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Research Article

Performance and environmental impact analysis of alkali activated slag and OPC concretes with polypropylene fiber in sustainable construction

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Abstract

Apart from its major contribution to the generation of greenhouse gases and environmental degradation, the building industry consumes a lot of natural resources and energy. Concrete largely made of cement, should be given great importance in the study of sustainability since its main binding component. This work aims to study, using four different mixes, the mechanical, microstructural, and environmental performance of M20 grade concrete. Conventional concrete (CC); conventional concrete with polypropylene fibre (CCPF); alkali activated slag concrete (SC); and alkali activated slag concrete with polypropylene fibre (SCPF). Among the tests performed were microstructural analysis, compressive strength, flexural strength, and Life Cycle Assessment (LCA). Using the SimaPro 9.1 program and the Eco Invent database; the life cycle assessment (LCA) midpoint analysis was conducted to examine the impacts these combinations have on the environment. The results clearly showed that SCPF had better mechanical properties and microstructural performance than CC. Furthermore, although if it had a higher impact than Ordinary Portland Cement (OPC) used on its own, the inclusion of alkali-activated slag resulted in a notable improvement in environmental sustainability. Because of its enhanced durability, better mechanical performance, and lower ecological imprint, the findings of this study show the possibilities of SCPF as a material for ecologically conscious building projects including rural rigid pavements.

1. Introduction

During When polypropylene fibers are included into concrete instead of conventional concrete, the durability characteristics of the concrete alter somewhat significantly. These fibers impact on the concrete's tensile, flexural, compressive strength as well as its resilience and cracking resistance. They also help the concrete to last longer. The main strength differentiations between traditional concrete and concrete with polypropylene fibers are tensile and flexural strength, compressive strength, and durability enhancements. These qualities largely relate to the fact that conventional concrete is more durable. The tensile and flexural strengths of concrete are enhanced by including polypropylene fibers into the mix. For instance, adding macro-PP fibers to regular concrete can provide up to 34.5% in breaking tensile strength and up to 100% in flexural strength correspondingly [1]. It has been shown that flexural strength is much enhanced by using new polypropylene monofilament fibers. The characteristic of this improvement is a change from 12.9111 N/mm^2 in conventional concrete to 14.9611 N/mm^2 in fiber-reinforced concrete. Commonly included in traditional concrete, polypropylene fibers also help to generate strain-hardening activity [2]. Usually, concrete does not show this phenomenon. Though the main benefit of polypropylene fibers is not a rise in compressive strength, nonetheless there is a notable

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improvement. For example, the addition of polypropylene fibers can increase compressive strength by 9.67% [3]. Using innovative polypropylene fibers, it has been shown that the compressive strength of concrete from 27.46 N/mm^2 to 30.24 N/mm^2 increases. This is a major development above the conventional concrete construction [4]. One of the ways polypropylene fibers helps concrete to be more resilient against environmental damage and cracking is by strengthening it. Application of the concrete improves its resistance to sulfate and acid attacks as well as shrinkage cracking [3, 5]. As crack stoppers, fibers help to reduce the rate of bleeding and shrinkage cracking in concrete when it is plastic [6]. Furthermore, seen is a higher resistance to abrasion and chloride ion penetration, all of which helps the concrete resist wear and tear over several years [3]. Polypropylene fibers added to concrete may cause the workability of the concrete to drop given the higher air content and fiber clumping. Careful mix design is necessary to sustain the reasonable degrees of workability [1,5]. Furthermore, polypropylene fibers improve the energy absorption capacity of concrete, which benefits uses requiring impact resistance [7,8,9,10]. Polypropylene fibers added to concrete can significantly enhance several mechanical properties; yet, they can also cause problems including a decrease in the workability of the concrete and the risk of fiber clumping during the mixing process [6,11,12,13]. To make the most advantages although the disadvantages should be minimized, to solve these challenges one must pay close attention to the mix design and fiber composition. Though the improvements in compressive strength are usually small in comparison to other kinds of fibers, such polyolefin fibers, which could offer great benefits in specific uses [3].

It is a well-known fact that the utilization of concrete is next to water, which in turn increases the demand for cement. Due to the manufacturing of cement, a huge amount of carbon dioxide is emitting into the atmosphere, creating ecological imbalances. So as an urgent need a replacement for cement is to be considered and one among them is GGBS (ground granulated blast furnace slag) which is an industrialized waste by-product attained from iron and steel industry [14]. Complete replacement is considered for cement with GGBS but it doesn’t fetch desirable results for mechanical properties. So, an alkali activator solution is taken in consideration. A mixture of potassium silicate and potassium hydroxide solution added at required proportions observed to achieve better strengths. To a great extent the rigid pavements are maintained for highways but not considerably for rural areas. It considered various preliminary blends to distinguish the ideal Activator Modulus (Ms) for every mix of GGBS [31,32].

Alkaline-activated slag concrete (SC) has microstructural characteristics unlike those of normal concrete when compared to conventional concrete. This is largely related to the difference binder composition and activation method SC uses. SC, which runs on ground granulated blast furnace slag (GGBS), has several advantages as a binder in terms of performance and environmental friendliness. To grasp the engineering aspects of the latter and the possible uses of the former, one must first fully understand the microstructural differences between ordinary Portland cement (OPC) concrete and SC concrete. SC concrete has a denser microstructure and a lower overall porosity than OPC concrete. This could be connected to the fact that the process of alkali activation reduces the pore volume and refines the pore size distribution produces a matrix more compact [15,16]. SC has a thick structure; however, hydration shrinkage causes small cracks to grow there, which can affect the material's permeability characteristics. OPC concrete usually follows a more constant hydration process, hence the occurrence of fissures like these is much less [16]. Alkali activated slag concrete (SC) can reach compressive strength equivalent to or even better than that of conventional concrete depending on the mix composition and curing conditions. For instance, several SC blends have shown better compressive and tensile strength than M20 grade OPC concrete [15,17]. For structural uses that call for more durability and load-bearing capacity, several SC combinations with higher flexural strength and toughness indices are favorable [17]. Enhanced resistance to chloride penetration a necessary component for longevity in salt environments, particularly those observed in maritime and de-icing applications has come from the SC materials. This is attributed to the material's refined pore network and dense microstructure [15,16]. Although the dense slag pastes employed in SC helps to lower the material's gas permeability, the presence of micro cracks may affect the material's general performance regarding carbonation [16,18].

SC has certain advantages over conventional concrete that ordinary concrete lacks, hence it's important to address the possible problems connected with its application. Its long-term durability may be affected by the existence of microcracks resulting from hydration shrinkage; the variety in the slag's composition may affect its uniformity of qualities [19,20,21]. Furthermore, enticing for usage in ecologically conscious building methods is SC's environmental advantages, including lowered CO_2 emissions [24]. Using alkaline aggregate slag concrete with polypropylene fibers has a multifarious effect on the environment, both positive and bad ones. Polypropylene fibers have the ability to increase the durable properties of concrete and so help to manage waste by means of recycled materials. Still, a life cycle analysis (LCA) has to consider the effects these fibers manufacturing and use have on the surroundings. Regarding such materials, the life cycle assessment (LCA) usually offers a whole picture of the sustainability of the materials by evaluating the environmental effects from the raw material extraction to the end of the life of the product. Recycled resources, including waste polypropylene, can provide polypropylene fibers; this helps to lower residual waste and promotes the appropriate waste management in an environment [24]. Since this recycling process generates no emissions, it is a greener substitute for the usual reinforcement materials [22,31]. Alkali-activated concrete (SC) including polypropylene fibers has a less carbon footprint than normal Portland cement concrete. With reductions of 86% and 34%, respectively, SCs are known to have substantially less effects on ecosystems and human health than standard concrete [23]. Curing plays a vital role in determining the mechanical properties of hardened concrete [33]. Slag composites activated by alkalis using polypropylene fibers offer more thermal stability than those devoid of these fibers. This is beneficial especially when the material is exposed to high temperatures since it helps to lower the energy consumption during its lifetime [24]. Polypropylene fiber manufacture calls for the use of fossil fuels and greenhouse gas emissions, both of which have the potential to offset some of the environmental advantages resulting from their usage in concrete [25,26,27]. Alkaline-activated concrete's manufacturing calls for large amounts of sodium silicate, which accounts for roughly thirty to fifty percent of the material's whole environmental impact [25]. Using polymeric materials like polypropylene fibers might cause the cost of manufacturing concrete to rise because of the need for specialized tools and the worker's skill level. The general application of this technology in the construction sector could not be without challenges [28]. Life cycle analysis (LCA) studies have shown that polymeric concrete especially those with polypropylene fibers has a lower global warming potential, acidification, and eutrophication than conventional concrete [30,31]. By reducing the amount of carbon emissions and the energy consumed, the combination of recycled aggregates and extra cementitious materials with polypropylene fibers could help to further increase the sustainability of concrete [32]. Specimen properties and its impact on mechanical and microstructural properties is discussed [34]. Research has shown that changing the mix design of geopolymer concrete with polypropylene fibers can produce mechanical properties similar to those of traditional concrete while considerably lowering the environmental consequences [29]. Although the use of polypropylene fibers in alkaline aggregate slag concrete has many benefits for the environment, including improved waste management and a reduced carbon footprint, it also generates several problems related with the production impacts and the resource intensity. Underlining the need of maximizing mix designs and using recycled components to increase the sustainability of the product is the life cycle assessment of these materials. Nonetheless, the higher expenses and technical restrictions related to polymeric concrete could restrict its application. Therefore, more study and development are needed to get over these constraints.

2. Materials

2.1 Binder

BS: 6699:1900 blast furnace slag that has been ground up (GGBS). Based on its chemical composition, the GGBS has all properties as per limits. Regular Portland cement (PC) of 53-mark following IS: 12269-1987 was utilized. The physical properties of cement were presented in the Table 1. The chemical composition of cement consists of 4.141% of Al2O3, 65.1414% of CaO, 22.144% of SiO2, 2.54% of Fe2O3, 0.4% of K2O, 0.9% of MgO, 0.2% Na2O and, 2.144% of SO3.

Table 1. Physical properties of cement

Properties	Values	Limit values based on IS: 12269-19814
Fineness - percentage weight of residue	1.21	<=10%
Standard consistency	32.1	-
Specific gravity	3.12	-
Initial setting time	72	Lower limit 30
Final setting time	218	Upper limit 600

2.2 Sand

Zone-3 sand is used in the mix design and has a bulk density of 1816 kg per cubic meter, relative density of 2.5 and a modulus of 2.03.

2.3 Coarse Aggregates

A combination of 20 and 10-mm aggregates with bulk density of 11442 kg per cubic meter, relative density of 2.7 and a modulus of 7.16 are employed as coarse aggregates.

2.4 Alkaline Solution

In general, potassium hydroxides with a virtue of 97% accessible in a stable organization by employing drops have been investigated for a successful evaluation. An important factor is the amount of water put into KOH beds. KOH pallets are purchased from a nearby retailer. Since it comes in a fluid (gel) form, potassium silicate is unique for being a potash glass that dissolves. With varying volumes of water, premium grades of the potassium silicate solution are available and are effective. 14 moles of KOH with 5% oxide content and a 1.25 modulus ratio were used in the mix formulation.

2.5 Polypropylene Fiber

These fibers, which have a hydrophobic characteristic, are used to replace 1% of the cement. After experimenting with three different doses (0.5, 1, and 1.5 percent by weight); the best results were achieved by replacing 1% of the cement with the polymer. The inquiry at hand takes into account polypropylene fibers with dimensions of 0.044-0.06 millimeters in diameter, 6.22-9 millimeters in length, and a specific gravity of 0.9.

2.6 Water

Locally available potable drinking water is used.

3. Methodology

This study investigates the use of polypropylene fibers as a percentage of cement weight to evaluate their influence on the mechanical and environmental performance of M20 grade concrete. Fig 1 represents the flow chart of methodology. The research methodology encompasses a comprehensive life cycle assessment (LCA) and an analysis of the engineering properties of various concrete mixes. The design of the M20 grade concrete was carried out in accordance with Indian Standard IS 10262-2019. Key strength metrics such as splitting tensile strength, flexural strength, and compressive strength were evaluated as per the relevant standards. Table 2 represents the mix proportions of concrete.

Conventional mixing techniques usually used for ordinary concrete were applied for the experimental process of creating alkaline-activated slag concrete (SC). The dry solid components aggregate and ground granulated blast furnace slag (GGBS) were first combined for three to four minutes. After that, extra water and an alkaline solution were added to the liquid components; the mixing process was kept on for three to four more minutes. The SC that had just been combined looked coherently and polished gray. The slump test enables the assessment of the workability of fresh concrete.

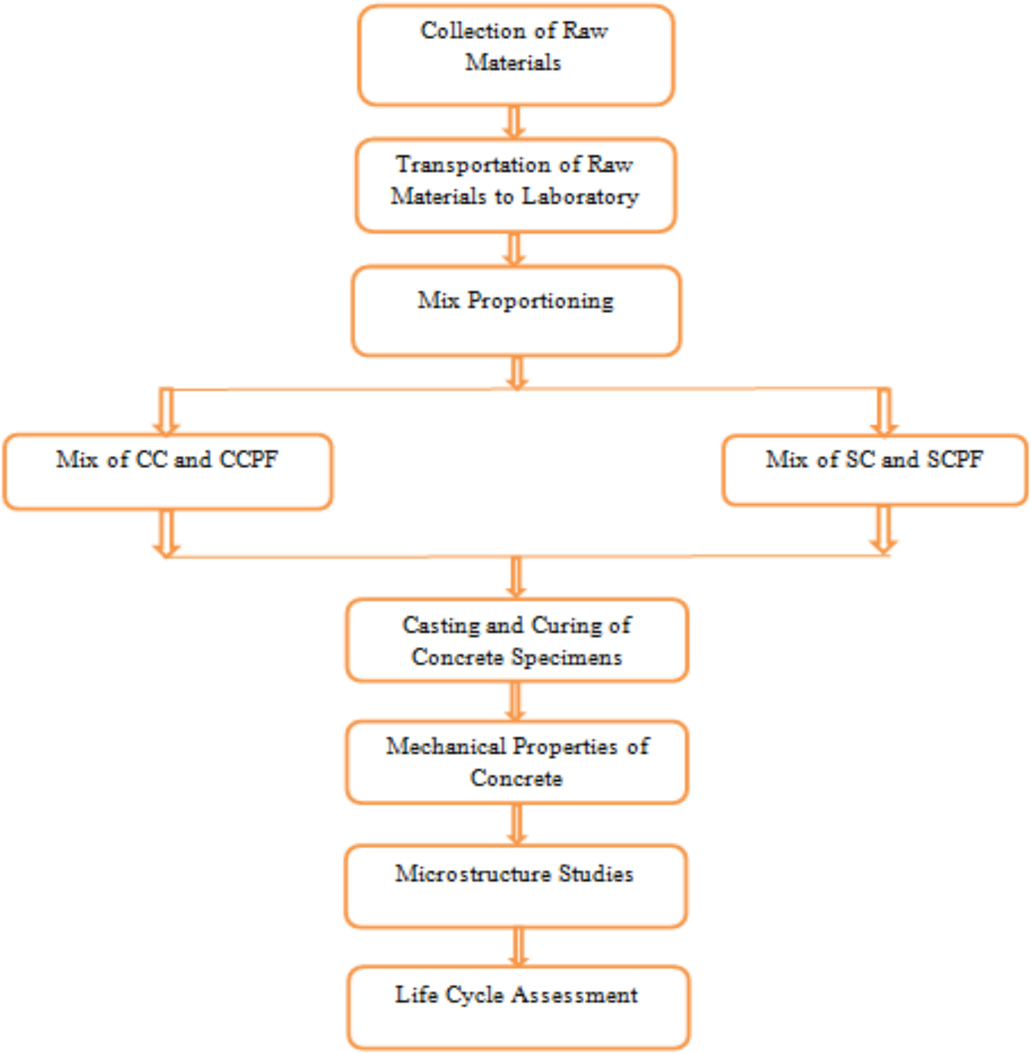


Fig. 1. Flow chart of methodology

Table 2. Mix proportions of concrete

Material		Mix Notations			
		CC	CCPF	SC	SCPF
Cement		320	316.8	-	-
GGBS in kg/m³		-	-	320	316.8
Fine Aggregate in kg/m³		695.28	694.34	694.3	694.3
Coarse Aggregate (kg/m³)	20 mm	815.8	814.6	814.6	814.6
	10 mm	407.9	407.4	407.4	407.4
Water (total) litre/m³		160	158.4	115.7	114.5
Polypropylene fiber (kg)		-	3.2	-	3.2
Activator Modulus		-	-	1.25	1.25
K_2SiO_3 (kg)		-	-	74.3	73.6
KOH solution (l)		-	-	6.7	6.7

CC = Conventional concrete; CCPF = Conventional concrete + 1% Polypropylene fiber; SC = Alkali activated slag concrete; SCPF = Alkali activated slag concrete + 1% Polypropylene fiber

The concrete mixture then was placed into steel cube molds, crushed on a vibrating table for thirty seconds, then finished externally to ensure a consistent and smooth surface. Comprising 5% potassium oxide, the combination showed a ratio of 1.25 for the activator modulus (SiO_2 relative to K_2O). The life cycle assessment modeling was determined to be done using the Eco Invent database and SimaPro program. Many components were given thought throughout the assembly phase. These ingredients were water, coarse and fine aggregates, GGBS, ordinary Portland cement (OPC), potassium hydroxide (KOH), potassium silicate (K_2SiO_2). Moreover, the modeling technique included the consumption of energy as well as the transportation related procedures. We assessed the environmental effects experienced during the cradle-to---gate phase using the Recipe 2016 (H) mid-point approach. This approach covered the analysis of categories including the possibility for global warming, the depletion of the ozone layer, the ecotoxicity of freshwater, the generation of particulate matter, the shortage of resources, the toxicity of carcinogenic compounds, and the ecotoxicity of terrestrial environments.

4. Results and Discussions

4.1 Compressive Strength

Comparatively to conventional concrete (CC), the results of the compressive strength tests conducted on the concrete mixes at 14, 28, 56, and 91 days (Fig. 2) show that the addition of polypropylene fibers and components based on slag can considerably increase the strength performance of the concrete mixes. Over all ages, the alkaline-activated slag concrete with polypropylene fibers (SCPF) mix consistently outperformed the others, followed by slag-based concrete (SC) and conventional concrete with polypropylene fibers (CCPF). The performance trends are attributable to the synergistic effects of polypropylene fibers and the enhanced reactivity of GGBS in alkali-activated systems, which contribute to improved microstructural development and crack-bridging properties.

SCPF's performance in compressive strength is consistently superior to CCPF. At 14 days, it exhibited a strength of 33.8 MPa, 34.1% higher than CCPF (25.2 MPa). This trend continued at 28 days, with SCPF achieving a strength of 37.1 MPa, a 20.8% increase over CCPF (30.7 MPa). At 56 days, SCPF reached 39 MPa, surpassing CCPF (32.9 MPa) by 18.6%. At 91 days, the SCPF mix reached its peak, achieving the highest compressive strength of 40.8 MPa, a significant 21.4% higher than CCPF (33.6 MPa).

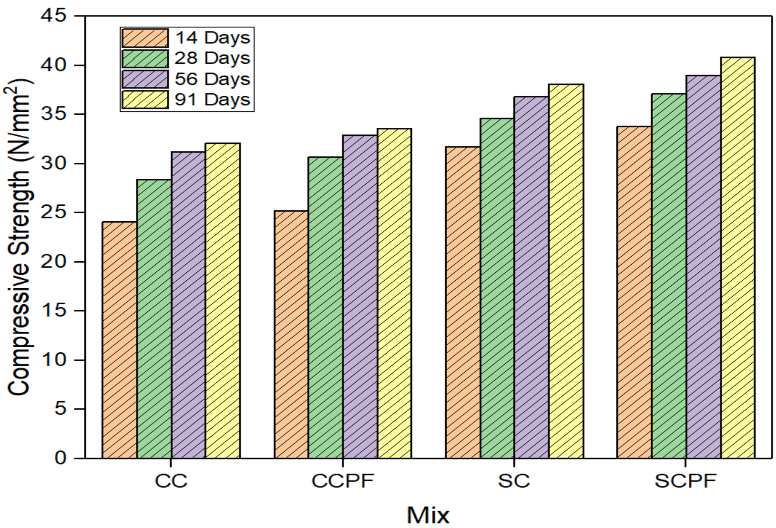


Fig. 2. Compressive strength of different mixes

The improved performance of the SCPF mix is due to the enhanced bond strength and crack resistance provided by polypropylene fibers combined with the superior pozzolanic reactivity of GGBS. This mix produces lower porosity, denser microstructure, and improved long-term strength gains. Furthermore, alkali activation in the SC and SCPF mixes accelerated the hydration process, producing early-age strength development above that of CC and CCPF.

4.2 Flexural Strength

The flexural strength values at 14, 28, 56, and 91 days (Fig.3) represents that adding of polypropylene fibers and slag-based components improves the strength of concrete mixes relative to conventional concrete (CC) under 3-point bending. The alkali-activated slag concrete with polypropylene fibers (SCPF) mix constantly showed the highest flexural strength across all ages; slag concrete (SC) and conventional concrete with polypropylene fibers (CCPF) followed in order. The combined actions of polypropylene fibers, which improve the tensile and crack-resistance characteristics, and the pozzolanic reactivity of GGBS, which results in denser and stronger microstructures, account for much of this improvement.

At 14 days, SCPF achieved a flexural strength of 3.9 MPa, 14% higher than CCPF (3.42 MPa). By 28 days, SCPF recorded 4.31 MPa, exhibiting a remarkable 11.4% increase compared to CCPF (3.87 MPa). At 56 days, the SCPF mix displayed a flexural strength of 4.7 MPa, surpassing CCPF (3.95 MPa) by an impressive 19%. At 91 days, SCPF achieved the highest flexural strength of 4.81 MPa, a significant 19.7% higher than CCPF (4.02 MPa).

The superior performance of SCPF can be attributed to the ability of polypropylene fibers to bridge microcracks, thereby improving tensile capacity and flexural behavior, and the enhanced binding characteristics of alkali-activated slag. The accelerated hydration and dense microstructure formed in the SC and SCPF mixes further contribute to their improved performance compared to conventional concrete.

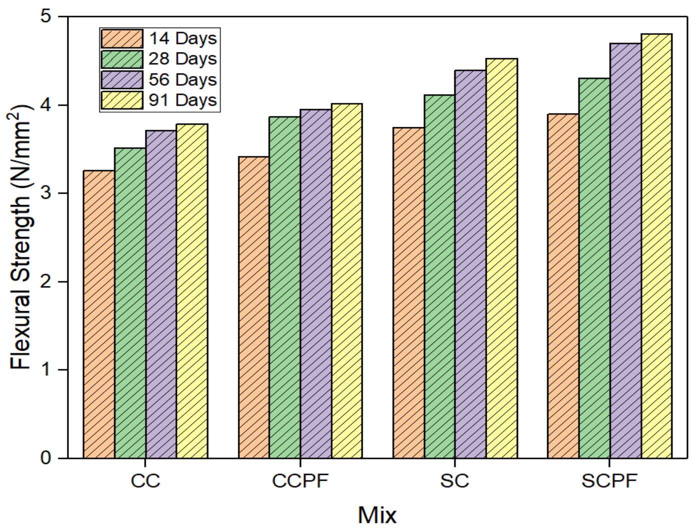


Fig. 3. Flexural strength of different mixes

4.3 Durability Studies

The concrete test specimens were 100 millimeters in diameter and were submerged in a solution of 0.3 and 1% sulphuric acid containing a pH of 1. The tests for sulphuric acid resistance were carried out on the specimens. A hand-held digital pH meter was used to determine the pH values of the sulphuric acid solutions. The average strength and weight loss observed in all mixes were presented in Tables 3 and 4.

At 0.3% and 1% fixation, all slag blends surpass CC blends regarding corrosion resistance. Compounds debase in the presence of calcium hydroxide and C-S-H gel. Low calcium concentration and a lack of calcium hydroxide in slag-based substantial blends lead to less corrosion under corrosive conditions than CC blends. However, the decalcification process that SC blends undergo results in continuous volume-led strength loss that is still less than that caused by CC blends. Substituting GGBS with a potassium hydroxide and potassium silicate mixture improves corrosion resistance

Table 3. 0.3% H_2SO_4 acid attack on different concrete mixes

	14 Days		28 Days		42 days		56 days		91 days	
	Avg Str	%w loss	Avg Str	%w loss	Avg Str	%w loss	Avg Str	%w loss	Avg Str	%w loss
CC	26.8	0.15	26.1	0.22	25.4	0.41	23.6	0.53	21.1	0.69
CCPF	27.1	0.22	26.1	0.29	24.9	0.46	23.1	0.62	21.4	0.14
SC	31.6	0.11	30.14	0.11	29.4	0.24	28.2	0.33	26.1	0.51
SCPF	33.2	0.14	31.9	0.18	30.4	0.21	28.3	0.4	26.2	0.56

Table 4. 1% H_2SO_4 acid attack on different concrete mixes

	14 Days		28 Days		42 days		56 days		91 days	
	Avg Str	%w loss	Avg Str	%w loss	Avg Str	%w loss	Avg Str	%w loss	Avg Str	%w loss
CC	26.2	0.26	25.3	0.38	24.2	1.13	22.8	1.88	19.6	2.1
CCPF	27	0.32	25.8	0.48	24	1.26	21.9	2.114	19.2	2.32
SC	30.14	0.20	29.2	0.32	28.1	0.1414	26.4	1.53	24.1	1.141
SCPF	32.8	0.24	30.4	0.40	28.4	0.89	214	1.59	25.2	1.92

4.4 Microstructural Analysis

4.4.1 Energy Dispersion X-Ray Analysis

Through EDAX analysis, surface materials can be further explored using SEM. This allows for a deeper understanding of the material's structure and characteristics. In addition, it allows for the acquisition of oxide and elemental composition. This technique is useful in conducting quantitative studies to evaluate the materials properties. For this study, the EDAX analysis is utilized to analyze the binding materials characterization. Elemental composition of two concrete mixes (CC and SC) and EDAX analysis is presented in Table 5 and Fig.4 respectively. From EDAX analysis of both CC and SC mixes, it is observed that the present of lime content is noticed more in SC mix when compared to CC mix. The below table represents the elemental and oxide compositions, from which it is observed as SC mix is having better lime content than the CC mix. This attributes improvement in strength and hydration process of SC mix when compared to CC mix. Similarly, there is no much variation in silica content noticed in both the mixes. The presence of silica content exhibits the enhancement in initial strength of concrete. Like CC mix, the presence of MgO, FeO, Al_2O_3 and ZnO was also noticed in SC mix.

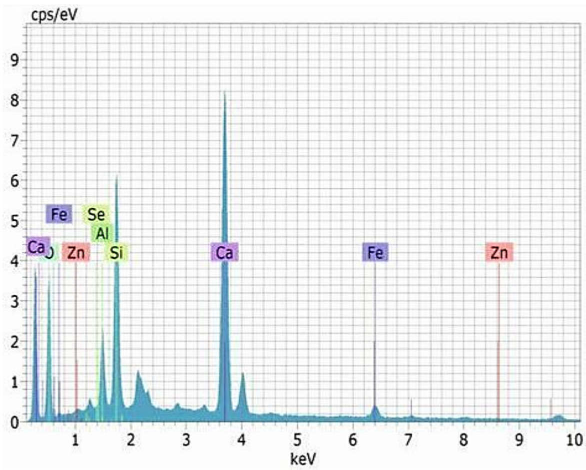
Nature of EDAX Output: Elemental vs. Oxide Composition, EDAX/EDS analysis is primarily used to determine the elemental makeup of a sample by detecting the characteristic X-rays emitted from elements like Calcium (Ca), Silicon (Si), Aluminum (Al), and Oxygen (O), among others. However, when dealing with construction materials such as cement, fly ash, slag, and concrete binders, the results are typically presented in terms of oxides (CaO, SiO_2, Al_2O_3) to align with standard practices in materials science and cement chemistry. Consequently, in our research, the elemental data obtained from EDAX was converted into oxide equivalents using standard oxide conversion factors, a widely accepted method in the literature and guided by ASTM E1508 and SEM/EDS best practices.

4.4.2. Why Oxides Are Reported Instead of Raw Elements

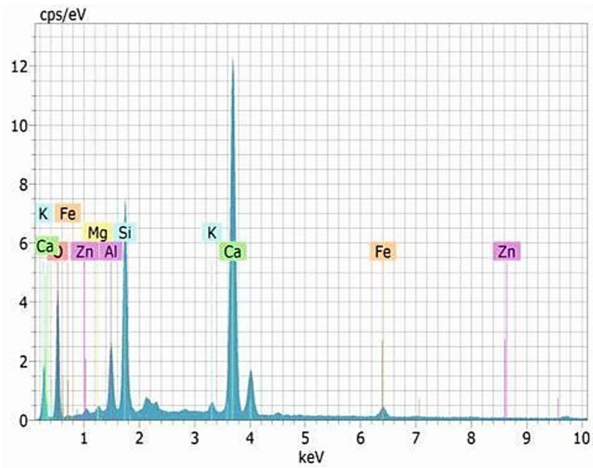
Cementitious and geopolymer binders undergo reactions through pozzolanic or alkali-activation processes that involve oxides rather than pure elements. Representing calcium as CaO and silicon as SiO_2 offers a more chemically insightful perspective on the phase composition, such as C-S-H gel and N-A-S-H gel. This approach also facilitates more accurate comparisons with XRF and XRD results, which naturally report in terms of oxides.

4.4.3 Interpretation of EDAX Figures in the Study

The Calcium (Ca) signal detected in the EDAX spectra was attributed to Calcium Oxide (CaO), which is a predominant component in Ordinary Portland Cement (OPC), C-S-H gel, and hydration products. The Silicon (Si) peak was interpreted and documented as Silicon Dioxide (SiO_2), signifying the presence of quartz, fly ash, or silicate phases within the microstructure. Similarly, Aluminum (Al) was converted to Al_2O_3, indicating the formation of alumino-silicate phases in the alkali-activated slag mixtures. The spectra were obtained from polished sections and were confirmed to represent binder-rich areas, ensuring the accuracy of phase identification.



CC Mix



SC Mix

Fig. 4. Elemental composition of CC and SC mixes using EDAX analysis

Table 5. Elemental and Oxide composition of CC and SC mixes

Mixes	Elements	Weight (%)	Oxide compounds	Weight (%)
CC Mix	Oxygen	35.79	CaO	56.97
	Calcium	39.26	SiO_2	28.63
	Silicon	12.92	Al_2O_3	8.90
	Aluminum	4.71	FeO	5.10
	Iron	3.96	ZnO	0.40
	Zinc	0.12	--	--
	Selenium	1.17	--	--
SC Mix	Oxygen	33.83	CaO	64.72
	Calcium	46.11	SiO_2	23.59
	Silicon	11.54	Al_2O_3	6.85
	Aluminum	1.98	FeO	3.48
	Iron	3.09	ZnO	0.38
	Zinc	0.15	MgO	0.40
	Magnesium	0.23	K_2O	0.58
	Potassium	0.23	--	--

4.4.4 Scanning Electron Microscope Analysis (SEMA)

SEMA is a type of test that involves scanning a sample using an electron beam. It is commonly used for analyzing and studying solid inorganic materials. This method can be very useful in determining the failure of certain materials. In addition to generating high-quality images, it can also measure small objects and features. Using signals generated by SEMA, a two-dimensional impression is created. This information is useful in identifying the characteristics of the sample, such as its external morphology and chemical composition. EDS is a component utilized in combination with SEMA to determine the presence of certain elements on a sample's surface. In addition, it can analyze the elemental composition of the materials and identify foreign substances. Fig 5 presents the SEMA of CC and SC mixes at 28 days curing period. From SEMA of CC and SC it is observed that, formation ettringite is clearly visible and it is more in SC mix when compared to CC mix. It indicated SC mix is more susceptible to chemical attack and longer durability. Similarly, dense microstructure is noticed in SC mix when compared CC due to the use of GGBS in SC mix. Likewise, CH and CSH gel formation is more in SC mix when compared CC mix. Hence the presence of CH and CSH describes the improvement in compressive strength in SC mix when compared to CC mix.

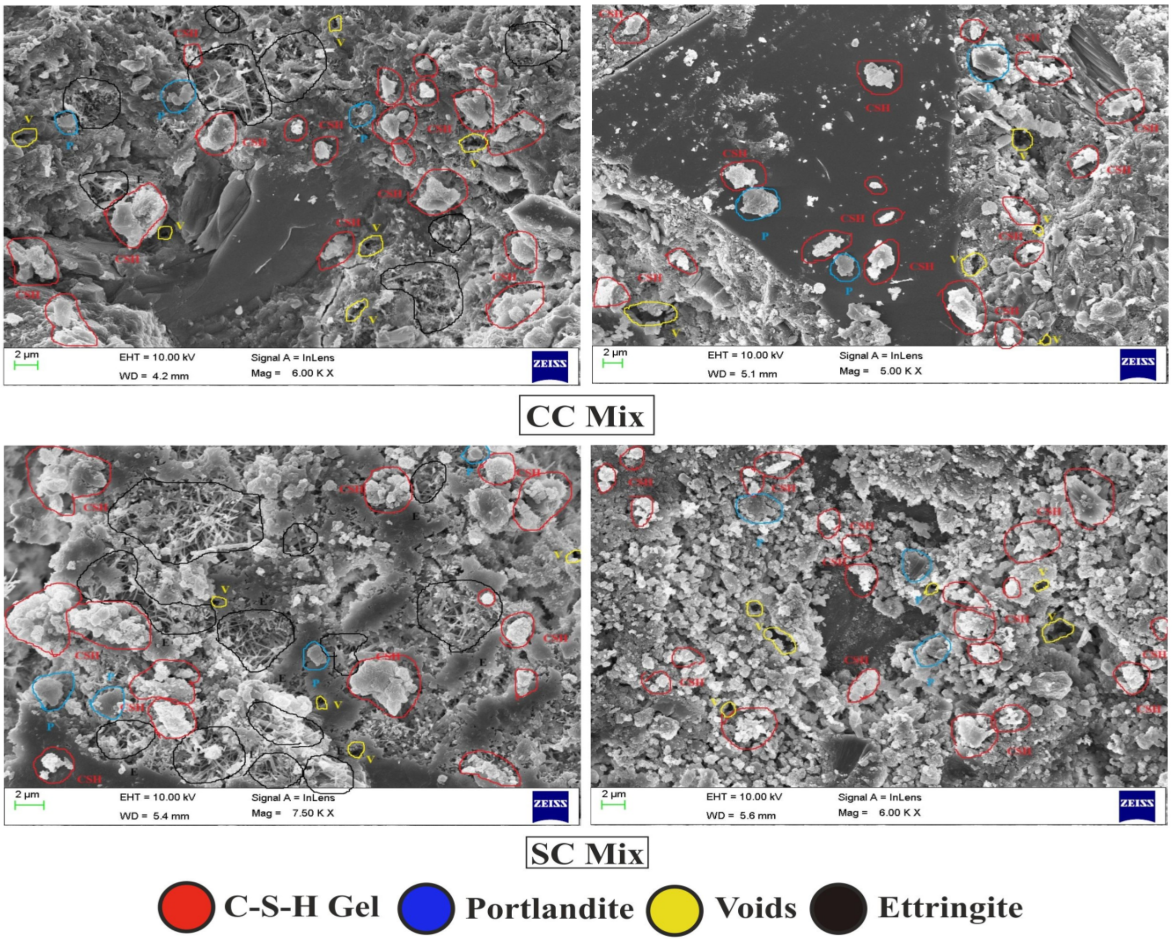


Fig. 5. SEM analysis of CC and SC mix

4.4.5 X-Ray Diffraction Analysis (XRD)

XRD is primarily used to detect early hydrated cement products, it can also function as a control tool for the process. Cement clinker's mineralogy can be regulated with the help of this technique, as it pinpoints the crystalline phases of the component at various stages, such as $CaCO_3$, $CaSO_4$, and $CaSO_2$. Other phases of the cement, such as quartz, periclase, and free lime, can also be determined using this method. The Rietveld technique provides a detailed analysis of the crystal structures in cement, including the various types of Alite and Blite, as well as calcium sulphates, free lime, and calcite. Figure 6, 7 represents the XRD analysis of CC and SC mix respectively. From XRD analysis, it is noticed that presence of SiO_2 and CH gel formation (Portlandite) is clearly visible and maximum intensity is noticed for the two elements. The presence of SiO_2 and Portlandite exhibits the long-term strength and durability of CC and SC mix. When compared CC mix the presence of these two elements intensity is slightly more in SC mix. In addition to these elements the presence of sinnerite is observed in SC mix. It is only observed in SC mix and not in CC mix. Sinnerite is a mineral (Cu6As4S9) helps in enhancing compressive strength and durability of SC mix. It also acts as a nucleation site for cement hydration products, helping to form a denser and more compact microstructure.

The XRD analysis was conducted to identify the crystalline phases present in both conventional concrete (CC) and alkali-activated slag concrete (AASC), with and without the addition of polypropylene fibers. For conventional concrete, the main phases identified were portlandite ($Ca(OH)_2$), calcium silicate hydrate (C-S-H), and ettringite, which are typical of OPC hydration products. The intensity of the portlandite peaks reflects the progress of hydration and the presence of free lime in the matrix. Additionally, minor peaks corresponding to unreacted clinker phases such as alite and belite were noted, particularly in the early stages of curing, indicating incomplete hydration.

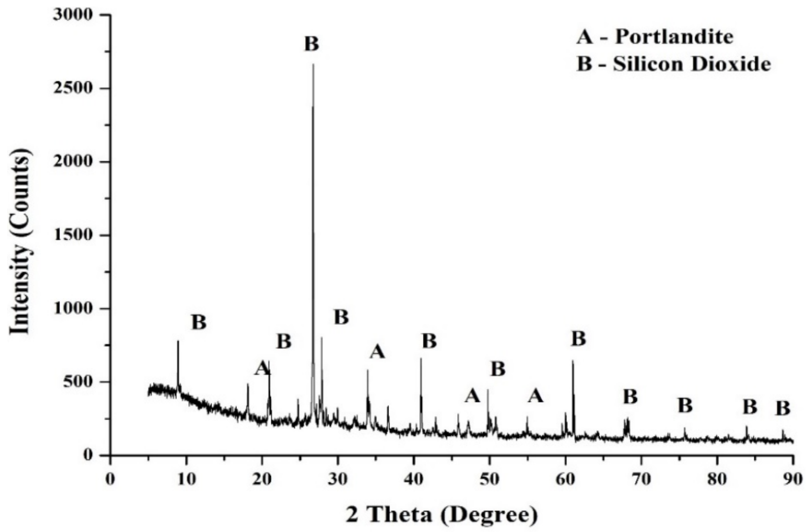


Fig. 6. XRD analysis of CC mix

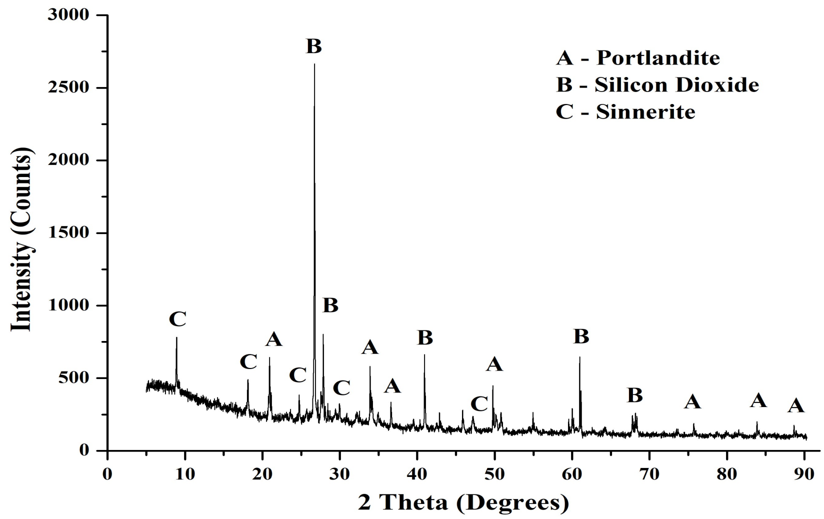


Fig. 7. XRD analysis of SC mix

Conversely, the XRD patterns of AASC mixtures revealed markedly distinct mineralogical characteristics. The emergence of low-crystalline or amorphous alumino-silicate phases, such as N-A-S-H gel and C-A-S-H type gels, was suggested by a broad hump in the 20–35° 2θ range, indicative of poorly crystalline or gel-like structures. Furthermore, crystalline phases like hydrotalcite, calcite, and residual slag components such as akermanite were observed. The presence of hydrotalcite implies the formation of secondary reaction products under high alkaline conditions, enhancing chemical stability. In certain AASC samples, rare trace phases like sinnerite were also detected, pointing to complex secondary reactions involving trace elements within the slag matrix. Additionally, the inclusion of polypropylene fibers did not significantly change the primary crystalline composition but might have affected the degree of crystallinity and microstructure refinement. Overall, the comparison between the mixes shows that AASC systems have a higher proportion of amorphous content compared to CC, aligning with their geopolymer-like reaction mechanism. These distinctions are vital for understanding the long-term performance, durability, and sustainability of alkali-activated systems. This expanded discussion has been incorporated into the revised thesis to offer clearer insights into the mineralogical behavior of the binders and the influence of material chemistry on phase development.

5. Life Cycle Assessment (LCA)

LCA is a process utilized to evaluate a product or service's environmental impact. This analysis can be performed by comparing the energy consumption of different processes and activities within a supply chain. Various software and databases are utilized in this process. Researchers are currently extending LCA to cities. This process estimates a product's impact on the environment. The framework provides an in-depth analysis of the lifecycle of a product. This process involves considering the various elements that impact the planet during a service's lifecycle, including extraction of raw materials, the production phase, and the product's end. The life cycle stages of a product are referred to as the elements of a product's lifecycle. Using LCA, an organization can determine the impact of its products and services on the environment at the beginning, middle, and end. The life cycle analysis process iteratively updates the elements of the analysis. It is referred to as LCA, and it utilizes a standardized approach. This process is reliable, transparent, and conforms to ISO 14040 and 14044 specifications. Fig. 8 represents the LCA framework.

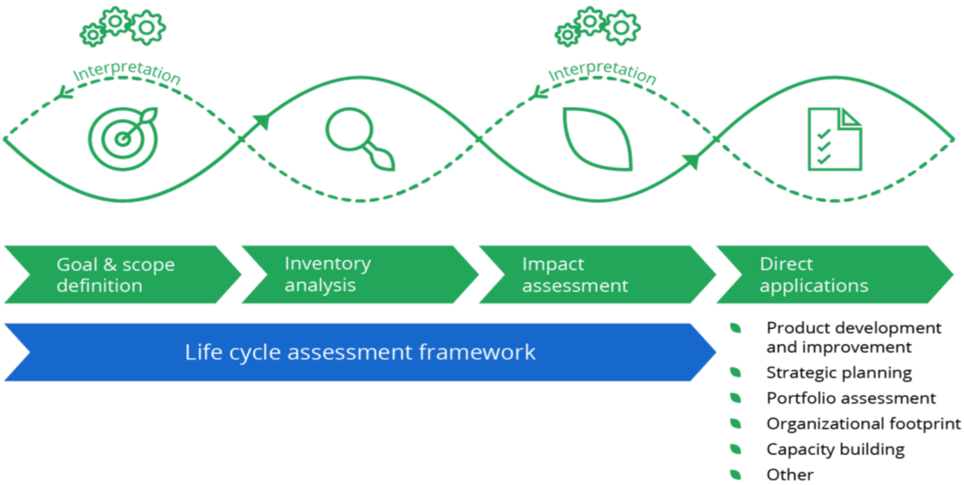


Figure 8. LCA framework

5.1 Global Warming Potential (GWP)

From Fig.9 it is observed that impact GWP is more for OPC in CC and CCPF mixes. Manufacturing of OPC for CC and CCPF contributes almost 283.57 and 280.74 kg of CO_2 for a cubic metre of concrete respectively. However overall impact of CO_2 contribution for CC and CCPF mixes is found to be 299.02 and 308.01kg respectively. From CC and CCPF mixes, it is observed that manufacturing of OPC and its usage in CC and CCPF mixes was found to be hazardous to the environment and causes depletion of ozone layer and natural resources consumption. Similarly, the overall impact of SC and SCPF mixes is found to be 97.03 and 77.95 kg CO_2 to the environment. When compared to CC, CCPF and SC, SCPF mixes slag based concrete mixes helps in reducing the overall emission of carbon emission to the environment. Not only strength and durability point of view, SC and SCPF mixes are found to sustainable and environmentally friendly in comparison to CC and CCPF mixes.

- TP: overall Impact of Transportation in LCA studies from cradle-gate stage
- E: overall Impact of Electricity in LCA studies from cradle-gate stage
- W: overall Impact of water in LCA studies from cradle-gate stage

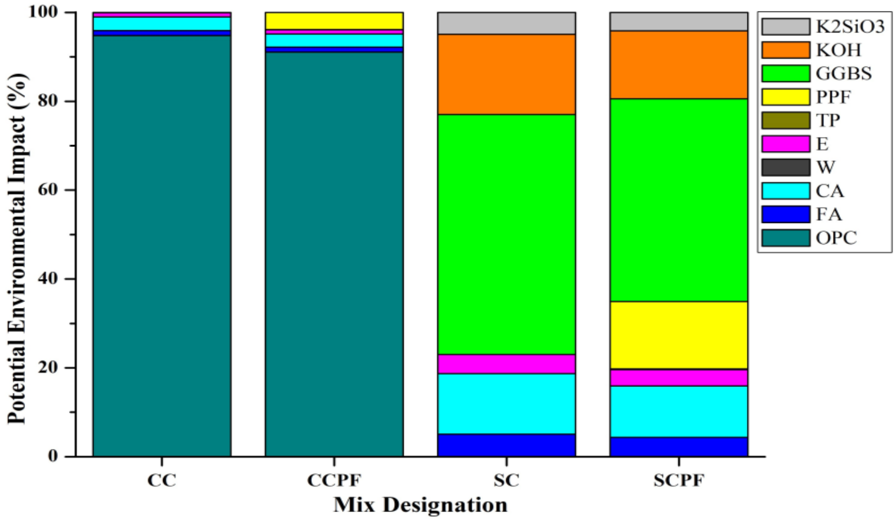


Fig. 9. Impact of global warming potential

5.2 Potential Stratospheric Ozone Depletion (PSOD)

The reduction of the ozone layer over the surface of Earth can lead to various environmental issues. Some of the harmful substances that can affect the environment include freons, chlorofluorocarbons, and methyl chloroform. From Fig. 10 it is observed that, overall impact of PSOD for CC and CCPF mixes are found to be 000466 and 000490 kg CFC11 respectively. Similarly, the overall impact of PSOD for SC and SCPF mixes are found to be 0065 and 00363 kg CFC11 respectively. Compared to SC and SCPF mixes, the impact of PSOD is greater in CC, and CCPF mixes due to the usage of OPC in CC mixes, as observed in GWP. Hence, slag-based mixes are more sustainable and friendly than conventional concrete mixes.

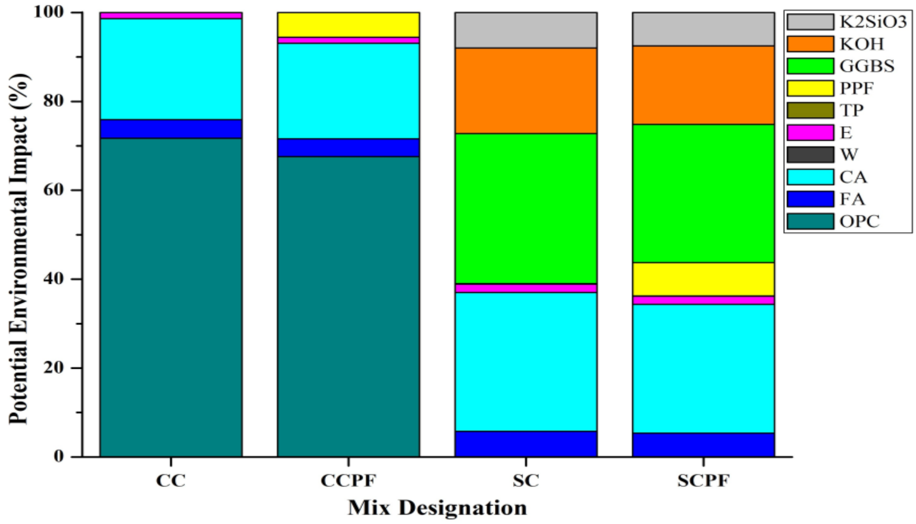


Fig.10. Impact of potential stratospheric ozone depletion

5.3 Freshwater Ecotoxicity (FE)

The accumulation of chemicals in the environment can happen throughout a service or product's lifecycle. Fig. 11 shows the impact of FE impact of all the ingredients used in CC and CCPF mix is found to be 0.05 and 0.06 kg 1,4-DCB respectively. Similarly for SC mixes it is found to be 0.37 and 0.22 kg 1,4-DCB respectively. It is also observed that the impact of SC and SCPF mixes on FE is found to be minimum in comparison to CC and CCPF mixes. Hence the use of GGBS and other waste ingredients in concrete manufacturing helps in reducing the pollution and contamination of freshwater and improves the quality of water and human health.

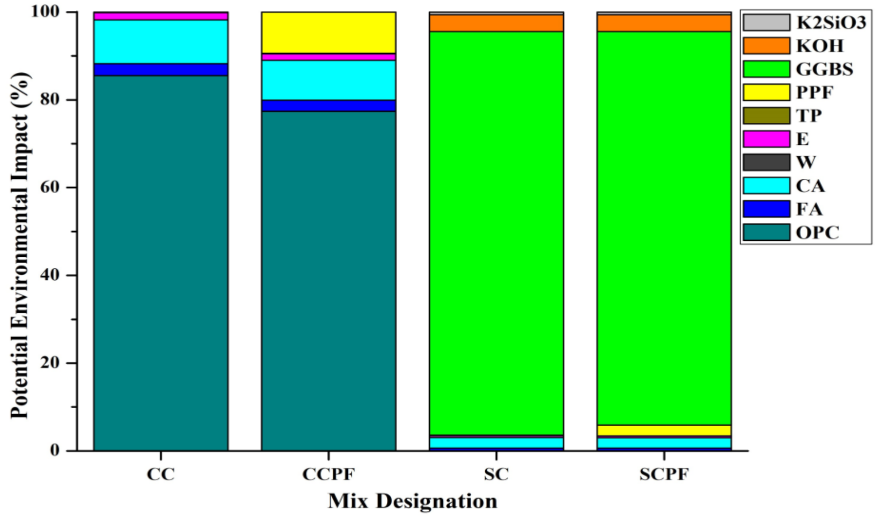


Fig. 11. Impact of Freshwater ecotoxicity

5.4 Fossil Resource Scarcity (FRS) and Mineral Resource Scarcity (MRS)

Enhanced oil recovery is one of the techniques that can be used when conventional resources are no longer available. Impact assessment of various types of CC and SC mixes using waste industrial by-products are presented in Fig.12 & 13. As desired, cement manufacturing industries consume large quantities of natural resources, and they are energy intensive. Hence the use of OPC in CC is responsible for the impact on FRS and MRS is found to be 40.01 kg oil eq and 0.41 kg cu eq respectively. Similarly, for CCPF mix it is observed that, impact of FRS and MRS in slightly more (46.25 kg oil eq and 0.43 kg cu eq respectively). Likewise, SC and SCPF mixes for FRS is found to be 20.76 and 22.00 kg oil eq. This is less when compared to CC and CCPF mixes. It is also observed that, MRS for SC and SCPPF mixes found to be slightly more when compared to CC and CCPF mixes. It is mainly due to the use of KOH and K_2SiO_3 in SC and SCPF mixes to improve the hydration process. Overall, the use of CC and CCPF concrete manufacturing, surface finishing and transportation causes a lot of health hazards and polluting environment. From Fig. 12 & 13, it is also observed that, not only FRS, use of these waste by-products will also result in reducing the consumption natural mineral resources and overcome the depletion challenges and help in saving mother earth for future generations.

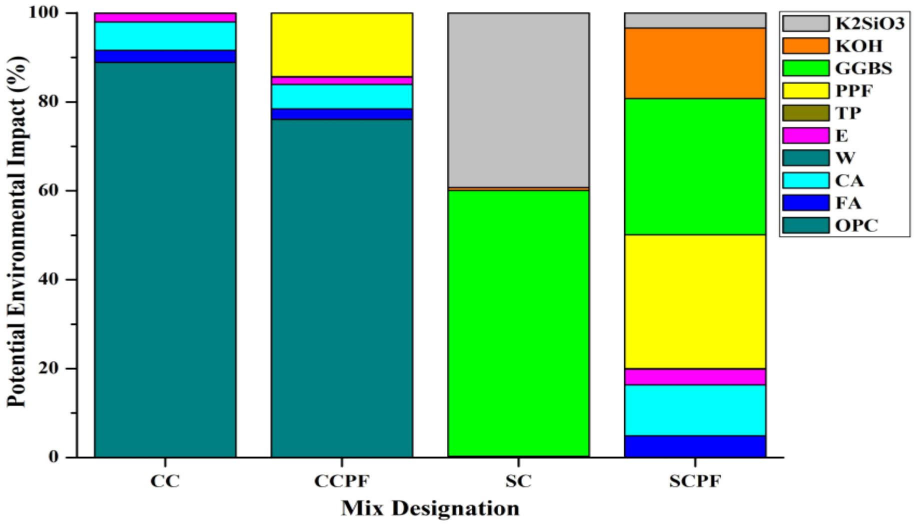


Fig.12. Impact of fossil resource scarcity

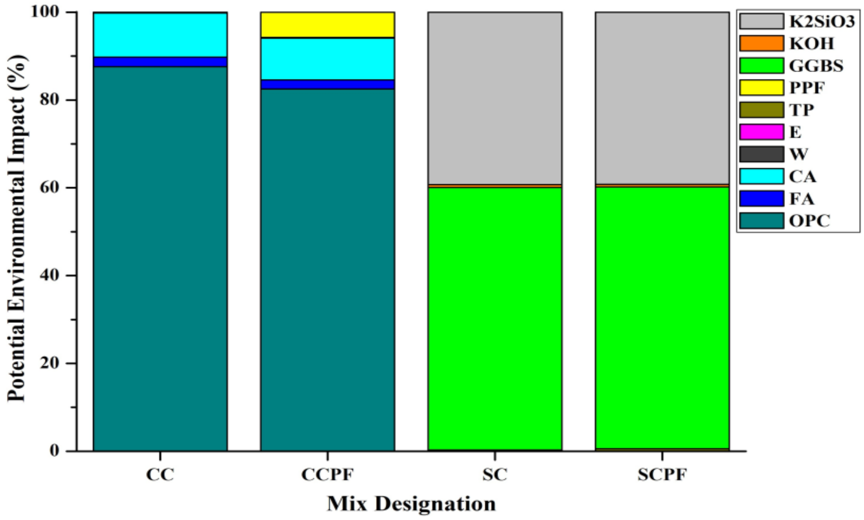


Fig. 13. Impact of mineral resource scarcity

5.5 Human Carcinogenic Toxicity (HCT)

The release of chemicals into the air and water can happen throughout a service or product's lifecycle. The estimated stocks of products contain hundreds of chemicals, which can result in varying toxic effects on individuals. Some of these include NOx, PM10, SOx, and CO. An impact category is used to explain how exposure to harmful substances can affect people. These include the effects of food, water, or air inhalation, as well as skin penetration. Impact of all the ingredients used for manufacturing bricks on HCT is presented in Fig. 14. Not only environmental pollution, it is also affecting human health in two ways HCT and HNCT diseases. If we compare all the ingredients and their effect on HCT, KOH and K_2SiO_3 and OPC plays a major role in causing the diseases to living life. To improve the quality of living life and human health, use of waste industrial by-products in concrete will give justice in reducing the disposal challenges, landfill challenges and helps in reducing the diseases related to HCT.

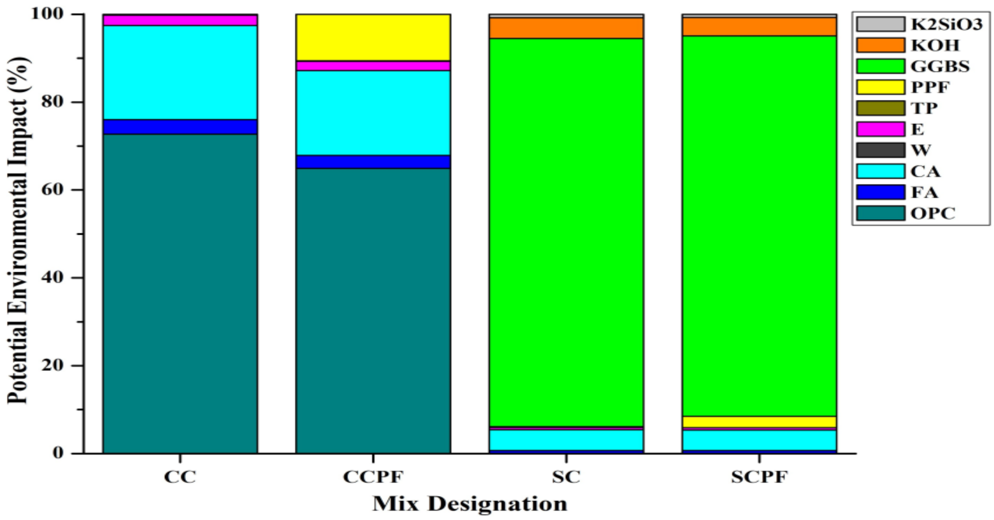


Fig.14. Impact of human carcinogenic toxicity

5.6 Terrestrial Ecotoxicity (T-ECO) and Marine Ecotoxicity (M-ECO)

The deposition of certain nutrients, like sulfur and nitrogen, in acidified forms can affect the chemical properties of soil. Various ecological factors, such as exposure to harmful chemicals, environmental fate, and ecological damage can also influence Eco toxicity's effects. There are various factors that can affect the well-being of the environment, and these are categorized into three main categories: fate; exposure; and damage. Fate determines how many chemicals are released into the ecosystem, while exposure measures the level of pollutants that can be exposed. Impact of ingredients used in various types concrete (CC, CCPF, SC and SCPF) is presented in Fig.15 & 16. From the figure it is observed that, impact of T-Eco and M-Eco is more due to the consumption of OPC, GGBS, PF KOH and K_2SiO_3. The consumption of the waste related by products like GGBS will also help in reducing the impact of these wastes on terrestrial activities to save animals, birds and human beings and overcomes the challenges associated with these wastes.

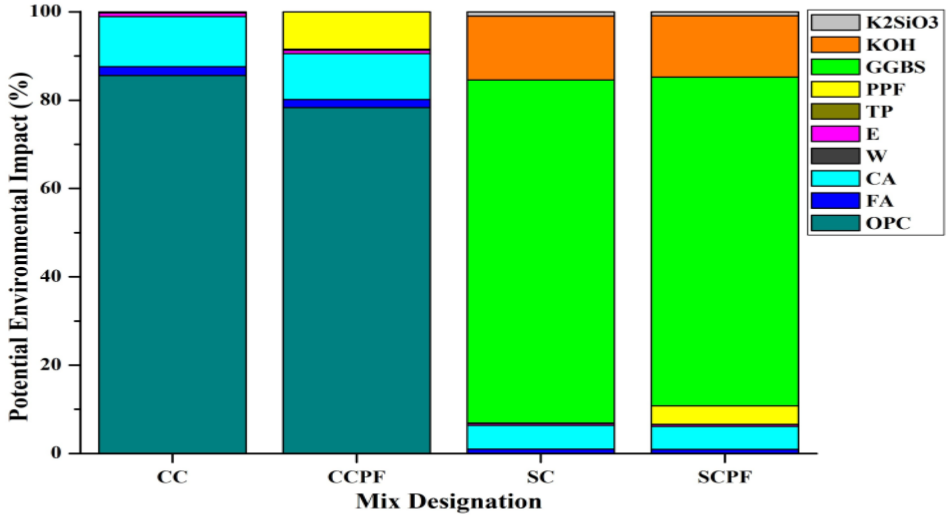


Fig. 15. Impact of Terrestrial ecotoxicity

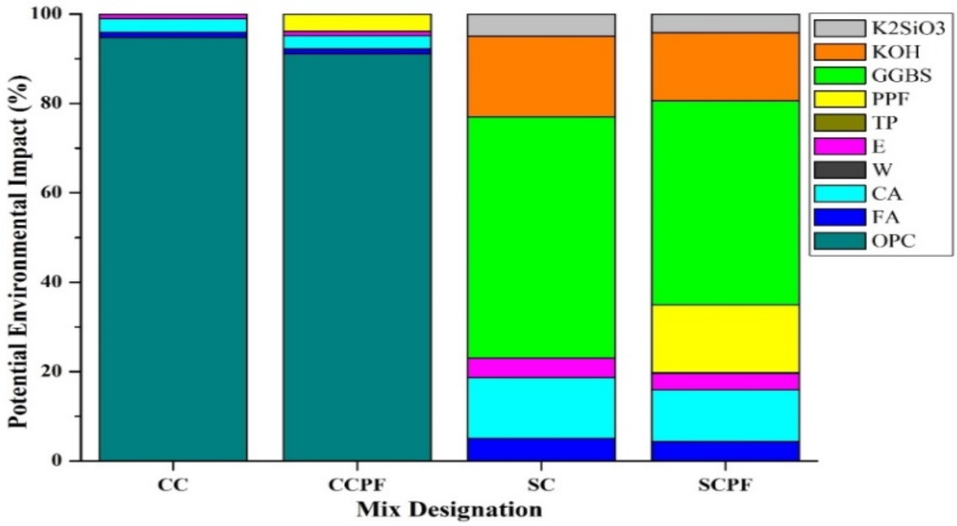


Fig. 16. Impact of Marine ecotoxicity

5.7 Fine Particulate Matter Formation (FPMF)

The initial release of NOx, SO_2, and NH_3 into the atmosphere triggers the formation of PM2.5. These particles are then converted into secondary aerosols through atmospheric chemistry. In addition to causing premature death, exposure to PM2.5 can also lead to other health conditions. From Fig. 17 it is observed that, consumption of these industrial wastes by products will reduce the further contamination of fresh air and to overcome the challenges associated with human health, it can be used effectively in concrete manufacturing. Similarly, from the Figure 17 it is observed that the overall impact of CC and CCPF mixes is found to be 0.29 and 0.31 kg PM2.5 eq, respectively. Similarly, SC and SCPF have marginally less impact of about 0.22 and 0.17kg PM2.5 eq, respectively. Use of GGBS in SC and SCPF mixes can be minimized further its concentration contamination with air, water, and soil by replacing it with cement by GGBS in SC and SCPF manufacturing to save mother earth.

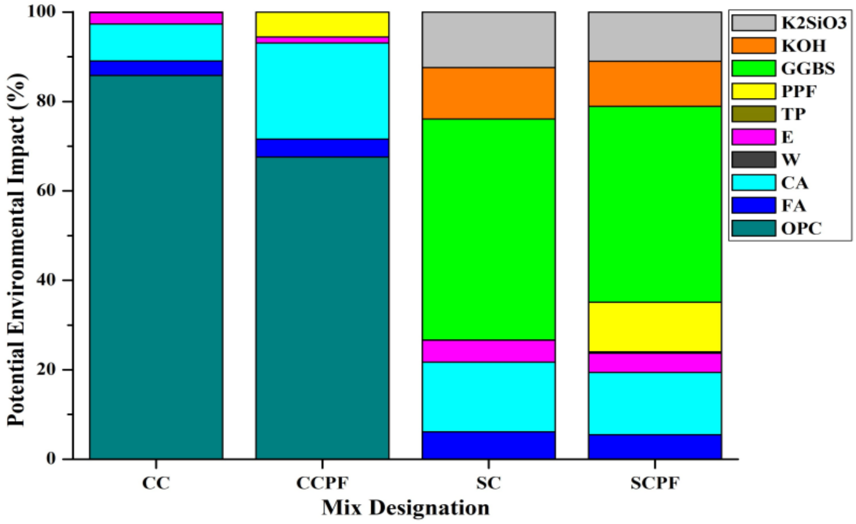


Figure 17. Impact of fine particulate matter formation

5.8 Scientific Relevance and Practical Implementation

This research mainly focuses on the use of fibers in concrete. It improves the durability and performance of concrete. When mixed with concrete, they increase the stiffness of the concrete members also increases the cracking resistance. It improves structure lifespan. Its ability to endure environmental stresses and chemical degradation helps minimization under adverse climatic conditions. This helps reduce the cost of repairs and maintenance.

6. Conclusions

- According to the results, the compressive strength is around 20.8% higher, and the flexural strength is about 11.4% higher in slag mixes than in cc mixtures at 28 days. The extra lime and alumina in GGBS aid in the formation of C-S-H gel by reacting with cementitious substituents, improving durability and strength. The presence of polypropylene fibers aids in the arrest of microcracks, increases density, and makes the formation less porous. The presence of PPF makes concrete impact and abrasion resistant which helps in pavement durability. SC mixtures had higher pozzolanic reactivity and created superior C-S-H and C-H gels.
- The life cycle assessment studies on CC and SC mixes indicates the impacts of several categories on ecology. It is observed and concluded that, replacement of cement with other conventional materials reduces the impact on environment and also helps to make green concrete. The incorporation of polypropylene fibers has resulted in improvable properties of durability and mechanical. The utilization of GGBS in SC and SCPF helps in the improvement of environment by reducing the carbon footprints.
- It is examined that the strength of the M20 graded SC mix under ambient curing conditions almost equated with the target mean strength of the M30 grade conventional concrete mix, which is suitable for the construction of low-volume roads as per IRC: SP:62-2014. Due to the suitable criteria, the SC mix is considered for the project continuation. The highest flexural strength of 4.53MPa is achieved at 91 days of ambient curing. For traffic less than 50 CVPD (commercial vehicles per day), compressive and flexural strengths should not be less than or equal to 30 and 3.8 MPa. For low-volume concrete roads, 90 days strengths are used. Fatigue is not considered for tribal area pavements and low-volume roads. The standard concrete-connected slabs for rural roadways do not need to be reinforced. Due to the higher flexural strengths observed in SC and SCPF mixes, they can resist significant stresses, which in turn helps reduce the pavement's thickness, making it cost-effective.

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