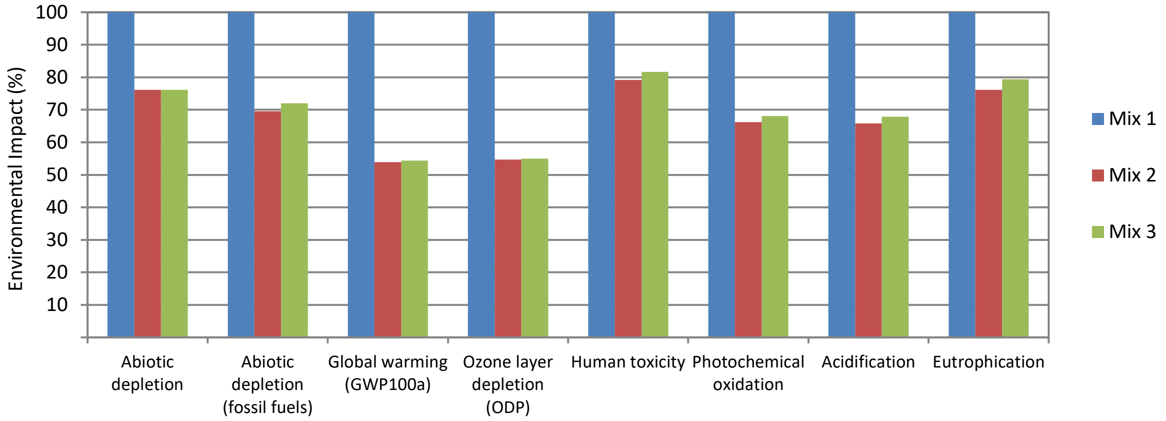

Figure 3.3: Environmental impact assessment – economic allocation scenario

Furthermore, Figure 3.4 illustrates the contribution of each stage to concrete manufacturing when economic allocation is adopted. The results clearly indicate that cement production remains the major contributor to the global warming potential in concrete production, consistent with the findings of the no allocation scenario.

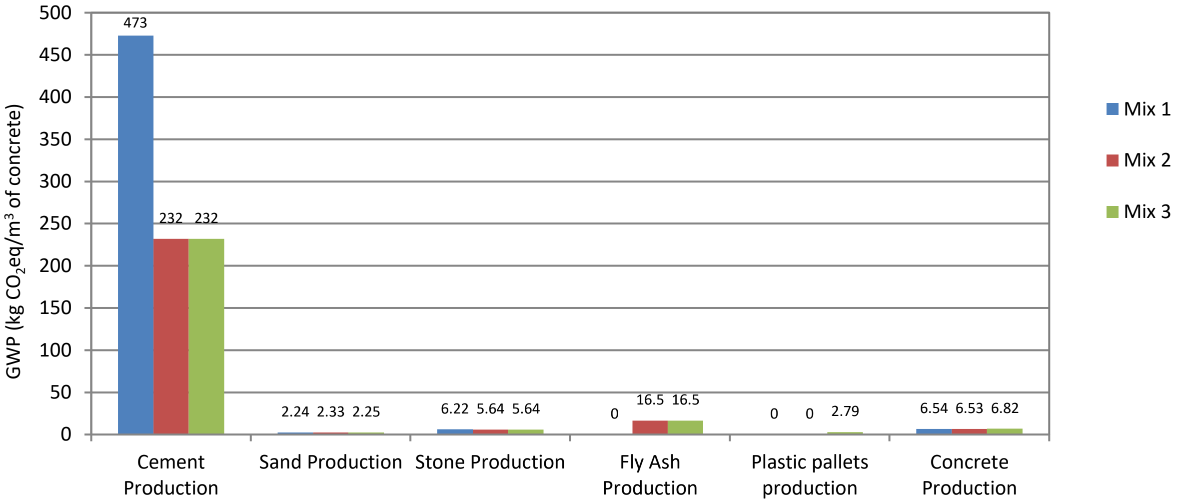

Figure 3.4: Global warming potential for each stage for the production of concrete for economic allocation scenario

3.3. Environmental impacts: Mass allocation scenario

Finally, when mass allocation was applied, it was observed that mix 2 and mix 3 with fly ash, emerged as the major contributors to the environmental impacts of concrete production, as depicted in Table 3.3 and Figure 3.5. The study revealed that, with mass allocation, all concrete mixes containing fly ash (mix 2 and mix 3) exhibited higher impacts than Portland Limestone Cement (PLC) concrete (mix 1). This was attributed to the relatively large mass of fly ash generated during electricity production, resulting in a substantial mass allocation coefficient. Similar results were obtained by Marinković et al. (2016), who reported that with mass allocation, recycled aggregate concrete (RAC) with fly ash (FA) had significantly higher impacts compared to RAC with no FA.

As seen in Table 3.3 and Figure 3.5, mass allocation of fly ash imposes significant environmental impacts, which poses a critical issue. The primary purpose of using supplementary cementitious materials like fly ash is to reduce the clinker content in cement, thereby lowering environmental impacts. However, if mass allocation of fly ash is applied, the cement and concrete industries will not benefit from using fly ash.

Table 3.3: Environmental impacts when mass allocation scenario is applied based on CML-1A baseline.

Impact category	Units	Mix 1	Mix 2	Mix 3
Global warming	kg CO_2 eq	488	965	968
Acidification	kg SO_2 eq	1.33	8.12	8.15
Eutrophication	kg PO_4^{3-} eq	0.221	2.05	2.06
Ozone layer depletion	kg CFC-11 eq	7.27×10^{-6}	6.66×10^{-6}	6.69×10^{-6}
Human Toxicity	kg 1,4-DB eq	36.9	270	270
Abiotic depletion	kg Sb eq	4.18×10^{-4}	4.09×10^{-4}	4.1×10^{-4}
Abiotic depletion fossil	MJ	1.73×10^{3}	1.24×10^{4}	1.24×10^{4}
Photochemical oxidation	kg C_2H_4 eq	0.0502	0.277	0.277

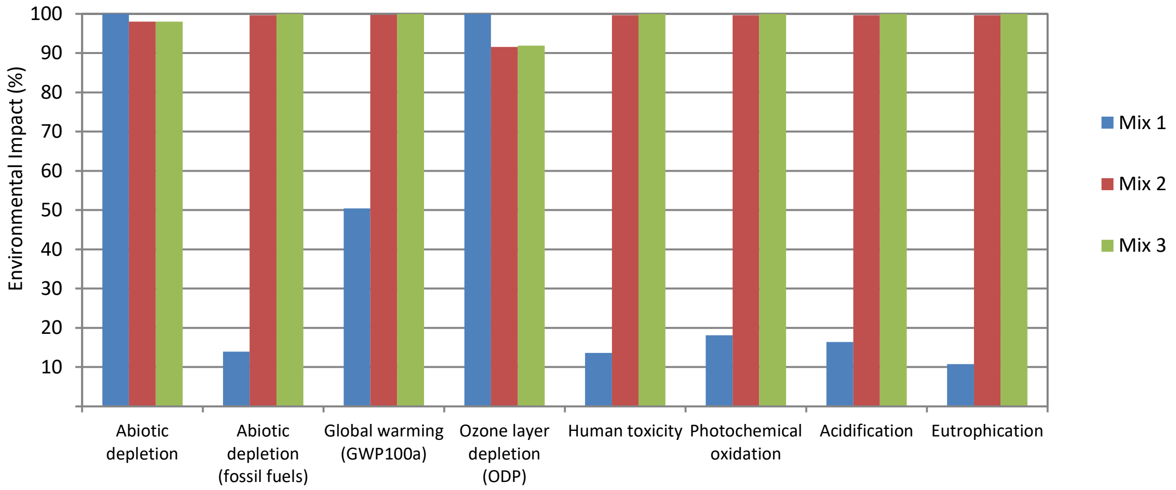

Figure 3.5: Environmental impact assessment – mass allocation scenario

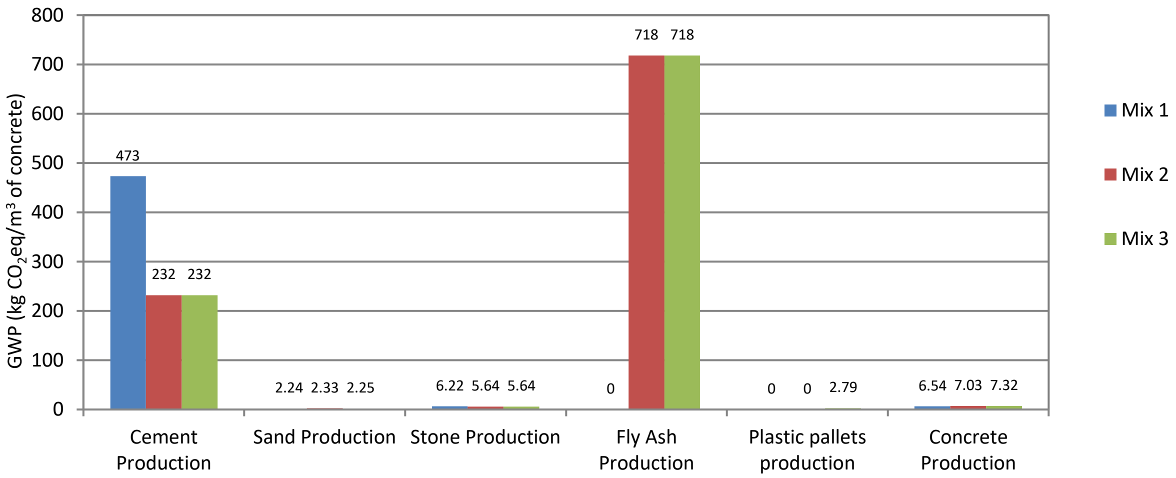

Figure 3.6: Global warming potential for each stage for the production of concrete for mass allocation scenario

Furthermore, Figure 3.6 illustrates the contribution of each stage to concrete manufacturing when mass allocation is adopted. Unlike the scenarios with no allocation and economic allocation, which indicated that cement production is the major contributor to the global warming potential in concrete production, mass allocation results show that fly ash production becomes the primary contributor to the global warming potential in concrete production. This is due to the increased environmental load of fly ash surpassing that of Portland Limestone Cement (PLC) when mass allocation is adopted.

3.4. Sensitivity analysis

When adopting the economic allocation scenario, one significant drawback is the instability in the price of fly ash, leading to notable fluctuations in LCA results. A sensitivity analysis was conducted to compare two prices of fly ash: R80/ton and R150/ton, reported as the price range for unclassified and classified fly ash, respectively (information obtained via phone call with Ulula Fly Ash). The economic allocation coefficients were found to be 0.62% and 0.33% for fly ash prices of R150/ton and R80/ton, respectively (refer to Table 3.4). The results showed that in both cases, the environmental impacts attributed to fly ash were lower. Consequently, all concrete mixtures incorporating fly ash (mix 2 and mix 3) exhibited lower impacts than Portland Limestone Cement (PLC) concrete (mix 1).

Table 3.4: Comparison of the CO_2 emissions results for the concrete with different mix designs using two economic allocation coefficients.

Type of concrete	Type of allocation	Ce = 0.62% ($kgCO_2eq/m^3$)	Ce = 0.33% ($kgCO_2eq/m^3$)
Mix 1	-	488	488
Mix 2	No allocation	253	253
	Mass allocation	965	965
	Economic allocation	277	263
Mix 3	No allocation	256	256
	Mass allocation	968	968
	Economic allocation	280	266

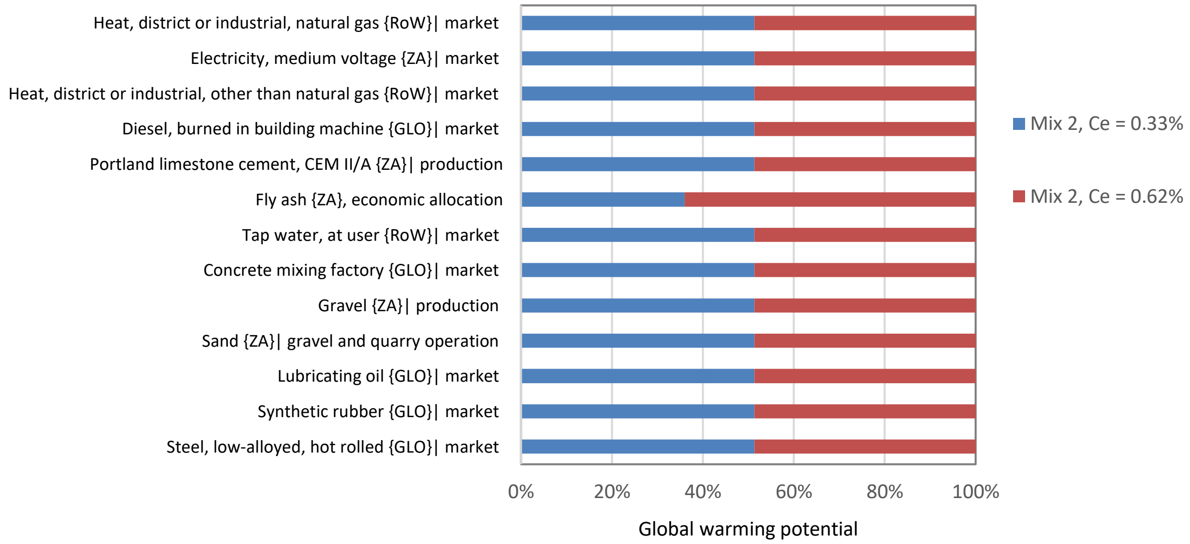

Figure 3.7: Global warming potential contribution analysis of concrete with fly ash (Mix 2) when fly ash price increases from R80/ton to R150/ton and economic allocation coefficients change from 0.33% to 0.62%

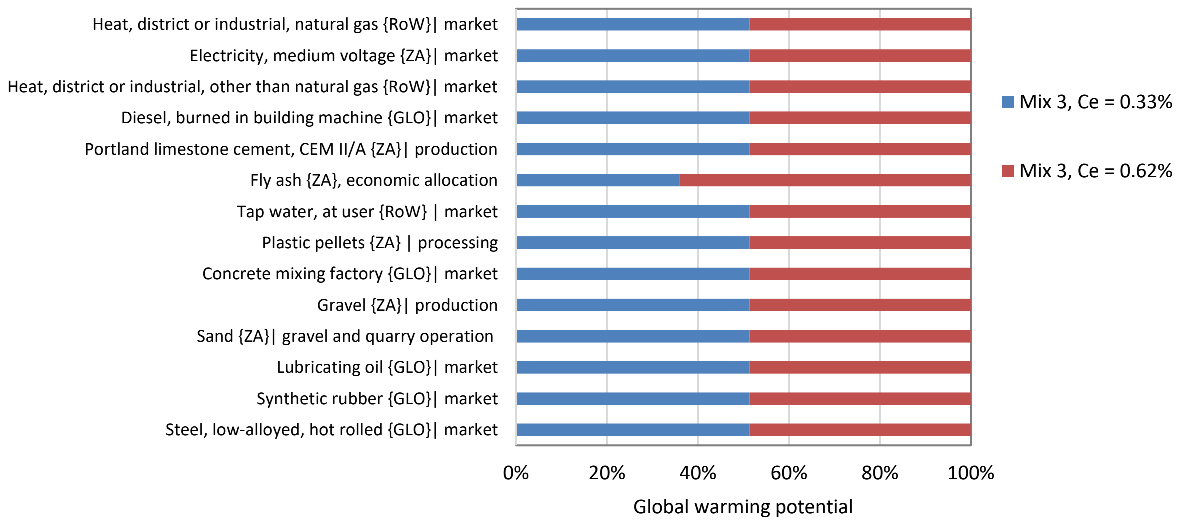

Figure 3.8: Global warming potential contribution analysis of concrete with fly ash and plastic pallets (Mix 3) when fly ash price increases from R80/ton to R150/ton and economic allocation coefficients change from 0.33% to 0.62%

Furthermore, as seen in Figure 3.7 and Figure 3.8, when the economic allocation coefficients change from 0.33% to 0.62%, the contribution of fly ash to the overall impacts increases, while the contributions of other components remain relative the same. However, this increase is not significant enough to outweigh the benefits of using fly ash as a cement replacement.

Furthermore, as indicated in Table 3.5, it was observed that the comparison of CO_2 emissions among different types of concrete mixtures was consistent regardless of the evaluation method. Both the ReCiPe midpoint (H) and CML-IA Baseline World 2000 methods yielded the same CO_2 equivalents.

Table 3.5: Comparison of the CO_2 emissions results for the concrete with different mix designs using ReCiPe midpoint (H) and CML-IA baseline (World 2000) methods

Type of concrete	**Type of allocation**	**ReCiPe midpoint (H) ($kgCO_2eq/m^3$)**	**CML-IA baseline (World 2000) ($kgCO_2eq/m^3$)**
Mix 1	-	488	488
Mix 2	No allocation	253	253
	Mass allocation	965	965
	Economic allocation	263	263
Mix 3	No allocation	256	256
	Mass allocation	968	968
	Economic allocation	266	266

4. Concrete laboratory investigation

A laboratory investigation was conducted in three stages to establish (i) the optimum content of fly ash as a cement replacement, (ii) the optimum replacement level of fine aggregate with plastic pellets, and (iii) national specification testing of concrete paving blocks produced from the optimal mix containing fly ash and plastic pellets.

Concrete cubes with varying fly ash contents—0%, 50% and 90%—in place of cement by mass were subjected to compressive strength tests during the initial stage of laboratory testing. All compressive strength tests were conducted as per SANS 5863. It was found that workability and compressive strength decreased as fly ash content increased. An increase in fly ash content was also associated with a decrease in water requirement while maintaining a workable mix in comparison to the reference mix (Mokoena and Mgangira, 2018a). By lowering the amount of water needed for mixing, this can also lessen the impact on the environment. For this round of testing, Mix 1 served as the reference mix, while Mix 2, which contained 50% fly ash was determined to be the most optimal mix with a 28-day compressive strength of 38 MPa given a target strength of 35 MPa, as per SANS 1058:1985, for Class 35 blocks.

The second stage of laboratory testing followed a similar program to substitute the fine aggregate component with plastic pellets at 5%, 15% and 35% replacement levels. The compressive and flexural strengths were observed to decrease as the plastic content increased, with the exception of the mix containing 5% plastic pellets which exhibited a slight increase in flexural strength. During this stage, an optimal level of replacement, while maintaining the compressive strength target of the concrete mix, was determined to be 5% which resulted in Mix 3, which had a compressive strength of 36 MPa (Mokoena, 2018b).

The final stage of laboratory testing was to produce the concrete pavers in the laboratory using Mix 3 to produce a concrete paving product that contains fly ash and plastic pellets as alternative materials with lower associated greenhouse gas emissions compared to conventional concrete ingredients.

The resulting pavers are illustrated in Figure 4.1 and were found to exceed all minimum requirements as per SANS1058:2012. The results for each required category (namely: *tensile splitting strength, abrasion resistance* and *water abrasion*) are presented below.

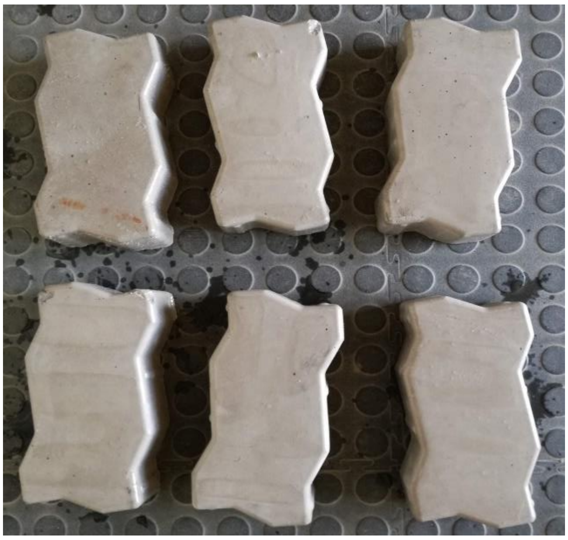

Figure 4.1: Interlocking concrete pavers

4.1 Tensile splitting strength

Tensile splitting strength tests were conducted on 6 interlocking pavers as per SANS 1058:2012. The average tensile strength for the pavers was 2.52 MPa and is 0.5 MPa over the required tensile strength for blocks with a design compressive strength of 30 MPa. All individual results are also above 1.5 MPa as per the standard as illustrated in Figure 4.2.

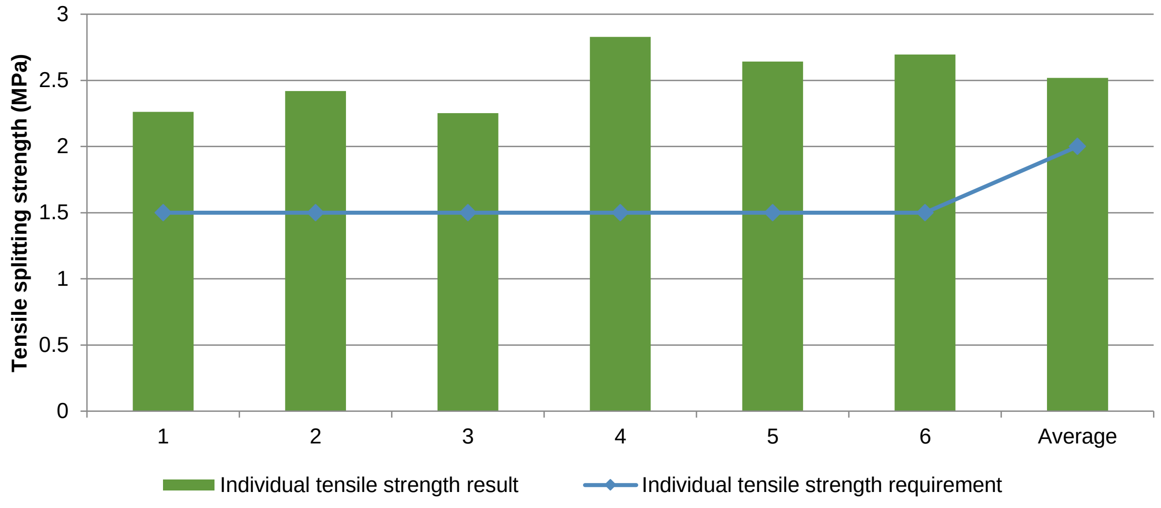

Figure 4.24.1: Comparison of tensile strength results vs individual strength requirement

4.2 Abrasion resistance

Results for abrasion resistance showed no loss and therefore in compliance with the standard. Specifications require a maximum average and individual mass loss of 15g and 20g respectively.

4.3 Water absorption

Water absorption (W_a) tests were conducted on the interlocking pavers as per Equation (3),

$$W_a = \frac{M_2 - M_1}{M_1} x\ 100 \qquad \text{...Equation (3)}$$

Where M_2 = wet mass of specimen after submersion

M_1 = mass of oven-dried specimen

Water absorption was calculated for a 24-hour period as per the standard and after 96 hours and 120 hours for observation because higher water absorption values were anticipated even after 24 hours. However, as seen in Table 4.1, only a slight increase was observed. The average and individual water absorption of the blocks were below 6.5% and 8.0% respectively (See Figure 4.3). Therefore, the pavers are following the water absorption requirements of the national standard.

Table 4.1: Average water absorption results

Duration	Water absorption (W_a) %
After 24 hours	2.95
After 96 hours	3.02
After 120 hours	3.08

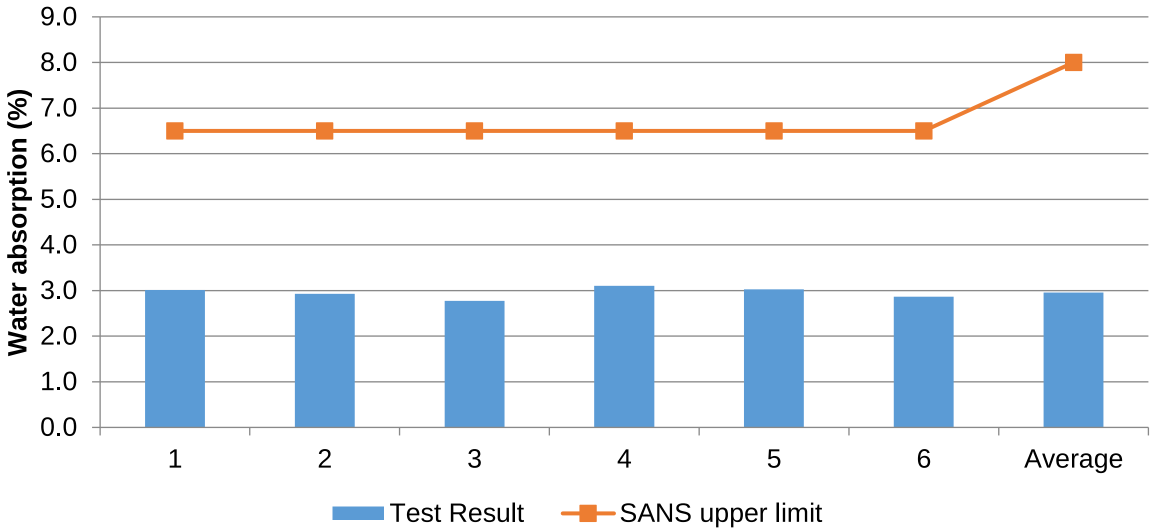

Figure 4.3: Individual and average results for water absorption

5. Conclusion

This study focussed on quantifying the environmental impacts of a sustainable concrete mix for concrete block paving. Following an experimental laboratory program to optimise the fly ash and waste plastic content, concrete paving blocks were produced in the laboratory to assess compliance with performance criteria as per the national specification for concrete blocks (SANS1058:2012). The innovative concrete mix was found to produce concrete paving blocks that meet the performance criteria of the specification and presents an opportunity to reduce greenhouse gas emissions and preserve natural resources with the use of alternative materials for road construction. This strategy can also reduce material costs without sacrificing relevant performance requirements for concrete paving blocks. Overall, this study aims to contribute towards knowledge generation on sustainable local production of "green" concrete mixes and concrete pavers, particularly for communities near ash sources by also promoting labour intensive construction methods.

Following the laboratory investigation, a detailed assessment of the environmental impacts associated with various concrete mix designs, that were used during the laboratory investigation, using LCA methodology. Results showed that incorporating fly ash in a concrete mix can reduce environmental impacts, contingent on the allocation method. Three scenarios were compared: no allocation, mass allocation, and economic allocation.

Under no allocation, all fly ash concrete mixes exhibited lower impacts than Portland limestone cement concrete. However, mass allocation increased fly ash's environmental load beyond that of Portland limestone cement, while economic allocation reduced it.

Replacing cement with fly ash, beyond 35%, as stipulated in the national cement specification for common cements (SANS 50197-1:2013), presents a significant opportunity to reduce environmental impacts while maintaining structurally sound concrete paving blocks that surpasses minimum specification criteria. Nonetheless, mass allocation results in substantial environmental impacts, potentially discouraging the use of supplementary cementitious materials. Fly ash incorporation reduces environmental impacts under no allocation and economic allocation scenarios. Conversely, substituting fine aggregates with plastic pellets does not significantly reduce concrete's environmental impact, in comparison to the substitution of cement with fly ash. However, the use of plastic pellets as a sand replacement may alleviate the increasing need for sand as a construction material.

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