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Sachdeva, Nishant
Malaviya National Institute of Technology

Shrivastava, Neha
Malaviya National Institute of Technology

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Sustainable Use of Solid Waste as Additives in Soil Stabilization: A State-of-Art Review

Nishant Sachdeva[1,2], Neha Shrivastava[1,*]
[1]Malaviya National Institute of Technology, J. L. N. Marg, Jaipur-302017, Rajasthan, India
[2]Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur-302017, Rajasthan, India

Author to whom correspondence should be addressed:
*E-mail: neha.ce@mnit.ac.in

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Abstract: Expansive soils usually face problems related to excessive expansion and contraction, high water retaining capacity, poor drainage, high compressibility and poor load transfer mechanism. The rate of failures in these soils is relatively high and these soils are considered as most vulnerable for construction purposes. The amendment of using waste materials in soil stabilization serves the purpose of limiting the high volume of waste generated from different sources. This in turn also restricts the consumption of natural resources which are conventionally used to stabilize the soil. Out of several waste materials generated from various sectors: agricultural, industrial, construction and demolition and mining, twenty-one highly generated but underutilized waste materials have been designated for review in this study. Their utilization as additives in soil stabilization as a partial or full replacement of conventional/traditional additives has been appraised in the present study. Among the various agricultural waste products considered, palm oil fuel ash (POFA) has been found to be the most effective with the optimum dose of 10 % - 30 % in soil stabilization. Cement kiln dust (CKD) and iron ore tailings (IOT) with 50 % lime were found out to be effective with the optimum dosage of 20 % and 16 %, respectively. C&D waste was applicable in the range of 10 % - 24 % in the presented research work owing to the variable characteristics of the source. This paper would be helpful to industry persons in adopting alternative additives and researchers in knowing the areas which require further research.

Keywords: Expansive soils; Waste materials; Soil stabilization; Lime stabilization; Sustainability; Waste to resource

1. Introduction

The development that fulfills the requirements of the present without compromising the needs of future generations is known as sustainable development. The goals of economic and social development in developing and developed countries must be defined in terms of sustainability.1) In geotechnical applications, environmental and economical alternatives to natural materials can be obtained by using recyclable materials and industrial byproducts. Sustainability in the construction of various elements of transportation systems can be achieved by using large quantities of locally available recyclable materials.2) The extraction of natural materials for construction leads to pollution and waste, which simultaneously increases the construction cost.

Due to the high swell and shrink behavior of expansive soil, construction on this soil is always problematic for civil engineers.3) Expansive soils swell excessively when it comes in contact with water and shrink when the water squeezes out.4) As of these problems, volumetric change is observed in the soil, which applies pressure on the structure. This pressure leads to the development of cracks and differentiation settlement which causes deterioration of the structure.5) This swell/shrink behavior of expansive soils may cause damage to roads and also leads to shallow slope failures.6)

Soil stabilization is the method of improving the strength parameters and reducing the shrink and swell parameters of expansive soil. It results in the improvement of load-carrying behavior of subgrade soil. The first test of soil stabilization was performed in the United States in the year 1904. There are different methods of soil stabilization, i.e., lime stabilization, cement stabilization, chemical stabilization, bituminous stabilization, etc.7), 8) The majority of these traditional methods of stabilization require natural resources as fillers which may create a harmful impact on the environment.

Despite all these difficulties, the construction of infrastructure facilities can’t be constrained as it plays an essential role in the social and economic growth of a country. Therefore, a sustainable approach of using alternatives instead of natural resources is required. Utilization of locally generated waste materials is a remarkable expedition towards sustainable development. This review paper aims to accumulate the results obtained by utilizing various highly generated solid waste materials as an alternative stabilizing agent in soil stabilization.

2. Mechanism of soil stabilization

For decades, lime has been used conventional/ traditional additive to stabilize clayey soil.[9] Lime in the form of quick lime (CaO) or hydrated lime [$Ca(OH)_2$] is very efficient in improving the engineering parameters of soil.[10] There are several stages involved in the mechanism of lime stabilization; in the first and second stage, the exchangeable sodium, magnesium and other cations of clay are replaced by calcium cations present in lime.[11] The cementitious properties of clay particles in the presence of a stabilizer get increased during the process of flocculation. The mechanism behind this is the formation of bonds of tetra calcium alumina hydrates and the adsorption of calcium hydroxide on the edges of clay particles which increases its effective grain size.[12] Then the lime reacts with the carbon dioxide present in the atmosphere to form calcium carbonate, which is responsible for cementing action. This process is known as carbonation. In pozzolanic reactions, new minerals of cementitious properties are developed. The tabular representation of the mechanism of soil stabilization by lime is shown in Fig. 1.

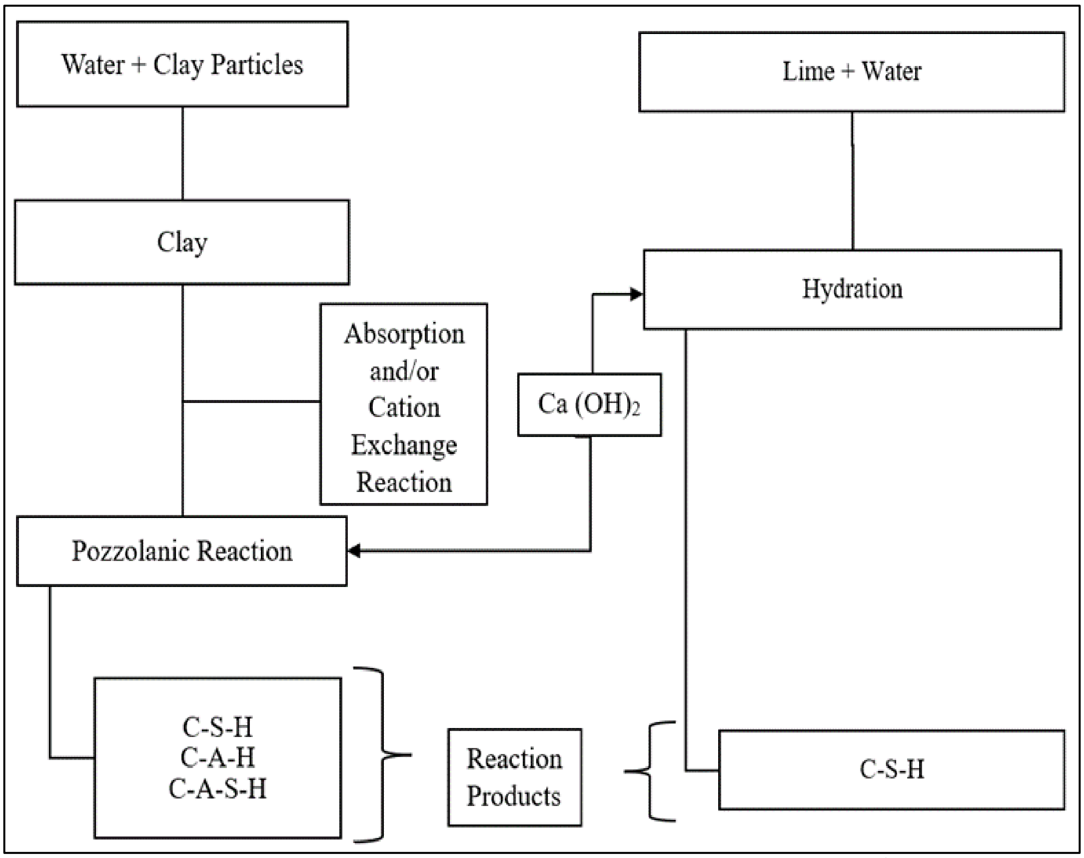


Fig. 1: Reaction of lime with clay particles during lime stabilization[13]

3. Standards/Specifications required for waste to be used as an additive in soil stabilization

There are several standards and specifications set by every country for resources to be utilized in construction. Alternative/recycled/waste material to be used for construction purposes must match the properties of conventional/traditional material. The final mix obtained by partial or full replacement of conventional/traditional additives by waste material must also fulfill the minimum strength, durability and other necessary parameters.

The practice of utilization of waste has been increasing around the globe. The basic requirement is that the material must not contain any toxic, hazardous and organic impurities. Table 1 shows the necessary parameters upon which the suitability of the material to be used in soil stabilization is evaluated.

Table 1. Property determination of stabilized soil

Name of Experiment/Property	**Code**
Sieve analysis/ Particle size distribution	ASTM D6913/D6913M – 17
Liquid limit and Plastic limit test/ Consistency limits	ASTM D4138 – 17e1
Specific gravity by Pycnometer	ASTM D854 – 14
California bearing ratio (CBR) Test/ Mechanical characteristics of soil	ASTM D1883 – 16
Unconfined compressive strength (UCS) test/ Strength parameters of soil	ASTM S2166/D2166M – 16

Great amount of energy and materials have been spent to meet the goals of urbanization and industrialization.[14] Rapid growth in industrialization, urbanization, increase in population and standards of living have given rise to in comprehensive increase in the volume and variety of solid wastes produced by agricultural, industrial, construction and mining activities. Ingorance is a fundamental cause of environmental degradation.[15] Around 960 million tonnes of solid waste is generated in India from agricultural, industrial, mining and municipal sectors. Out of this total solid waste generated, agricultural activities are responsible for more than 50 % (approx. 500 million tonnes) of the solid waste. The Industrial and mining sector generates approx 290 million tonnes of inorganic waste.[16],[17] Some commonly used methods by which waste disposal is done are incineration, landfilling and composting. Around 90% of waste disposal is done by open dumping.[18] Fig. 2 represents the quantity of industrial waste materials generated in India. Dumping of organic waste results in release of high mount of methane (CH_4) in the environment. Methane (CH4) emissions from landfills are increasing constantly due to increasing of population growth and increased waste generation.[19] This gas is having 28 % higher global warming potential than that of carbon dioxide.[20]

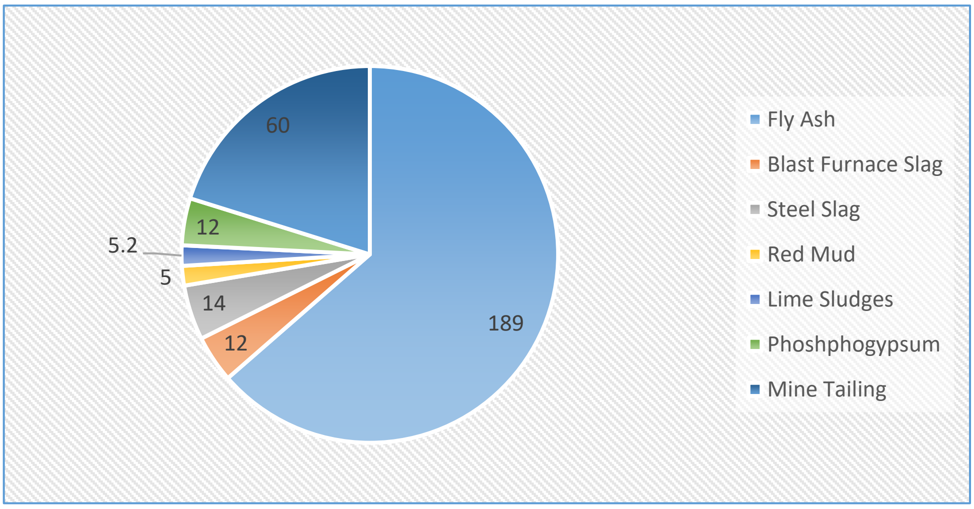


Fig. 2: Quantity of industrial waste generated in India (in metric tons) [21]

The United States is the biggest producer of solid waste in the world as it accounts for less than 5 % of the global population and generates nearly 12 % of global solid waste. It is the biggest generator of solid waste per capita. On average, American produce slightly more than 800 kilograms of solid waste every year.[22] Hence utilization of waste materials in soil stabilization will not only ensure their safe disposal but also move the construction industry toward sustainability.

The necessity of eliminating or at least reducing the high quantity of waste materials is a priority for the researchers. Their use in the construction industry is one of the best alternatives to keep the environment clean.[23] Table 2 shows the list of identified waste materials and their prominent use in the construction sector as presented by[16], [24]

Table 2. List of identified waste materials and their major use in the construction Sector 16), 24)

The domain of Solid Waste	Waste Generated	Reutilizing in Construction Sector as
Agricultural Waste	Rice, wheat straw and husk, sawmill waste, baggage, cotton stalk, vegetable scums, jute	Polymer composites, Cement and insulation boards, coir fiber, roof sheets, binder, fibrous panels, panels for walls, bricks, reinforced composites
Industrial Waste	Steel slag, red mud from bauxite, construction and demolition waste, coal combustion waste	Fine and coarse aggregates, tiles, cement, paint, concrete, wood substitute products, bricks, blocks
Mining Waste	Coal mine waste, mining waste generated from other industries	Bricks, tiles, fine and coarse lightweight aggregates

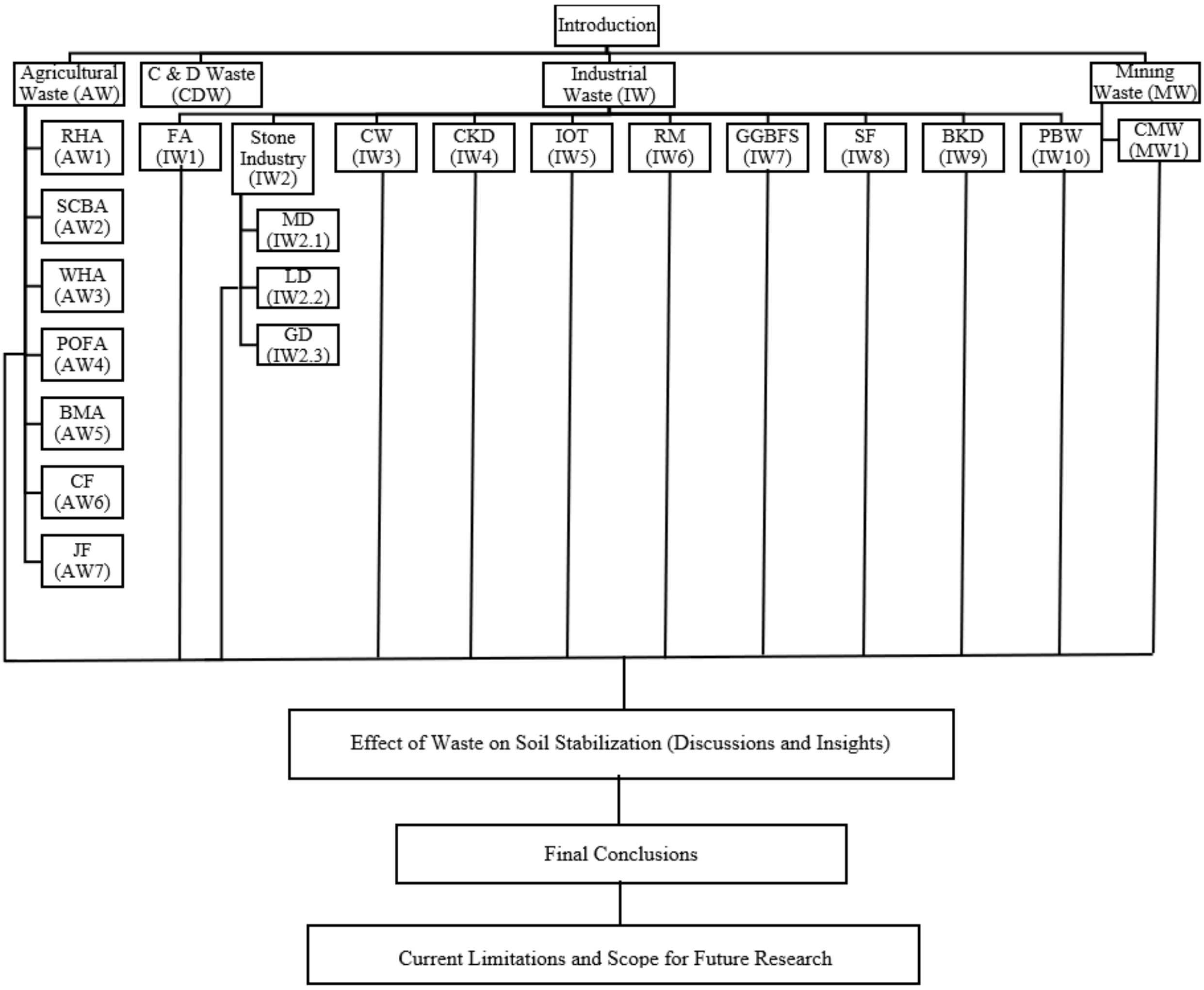
many researchers have been working on finding alternatives which can be used in place of conventional/ traditional fillers. Among the various waste products obtained from the agricultural, industrial and mining sectors, there are numerous materials such as rice husk ash, sugarcane bagasse ash, wheat husk ash, fly ash, cement kiln dust, stone industry waste, ceramic waste, coal mine waste and similar products have shown very promising results in improving the engineering parameters of soil by adding these in an optimum quantity.

4. Scope of the study

This study focuses on the performance of selected twenty-one waste materials obtained from significant sources. Fig. 3 shows a pictorial representation of the waste materials considered in this study. All waste materials studies are available in large quantities in their respective fields as specified in various research. Various characterization properties of waste materials that affect soil performance are also discussed. Emphasis is given to the effects on the engineering properties of soil after the addition of waste materials. In the end, the study concludes, bringing the important findings of the current topic, including its limitations. This also establishes the scope for future research. The flow chart presented in Fig. 4 shows the outline of the study in form of a flow chart.

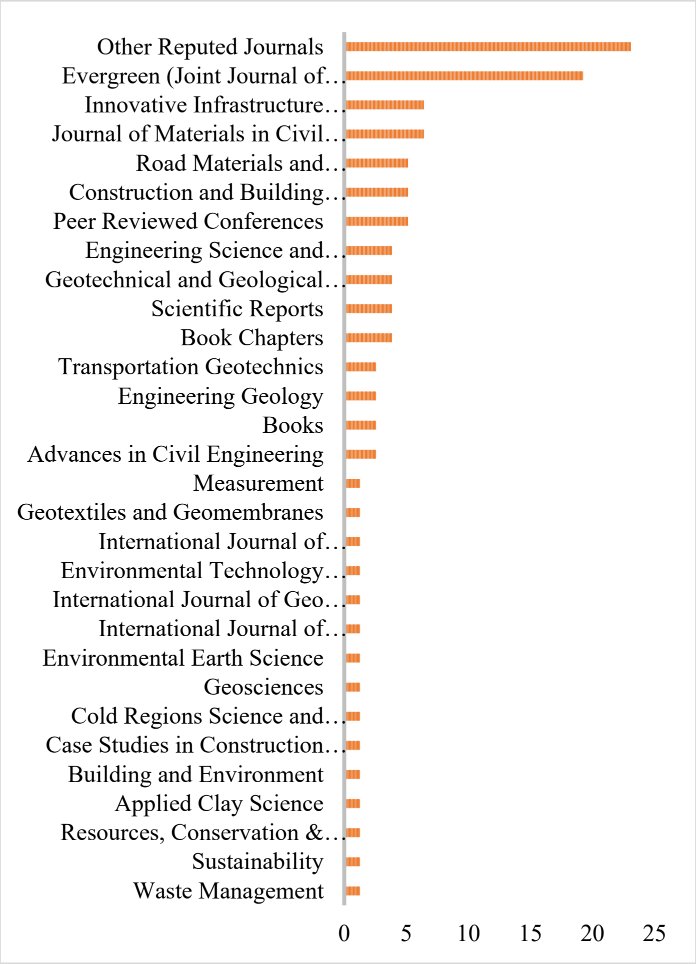
Fig. 3: Pictorial representation of waste materials identified for this study

An organized literature study has been carried out. Relevant literature is found using keyword-based search. Majorly used indexed data-base are Google Scholar (www.scholar.google.com) and Web of Science (www.webofknowledge.com). Although the primary focus has been given to studies taken after 2000, relevant older studies are also included in this analysis. Fig. 5 shows the chronological order of publication of the reviewed articles. Most of the research papers are published after 2000, indicating the increased trend in research on the current topic recently.

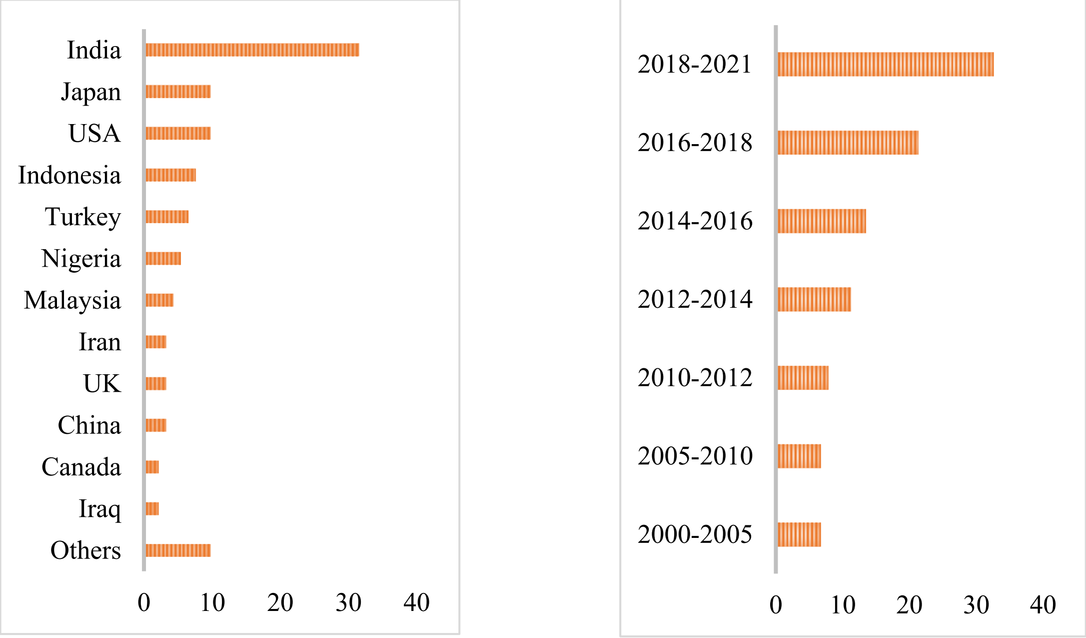


Abbreviations: RHA-Rice husk ash, SCBA-Sugarcane bagasse ash, WHA-Wheat husk ash, POFA-Palm oil fuel ash, BMA-Bio mass ash, CF-Coir fiber, JF-Jute fiber, FA-Fly ash, MD-Marble dust, LD-Limestone dust, GD-Granite dust, CW-Ceramic waste, CKD-Cement kiln dust, IOT-Iron ore tailings, RM-Red mud, GGBFS-Ground granulated blast furnace slag, SF-Silica fume, BKD-Brick kiln dust, PBW-Plastic bottle waste (HDPE/ PET), CMW-Coal mine waste

Fig. 4: Step by step illustration of this study



(a) Various sources of literature



(b) Origin of various literatures (c) Year of study of various literature

Fig. 5: Details of literature included in the study (in percentage)

5. Effect of different types of solid waste in soil stabilization

Strength and performance of any infrastructure not only depend on the strength on the structure, also on the strength/properties of the subgrade. A quality subgrade reduces the construction cost of the infrastructure. The conventional method of stabilization of soil containing fine particles or clay particles is by lime. Addition of 6 % lime can reduce the collapsibility index of expansive soil by 2.92 %.25) Cement stabilization is used in soil having relatively less fine/cohesive particles. The reason behind it is, in cohesive soil, majority particles are finer than anhydrous cement particle which makes it difficult to coat and distribute anhydrous stabilizer among cohesive soil.26)

Many research papers are available in which locally generated waste materials are used to improve the engineering parameters of soil.

From the earlier studies conducted in this field, it has been observed that waste materials having comprehensive amount of lime can be used as an alternative material in improving the engineering properties of soil. Their standards/specifications are not sufficient to be used as a single additive. So, waste materials are used in combination/replacement with the conventional additive i.e., lime or cement. Table 3 represents the mineral composition of identified waste/alternative materials which have been used in various studies to improve properties of soil.

Table 3. Mineral composition of waste/ alternative materials (in percentage) in comparison to lime

Category of waste	Material type	Calcium Oxide (Cao)	Silica (SiO_2)	Alumina (Al_2O_3)	Iron Oxide (Fe_2O_3)	Magnesia (MgO)	Potash (K_2O)	LOI	Refs
Conventional Additive	Lime	60.6-65.15	-	-	-	1-2	-	-	27)
Agricultural Waste (AW)	RHA (AW1)	0.41-2.4	91.3-93.15	0.21-1.4	0.21-0.6	0.45-2.1	1.9-22.31	0-2.35	28, 29)
	SCBA (AW2)	3.41	70.87	6.86	4.87	3.25	-	-	30)
	WHA (AW3)	5.46	43.22	-	0.84	0.99	11.30	-	31)
	POFA (AW4)	17.93	44.78	19.29	7.17	-	7.79	1.5	32)
	BMA (AW5)	5.91	74.12	0.57	0.88	1.54	1.71	7.45	33)
	CF (AW6)	-	-	-	-	-	-	-	
	JF (AW7)	-	-	-	-	-	-	-	
Industrial Waste (IW)	FA (IW1)	12.0	55.0	20.3	6.3	3.5	-	0.2	34)
	MD (IW2.1)	55.0-55.7	0.178–0.4	0.0708-0.4	0.0641-0.1	1.22-2.5	-	0-41.4	35, 36)
	LD (IW2.2)	38-42	15-18	1.02-1.53	1.02-1.53	13.74-15.32	0.35-0.62	32-34	37)
	GD (IW2.3)	1-3	73-76	18.78-21.12	18.78-21.12	5.12-7.15	0.04-0.09	<0.5	37)
	CW (IW3)	2.35	59.45	27.15	7.31	0.59	-	2.25	38)
	CKD (IW4)	41-67.72	9.64–17.62	1.90-4.90	1.50–4.06	0.64-1.93	0-2.18	4.94-31.30	39)
	IOT (IW5)	0.607	45.64	3.36	47.7	0.393	0.607	3	40)
	RM (IW6)	1.8	4.6	18	51	-	-	-	41)
	GGBFS (IW7)	41.5	34.8	11.3	0.6	7.2	0.3	-	42)
	SF (IW8)	0.43	99.39	0.08	0.02	-	0.08	-	43)

	BKD (IW9)	2.0	48.3	28.6	11.0	1.60	0.60	-	[44]
	PBW (IW10)	High density polyethylene (HDPE)/ Polyethylene terephthalate (PET)							
C & D Waste (CDW)	CDW	-	-	-	-	-	-	-	
Mining Waste (MW)	CMW (MW1)	1.30	34.40	14.40	3.40	0.93	3.50	38.7	[45]

6. Effect of agriculture based solid waste products on soil stabilization

Plenty of waste products are generated due to increase in activity of modern agricultural sector which leads to tremendous threat on environment. The main fiber waste available from agriculture is cellulose fiber which is having potential of providing reinforcement to materials due to its property of low weight, renewable, degradable, cheaper and low abrasive property. Bagasse is having high content of cellulose in it.[26], [46] Addition of reinforcement materials result in improvement of mechanical characteristics of composites.[47] Natural fiber also faces some limitations such as environmental durability and high temperature exposure.[48]

AW1 (Rice husk ash) AW2 (Sugarcane bagasse ash) and AW3 (Wheat husk ash): In a study conducted by Anwar Hossain K[28] to check the effect of rice husk ash (RHA) on properties of clayey soil. In this Study, RHA was used in combination of cement kiln dust (CKD). An increase of 282% in CBR value was observed on addition of 20 % RHA content. Convincing increase was also seen in 91-day UCS value of soil and decrease in shrinkage of soil was observed. Basha et al.[29] evaluated that RHA performs better when used in combination with cement. Addition of RHA resulted in reduced plasticity. An increase in optimum moisture content (OMC) and reduction in maximum dry density (MDD) was also observed. Cement in the range of 6 – 8 % and 15 – 20 % of RHA was recommended as optimum content to be used for stabilizing residual soils.

A sugar manufacturing unit produces 280 Kg of bagasse on processing 1 ton of sugarcane.[49] Yadav et al.[30] investigated the effect of RHA, sugarcane bagasse ash (SCBA) and cow dung on stabilization of alluvial soil. Each additive was used individually in proportions of 2.5 %, 5 %, 7.5 %, 10 % and 12.5 %. Optimum value of CBR and UCS for all the additives was obtained at 7.5 % replacement of soil. Singh et al.[31] used combined wheat husk ash (WHA) and SCBA in the proportion of 3 %, 5 %, 7 %, 9 % and 11 %. Optimum moisture content was achieved at 7 % additive content. Optimum content was observed at 7 % of additive content in which CBR and UCS showed very impressive results.

AW4 (Palm oil fuel ash): POFA is a byproduct of oil palm industry generated by combustion of empty fruit bunches, fiber and palm oil shells which are utilized as fuel for generation of electricity. Pourakbar et al.[32] stated that individual use of POFA can slightly improve the properties of clayey soil but if used with cement, it is very effective in increasing property of clayey soil. In this Study, SEM tests shows that use of POFA and POFA/ cement mixtures increases the property due to cementitious pozzolanic reactions between soil and binders.

AW5 (Biomass ash): Biomass energy is attaining high interest because of CO_2 neutral property. Use of biomass will increase in developing countries.[50] Songsuda et al.[33] investigated the effect of mixture of calcium carbide residue (CCR) and biomass ash (BA) on stabilization of clayey soil. It was stated that the strength parameters depend on CCR:BA ratio, water content of soil, binder content, and curing time. Highest strength of stabilized clay was achieved at CCR:BA ratio of 60:40. It was determined that 15 % of binder content was the optimum content of binder to be used in clayey soil. It was observed that silica from the BA and clay is steadily dissolved and reacted with the calcium carbide residue to form supplementary cementitious products which resulted in higher strength of soil mass. In a study conducted by Cabrera et al.[51], biomass bottom ash was used to stabilize clayey soil. It was observed that 50 % of BMA replacement can lead to highest CBR value in unsoaked, 4-days soaked and 90-days soaked condition. Highest deviator stress was also obtained at same replacement for 650, 750 and 850 kPa confining pressures. It was resulted that the strength parameters increased due to high calcium content in BMA which in turn increased the pozzolanic activity in the soil. Similar free swelling was observed at 50 % BMA replacement as obtained in 5 % lime replacement.

AW6 (Coir Fiber): Khatri et al.[52] checked the behaviour of chemically treated coir fiber with clayey soil. Three types of coir fiber- untreated, sodium hydroxide treated and potassium permanganate treated coir fiber were used in this study. The proportion of coir fiber was taken from 0.25 % to 1.5 %. The study was conducted to check UCS, direct shear and CBR test results. Highest value of axial strain was 356.04 kPa obtained at 1.5 % addition of $KMnO_4$ treated fibers. Both c and Φ values increased with addition of $KMnO_4$ treated fibers. Significant improvement was also seen in soaked and unsoaked CBR values on addition of NaOH and $KMnO_4$ treated fibers. In a study conducted by Jairaj et al.[53], lime was found unsuitable when used with treated and untreated coir fiber. In this study, it was found that the properties of modified black cotton soil improved in initial days of curing but deteriorate with further increase in curing period. From SEM test results, it was found that fiber characteristics were affected by heat of hydration of lime reaction.

AW7 (Jute fiber): The length of fiber also influences the strength characteristics of a composite.[54] Wang et al.[55] used jute fiber to check the strength characteristics of expansive soil. The length of jute fiber was taken as 6 mm, 12 mm and 18 mm and the content of jute fiber was taken as 0.3 %, 0.6 % and 0.9 % to the dry weight of soil. The strength characteristics were determined using direct shear test and consolidated undrained tri axial test. Fiber content, fiber length and fiber orientation were taken into consideration. Direct shear strength, cohesion and strength ratio were found to be increasing till 0.6 % replacement. 12 mm and 18 mm length fiber were found to be optimum for reinforcing expansive soil. Adverse effect of increase in orientation was observed as peak deviator stress decreases linearly with increase in orientation angle because they are located in the compressive strain domain and suffers from kinking which reduces the integrity of the soil. In a similar study conducted by Ramkrishnan et al.[56], effect of jute fiber on two different types of clayey soil was determined using UCS and CBR test results. Length of soil was taken as 0.5 cm, 1.0 cm and 1.5 cm while the percentage replacement was taken from 0.25 % - 1.25 %. In case of varying jute content, both the soils showed best results in the range of 0.75 % - 1.0 % replacement. It was observed that, irrespective of soil type, 1 cm long fiber showed best results. Similar results were obtained using mathematical calculations. Gullu and Khudir[57] did a study to check the effect of freeze and thaw cycles on UCS parameter of fine grained soil treated with jute fiber, steel fiber and lime. The proportion was used as a combination of 2 % - 10 % of lime and 0.25 % - 1 % (with a variation of 0.25 %) for both jute and steel fibers. Best results were obtained at 4 % lime + 0.75 % Jute fiber + 0.25 % steel fiber. A tremendous increase in UCS value from 220 kPa to 1300 kPa was observed in native soil. Similar results were obtained in 1, 2 and 3 freeze-thaw cycles. Improvement in UCS value by 534 %, 605 % and 689 % was observed in treated soil samples after one, two and three freeze-thaw cycles. It was also concluded that jute fiber showed better stress-strain responses than steel fiber and lime at all freeze-thaw cycles.

Based on the above research, many agricultural wastes can be used as an additive in the process of soil stabilization. Out of the research included in this study, remarkable results were obtained when agricultural waste materials were used with secondary additives like cement lime etc. Although RHA, CF and JF were found to be effective, POFA was the finest when used as a partial replacement of cement. Based on UCS value, optimum dosage of binder was found out to be 15 % (10 % - 30 % POFA and rest cement). There are studies available in which improvement in mechanical properties of natural fiber was observed when it was used in combination with nanocellulose binders.[58] So, there is a future scope in the field of nanocellulose composites.

Table 4. Outline of major studies carried in application of agriculture based solid waste in soil stabilization

Primary Additive	Secondary Additive	Evaluated Parameters	Outlines/ Conclusion	Refs.
RHA (AW1)	Cement Kiln Dust	Compaction parameters, UCS, CBR, Shrinkage	- Both can be used to stabilize soil, CKD-stabilized soils showed superior results compared RHA.	28)
RHA (AW1)	-	Plasticity index, CBR, UCS	- Soaked CBR increased by 134 % on addition of additive - UCS increased by 45.94 % as compared to unstabilized soil - 7.5 % was resulted as optimum content	30)
RHA (AW1)	Cement	Compaction parameters, UCS, CBR, Atterberg limits	- Maximum CBR value is achieved at 4 % cement and 5 % RHA - 6 – 8 % cement and 15 – 20 % RHA gives optimum results	29)
SCBA (AW2)	-	Plasticity index, CBR, UCS	- Soaked CBR increased by 79.81 % on addition of additive - UCS increased by 27 % as compared to unstabilized soil - 7.5 % was resulted as optimum content	30)
WHA (AW2) and Sugarcane Straw Ash	-	Compaction parameters, UCS, CBR, Atterberg limits	- Highest CBR of 29.33 % obtained at 7 % additive content - Highest UCS of 357.65 kN/m^2 was also obtained at 7 % additive content	31)

			- Optimum dose of WHA and RHA mix was 7 %	
POFA (AW4)	Cement	Compaction parameters, Consistency limits, UCS, Microscopic analysis	- 15 % binder (90 % cement + 10 % POFA) showed highest UCS value - Microscopic tests showed formation of CSH and CAH gels due to pozzolanic reaction.	32)
BMA (AW5)	Calcium Carbide Residue	UCS, Microscopic analysis	- CCR:BA ratio of 60:40 is the best proportion in achieving the highest strength - 15 % binder content was optimum - Silica from biomass ash, clay and calcium carbide residue reacts to form cementitious materials.	33)
BMA (AW5)	-	CBR, Tri-axial, Free swelling	- Unsoaked, 4-days soaked and 90-days soaked CBR was obtained highest at 50 % BMA replacement. - Highest deviator stress at 650, 750 and 850 kPa confining pressure was also obtained at same replacement. - Free swell index reduced by 99.5 %.	51)
CF (AW6) (Untreated, Sodium Hydroxide treated and Potassium Permanganate treated)	-	UCS, Direct shear test and CBR	- Highest value of axial strain was 356.04 kPa obtained at 1.5 % addition of $KMnO_4$ treated fibers - Both c and Φ values increased with addition of $KMnO_4$ treated fibers - Soaked and unsoaked CBR values also increased on addition of NaOH and $KMnO_4$ treated fibers	52)
CF (AW6)	Lime	UCS, XRF and SEM	- Deterioration in properties of treated and untreated soil on addition of lime. - Fiber characteristics were affected by heat of hydration of lime reaction.	53)
JF (AW7)	-	Direct shear test and Consolidated undrained Tri-axial test	- 0.6 % replacement was found optimum. - 12 mm – 18 mm fiber length was more effective - Deviator stress reduced linearly on increasing orientation angle.	55)
JF (AW7)	-	UCS and CBR	- 0.75 % - 1.0 % replacement showed best results - 1 cm length fibers were found best suitable.	56)
JF (AW7)	Steel Fiber, Lime	Freeze-thaw cycles on UCS	- UCS increased from 220kPa to 1300 kPa in native soil - 534 %, 605 % and 689 % improvement observed in treated soil samples after one, two and three freeze-thaw cycles - Best proportion was 4 % lime + 0.75 % Jute fiber + 0.25 % steel fiber	57)

7. Effect of industrial based solid waste products on soil stabilization

Solid waste generated from industries causes air, land and water pollution. Dumping of solid waste also requires large area of land. It is a major issue for developing countries like India. The pollution is due to high toxic substances/ pollutants present in the waste. Industrial solid wastes includes fly ash, stone industry waste, ceramic waste, cement kiln dust, ceramic waste, red mud etc.59)

IW1 (Fly ash): Coal powered plants are highly adopted plants in many countries to provide inexpensive energy for residential and commercial purposes.[60)] Coal accounts for 29% of total world's total energy use.[61)] Fly ash is a waste generated from coal powered thermal power plants. Sharma et al.[62)] investigated the effect of fly ash (FA) and lime on stabilization of clayey soil. Optimum dosage of FA was found out to be 20 % using unconfined compressive strength (UCS) test of soil. The parameters of soil were still not sufficient to be used as foundation soil. So, on further addition of 8.5 % lime, UCS value increased by 66 % and CBR value increased by 41 %. So, optimum content was taken as 20 % FA and 8.5 % lime. Presence of pozzolanic reaction was confirmed by XRD and SEM tests. A comparative study between activated low calcium FA and traditional binders (i. e., lime and cement) was conducted by Correa-Silva et. al.[63)] In this study, sodium hydroxide and sodium silicate were used as alkali activators. It was observed that on addition of all binders, CBR value increases. In comparison to CBR value, soaked CBR value of traditional binders reduced by 70 % but maximum reduction of 14 % was observed in case of FA. Although 28 days stiffness of cement modified soil was higher but 90 days stiffness of FA was higher than that of cement and lime.

IW2 (Stone industry): Mining industries causes environmental pollution by water, air, soil and water.[64)] Oncu and Bilsel[35)] studied the effect of sand and marble dust (MD) on swell, shrink and flexural strength parameters of soil. MD was used as partial replacement of sand in samples. Five different groups of soil specimen were made – first group consists of 100 % silt. Second group consists of 50 % sand and 50 % silt, whereas the third group was having 47.5% silt and 5% MD. Fourth and fifth group consists of 10 % and 20 % proportion MD with sand and silt in equal divided proportion. It was reported that 10 % MD enhanced properties of soil by reducing swell percentage by 3 % and improving flexure strength by 3N. It was concluded that in low volume roads, MD should be used as an additive. Firat et al.[36)] used MD, FA and waste sand to be used as road sub-base filling material. Alternative materials were added individually in proportions of 0 %, 5 %, 10 %, 15 % and 20 % by weight of soil. Results reported that these additives had huge potential to be used as filler materials. On the basis of test results conducted it was reported that use of waste materials substantially improves CBR, swell ratio and water conductivity. 15 % was determined as optimum dosage of alternative material that can replace soil. The effect of freeze and thaw cycles on utilization of MD in soil was presented by Gurbuz Ayhan.[65)] Proportion of MD used were 2.5 %, 5 %, 10 %, 15 %, 20 % and 25 % by dry weight of soil. It was observed that UCS value of freeze and thaw seduced specimen reduced to 2417.90 kN/m^2 as compared to 3219.55 kN/m^2 of non-freeze and thaw seduced specimen on addition of 10 % MD content. Higher strain rate at peak strength was observed in specimen exposed to freeze and thaw cycles. Approximately 5 % of mass loss was observed after conducting 12 freeze and thaw cycles.

Brooks et al.[34)] utilized FA and limestone dust (LD) in stabilization of locally available 2 soil specimens. Major properties studied were CBR, swelling and UCS. LD was added in proportions of 0 %, 3 %, 6 % and 9 % while FA was added in 0 %, 15 % and 25 % replacement of fine soil. Combinations of FA and LD were also used in blend of 15 % and 3 % by weight. CBR increased by 170 % for 15 % LD and 3 % FA. Highest UCS achieved was 1712 kPa for soil 1 and 1120 kPa for soil 2 at 15 % LD and 3 % FA content after 28 days curing. Improvement in mechanical, and durability parameters was reported in the study. It was resulted that stabilization with FA and LD is applicable to soil sub-base and base courses that are only subjected to light traffic loads. Okagbue and Yakubu[66)] replaces LD in place of lime in stabilization of laterite soil. LD was used in the proportion of 2 %, 4 %, 6 %, 8 % and 10 % by dry weight of soil. Results were drafted on the basis of Atterberg limits, compaction characteristic, CBR value and undrained triaxial test. It was reported that addition of LD resulted in improved workability, increased CBR value and shear strength of soil. Optimum dosage of LD was determined to be 6 %. It was concluded that double quantity of LD is required than lime to obtain similar results. It was also stated that limestone waste is a good substitute of lime in stabilization of laterite soil.

Zainuddin et al.[67)] used granite waste (GD) to improve the engineering properties of marine clay. GD was obtained from disposed tile material. GD was used in mixing proportions of 5 % - 20 % of dry unit weight of soil. Results were recorded based on Atterberg limits, compaction, UCS and pH characteristics. It was observed that addition of GD reduced the plasticity from 33 % to 29 % and increased the maximum dry density of soil. The strength of soil improved with curing period but was not able to surpass the optimum strength which was obtained before addition of GD. Microscopic analysis reported that GD fills voids present in the soil. Cementitious materials were formed on reaction of GD with marine clay but they were not sufficient to provide high strength to soil.

IW3 (Ceramic waste): In a study, Sabat[68)] used ceramic waste (CW) to stabilize expansive soil. Effect of CW was determined using Atterberg limits, compaction characteristics, UCS, CBR, shear strength parameters and swelling pressure parameters. Proportion of CW was used from 0 % to 30 % with a variation of 5 %. It was observed that on addition of CW, plasticity index, OMC, cohesion and swelling pressure decreased while UCS, CBR and angle if internal friction increased. 30 % was resulted as optimum dosage of CW in expansive soil. It was also analyzed that substantial cost of construction of flexible pavement can be reduced by adding CW in subgrade. It was calculated that 15.3 % - 23.8 % of cost of flexible pavement can be reduced by using CW as stabilizer in clayey soil. Sharma[38)] investigated the effect of FA and CW to improve the properties of clayey soil. The study was conducted in 3 stages – optimum content of sand was determined in stage 1, optimum dosage of FA in stage 1 was determined in stage 2 and at the end optimum content of CW was determined in the mix obtained in stage 2. Two trial mixes 60:40, 70:30 (soil: sand) were determined by compaction tests. FA was added in both the mixes in a variation from 5 % to 20 %. Optimum dosage of FA came out to be 10 % from compaction test. In stage 3, CW was added in proportion of 2 % - 8 %. Conclusions were drafted based on soaked CBR and permeability characteristics. The best suitable mix was obtained as 70:30:10:2 (clay: sand: FA: CW).

IW4 (Cement kiln dust): Mosa et al.[69] determined the effect of cement kiln dust (CKD) on poor subgrade soils. CKD was used in varying proportions of 0 % to 30 %. Soaked CBR, swell value tests were conducted on soil specimen. It was observed that the CBR value of soil increased with increase in CKD content and curing period. After 14 days of curing, very slight change in CBR value was observed. There was a significant rise in CBR value upto 20 %. Least swell value was also obtained at 20 % CKD content. Sreekrishnavilasam et al.[70] did a comparative study of fresh and landfilled CKD on soil. The tests were conducted on 2 types of soils. CKD was used in the range of 8 % - 20 %. It was reported that addition of CKD leads to reduction in swelling and increase in UCS value of soils. Amadi[39] studied the effect of CKD on black cotton soil modified with quarry fines. The research was conducted using fixed dosage on 10 % for quarry fines and varying dosage of 0 %, 4 %, 8 %, 12 % and 16 % by dry weight of soil for CKD. Results stated that 8 % - 16 % replacement by CKD showed improved CBR and swell requirements. The loss of strength after saturation also reduced drastically in this range of CKD. Other properties were determined by same author in another paper Amadi et al.[71], UCS and stiffness modulus of soil were also significantly improved by addition of same composition of quarry fines and CKD. Miller and Azad[72] checked the effect of CKD on different types of soil. Soils taken in this research were CH, CL and ML. The results were drafted on the basis of UCS value of soils. It was observed that UCS value significantly increased on addition of CKD and curing time. Effect on UCS value was higher in soils having low plasticity index i. e., ML was high as compared to CH and CL. Optimum results were obtained at 15 % CKD content and 14 days of curing time.

IW5 (Iron ore tailings): Iron ore tailings (IOT) is generated during the extraction process of iron ores. Etim et al.[40] conducted a study using lime and IOT for stabilization of black cotton soil. IOT was used in proportion of 2 % - 10 % with a variation of 2 % and lime was added in proportion of 2 % - 8 % with same variation. Results were drafted based on index properties, compaction characteristics, strength and durability properties of the treated soil. On increasing replacement ratios, increase in MDD and decrease in OMC was observed through compaction test results. The reason behind this is formation of flocculated particles and increase in specific gravity after accumulation of IOT. Optimum results were obtained at 16 % replacement (with 50 % lime). Highest CBR value of 50 % and 40 % in unsoaked and soaked condition was obtained at optimum dosage. Higher UCS value of cured samples was observed in comparison to control samples. SEM and fiber matrices results showed formation of crystalline hydration product in the treated soil.

IW6 (Red mud): Around 35 % - 27 % per ton of red mud (RM) waste is generated during treatment of bauxite using Bayer process. Kalkan[73] utilized RM in stabilization of clay liners. In this Study, RM was used individually and in combination with cement. Effect of RM on UCS, swelling pressure and hydraulic conductivity were examined in this study. It was observed that UCS value increased upto 20 % RM content then decreased. Significant improvement in UCS value was seen with RM and CRM after 7 days of curing. Very remarkable results were obtained in swelling pressure of soil as on addition of CRM, it reduced from 23.6 % to 1.8 %. It was concluded that addition of RM and CRM resulted in improved UCS, decreased hydraulic conductivity and swelling pressure of soil.

IW7 (Ground granulated blast furnace slag): McCarthy et al.[42] investigated the effect of quick lime, two varieties of FA and ground granulated blast furnace slag (GGBFS) to enhance the properties of soil which is having sulphate content in it. In this study, two soil samples having sulphate content higher than 10 % were obtained from two different locations. Results were drafted using bearing index, UCS, indirect tensile strength (ITS), and permeability tests. Proportion of lime was fixed as 3 %, dosage of fly ash was taken as 0 % to 24 % at an interval of 6 %, and 3 %, 6 % and 9 % for GGBFS. Improvement in compaction parameters, bearing index and UCS values of both soil samples was observed on addition of FA and GGBFS. On addition of lime, water permeability increased, which increased further on addition of coarse FA. Properties of samples stabilized from fly ash and GGBFS were similar to that of samples stabilized from lime. It was concluded that addition of FA resulted in improved durability of lime stabilized sulphates soil. Similar results were observed in study conducted by Maneli et. al.[74] He used combination of lime, GGBFS and FA to stabilize clayey soil. The proportion of all the additives were taken as 12 % FA, 8 % GGBFS and 6 % lime. Results were noticed at different levels of compactive efforts and curing time. It was also stated that UCS and CBR values increases with increase in amount of compaction, curing time. Eyo et al.[75] utilized GGBFS and a nanomaterial RoadCem (RC) as a partial replacement of traditional/ conventional additive cement. The objective of the study is to reduce problem of heaving in sulphate bearing soils. The research was carried out using free swelling test, unconfined compression test and microstructural analysis of modified soil. Cement content used was 8 %. It was observed that on replacement of 50 % cement by GGBFS resulted in reduction of swelling by 53 %. More promising results were obtained when 1 % RC was added to GGBFS and cement. It was seen that more reduction in swelling by 29 % was observed on addition of RC to GGBFS and cement.

IW8 (Silica fume): Silica fume (SF) is an industrial waste generated by production of metallic silicon or ferrosilicon alloys. It is having high pozzolanic properties, so it is used in construction activities. Tiwari and Satyam [76] checked the effect of polypropylene fiber and SF on the swelling behavior of expansive soil. The research was conducted in 3 stages. Stage 1 consists of untreated soil with 0.25 %, 0.5 % and 1.0 % fiber, stage 2 consists of effect of 2 %, 4 % and 8 % of SF on soil and in stage 3, both SF and fiber were added simultaneously. The experimental results illustrate that both polypropylene fiber and SF has been able to substantially reduce swelling pressure in soil. It was also resulted that influence of SF was more than polypropylene fiber. In a similar study by same authors, Tiwari and Satyam[43] checked the performance of lime and silica treated coir geotextile on expansive soil. Coir fiber geotextile was binded with polypropylene fiber mat was dipped in a 400 gm silica fume and 100 gm lime blended with 1000 ml water suspension. Observations were taken by applying single (at 1/3 height from top) and double fiber (1/3 height from top and ½ height from bottom). Results were drafted by conducting swelling pressure, CBR and shear strength of soil. It was observed that swelling pressure reduced by 52.19 % for single layer and 81.89 % for double layer in lime coir fiber. Silica coir fiber doesn't have much effect of swelling properties. CBR value of lime treated coir fiber also showed impressive results by increasing CBR value by 399 % and 435 % for single and double layer. CBR value of silica fume treated fiber showed similar results to that of non-treated fiber. Substantial increase in angle of internal friction was also observed.

IW9 (Brick kiln dust): Construction and demolition wastes includes the debris generated during the construction, demolition and renovation processes of buildings, roads or any other infrastructure. It consists of many wastes such as bricks, concrete, plastic, timber, glass etc. In this review, main focus is put upon brick dust and concrete waste. Brick dust is also generated through brick klins which may also be used as a soil stabilizer[44],[77]. India is having around 100,000 brick kilns which manufactures approximately 150 billion bricks annually. Therefore, it is one of the biggest sources of brick kiln dust (BKD) [78]. Baidhani and Taie [79] conducted a study to check the effect of BKD on high plastic clays. The BKD content was used as 10 % - 30 % by dry unit weight of soil. Effect of BKD was determined based on shrinkage and shear strength parameters. It was observed that shrinkage behaviour of high plastic soils may be reduced by addition of BKD. Hugh impact of brick dust was seen in undrained shear strength of soil. It was resulted that the shear strength of soil increases with increase in duration of curing period. Best improvement was achieved at 20% BKD content and 7 days curing which increases the shear strength of soil by over 100 %. Gupta et al.[77] studied the effect of BKD on six different varieties of soils. Soil samples varying from the intermediate plastic clay to sand (with good amount of silt) were taken in this study. The dosage of BKD was taken from 10 % to 40 % with a variation of 10 %. The compaction and CBR parameters were studied in this research. As the BKD content increases, MDD decreased. It might be due to the substitution of soil particles with lighter BKD particles. The results stated that the CBR value of soil was remarkably enhanced with the addition of BKD. 30 % was observed as the optimum dosage of BKD in all type of soils.

In a similar study conducted by Hidalgo et al.[44] to check the effect of alkali activated brick dust on two different types of soils (S1 and S3) by conducting UCS test on 7 days and 28 days cured soil samples. The quantity of brick dust was used as 7 %, 14 % and 21 % of dry weight of soil. The experimental work was done using alkali activator (RC and NaOH separately). Three factors were taken into consideration i. e., curing temperature of 20 °C – 30 °C and 40 °C – 50 °C, curing humidity of 59 % in environment and 95 % in moist room and curing age of 7 and 28 days respectively. It was resulted that on addition of alkali activated brick dust, soil strength increased by 1.7 – 2.3 times to that of non-stabilized soil. It was also reported that addition of alkali activated brick dust was efficient when the content was kept less than 14 %.

Reddy et al.[80] used lime and BKD to stabilize black cotton soil. The effect was studied by means of CBR test results as the final material was to be used as a sub base material. On the basis of preliminary tests, it was obtained that 4 % lime content is optimum dosage for soil but CBR value obtained at this content wasn't enough to satisfy the MoRTH specifications for sub base material. BKD was mixed in proportion of 20 % to 80 % as a replacement of lime stabilized soil. Highest results were obtained at BKD content of 20 %. In comparison to 4 % lime stabilized soil, an increase in the maximum dry density by 33.8 % and soaked CBR value by about 135% were observed at optimum BKD content.

IW10 (Plastic bottle waste HDPE/ PET): Bozyigit et al.[81] investigated the effect of waste PET bottle strips on stabilization of cement stabilized clayey soil. PET bottle were used in strips and added in proportions of 0 % - 2.0 % with 0 % - 9 % of cement. It was observed that on increasing cement content, strength increases and on increasing PBW strip content, ductility increases. Optimum content of PBW was observed between 1 % - 1.5 %. Botero et al.[82] checked the stress-strain behaviour of silty soil reinforced with PBW (PET). Stress-strain behaviour was observed by unconsolidated undrained tri-axial test. PBW was used in fiber form in proportion of

0 %, 0.1 %, 0.3 %, 0.6 % and 1.0 % by dry weight of the soil. Ductile behaviour was observed in PBW reinforced specimens which shows improvement in resistance to soil cracking. Addition of PBW fiber content decreases friction angle and increases cohesion.

Fauzi et al.[83] used HDPE plastic bottles and glass in stabilization of clayey soil. Both the materials were used individually in proportions of 0 %, 4%, 8 % and 12 %. PBW was used in shredded form. Best dosage of both the waste materials was found to be 8 % as at this content, OMC decreases, dry density and soaked CBR value increases. Dhar and Hussain[84] used PBW along with line to stabilize clayey soil. Results were drafted on the basis of UCS, split tensile strength and CBR tests after curing periods of 7, 14 and 28 days. Proportions of lime were taken as 3 %, 5 % and 9 % while PBW was taken as 0.5 % - 2 % by dry unit weight of soil. The UCS increased by 1.63 times and split tensile strength increased by 3.63 times of lime stabilized fiber reinforced soil as compared to virgin soil, these optimum results were obtained at 5 % lime and 1.5 % PBW content after 7 days of curing.

Summarizing all the selected literature related to utilization of industrial waste in soil stabilization, it is found that CKD, LD and IOT were most superior in improving the engineering properties of soil. Very notable and almost similar results were obtained in case of UCS and CBR values of soil when treated with CKD and IOT. Optimum dosage of CKD was found out to be 20 %. IOT was used in combination with conventional additive i.e., lime. Optimum dosage of IOT was 16 % (with 50 % lime).

Table 5. Outline of major studies carried in application of industrial based solid waste in soil stabilization

Primary Additive	Secondary Additive	Evaluated Parameters	Outcomes/ Conclusion	Refs.
FA (IW1)	Lime	UCS, CBR, XRD, SEM	- Optimum dosage was determined as 20 % fly ash and 8.5 % lime.	62)
Alkali activated low calcium FA (IW1)	-	UCS, soaked and unsoaked CBR, pulse velocity, tri axial	- CBR increased on addition of all binders. - Reduction in soaked CBR value under soaked condition was very less in FA as compared to traditional binders. - 28 days stiffness was higher in cement, but 90 days stiffness was higher in FA.	63)
MD (IW2.1)	-	Swell, Flexural strength	- Optimum dosage was 10 %.	35)
MD (IW2.1) (Fly ash and waste sand was also used)	-	Permeability, CBR, Swell	- FA, MD and Waste Sand can be used for the stabilization. - These materials can be used as road subbase filling materials.	36)
MD (IW2.1)	-	UCS, Mass loss, Strain absorption	- Difference in peak strength of around 22 % was observed in non-freeze and thaw specimen and freeze and thaw exposed specimen. - Mass loss of around 5 % was observed. - Higher strain rate was observed in freeze and thaw exposed specimen. - 10 % of MD can be used.	65)
LD (IW2.2)	Fly ash	Compaction, CBR, Swell and UCS	- Blend of 15 % limestone dust and 3 % fly ash gave optimum result.	34)
LD (IW2.2)	-	Atterberg limits, Compaction, CBR, Shear strength	- Decrease in plasticity index, increase in CBR and shear strength with the addition of up to 6% LD - Results of LD and lime are similar - Twice dosage of limestone is required than lime to obtain similar results	66)
GD (IW2.3)	-	Atterberg limits, UCS, pH	- Reduction in water holding capacity resulted in reduction in plasticity of clay. - Highest UCS was obtained before addition of GD. - GD is unsuitable to test strength of clay - pH increased from 2.88 to 3.40 when proportion of granite dust was 20 %	67)

CW (IW3)	-	Atterberg limits, Compaction, UCS, CBR	- CBR value increased by 150 % on addition of 30 % CW. - UCS kept on increasing on addition of ceramic waste. - Swelling decreased by 81.5 % on addition of 30 % CW.	68)
CW (IW3)	Fly ash	CBR, Permeability	- Highest CBR of 14.44 % was obtained at 70 : 30 : 10 : 2 (clay : sand : fly ash : ceramic waste) - Permeability of 2.16 x 10^{-4} cm/s and had better drainage characteristics	38)
CKD (IW4)	-	CBR, Swell ratio	- CBR value improves from 3.4% to 48% after curing for 14 days at 20 % CKD content - Swell ratio minimum at 20 % CKD content	69)
CKD (IW4) (2 varieties of fresh and 1 variety of landfilled CKD)	-	Atterberg limits, Compaction, UCS, Swelling	- Performance of CKD is dependent on presence of free lime. - UCS value varies from soil to soil - CKD can be used upto 20 %	70)
CKD (IW4)	Quarry fines	CBR, Swell, UCS	- Poor CBR and swell results were obtained at 0 % and 4 % replacement while good results were obtained at 8 % - 16 % replacement. - Loss of strength on saturation reduced on 8 % - 16 % CKD replacement.	39)
CKD (IW4)	-	Atterberg limits, UCS, pH	- Optimum dosage of CKD was found as 15 %. - Rapid increase in UCS upto 14 days, thereafter speed reduces.	72)
IOT (IW5)	lime	Compaction, CBR, UCS	- Peak CBR value of 50 % and UCS value of 1074.54 kN/m^2 obtained at 8 % IOT and 8 % lime content	40)
RM (IW6)	-	Atterberg limits, Compaction, UCS, Permeability, Swelling	- RM and CRM results in high compressive strength of soil. - Decrease in hydraulic conductivity and swelling pressure was observed on addition of RM and CRM. - Optimum content of RM was 20 % and cement can be added in small dosage of 1 %, 2.5 % and 5 % for better results	73)
GGBFS (IW7) (Two varieties of low lime FA and GGBFS)	Lime	Strength, Durability and Water permeability	- Better results were obtained with fine FA than coarse FA. - Improvement in engineering and durability parameters were observed on addition of GGBFS.	42)
GGBFS (IW7) and cement	RC	Swelling and UCS	- Replacement of 50 % cement by mixture of GGBFS and RC resulted in reduction of swelling by 67 %.	75)
Lime, GGBFS (IW7) and FA	-	UCS and CBR	- On increasing compactive effort, UCS and CBR value increases. - Highest UCS was observed after 7 days of curing and CBR increases on increase in curing time.	74)

SF (IW8)	Polypropylene fiber	Swelling	- Lowest expansion was observed at 2 % SF content - Optimum percentage of PP fiber can be taken as 0.50 %.	76)
SF (IW8) (Lime and Silica Fume treated coir geotextile)	-	Swell, CBR, Shear strength	- Swelling pressure reduced by 52.19 % in case of single layer and 81.89 % in case of double layer of lime CF. - Silica CF doesn't have much effect of swelling properties. - CBR value of lime treated CF increased by 399 % and 435 % for single and double layer. CBR value of SF treated fiber showed similar results to that of non-treated fiber.	43)
BKD (IW9)	-	Linear shrinkage, Undrained shear strength	- 10 % replacement has no effect on shrinkage, 20 % and 30 % showed decrease in shrinkage. - Highest shear strength was obtained at 20 % BKD content. - Shear strength increased on increase in curing period. - Optimum content of BKD was taken as 20 % and 7 days of curing.	79)
BKD (IW9)	-	Compaction and CBR	- MDD decreased on addition as soil particles were replaced by lighter particles. - CBR value was found maximum at 30 % of brick kiln dust in all types of soil.	77)
BKD (IW9)	Alkali Activator (RC and NaOH)	Compaction, UCS and XRD	- Increase the soil strength by 1.7 – 2.3 times on comparison with non-stabilized material. - Average increases of 235% for S1 and 176% for S3 in compressive strength of soil.	44)
BKD (IW9)	Lime	Free swell index, Compaction and CBR	- Initially optimum dosage of lime was found to be 4 %. - On addition of 20 % BKD to lime modified soil, CBR increased by 135 % as compared to 4 % lime.	80)
PBW (PET) (IW10)	Cement	UCS, brittleness, SEM analysis	- Strength increases on increasing cement content. - Ductility increases on increasing PBW strips content. - Optimum dosage of PBW was 1.0 % - 1.5 %.	81)
PBW (PET) (IW10)	-	Tri-axial test	- Ductile behaviour increases on increasing PBW fiber content. It shows resistance to cracking.	82)
PBW (HDPE) (IW10)	-	Compaction and soaked CBR	- OMC decreases, dry density and soaked CBR value increases on addition of PBW.	83)
PBW (IW10)	Lime	UCS, CBR	- Optimum dosage of lime was determined as 5 %. - 1.5 % plastic waste content was determined as optimum dosage with 5 % lime.	84)

			- Test results increased highly up to 7 days of curing. After this, it increases marginally.	

8. Effect of construction and demolition solid waste products on soil stabilization

CDW (Construction and demolition waste): Construction and demolition (C&D) waste included concrete, plastics, steel, bricks and variety of other building materials. There is high necessity for recycling these waste as it is emerging as a global concern leading to various problems such as: scarcity of natural resources, environmental degradation and disposal cost of landfills.[85] Around 2.2 billion tons of C&D waste is generated throughout the world. This quantity is expected to get doubled till 2025. Sharma and Sharma[86] used C&D waste to stabilize high plastic clayey soil. The results were presented based on various parameters attained from consolidated drained tests. The C&D waste was replaced in the clayey soil by 0 % to 32 % with a variation of 4 %. The test was conducted at 3 different values of confining pressures i. e. 49.03 kPa, 98.06 kPa and 147.1 kPa. Significant increase in deviator stress was observed at 8 % to 24 % replacement. The maximum deviator stress increased by 76 % for 49.03 kPa, 110 % for 98.06 kPa and 175 % for 147.1 kPa. The volumetric strain decreased by addition of C&D waste up to 24 %, beyond this the reduction was almost constant. Significant improvement was seen in shear strength and friction angle on addition of C&D waste while reduction in cohesion was observed. In a different study by same authors Sharma and Sharma[87], same waste material was used to determine some other properties of poor soil. In this study compaction, UCS, CBR and permeability parameters were studied. 0 % to 24 % of C&D waste was replaced in soil. Plasticity index at 24 % replacement of soil by C&D waste was found to be 7.6 % which is considered as suitable for sub grade soils. The OMC and MDD decreased on increase in C&D waste content. It was resulted that due to pozzolanic reaction between soil particles and C&D waste particles, the 28-days soaked UCS value kept on increasing on accumulation of C&D waste. It was observed that soaked CBR value increased due to presence of fine sand particles in the waste. Because of larger size of C&D waste particles, increase in permeability of soil was observed.

Abhijith et al.[88] also used C&D waste in montmorillonite clay soil. Proportions of waste was taken as 2 % to 14 % with an interval of 2 %. With accumulation of waste, plasticity index reduced and MDD increased. On addition of C&D waste, improvement in friction angle was also observed by conducting direct shear test. By calculating safe bearing capacity through Terzaghi's theory, it was resulted that optimum dosage of C&D waste is 10 % in which the SBB increased from 1411 to 2148 kN/m^3.

Since, properties of C&D waste varies with its origin and its type i.e., concrete waste/mortar waste/brick waste etc., its optimum dosage to be used in soil stabilization, will also vary. On the basis of included literature, C&D waste may vary in the range of 10 % - 24 % for getting optimum results.

Table 6. Outline of major studies carried in application of agriculture based solid waste in soil stabilization

Primary Additive	Secondary Additive	Evaluated Parameters	Outcomes/ Conclusion	Refs.
CDW	-	Tri-axial test results	- Deviator stress increased by 76 % for 49.03 kPa, 110 % for 98.06 kPa and 175 % for 147.1 kPa at 24 % C&D content. - Volumetric strain decreased by addition of C&D waste up to 24 % - Shear strength, friction angle and strength ratio also improved on addition of C&D waste. - Optimum dosage was found to be 24 %	86)
CDW	-	Compaction, UCS, Soaked CBR and Permeability	- 28-days UCS value is 709.03 kPA at 4 % C&D content which increased to 1352.68 kPa at 24 % C&D content. - Soaked CBR value is 2.07 % at 4 % C&D content which increased to 5.04 % at 24 % C&D content. - Permeability increased on increase in C&D content. - Optimum dosage was found to be 24 %.	87)
CDW	-	Compaction, Cohesion and	- Friction angle increased and cohesion decreased.	88)

		friction, Safe bearing capacity	- Highest SBB of 2148.46 kN/m^3 was found at 10 % replacement.	

9. Effect of mining solid waste products on soil stabilization

MW1 (Coal mine waste): Open pit coal mining is a surface mining technique where coal is extracted by digging, hauling, and stockpiling overburden to disposal area. [89] Disposal of waste generated from mines may lead to problem of contamination of surface and ground water and danger local as well as downstream ecosystem. There are 860 million tons of total coal reserves in the world. At the current consumption rate, these deposits that can meet the demand of the world for the next 112 years.[90] A study was conducted by Modarres and Nosoudy[45] to check the outcome of coal mine waste (CMW) and lime in stabilization of clayey soil. CMW was added in proportions of 3 %, 6 %, 9 % and 12 % while in composite mixes, CMW and coal waste ash (CWA) was used in proportions of 3 %, 6 %, 9 % and hydrated lime (HL) was used in proportion of 3 and 6 % by dry weight of soil. Results were drafted based on Atterberg limits, soaked and unsoaked CBR, swelling and UCS tests. On the basis of CBR value, it was determined that soils stabilized with CWA and HL showed better strength as compared to CMW and HL. In swelling behaviour, all stabilizers reduced the swelling. CW along with small amount of HL showed best properties. Higher compressive strength was observed in composite mixes of CW-HL and CWA-HL. Highest 28-day strength of 1.17 MPa was obtained with 6 % HL and 6 % CW. After 60 days of curing, pozzolanic reaction was observed in CW6HL6 modified specimen through XRD analysis. SEM micrograph of clay showed flaky structure to that of more integrated structure of stabilized soil due to sharp edge particles of CW. Formation of C-S-H was also confirmed due to addition of CW and CWA.

Table 7. Outline of major studies carried in application of agriculture based solid waste in soil stabilization

Primary Additive	Secondary Additive	Evaluated Parameters	Outcomes/ Conclusion	Refs.
CMW (MW1) (Coal Mine Waste and Coal Mine Ash)	Hydrated Lime	Atterberg limits, CBR, Swelling, UCS, XRD and SEM	- CWA and HL showed higher strength as compared to CW and HL. - CW along with small amount of HL showed best properties in swelling. - Highest 28-day strength of 1.17MPa was obtained with 6% HL and 6% CW. - Pozzolanic reaction was found in CW6HL6 through XRD analysis.	[45]

10. Conclusions

This review is concerned on reducing environmental impact by sinking use of natural resources and increasing use of waste materials generated from various sectors for soil stabilization. The following points summarizes the above critical review on utilization of waste for improving engineering properties of soil.

- Highly generated waste materials which are having problems related to disposal are identified and categorized into different categories viz. agricultural, industrial, C&D and mining.
- Their utility in soil stabilization has been established based on their engineering properties studied by various researchers.
- Application of solid waste for stabilizing problematic soils can be a solution of utilizing the waste material in an effective way. While comparing different types of agriculture based waste products, paramount results were shown when 10 % - 30 % of cement was replaced by POFA. This analysis was given on the basis of strength (UCS) parameters. A high degree of improvement in strength parameters was observed with increase in curing time. Thus, further research on agricultural waste based on curing time is highly recommended.
- Although all industrial waste was striking in improving engineering properties of soil, exceptional results were observed in case of CKD and IOT (used with lime). Both the waste materials showed almost similar improvement in improving CBR value of soil while UCS was only conducted in case of IOT. Optimum dosage of CKD was seen out to be 20 % while similar results were perceived with 16 % IOT (with 50 % lime) stabilized soil. Effect of curing time was not taken into consideration in majority of the research, thus there is a high scope of further research in this segment.

- C&D waste can be of different types i.e., concrete waste, mortar waste, brick waste etc. Thus, it is very difficult to specifically state the optimum dosage of C&D waste in soil stabilization. If the included research is taken into consideration, engineering properties were found to be improved with 10 % - 24 % of C&D waste in soil stabilization. In case of mining waste also, coal waste showed enhanced properties when used with hydrated lime. In this study, curing time was also considered and all the parameters were showing gradual increment with increase in curing time.
- In majority of the studies, UCS and CBR tests were suggested owing to their ease of performing and determining the strength parameters of stabilized soil. To determine the mineralogical properties and formation of chemical compounds, SEM and XRD were also conducted in many research. Direct shear and tri-axial test were performed in very limited research.

11. Current limitations and scope for future research

There might be many practical challenges in implementing these waste resources as soil stabilizers. Some issues related to quality control or replacement ratio may also arise. Despite of better alternative material, designers and contractors are forced to use natural materials on site. Technical authorities and stakeholders are also concerned about long-term performance of soil for any infrastructure project as they might have to face some financial losses or legal actions in case of early distortion of the structure.

To resolve these issues, further research on long term durability parameters and cost analysis of the waste resources as soil stabilizers must be carried out. The guidelines for utilization of waste resources as alternative material in soil stabilization must be established for its practical implementation.

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