The Utilization of Industrial Waste as a Stabilizing Agent—A Review

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1 Introduction

With the ever-increasing population and urbanization, the choices of land to choose for construction become lesser and lesser. In most geotechnical projects, it is always not possible to acquire construction sites that will meet the design necessity without ground moderation. This proves to be a significant engineering problem. And hence, the idea of soil stabilization comes into play. Soil stabilization is a broad term used for any physical or chemical treatment of altering a natural soil to meet an engineering cause.

In India, Expansive soils, also known locally as Black Cotton soil (BCS) are spread over 5,18,000 km^2 of land [1]. Due to seasonal fluctuations in moisture content, BCS is exposed to significant shrinkage and swelling, which can cause significant structural damage. Chemical stabilization will be used on this soil, which is described as the process of combining and blending chemical additives to improve the soil's geotechnical properties. Generally, Calcium-based additives, such as lime and cement, are commonly used for stabilization to increase strength, reduce swelling, and even out the settlement. However, mounting concerns about carbon dioxide emissions and the resulting climate crisis necessitate the innovation of more sustainable soil stabilization techniques based on waste materials [2].

On the other hand, as the rate of industrialization increases, so does the rate of production of industrial waste, resulting in a slew of environmental challenges around its disposal [3]. In developing countries, the utilization of waste material in soil stabilization creates a sustainable platform for the management of waste [4–6]. The use of Granulated Blast Furnace Slag (GBS) as a stabilizing agent was found to have increased the strength and physical properties of soil [7]. Certain engineering

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properties like the CBR resulted in an increase in value with the addition of CS as an additive in the problematic soil [8]. Stabilizing with cement kiln dust (CKD) showed enhancement in soil mixture strength with values increased up to a certain factor [9]. The use of rice husk ash (RHA) with calcium carbide residue (CCR) as an additive shows great feasibility and effectiveness as a cementing material giving a good performance, better economy and disposal costs, and lesser distress to the environment [10]. Coal combustion fly ash (CFA) blended with an additive like cement can be used in varying quantities to acquire the best possible stabilizing mixture [11] (Fig. 1).

The stabilizing efficiency and sustainability of various industrial wastes with pozzolanic character (as shown in Fig. 2) will be explored in terms of varying engineering physical strength qualities in this article. In summary, the paper intends to give a full understanding of the feasibility and possible aspects of soil stabilization through the utilization of various industrial wastes that would otherwise be disposed of and would have taken up space in landfills.

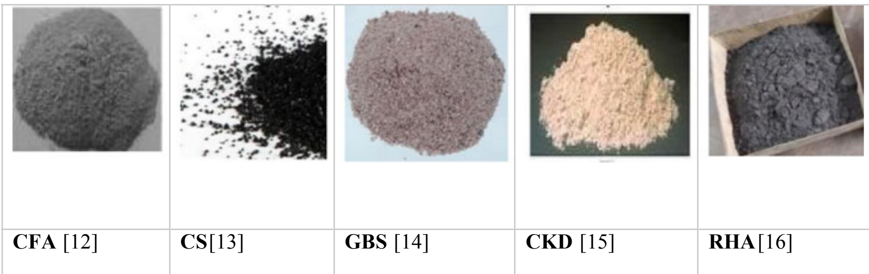

Fig. 1 Different types of industrial waste

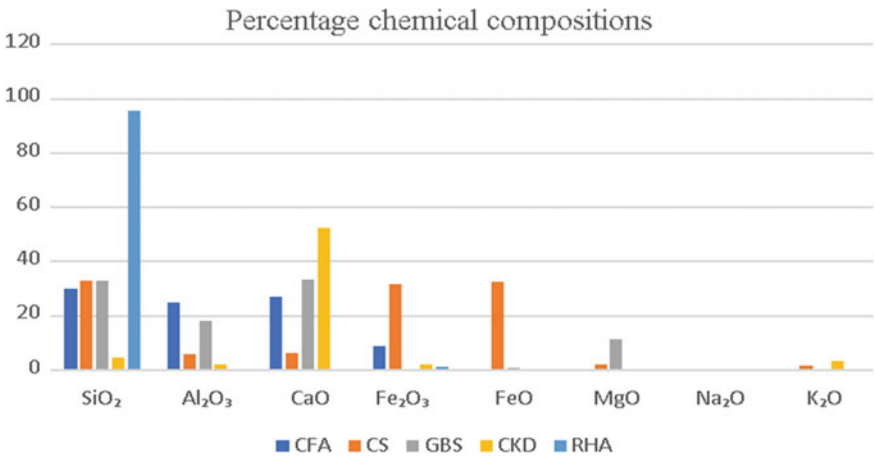

Fig. 2 Chemical composition of CFA [17], CS [18], GBS [19], CKD [20] and RHA [21]

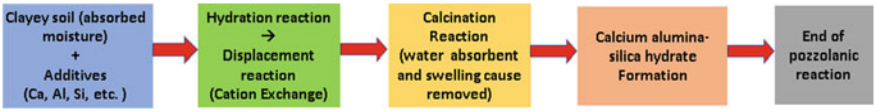

Fig. 3 The flow chart of pozzolanic reaction

2 Pozzolanic Reaction

The volume of clayey soils changes due to absorbed moisture, which forms a double diffused layer on the particles after contact with moisture. This leads to dispersion and flotation of the clayey particles forming voids and pores [2]. To close the gaps between the clayey soil particles, stabilizations of these soils are conducted using chemical additives. This can be attained by blending with a stabilizing agent containing Al, Ca, Si, etc. which causes a hydration reaction succeeded by a displacement reaction [22, 23]. Ca and Na-ions are then displaced during the calcination reaction. The entire process gives rise to a pozzolanic reaction, forming calcium alumina-silica hydrate as the final product, which is the main binding phase responsible for strength gain [24] (Fig. 3).

3 Effect of Industrial Waste on Geotechnical Properties of Soil

3.1 *Coal Combustion Fly Ash (CFA)*

Coal combustion fly ash is an industrial by-product obtained from the burning of coal for various purposes. In 2020, around 5% of electricity in India was generated by coal-fired thermal power plants [25]. The use of only CFA gives a negligible improvement in bearing capacity, owing to no pozzolanic reaction. In addition to secondary additives (such as cement, lime), there are visible improvements in the engineering properties [11]. The incorporation of CFA directly into soil reduces CBR because non-plastic fines replace plastic fines in the expansive soil, reducing cohesiveness [26]. As noted by Karami, lime was the best addition to enhance CBR, owing to its capability to activate CFA in the soil, promote pozzolanic reactions, and form cementitious materials [27] (Table 1).

3.2 *Copper Slag*

Copper slag is an industrial by-product formed during the pyrometallurgical processing of metals from copper concentrates. Approximately 2.2 tons of slag are

Table 1 The alteration in geotechnical properties of soil due to the addition of CBS

S. No.	% Added	Type	UCS (N/mm^2)	CBR (%)	MDD (gm/cm^3)	OMC (%)	PI (%)	Reference
1	15% CFA	Raw	–	3.20	1.73	19.2	–	[27]
	+Lime	Stabilized	–	2.9	1.8	18.8	–	
2	15% CFA	Raw	0.168	2.18	–	–	1.2	[11]
		Stabilized	0.177	2.26	–	–	1.4	
3	5% CFA+	Raw	0.500	–	2	22	30	[28]
	4% Lime	Stabilized	0.990	–	3	38	18	
4	10% CFA	Raw	0.31	25	1.79	17	–	[26]
		Stabilized	0.44	35	1.75	16	–	

Table 2 The alteration in geotechnical properties of soil due to the addition of CS

S. No.	% Added	Type	UCS (N/mm^2)	CBR (%)	MDD (gm/cm^3)	OMC (%)	PI (%)	Reference
1	3% CS	Raw		–	2.862	14	3.78	[29]
		Stabilized	–	–	2.280	12	5	
2	20% CS	Raw	–	7.50	1.597	12	–	[30]
		Stabilized	–	24.50	1.674	18	–	
3	20% CS	Raw	2.4	–	1.6	12	–	[13]
		Stabilized	3.4	–	2.1	7	–	
4	20% CS	Raw	–	–	1.570	18	–	[31]
		Stabilized	–	–	1.811	15.379	–	

generated per ton of copper produced. And around 37.8 million tons of CS are produced worldwide each year [18]. In their study, Shahiri and Ghasemi conclude that the use of CS decreases OMC and increases MDD, while the use of cement as a secondary additive reverses the effects. As CS absorbed water, the larger particles were able to penetrate the soil [13]. Gobinath reported an increase of up to 50% more in tensile strength on the use of CS as an additive. The noteworthy result is noticed in the CBR values of the soil, which is a result of the ceasing of the swell condition on the addition of CS [29]. The more addition of CS leads to higher MDD (up to 8.85% increase in MDD than the natural clay) resulting in a decrease in the plasticity [30] (Table 2).

3.3 Granulated Blast Furnace Slag (GBS)

GBS is a by-product of iron and steel production that is made by extinguishing molten iron slag from a blast furnace in water or steam, resulting in a glassy, granular product that is subsequently dried and grounded into a fine powder. In 2016, the production

Table 3 The alteration in geotechnical properties of soil due to the addition of GBS

S. No.	% Added	Type	UCS (N/mm^2)	CBR (%)	MDD (gm/cm^3)	OMC (%)	PI (%)	Reference
1	10% GBS+	Raw	<0.1	–	–	–	–	[33]
	1% cement	Stabilized	7.1	–	–	–	–	
2	20% GBS	Raw	1.02	3.12	1.75	8	11.26	[4]
		Stabilized	1.25	3.38	1.88	12	12.29	
3	12% GBS	Raw	1.18	8.14	1.72	11	17	[7]
		Stabilized	1.48	16.5	1.79	9.9	13.1	
4	12% GBS	Raw	1.34	–	1.6	22	18.4	[32]
		Stabilized	2.6	–	1.63	19.8	14	

of blast furnace slag in the world was 430 million tons. It's approximated to have produced 0.3–0.5 tons of slag per ton of pig iron. [19]. The addition to NaOH results in the formation of a cementitious compound, thereby increasing the UCS value as the proportion of GBS increases [7]. Pathak and Panday observed the PI and OMC values decrease while MDD increases with the addition of GBS. Even though there is improvement found in the soil on the addition of GBS, the values are not noteworthy. The study concludes GBS is a latent hydraulic material that requires an activator to disintegrate its glassy stage [32] (Table 3).

3.4 Cement Kiln Dust

The highly alkaline, solid, fine-grained industrial by-product extracted from cement kiln exhaust gas is referred to as CKD. The manufacturing of each ton of Portland Cement produces 54–200 kg of CKD. The global cement production was approximated to be 4.20 billion tons in 2019 [20]. As the need for cement as a construction material grows, vast production occurs, resulting in a large amount of CKD as a by-product. Thus, the use of CKD as a stabilizing agent becomes a sustainable cause. The inclusion of CKD, in various amounts, results in a considerable drop in PI. The highest PI decrease was observed with 10% CKD treated soil according to Rimal and Poudal [34]. The strength of the CKD stabilized soil increases gradually up to the 14th day but then increases dramatically by the 28th day. Amadi and Osu concluded that there is a delay in strength development during the initial stages of curing due to the initiation period required for the pozzolanic interaction between the chemical stabilizers and the soil particles to generate cementitious products [9] (Table 4).

Table 4 The alteration in geotechnical properties of soil due to the addition of CKD

S. No.	% Added	Type	UCS (N/mm^2)	CBR (%)	MDD (gm/cm^3)	OMC (%)	PI (%)	Reference
1	10% CKD	Raw	1.531	–	15.2	22.1	20	[34]
		Stabilized	10.156	–	16.9	24.2	–	
2	12.5% CKD	Raw	–	0.55	1.7	18	81.52	[35]
		Stabilized	–	16.5	1.73	20	51	
3	16% CKD	Raw	1.1	–	–	14.8	38.09	[9]
	+Quarry	Stabilized	6.2	–	–	13.4	19	
4	15% CKD	Raw	0.83	1.65	1.68	20	32.3	[36]
		Stabilized	2.6	8.03	1.72	19.3	15.2	

3.5 Rice Husk Ash (RHA)

RHA is an agricultural by-product obtained from the burning of rice husk. With agriculture providing a living for more than half of India's population, the country produces around 120 million tons of rice paddy each year, resulting in 24 million tons of rice husk per year [16]. Liu observed that the swelling properties can be hugely reduced by increasing RHA content with CCR as a secondary additive [10]. On increasing the proportion of the RHA, the OMC increases which is due to the elevation in mix proportion and lowering in the quantity of free silt [21]. There is as much as 3.1 times increase in strength of soil mixed with 15% RHA after curing for 28 days [10] (Table 5).

Table 5 The alteration in geotechnical properties of soil due the addition of RHA

S. No.	% Added	Type	UCS (N/mm^2)	CBR (%)	MDD (gm/cm^3)	OMC (%)	PI (%)	Reference
1	12%	Stabilized	1.1	–	1.925	13	–	[16]
	RHA	Raw	1.52	–	1.921	13.2	–	
2	10%	Stabilized	1.02	3.12	1.75	8	11.26	[4]
	RHA	Raw	1.07	3.29	1.67	8	31.56	
3	15%	Stabilized	0.9	–	1.47	–	–	[10]
	RHA + CCR	Raw	3.2	–	–	–	–	–
4	10%	Stabilized	1.5	6.5	1.64	17	12.2	[21]
	RHA	Raw	1.68	12	1.56	20	10	

4 Conclusion

An overview of various research papers on industrial waste used as stabilizing agents is presented in this paper. The majority of the industrial waste was found to improve certain soil geotechnical properties. However, the improvements found on the use of industrial waste as an additive were not enough to be recommended for use. For remarkable results, most of the papers recommended the use of secondary additives like lime, cement, enzymes, or quarry. The following are notable features of certain industrial waste and their effects on soil geotechnics or environmental impact.

- CFA alone does not significantly promote strength; however, combining it with lime and cement can lead to noticeable improvements. CFA has certain disadvantages, one of which is the fact that transportation is mostly limited to within 300 km of the Thermal Power Plant.
- In most of the studies, the use of CS as an additive increases MDD, resulting in a lower PI. And due to the ceasing of swell properties, it is found to have improved the CBR of the soil.
- GBS demonstrates improvement in UCS, CBR, and MDD of the soil, but it cannot be relied upon alone. As a result, it is recommended to use an activator when adding GBS as an additive, because GBS is a latent hydraulic material that requires activation to break the glassy phase.
- In tandem with the ever-increasing demand for cement, the manufacturing of CKD as a by-product has also increased. The presence of CKD as a stabilizing agent is shown to reduce the PI significantly. And most of the improvements in strength occur around the 28th curing day of being stabilized with CKD.
- India being an agriculture dominant society. RHA is one of the most vastly available by-products in every part of the country. The use of RHA alone does not result in significant increases in UCS value, but the inclusion of compounds such as CCR results in a significant rise in value.

A lack of systematic and independent research articles made it difficult for this paper to come to a valid conclusion. It was found that all industrial wastes improved the quality of soils up to a certain extent through better economic and environmental efficiency. This paper identifies a future need of the research on the protocols of obtaining the waste for public utilization, mass availability of materials, in situ engineering properties, durability, and sustainability issue of the industrial waste stabilized soil.

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