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Sustainability Assessment of Soil Stabilization using Ground granulated blast furnace slag

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ABSTRACT

To keep pace with the rapid growth in the infrastructure and construction industry, enormously huge demand exists for stabilization of soils across the globe. The conventional soil stabilization techniques lack a fit due to environmental impacts through unwanted emissions, by-products and depletion of natural resources. In this scenario, there is significant mounting interest in developing sustainable soil stabilization techniques which can effectively replace the conventional stabilizers like cement and lime with either natural or recycled wastes or agricultural/industrial byproducts viz, Ground-granulated blast furnace slag (GGBFS) as a soil binder is well established. Besides the increase in shear strength and maximum dry density and a lower optimum moisture content, previous research has proven that GGBFS is effective in reducing swelling properties of soil as well. From this perspective, this study intends to deliver an optimal proposal of a sustainable soil stabilization technique on the basis of studies on strength and sustainability indicators of GGBFS stabilized soil. Subsequently, the study addresses the feasibility of using GGBFS as a sustainable alternative to conventional soil stabilizer like cement, based on a life cycle assessment (LCA). The effects of binder content, moisture content and curing conditions being the major parameters observed, the environmental impacts of soil stabilization using cement and GGBFS are assessed. The LCA brings out a comparative environmental impact of these binders in soil stabilization. The study concludes that GGBFS can be used as an environment friendly and sustainable binder for all the types of soil considered in the study since the LCA results estimated very low climate change impacts for GGBFS compared to cement for the stabilization of 1 m^3 soil to achieve similar values of unconfined compressive strength.

Keywords: Sustainability, Soil Stabilization, GGBFS, Life cycle assessment

1 INTRODUCTION

Soil stabilization is an established practice where problematic soils are treated to enhance either the strength or hydraulic characteristics. Scarcity of good construction land to meet the demand of the construction industry enhances the significance of soil stabilization. Soil Stabilization can be utilized in pavement subgrade, parking areas, airports, landfill areas and many other situations where sub-soils are not adequate for construction. Stabilization can be used to improve a wide range of sub-grade soils, varying from expansive clays to granular soils. The stabilization process is accomplished using a wide variety of additives, including lime, cement and fly ash. Such conventional binding materials increase the strength and reduce the plasticity of soil significantly with very small binder content in most of the of soils (Rosone et al., 2020; Rogers and Glendinning, 2000; Zhang and Tao, 2008) however, lead to natural resource depletion and increased carbon footprint as they involve significant amounts of materials and energy.

Sustainability assessment incorporating the three E's (environment, equity, and economy) is becoming an important decision-making criterion in the construction industry as it consumes high level of natural resources and energy and results in huge production of waste (Farid, 2020). The construction industry is responsible for about 19 percent of the overall GHG emission globally, requiring urgent mitigation measures (Labaran et al., 2021). The cement industry is the second-largest industrial CO_2 emitter (around 25% of global industrial CO_2 emissions) globally (Chen et al., 2022). The production of 1 tonne of cement consumes 1.5 tonnes of natural resources and 5.6GJ of energy and emits 0.9 tonne of CO_2

per year (Higgins, 2007; Hendriks et al., 2004 and Fayomi et al., 2019). Also, the cement market is expected to grow at a rate of 5% each year.

According to Basu et al, (2015), a gap exists between sustainability concept and its practical application in engineering and a comprehensive approach taking into account environment, economy, equity and engineering design including reliability and resilience aspects (the 4 E's) is recommended for the sustainable development of civil infrastructure and society. The use of alternative materials and innovative engineering can develop sustainability assessment frameworks. Rocha et al, (2021) combined the strength and stiffness results of dispersive clay with environmental impact data to create a decision-making model for optimal dosages considering the economic and environmental dimensions of sustainability and arrived at equations for the porosity-lime index which creates the most cost-efficient dosage. The feasibility study using volcanic ash (VA)-based geopolymer as an alternative soil stabilizer to cement (Ghadir et al., 2021) by comparing their shear strength behavior and life cycle assessment estimated similar climate change impacts for cement and VA-based geopolymer used for stabilization of 1 m^3 functional unit of clayey soil with similar shear strength. Hossain et al, (2020) found that the use of calcium aluminate cement and supplementary cementitious materials as binders instead of OPC and reactive magnesia cement for stabilization/solidification treatment of hazardous wastes can significantly reduce the environmental impacts. By evaluating the lime stabilization technique and the geogrid reinforcement technique to stabilize expansive soil slopes (Zhang et al, 2019) the geogrid technique was found to have the advantages of energy-saving and emission-reduction when the embankment height is less than 10 m.

The expansive soils are highly unstable under seasonal moisture fluctuations and induces stresses in the soil mass which causes the damage of superstructure (Chen, 1988; Ito and Azam, 2013). As the seasonal damage is repetitive, the repair and maintenance cost sometimes even exceed the original cost of construction of the structure. In order to minimize energy consumption and greenhouse gas emissions in the process of extraction, processing, and transportation, it is important to make full use of expansive soils instead of discarding them (Correia et al, 2016). The addition of chemicals such as cement, fly ash, lime, or a combination of these often changes the physical and chemical properties of the treated soil with improvement in the soil gradation due to cementation, increase in shear strength, reduction in the plasticity properties, decreased compressibility and with absorption and chemical binding of moisture that will facilitate compaction (Asgari et al, 2013). Industrial or agricultural wastes or by-products possessing hydraulic or pozzolanic characteristics such as fly ash, rice husk ash and granular blast furnace slag (Sivapullaiah et al., 1996; Karatai et al., 2016; Sharma and Sivapullaiah, 2016) are under investigations to be utilized as supplementary cementitious materials. The use of the waste and by-product materials for soil stabilisation can help to mitigate the issues of disposal of waste and subsequent environmental pollution.

GGBFS, being a common binder material in cement industry, have proved its ability to stabilize the soil for the past few decades through laboratory studies (Cokca et al., 2009; Sharma and Sivapullaiah, 2016). However, definite and standard guidelines are not established for the practical implementation. Also, a sustainable solution simultaneously addressing strength, durability, economy and environment is very essential in this scenario. Hence, in this study, the performance of two stabilizers viz., GGBFS and cement (a conventional binder) is compared based on the strength characteristics of soil binder mix and environmental impacts of the soil stabilization process through a cradle to gate LCA of the stabilizers.

2 SOIL AND BINDER CHARACTERIZATION

Four types of soil mixes were prepared by mixing different proportions of Na-Bentonite clay (B) and sand (S) for making soils of different swelling potential. The soils are designated by 90B:10S (90% bentonite + 10% sand), 70B:30S, 50B:50S and 30B:70S and were mixed in dry condition. The grain size analysis, as performed according to IS: 2720 (Part 4) - 1985, shows bentonite contains 3.44% sand, 21.56% silt and 75% clay (Figure 1) and 99.12% of the particles were below 425 micron. According to the Unified Soil Classification System, the first two soil mixes were classified as high plasticity clay (CH) and the others were classified as clayey sand (SC). The river sand collected was classified as uniform sand (Figure 1) and its specific gravity is found to be 2.61. Modified free swell index of the soils proposed by Sridharan et al., (1985) were determined to assess the swelling nature of the bentonite-sand mixtures, see Table 1.

Maximum dry density (MDD) and optimum moisture content (OMC) were obtained from mini compaction tests developed by Sridharan and Sivapullaiah, (2005) for all the bentonite-sand mixtures and shown in Figure 2. The compaction curves for bentonite sand mixtures shows that maximum dry density increases and OMC decreases as the sand content is increased due the higher specific gravity of sand compared to bentonite.

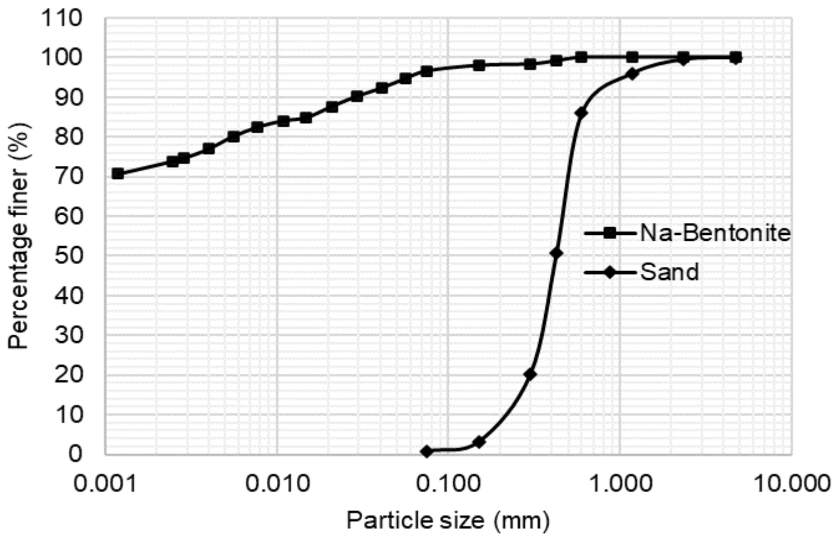

Figure 1. *Grain size analysis of Bentonite and Sand*

Ground granular blast furnace slag (GGBFS) is the by-product produced by Iron/steel industry. It mainly consists of lime, silica and alumina. GGBFS was collected from JSW cement Ltd., Bellary, Karnataka, India. Specific gravity and fineness of GGBFS were found to be 3.08 and 1.35 respectively. The chemical composition (Table 1) shows that GGBFS is a calcium-based admixture and can form cementitious products when added to expansive soils. To compare the performance of GGBFS in soil stabilization, conventional binder, cement (OPC 43 grade) was used in this study and specific gravity and fineness of cement were 3.13 and 2.86 respectively.

Table 1. *Characterisation of Bentonite-Sand mixtures*

Properties	Bentonite	90B:10S	70B:30S	50B:50S	30B:70S
% Sand	3.44	13.00	38.82	68.95	90.03
% Silt	21.56	19.50	13.93	7.43	2.88
% Clay	75.00	67.50	47.25	23.63	7.09
Liquid limit (%)	554.00	460.00	360.00	216.00	122.00
Plastic limit (%)	130.30	70.32	52.47	35.79	25.00
Plasticity Index (%)	423.70	389.68	307.53	180.21	97.00
Soil Classification (USCS)	CH	CH	CH	SC	SC
Max dry density (g/cc)	-	1.19	1.32	1.50	1.66
Optimum moisture content (%)	-	44.22	33.43	26.71	18.63
Shrinkage limit (%)	2.95	13.80	19.95	34.97	38.08
Specific gravity	2.51	2.56	2.60	2.62	2.69
Modified Free swell index (%)	149.60	142.36	118.60	98.70	50.03

Table 2. *Chemical composition of Bentonite, GGBFS and Cement*

Chemical Oxides	Bentonite	GGBFS	OPC
SiO_2	57.53	33.91	21.18
Al_2O_3	15.86	18.64	5.32
FeO	16.94	-	3.82
CaO	1.97	37.10	63.80
Na_2O	3.64	-	0.28
K_2O	-	-	0.54

MgO	4.07	7.18	1.79
SO_3	-	1.71	2.36
MnO	-	1.46	-

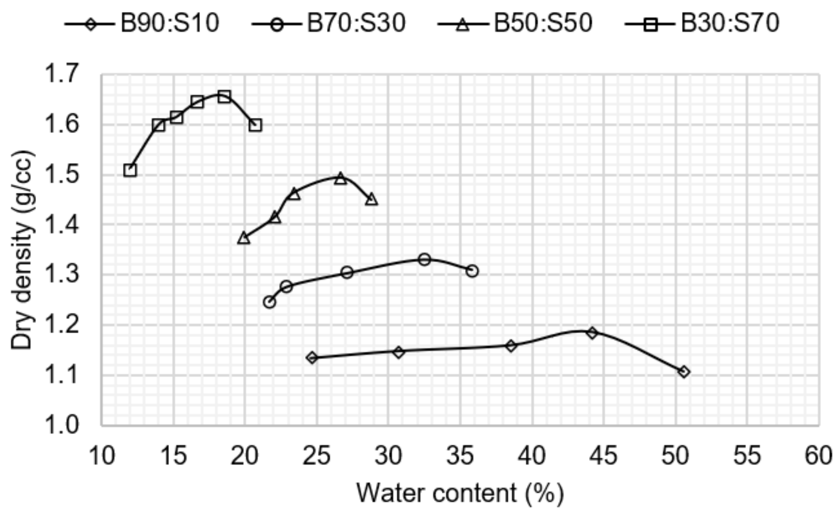

Figure 2. *Compaction curves for Bentonite-Sand mixtures*

3 TEST PROCEDURES

To identify the effect of binder content on compaction characteristics of bentonite-sand mixtures, mini compaction tests were conducted with the addition of 5, 10, 15, 20 and 25% GGBFS and cement separately. To assess the strength performance of the treated soil specimens, unconfined compressive strength (UCS) tests were conducted according to IS 2720 (Part 10): 1991, using a strain rate of 1.25 mm per minute. Oven dried soil was mixed with various percentage of binder and with three water contents such as optimum, 2% wet of optimum and 2% dry of optimum. The samples were compacted into standard iron mould of 38 mm diameter and 76 mm height, to attain an aspect ratio of 2:1. The moulds were of split type with two steel clamps to prevent lateral expansion during compaction. The UCS specimens were then removed from the moulds by releasing the clamps, wrapped in cling film and left to cure at 100 % humidity in a desiccator. Specimens were tested at 0, 7 and 28 days of curing to investigate the long-term strength performance of treated clays. Plasticity characteristic of the bentonite-sand mixture treated with GGBFS and cement were measured for the samples after 7 and 28 days of curing.

4 DISCUSSION ON HYDROMECHANICAL PROPERTIES

4.1 Effect of binders on compaction characteristics of soil

Bentonite-sand mixtures mixed with GGBFS show an increase in MDD and decrease in OMC up to a particular binder content, after which the variation is reversed. The optimum GGBFS content giving highest MDD was 15% for B90:S10, B70:S30 and B50:S50 and 20% for B30:S70. The increase in MDD may be attributed to the higher value of specific gravity of GGBFS and addition of non-plastic GGBFS particles reduces the resistance to compaction While, the initial decrease in the OMC may be the result of decreasing the quantity of free silt and clay fraction with the addition of GGBFS, thus the smaller surface area required less water (Alkhafaji et al, 2017; Yadu and Tripathi, 2013). Figure 3 shows the improvement in MDD of bentonite-sand mixtures with GGBFS. Effect on MDD is maximum (12.62%) for B70:S30 with 15% GGBFS. Mix with 50:50 and 30:70 proportion already have high MDD, hence less percentage improvement.

The same compaction behavior is obtained for soil-cement mixture, however the percentage improvement in MDD is found to be less compared to that with soil compacted with GGBFS. Effect on MDD is maximum (2.47%) for B50:S50 with 15% GGBFS. Mix with 30:70 proportion already has high MDD, hence less percentage improvement. The lower percentage improvement in MDD in soil-cement may be due to the larger fineness value of cement compared to that of GGBFS. For cement treated soils, binder content for maximum MDD is 15% for B90:S10, B70:S30 and B50:S50 and 20% for B30:S70.

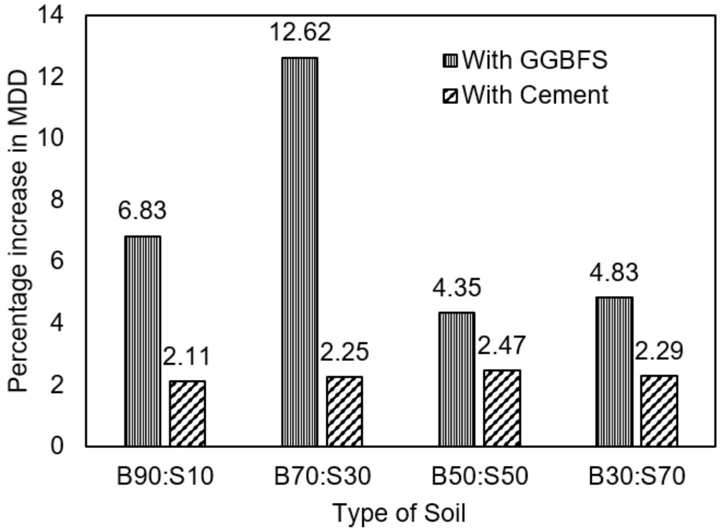

Figure 3. *Improvement in MDD for optimum GGBFS and Cement content*

4.2 Effect of binders on Unconfined compressive strength

Design of experiments (DoE) based on three numerical factors such as binder content (5, 10, 15, 20 and 25%), moisture content (optimum, 2% wet of optimum and 2% dry of optimum) and curing days (0, 7 and 28 days) were carried out to optimize the design. The central composite design in Response Surface method was used to make DoE and optimized design and corresponding UCS values for GGBFS and cement treated bentonite-sand mixtures are given in Table 3 and 4, respectively. For both the binders, maximum values of UCS were obtained for the samples at 28 days of curing.

Table 3. *Summary on UCS of GGBFS treated samples after 28 days of curing*

Soil	UCS of soil only (kN/m^2)	Optimum Binder content (%)	Optimum Water content (%)	UCS of GGBFS treated soil (kN/m^2)
B90:S10	92.17	21.67	42.18	505.73
B70:S30	116.26	20.70	31.96	539.50
B50:S50	129.67	18.94	25.79	687.57
B30:S70	138.08	25.00[a]	20.81	591.28

[a]For B30:S70, 25% is not the optimum binder content. UCS is increased continuously with GGBFS content.

Table 4. *Summary on UCS of Cement treated samples after 28 days of curing*

Soil	UCS of soil only (kN/m^2)	Binder content (%)	Optimum Water content (%)	UCS of Cement treated soil (kN/m^2)
B90:S10	92.17	20	42.44	1751.06
B70:S30	116.26	20	34.83	2320.41
B50:S50	129.67	20	26.32	2993.87
B30:S70	138.08	25	20.53	3370.33

Range of binder content for UCS studies were selected based on MDD from compaction studies. But UCS values are increasing with cement content beyond the selected range. Further increase in cement is not favorable in economical and sustainable aspects. In all the bentonite-sand mixtures, cement treated samples give very high results. UCS values of GGBFS treated soils are found to be lower than cement stabilized soils. The available amount of CaO in GGBFS is not sufficient to make a higher pH environment to make silica and alumina present in the soil soluble. Also, the pozzolanic elements such as silica and alumina present in GGBFS along with those in clay lattice do not react completely with the comparatively lesser amount of CaO available in GGBFS, thus limiting the formation of cementitious compounds (Rogers and Glendinning, 2000; Al-Rawas, 2002). This seemed to be the reason for lower strength gain in soil treated with GGBFS compared to cement-treated soil. For Life cycle assessment of both the binders, the percentage of cement giving similar results of GGBFS treated samples were obtained from DoE results.

5 LIFE CYCLE ASSESSMENT (LCA)

5.1 Goal and scope definition

A comparative estimation of environmental impacts of the binders, GGBFS and cement, has been performed using LCA. It is worth mentioning that the LCA framework was chosen to assess the environmental impacts of the products according to ISO14040:2006. The scope of LCA in this study is limited to the production of the required GGBFS and cement for stabilization of 1 m^3 functional unit of soil mixes with similar UCS. The cradle-to-gate analysis was conducted since the LCA study includes the production system. System boundary for the LCA of cement included materials and energy required for cement production (i.e., quarrying limestone, transportation to cement production plant, crushing and cement production process), packing and the distribution to the consumer level. System boundary for the LCA of GGBFS production included materials and energy required for GGBFS production (i.e., quenching/granulation, dewatering and/or drying, crushing, grinding, treatment of wastewater generated in the granulation process step, packing and distribution of final product to the consumer level) as shown in Figure 4. The energy required for transporting the materials to the construction site, site preparation, mixing the binders with soil, and soil compaction was not considered, as the implications of such operations are same for both the materials.

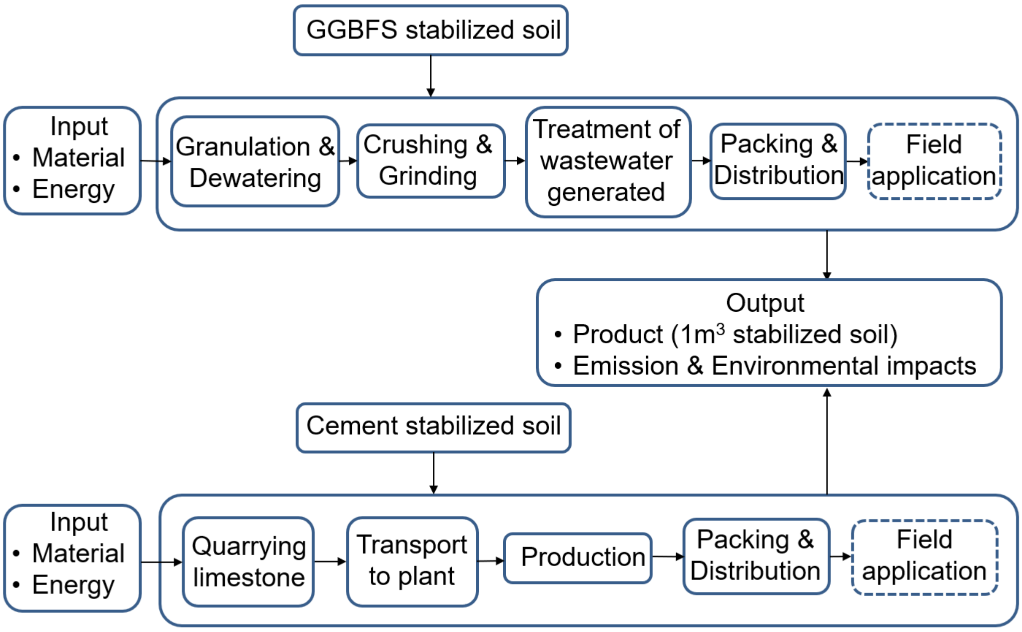

Figure 4. Cradle-to-gate system boundary for soil stabilization using GGBFS and Cement

5.2 Life Cycle Inventory (LCI) data

At this stage of the LCA, it is necessary to collect all inputs and outputs of the productive system (Ghadir et al, 2021; Rocha et al, 2021). Appropriate Life Cycle Inventory (LCI) data for GGBFS and cement for this study conducted in India were obtained from Ecoinvent v.3 database. Open LCA software was used for analyzing the environmental impacts based on both the binders. As the GGBFS treated soils showed increased UCS values at 28 days of curing, the corresponding cement content, water content and curing days were obtained from DoE results giving similar results of GGBFS treated soils (Table 5). The quantity of binder and water required for the stabilization of 1 m^3 of different bentonite-sand mixtures are shown in Table 6. The environmental impacts from the production of binders required for the stabilization of 1 m^3 soil were obtained from LCA analysis.

Table 5. *Cement content, water content and curing days giving similar results of GGBFS treated soils*

Soil	Binder content (%)	Water content (%)	Curing days	UCS of Cement treated soil (kN/m^2)
B90:S10	10	37.13	8.43 days	505.3
B70:S30	10	28.62	6.09 days	539.5
B50:S50	10	21.32	7.03 days	687.57
B30:S70	15	15.67	2.35 days	591.28

Table 6. *Quantity of binder and water required for the stabilization of 1 m^3 of different bentonite-sand mixtures*

Soil	For GGBFS treated soil		For Cement treated soil	
	Quantity of binder (kg)	**Quantity of water (kg)**	**Quantity of binder (kg)**	**Quantity of water (kg)**
B90:S10	271.96	529.47	120.20	446.35
B70:S30	296.01	457.12	134.60	385.26
B50:S50	294.52	401.11	151.40	322.82
B30:S70	422.50	351.78	252.30	263.61

5.3 Life cycle impact assessment and interpretation of the results

The life cycle impact assessment is a tool used for estimating the resource depletion and evaluating the potential environmental impacts in the modeled system. The life cycle impact assessment was conducted using the Open LCA software. Life cycle impact assessment of cement and GGBFS shows their environmental impacts in terms of 16 impact categories, obtained using the problem-oriented (mid-points) methodology (ReCiPe midpoint (H) method). Table 7 provides the ReCiPe midpoint (H) method results for cement and GGBFS production in different impact categories for the stabilization of 1 m^3 of B90:S10 mixture (considering the poor mixture). Subsequently, Fig. 5 shows the percentage contributions by different life cycle inventory of both products.

Table 7. *ReCiPe midpoint (H) method results for Cement and GGBFS for stabilization of 1 m³ of B90:S10 mixture with similar UCS*

Impact categories	Unit	Cement		GGBFS	
		Cement production (120.2kg)	**Percentage contribution**	**GGBFS production (271.96kg)**	**Percentage contribution**
Fine particulate matter formation	kg PM2.5 eq	0.0904978	78.54	0.0247212	21.46
Fossil resource scarcity	kg oil eq	12.533070	69.78	5.4288800	30.22
Freshwater ecotoxicity	kg 1,4-DCB	1.0479248	60.45	0.6856576	39.55
Freshwater eutrophication	kg P eq	0.0225986	90.07	0.0024905	9.93
Global warming	kg CO_2 eq	90.244931	83.96	17.244747	16.04
Human carcinogenic toxicity	kg 1,4-DCB	1.5348688	79.82	0.3879778	20.18
Human non-carcinogenic toxicity	kg 1,4-DCB	39.178740	68.82	17.751302	31.18
Ionizing radiation	kBq Co-60 eq	0.0887495	63.41	0.05121114	36.59
Land use	m^2a crop eq	3.2393522	77.13	0.96027879	22.87
Marine ecotoxicity	kg 1,4-DCB	1.4694276	58.98	1.02184211	41.07
Marine eutrophication	kg N eq	0.0015381	78.17	0.00042957	21.83
Ozone formation, Human health	kg NOx eq	0.2491583	74.66	0.08457925	25.34
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.2578133	74.46	0.08845125	25.54
Stratospheric ozone depletion	kg CFC11 eq	0.0000080	62.54	4.76508E-06	37.46
Terrestrial acidification	kg SO_2 eq	0.1877748	79.42	0.04866988	20.58
Water consumption	m^3	0.0636625	57.30	0.04744108	42.70

Comparing the contribution to different impact categories, GGBFS shows very low impact in all the categories compared to cement as shown in Table 7 and Figure 5. The cement production is making up to 90% of the total global warming, which is mainly due to the decomposition of $CaCO_3$ during the production of cement clinker, which releases up to 60% of the total CO_2. Furthermore, cement production is an energy-intensive process. As GGBFS is a byproduct from steel industry, the energy is utilized for the grinding and processing only and the contribution of GGBFS production process in different impact categories is found to be very less. However, UCS values obtained for stabilization using GGBFS can be improved by activating it with cement or lime in very small quantity, the life cycle assessment results of which need to be investigated further.

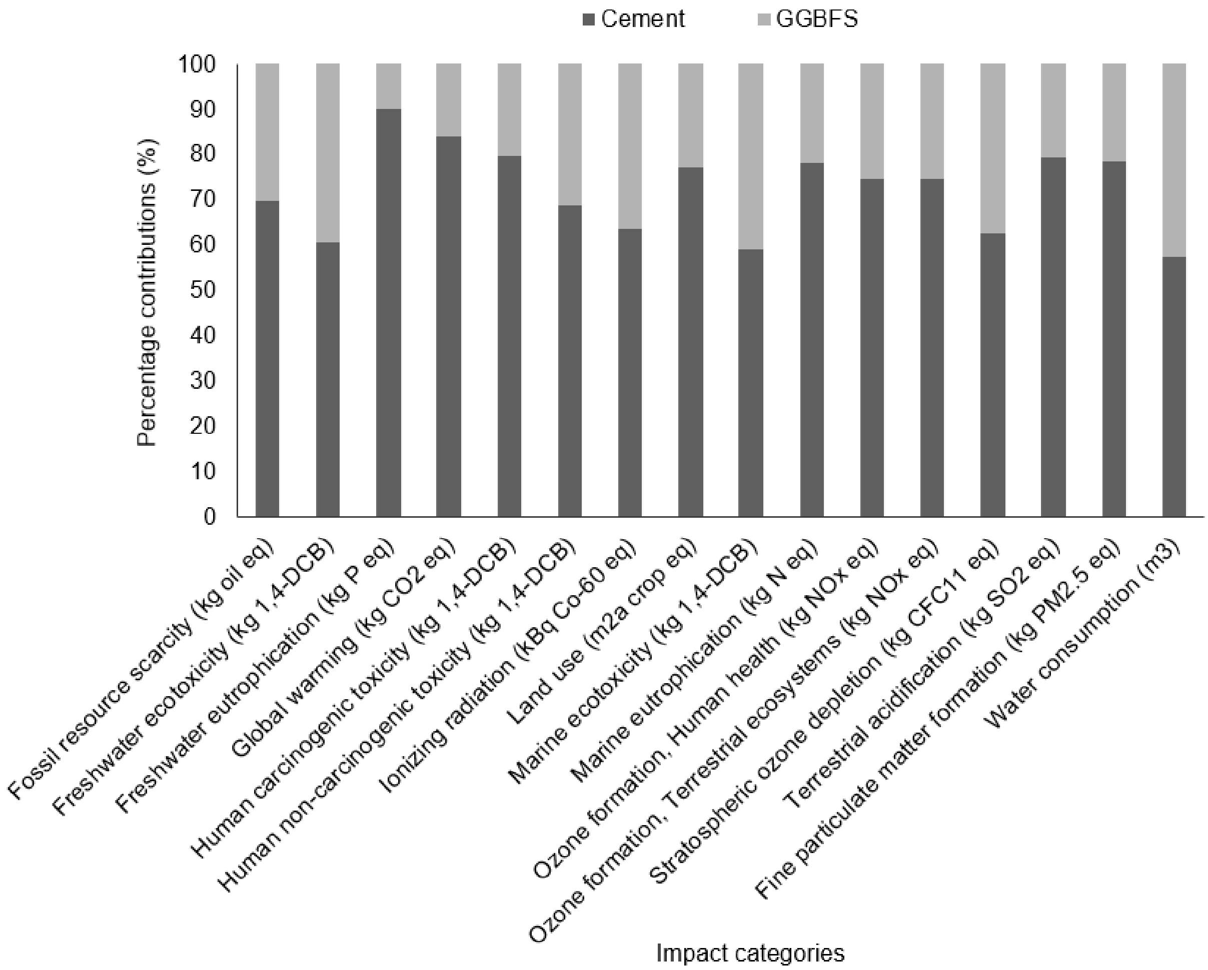

Fig. 5. *Percentage contributions of each impact category for Cement and GGBFS*

6 CONCLUSION

The study investigated the potential of using GGBFS as an alternative binder to the conventional cement for soil stabilization by assessing strength and sustainability. The effects of binder content, curing time and moisture content were examined for GGBFS and cement. The results showed that UCS of GGBFS treated specimens was improved at higher binder content, longer curing duration, and higher moisture content (mainly in bentonite-sand mixtures with more bentonite). The increase in UCS with cement and GGBFS can be attributed to the cation exchange, flocculation and agglomeration, and pozzolanic reactions in the soil binder mixture. UCS values of GGBFS treated soils are found to be lower than cement stabilized soils. However, the LCA results estimated very low climate change impacts for GGBFS compared to cement when used for stabilization of 1 m^3 soil with similar UCS. Thus, GGBFS is proved to be an environment friendly and sustainable binder for all the types of soil considered in the study. UCS values obtained for stabilization using GGBFS can be improved by activating it with cement or lime in very small quantity, the life cycle assessment results of which need to be investigated further. Furthermore, short term and long-term leachability of both the binders are to be studied in detail to avoid the post stabilization impact.

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