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Soil Stabilization as an Avenue for Reuse of Solid Wastes: A Review

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Review article

Abstract

Industrialization has resulted in rapid improvement in the standards of living; however, it has also resulted in pollution and generation of solid wastes that have recently reached epic proportions. An effective waste management alternative is the need of the hour. Reuse of waste materials have been advocated for quite a while now and the utilization of industrial wastes in improving the properties of poor soils open up a new avenue for solid waste management. Expansive soils have been one of the most problematic soils encountered by a Civil Engineer. A lot of techniques are available for stabilization of such poor soils including lime and cement stabilization. However, the utilization of solid wastes in soil stabilization is an area of potential and promise. And it also provides the double advantage of waste management along with soil improvement. With this as base, this paper attempts to review the various industrial wastes that have been adopted in soil stabilization as a standalone stabilizer without lime or cement, in order to shed light into the prospects of increased utilization of solid wastes in soil stabilization.

Keywords: Solid Wastes, Soil Stabilization, Industrial Wastes, Agricultural Wastes, Geotechnical Properties

1. Introduction

After the industrial revolution, there was a rapid increase in the standards of living of the society due to mass production of goods, job opportunities and wages. However, the downside of industrialization was the production of byproduct wastes which rapidly assumed unmanageable proportions. This resulted in huge problems of pollution, disposal and management. A lot of efforts have been put into effective waste management practices. One avenue for the management of industrial wastes is to find suitable uses for it in various sectors of engineering and manufacturing. Usage of industrial wastes in manufacture of materials has been one of the most effective avenues in the field of Civil Engineering. In the same line, utilization of industrial wastes in soil engineering is being researched heavily in recent times, especially in soil stabilization.

Expansive soils have been one of the most frequently encountered and challenging soils by a geotechnical engineer. Such soils are extremely difficult to deal with during construction and have very poor strength and low bearing capacity. Perhaps the most difficult of its properties is its extremely poor swell-shrink characteristics. Expansive soils are the soils which swell significantly

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when they come in contact with water and shrink when there is removal of water from the soil [1–3] More regions of expansive soil deposits are being discovered due to increased construction activities especially in underdeveloped nations [4]. Expansive soils pose a major challenge to civil engineers all over the world as they cause severe distress to structures constructed on them [5]. Damages sustained by such buildings include distortion and cracking of pavements and on-grade floor slabs, cracks in grade beams, walls and drilled shafts, jammed and misaligned doors and windows, failure of concrete or steel plinth supporting grade beams. Lateral thrusts may result in buckling of basement and retaining walls [6]. The structural distress caused by expansive soils is well documented in literature [7–11]. Damage to lightly loaded structures founded on expansive soils has been widely reported in many countries such as Australia, China, India, Israel, South Africa, the United Kingdom and the United States of America [11]. Such soils need to be improved before stable and safe construction can be carried out on them.

Soil stabilization is a common engineering technique used to improve the physical properties of weak soil and make it capable of achieving the desired engineering requirements [12]. Soil stabilization using chemicals like lime and cement have been well documented in literature [13–21] However, with a rapid rise in the generation of solid wastes, a sustainable approach needed to be devised for effective management of wastes. Utilization of solid wastes in soil stabilization provided one such avenue to waste management. Especially in developing countries, this approach provided double advantage of waste reutilization resulting in reduced disposal problems and at the same time provided a cost effective resource in construction activities. This paper reviews the major research works carried out in utilization of various solid wastes without the use of any primary binder like lime or cement in soil stabilization.

2. Solid Waste Production around the World and in India

In the recent times, utilization of industrial wastes in civil engineering has increased in order to achieve sustainable waste management practices. Industrial wastes have been recycled in manufacture of bricks, blocks and pavers, as aggregates in concrete and mortars, as raw materials for manufacture of cement and building lime, plaster boards, floor and wall tiles to name a few. However, their use in soil stabilization has recently gained widespread acceptance with more and more industrial wastes being researched for their efficiency in modifying soil properties and serving as mechanical and chemical stabilizers. Some industrial wastes have also been used in geotechnical fill applications.

The number and quantity of industrial wastes produced around the world is huge. Globally, cities generate about 1.3 billion tonnes of solid waste per year. This volume is expected to increase to 2.2 billion tonne by 2025, says a 2012 report by the World Bank [22]. Merely cataloging the various types of wastes and quantity produced around the world is a huge task. However, a general idea of the proportion of the problem can be drawn by analyzing the waste production statistics of some of the most widely generated wastes. According to 2010 data, the worldwide generation of coal combustion products (CCP) including flyash, bottom ash, cenospheres, conditioned ash and flue gas desulphurization gypsum, was approximately 780 million tonnes. The largest CCP producers were China 395 million tonnes, North America 118 million tonnes, India 105 million tonnes, Europe 52.6 million tonne, Africa 31.1 million tonnes and Middle East a minor contributor [23]. The production and utilization rates of CCP of various regions of the world are shown in table 1.

Table 1 CCP Production around the world [23]

Country/Region	CCP Production (Mt)	CCP Utilisation (Mt)	Utilisation rate (%)	CCP Production / Person (Mt)	CCP Utilisation / Person (Mt)
Australia	13.1	6.0	45.8	0.60	0.27
Canada	6.8	2.3	33.8	0.20	0.07
China	395.0	265.0	67.1	0.29	0.20
Europe	52.6	47.8	90.9	0.11	0.10
India	105.0	14.5	13.8	0.09	0.01
Japan	11.1	10.7	96.4	0.09	0.08
Middle East and Africa	32.2	3.4	10.6	0.02	0.01
United States	118.0	49.7	42.1	0.37	0.16
Other Asia	16.7	11.1	66.5	0.05	0.03
Russian Federation	26.6	5.0	18.8	0.19	0.04
	777.1	415.5	53.5		

The worldwide annual production of blast furnace slag is approximately 400 million tonnes whereas the production of steel slag is around 350 million tonnes [24]. Red mud production, another waste product generated during Bayer process for manufacture of aluminum, is estimated to be between 70 -120 million tonnes worldwide [25–27]. Another major solid waste developed is phosphogyspum, from fertilizer industries. The worldwide phosphogypsum production is estimated to be in the order of 100-280 million tonnes [28,29]. The worldwide generation of cement kiln dust, a byproduct of cement manufacturing process is approximately in the order of 510-680 million tonnes [30]. It can be seen that solid wastes generated around the world is mounting to huge proportions and needs to different strategies for their effective management.

Coming to the status in India, the flyash production in India was 163.56 million tonnes in the year 2012-13 [31] which increased to 184.14 million tonnes in 2014-15 [32]. With increasing waste production, the Government of India is making a conscious effort to reduce waste disposal and associated problems with its reutilization in construction activities. It has periodically released documents related to industrial waste materials produced in India and its utilization in various construction related industries especially in cement manufacture. Flyash being one of the largest industrial wastes produced in terms of quantity, there has been keen efforts by the government in enhancing its utilization in various ways and means. It has also maintained a regular record on the production and utilization of flyash in the country. The utilization of flyash in the year 2012-13 was 100.37 million tonnes which is 61.37% of the total waste produced that year [31]. Fig. 1 shows the breakup of utilization of flyash in the year 2012-13. It can be seen that a significant portion (41.18%) of the flyash is utilized by the cement industry whereas the utilization of flyash for reclamation of low lying areas and as fill for roads, embankments and flyovers at 11.78% and 6% respectively, is comparatively smaller.

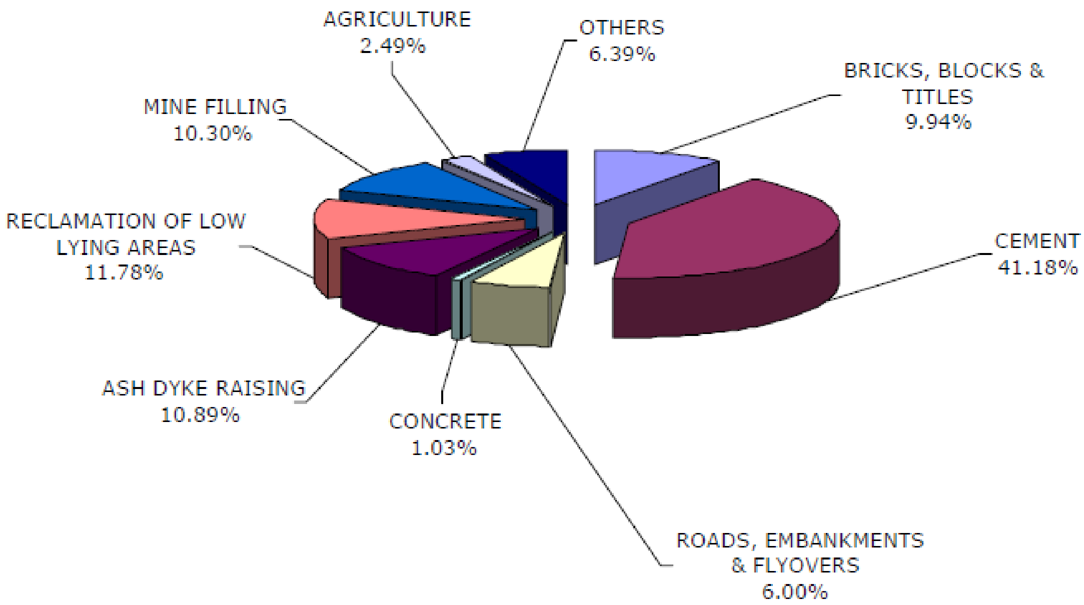

Figure 1. Modes of Flyash Utilization in 2012-13 [31]

Similarly, several other industrial wastes are produced in the country. Table 2 gives a list of major industrial wastes produced in India. With so much waste being produced in a developing nation like India, there is need for its effective management and at the same time a potential for reuse of the waste in the field of Civil Engineering, especially in an avenue like soil stabilization.

Table 2 Major Industrial Wastes Produced in India

Name of the Industrial Waste	Annual Production (Million Tonnes)	Reference
Flyash	184.14	[32]
Blast Furnace Slags	10	[33]
Steel Slag	12	[34]
Red Mud	4.71	[35]
Lime Sludges	4.5	[36]
Lead-Zinc Slag	0.5	[36]
Phosphorus Furnace Slag	0.5	[36]
Phoshphogypsum	11	[37]
Jerosite	0.6	[36]
Kimberlite	0.6	[36]
Mine Rejects	750	[36]

Solid wastes can be categorized into Municipal solid wastes, Industrial solid wastes, Agricultural wastes and Special wastes. In this, industrial wastes and agricultural wastes form a major chunk that can be reused effectively. In the subsequent sections, the various investigations carried out in utilizing wastes in soil stabilization have been discussed.

3. Soil Stabilization using Industrial Solid Wastes

Industrial solid wastes are usually by products of various industrial processes and are formed during or as result of the process involved. They are usually dumped in the open or stored in ponds for disposal in the vicinity of the plant. There are several industrial wastes that are produced all over the world which can be used in soil stabilization. Some of the industrial wastes that have been used in soil stabilization include flyash, phosphogypsum, cement kiln dust, steel slag, silica fume, lime kiln dust, waste water sludge ash, calcium carbide residue, glass waste, limestone waste ash, cement bypass dust, copper slag, granulated blast furnace slag to name a few.

Tastan et al. [38] explored the effectiveness of flyash as an organic soil stabilizer and studied the possible factors that are likely to affect the degree of stabilization. Unconfined compression and resilient modulus tests were carried out on the stabilized soil specimens. They concluded that the strength of organic soils can be increased by adding flyash but the increase in strength depended upon the type of soil and the characteristics of flyash. Unconfined compressive strength of organic soils can be increased using fly ash, but the amount of increase depended on the type of soil and characteristics of the fly ash. The significant properties that affected the degree of stabilization were the calcium oxide content and the ratio of calcium oxide to silica in the specimens. Their final conclusion was that organic content was detrimental to the stabilization process with strength of stabilized specimens dropping exponentially with increase in the organic content.

Nalbantoglu [39] studied the effectiveness of class C flyash in stabilization of an expansive soil. Soils from two regions in Cyprus were stabilized with two different proportions of class C flyash. The samples were then tested for various properties including plasticity characteristics, swell and cation exchange capacity. The addition of 25% flyash resulted in the reduction in the swell potential from 19.6% to 3.7%. For the second soil, addition of 15% flyash resulted in the swell potential reducing marginally from around 6.5% to 5%. He concluded that the addition of flyash resulted in a reduction in plasticity characteristics, swell pressure and cation exchange capacity of the soils thus indicating the formation of new reaction products changing the mineralogy of the soils as a result of which the soils became more granular in nature and absorbed less water.

Ramesh et al. [40] investigated the effect of soaking on Neyveli flyash stabilized shedi soil. The optimized dosage of Neyveli flyash was determined by conducting unconfined compressive strength test on soil stabilized with increasing dosage of flyash from 0% to 90%. It was found that 20% addition of Neyveli flyash gave the maximum strength of the stabilized soil. The results of the test revealed that the addition of 20% Neyveli flyash to shedi soil resulted in an 18 fold increase in the strength of the stabilized soil for unsoaked conditions whereas soaked specimens exhibited a strength increase of 14 fold. The increase in curing periods resulted in a strength increase for both soaked as well as unsoaked conditions.

Singh et al. [41] explored the effects of addition of sand, flyash and tile waste in the improvement of locally available clay soil as a subgrade material. The effect of the addition of waste materials was studied by determining the CBR test for the various blends. 70:30 was found to be the optimal blend for soil with sand due to the maximum dry density achieved for that combination. The addition of flyash to the mix resulted in decrease in dry density and increase in the optimum moisture content of the blend. Addition of tile waste resulted in an increase in the dry density initially followed by a decrease on further increase in the tile waste content in the blend. Both the soaked and the unsoaked CBR increased with the addition of sand, flyash and tile waste in the optimal proportions based on the compaction characteristics.

Degirmenci [42] compared the stabilization performance of phosphogypsum and natural gypsum in the stabilization of adobe soil. Adobe has serious disadvantages of low mechanical strength and poor water resistance. Compressive strength, flexural strength, drying shrinkage, softening in water and dry unit weight of clocks were determined to study the performance of natural adobe blocks as well as stabilized adobe blocks. 25% phosphogypsum stabilized adobe produced the maximum compressive strength and the least shrinkage upon drying. The water softening of phosphogypsum stabilized samples also was better than the minimum requirements specified. It was concluded that 25% phosphogypsum was optimal in stabilizing adobe for low cost blocks for rural construction.

Al-zaidyeen and Al-qadi [43] used phosphogypsum for stabilization of soil pavement layers. Their experimental programme involved determination of the compaction characteristics and CBR of the soil stabilized with phosphogypsum. Upto 25% phosphogypsum was admixed by weight of soil for stabilizing it. The results indicated that the addition of phosphogypsum resulted in an increase in the dry density of the soil until 20% addition beyond which the dry density decreased. CBR test results indicated that the addition of phosphogypsum results in an increase in the bearing of the soil with phosphgypsum until 20% addition. The test results were used for correlating the phopshphgypsum dosage with the CBR value of the stabilized soil. Based on the correlation, it was concluded that 21.4% phopshogypsum was optimal for increasing the bearing of the soil.

James et al. [44] studied the effect of phosphogypsum on the strength and index properties of an expansive soil. The experimental programme involved the determination of index properties and the unconfined compressive strength of the expansive soil admixed with phosphogypsum in increments of 10% upto 50% addition. It was found that the addition of phosphogypsum reduced the liquid limit, plasticity index and free swell index and increased its plastic limit and shrinkage limit. Addition of phosphogypsum resulted in a change in the soil classification from high plastic clay to low plastic silt. The unconfined compressive strength of the soil increased close to four times on addition of 40% phosphogypsum beyond which the strength reduced.

Krishnan et al. [45] investigated the early strength of expansive soils stabilized using a combination of industrial wastes. They adopted phosphogypsum and flyash combination for stabilizing the soil. Unconfined compressive test samples were prepared and cured for a period of 3 and 7 days. The flyash content was kept constant at 5% were as the phosphogypsum content was varied in increments of 2% upto a maximum value of 6%. The addition of industrial waste combinations to two different types of soils were explored and it was found that the early strength of the stabilized samples increase by 1.72 times and 2.25 times that of the untreated sample at the end of 7 days of curing. SEM images revealed changes in the microstructure of the stabilized soils.

In an extension of this work, Krishnan et al. [46] studied the effects of extended curing period on the development of the strength of the soils stabilized with phosphogypsum and flyash. The tests revealed that the strengths of the two clayey soils stabilized with phosphogypsum and flyash increased to 4.99 and 5.63 times of the untreated samples at the end of 60 days of curing. SEM images further confirmed a complete change in the soil microstructure on extended curing period leading to more formation of reaction products. They also concluded that the presence of Si and Al products in the stabilized samples are responsible for the changes in microstructure and strength of the soil.

Hossain and Mol [47] probed the use of cement kiln dust in stabilization of clayey soils. Cement kiln dust was added upto 20% in various dosages in the soil to study its influence on the various properties. A number of tests including index properties, compaction characteristics, strength, bearing and durability tests were done in order to evaluate the performance of cement kiln dust in stabilizing clayey soils. The study concluded that cement kiln dust stabilized clay enhanced all the properties studied and also was durable. The addition of cement kiln dust to soil resulted in very high CBR values which led the authors to conclude that cement kiln dust can be used to manufacture soil blocks for low cost housing and subgrade stabilization for local population.

Hossain [48] evaluated stabilized clayey soils with different proportions of cement kiln dust and rice husk ash. Both were used upto 20% by weight in stabilization of soil. Correlations were derived between properties modulus of elasticity, unconfined compressive strength and CBR. The test results indicated that cement kiln dust and rice husk ash stabilized soil performed significantly superior in comparison to unstabilized soil samples. CKD-stabilized soils showed higher strength, elastic modulus, CBR, water resistance, shrinkage values and lower water absorption compared to their RHA counterparts due to the self-cementing capability of cement kiln dust.

Moses and Saminu [49] investigated the potential of cement kiln dust to stabilize black cotton soil. Locally obtained black cotton soil was stabilized with cement kiln dust upto 16% by weight of soil in increments of 4%. Index properties of soil stabilized with cement kiln dust were tested for index properties, unconfined compressive strength and CBR value. The authors found that the addition of cement kiln dust to black cotton soil did not yield the desired results. The plasticity index of the soil did not reduce much with addition of cement kiln dust. The unconfined compressive strength and CBR value of the soil increased with the addition of cement kiln dust however it did not meet the minimum values required by standards for pavements.

Sreekrishnavilasam et al. [50] undertook a laboratory study to investigate the potential of two fresh and landfilled type of cement kiln dust (CKD) for soil improvement. The soil treated with CKD was subject to atterberg limits test, compaction, pH, unconfined compressive strength and a limited number of swelling tests. The results of the tests indicated that the suitability of CKD as a soil stabilizer was dependent on the availability of free lime. pH measurements indicated that CKD's ability to raise the pH of the soil could be used as an indicator to gauge the stabilization potential of CKD. CKD content in excess of 15% was required for development of sufficient strength of the stabilized soil. Only one of the two fresh CKDs was suitable for soil stabilization whereas the other two were recommended for use in stabilization of extremely wet soils.

Akinwumi [51] conducted a laboratory investigation on the stabilization of lateritic soil with steel slag. The addition of steel slag resulted in an increase in the specific gravity of the soil, reduction in liquid and plastic limits and plasticity index. Compaction characteristics were altered due to the addition of steel slag, with increase in dry density and reduction in optimum moisture content. Steel slag resulted in an increase in the unsoaked and soaked CBR, the unconfined compressive strength and permeability of the soil. The swell potential of the soil steadily reduced with the addition of steel slag. Akinwumi concluded that steel slag can be used as a low cost soil modifier for use in subgrade stabilization.

Liang et al. [52] described the influence of water content on the mechanical behavior of clayey soils treated with steel slag fines. Based on triaxial test results, it was found that the cohesion increased and friction angle decreased with increase in curing period and water content. 18% water content and 30% steel slag was identified as the optimal combination as it produced the maximum stress difference. This led to the conclusion that steel slag scrap can be used in improvement of soft foundation soil to increase its bearing capacity, reduce foundation settlements and enable long term use of the building.

Kalkan [53] modified expansive clayey soils with silica fume in order to improve its durability and resistance against cyclic wetting and drying conditions. The modified expansive soils were studied for their swelling behavior in the laboratory conditions. The swelling pressure and swell potential tests were done in one dimensional consolidation oedometer. Along with the swell tests the modified expansive soils were also subject to cation exchange capacity, specific surface area, pH, consistency and compaction characteristics tests as well. It was found that the modification of expansive soils by silica fume resulted in reduced cation exchange capacity, plasticity index, maximum dry density and specific surface area and increased pH and optimum moisture content. The swell potential and swell pressure reduced consistently with increase in silica fume. The addition of silica fume to expansive soil also improves its durability by increasing its resistance to swell even under conditions of alternate wetting and drying.

Jung et al. [54] performed an extensive field study to evaluate the post construction performance of pavements stabilized with lime kiln dust (LKD) with a minimum of five years of service period. Six sites were selected to perform standard penetration test, dynamic cone penetration test and falling weight deflectometer test to evaluate the strength and stiffness of the stabilized soil. In addition, soil samples were collected using split spoon samplers which were tested in the laboratory for index properties and were compared with that of natural soil. They concluded that the addition of LKD reduced the plasticity characteristics of the soil significantly. Long term improvement of the soil was confirmed as the lime from LKD was present in the soil even after 11 years of service of the pavement. They finally concluded that LKD is a good quality and reliable material for stabilization of pavement subgrade materials provided good control over quality of construction is maintained.

Kampala and Horpibulsuk [55] investigated the use of calcium carbide residue from acetylene gas factories in soil stabilization. The soil stabilized with the residue was tested for its index properties immediately after it was thoroughly mixed with the residue. Mechanical properties of the soil were determined by performing unconfined compression, oedometer, water immersion and CBR tests. The soil sample was also stabilized with hydrated lime for comparing the performance of the residue with that of conventional lime stabilization. From the results of the experimental program, it was revealed that the optimum water content provided the best engineering properties upon stabilization with lesser water being insufficient for the pozzolanic reactions. It was concluded that the soil stabilization using calcium carbide residue was even better than lime stabilization due to presence of pozzolanic materials in the residue as well.

Okagbue and Yakubu [56] adopted limestone waste ash as a substitute for lime in soil stabilization. Limestone ash is grey cement like byproduct of cement manufacture. The effect of limestone ash on the soil investigated lead to reduction in plasticity index of the soil, maximum dry density reduced whereas the optimum moisture content increased with the increase in the limestone ash content. The unsoaked and soaked CBR of the soil initially increased with increase in ash content reached an optimum and reduced on further addition of ash to the soil. 6% limestone ash was found to be optimal for increasing the CBR of the soil. Unconsolidated undrained shear strength tests were also done on the stabilized soil samples. The tests revealed that the cohesion of the stabilized soils samples increase with limestone ash content whereas the angle of internal friction reduced with the same. The authors concluded that the treatment of laterites with limestome ash showed trends similar to that of lime stabilization, however, the quantity required for achieving similar results to that of lime was double.

Machado et al. [57] investigated the utilization of white wash mud in stabilization of forest road pavement. Two types of soil were selected for the program and investigated in the laboratory with different dosages of whitewash mud. Whitewash mud was obtained from the pulp and paper processing an industry which was disposed off in embankments. The experimental program in the laboratory investigated atterberg limtis, compaction characteristics, CBR and permeability. The laboratory results indicated that the addition of whitewash mud to soil in the range of 20 to 25%5 gave the best results in terms of soil bearing, despite adopting a curing period of one day adopted in the study.

Al-Rawas et al. [58] did a comparative evaluation of different industrial wastes on their stabilization potential of an expansive soil. The industrial wastes adopted were cement bypass dust, copper slag, granulated blast furnace slag. The objective of the study was to investigate the influence of different industrial waste stabilizers on the swell potential, plasticity and chemical properties of the stabilized soil. The stabilizers were adopted in proportions of 3, 6 and 9%. The results concluded that the addition of industrial wastes resulted in a reduction in the liquid limit and plasticity of the samples, reduction in the cation exchange capacity, swell pressure and swell percent with the exception of copper slag treated specimens which showed opposite trends, which was attributed to the high amount of Na^+ ions present in it. Cement by pass dust produced the best improvement in the studied characteristics of the soil. The study concluded that the concentration of Na^{+} and Ca^{2+} and cation exchange capacity as effective parameters for studying the stabilization potential of waste materials.

A comparison of the improvements obtained due to stabilization of soil using industrial wastes is tabulated in table 3. It can be seen that the addition of industrial solid wastes has resulted in improvement of the properties investigated by various researchers. A lot of them have adopted unconfined compression and CBR tests in their investigations, concentrating mainly on the strength aspect of the stabilized soil. It can be seen that some of the industrial wastes give very good improvements with strengths as high as 6 MPa in the case of cement kiln dust and 2.5 MPa in the case of calcium carbide residue even in soaked conditions. There are also instances wherein cement kiln dust produces strengths of around 255-710 kPa, flyash giving strength as high as 2000 kPa in soaked conditions with one soil whereas it produces around just 400 kPa with some other type of soil. There are also instances of CBR rising from 11% to 176% in the case of cement kiln dust and just by 1% in the case of white wash mud. This indicates that development of strength is influenced by soil type and type and nature of the industrial waste. Some of them have concentrated on the swell potential, swell percent and swell pressure exerted by the stabilized soil. Swell pressures as high as 480 kPa have been reduced to zero whereas in others the pressure reduction is moderate to low as in from 249 kPa to just below 202 kPa. Very few have undertaken to study the influence of industrial waste stabilization on the permeability of the soil. And utilization of triaxial test in evaluating shear strength parameters is also seems to be not much favoured.

4. Soil Stabilization using Agricultural Solid Wastes

Wastes originating from agricultural sources like rice husk ash, bagasse ash, ground nut shell ash, cassava peels and rice straw ash have also been adopted in soil stabilization. Despite the agricultural origins of some of the wastes, the ashes are usually produced due to incineration of the wastes during processing at the industrial level. However, open burning of the wastes at small scale levels are also known to produce these wastes.

Yadu et al. [59] investigated the potential of rice husk ash and flyash on the stabilization of black cotton soils. The black cotton soil was stabilized with different percentages of both ashes and the stabilized soils were tested for their atterberg limits, compaction characteristics, unconfined compressive strength and CBR. It was found that the addition of the wastes resulted in the reduction in the plasticity index and the specific gravity of the stabilized soil. The addition of fly ash resulted in a decrease in optimum moisture content and maximum dry density whereas the addition of rice husk ash resulted in an increase in the optimum moisture content and decrease in the maximum dry density. The unconfined compressive strength and the CBR of the soil increased with the addition of both. They concluded that the optimum dosage of flyash and rice husk ash were 12% and 9% respectively. Economic analysis of pavement designed with stabilized soil resulted in cost savings of 14% and 20% for rice husk ash and flyash stabilized soil respectively.

Anupam et al. [60] studied the effect of soil stabilization using various wastes viz. flyash, rice husk ash, bagasse ash and rice straw ash to improve the load bearing capacity of the soil. The four waste materials were used in percentages varying from 5 to 35 % for improving the soil. The properties that were tested include the shrinkage limit, compaction characteristics and CBR. They concluded that all four industrial wastes resulted in the increase in optimum moisture content and decrease in the maximum dry density of the stabilized soil. Flyash, rice husk ash and bagasse ash upto 25% and rice straw ash upto 20% addition resulted in an increase in the CBR of the soil for all curing periods. Rice straw ash produced much better bearing compared to the other three industrial waste materials.

Table 3 Comparison of Improvement Achieved by Industrial Solid Waste Stabilization

Author	Soil - Optimum Waste Combination	Major Geotechnical Properties Tested	State before stabilization	Effect after Stabilization
Tastan et al. [38]	Organic soils + <10% Flyash	Unconfined Compression	15-30 kPa	100-400 kPa
		Resilient Modulus	Test could not be done	10-100 MPa
Nalbantoglu [39]	Degirmenlik(D) and Tuzla (T) soils + 25% Flyash	Swell Potential	19.6%(D); ~ 6.5%(T)	0%(D); 2% (T)
		Swell Pressure	480 kPa(D); 320 kPa(T)	0 kPa (D); ~50 kPa(T)
Ramesh et al. [40]	Shedi soil + 20% Neyveli Flyash	Unconfined Compression, Soaked(S)&Unsoaked (U)	145.5 kPa	~2000 kPa (S) Close to 4000 kPa(U)
Singh et al. [41]	Clay with Sand, Flyash (63:27:10) + 9% Tile Waste	CBR, Unsoaked	5.39%	12.16%
		CBR, Soaked	2.78%	5.59%
Degirmenci [42]	Adobe soil + 25% Phosphogypsum	Compressive Strength	1.01 MPa	4.38 MPa
		Drying Shrinkage	4.20%	2.49%
Al-zaidyeen and Al-qadi [43]	Non plastic soil with 20% Phosphogypsum	Max. Dry Density	1.69 g/cc	1.92 g/cc
		CBR	11.1%	45.4%
James et al. [44]	High plastic clay with 40% Phosphogysum	Plasticity and Swell	43.74% and 100%	~15% and <40%
		Unconfined Compression	60 kPa	250 kPa
Krishnan et al. [45] [46]	Soil 1 and Soil 2 + 5% flyash + 6% Phosphogypsum	Unconfined Compression	75.41 kPa (S1)	452 kPa
			112 kPa (S2)	744 kPa
Hossain and Mol [47]	Soil + 20% Cement kiln dust	Unconfined Compression	0.1 MPa	6.01 MPa
		CBR	11%	265%
Hossain [48]	Soil + 15% Rice husk ash + 5% Cement kiln dust	Unconfined Compression	0.15 MPa	3.70 MPa
		CBR	11%	176 %
Moses and Saminu [49]	Black cotton soil + Cement kiln dust	Unconfined Compression CBR	~100 kPa 2%	~650 kPa 5%
Sreekrishnavilasam et al. [50]	Soil G + 20% Cement Kiln Dust	Unconfined Compression	254 kPa	710 kPa
	Soil W + 15% Cement Kiln Dust		187 kPa	545 kPa
	Soil S + 20% Cement Kiln Dust		320 kPa	255 kPa
Akinwumi [51]	Lateritic Soil + 8% Steel slag	Unconfined Compression CBR Swell Potential	104 kPa 51% ~0.20%	170 kPa 30% ~0.16%
Liang et al. [52]	Clayey soil + 30% steel slag	Triaxial Compression	~325 kPa (Deviator Stress)	~500 kPa (Deviator Stress)

Kalkan [53]	Soil + 30 % Silica fume	Plasticity	30%	21%
		Swell Potential	~54%	~5%
		Swell Pressure	~270 kPa	<200 kPa
Jung et al. [54]	Silty Clayey Soil + 5% Lime kiln dust	CBR through DCPT Tests	Low CBR	Increase in CBR by 500% to 1500%
Kampala and Horpibulsuk [55]	Soil + 7% Calcium carbide residue	Soaked Unconfined compression	Close to 0 kPa	Close to 2500 kPa
		Soaked CBR	Close to 0%	80%
		Vertical Swell %	6%	< 1%
Okagbue and Yakubu [56]	Laterite soil + Lime stone ash waste	Triaxial Shear Strength Cohesion Friction Angle	 33 kPa 21^o	 73 kPa 15^o
		CBR, Soaked	25%	60%
		CBR, Unsoaked	66%	85%
Machado et al. [57]	Subgrade sand + 20% Whitewash mud	CBR Permeability	26.40% 4.2×10^{-4} cm/s	27.30% 3.8×10^{-4} cm/s
	Silty Gravel + 25% Whitewash mud		35.50% 2.6×10^{-4} cm/s	52.00% 1.1×10^{-3} cm/s
Al-Rawas et al. [58]	Soil + 9% cement by pass dust	Plasticity, Swell Percent and Swell Pressure	20.5 %, 9.39% & 249 kPa	17.4%, 4.1% & 202 kPa
	Soil + 3% copper slag			20%, 10.2% & 353 kPa
	Soil + 9% slag cement			22%, 5% & 200 kPa
	Soil + 9% blast furnace slag			22%, 8% & 190 kPa

Chittaranjan et al. [61]investigated the stabilization potential of waste materials viz. bagasse ash, rice husk ash and ground nut shell ash in soil stabilization. Weak subgrade soil was stabilized with the three waste materials upto 15% in increments of 3% and the CBR of the stabilized soils were evaluated. It was found that irrespective of the waste, the increase in the waste content in the soil resulted in an increase in the CBR of the soil upto 15% addition of the waste materials. However, in comparison with each other, sugar cane bagasse ash produced the best bearing values whereas ground nut shell ash resulted in the least of the bearing values.

Sabat [62] evaluated the suitability of using sugarcane bagasse ash and lime sludge as stabilizing agents for soil stabilization of pavement subgrades. The objective of the work was to investigate the combined effects of baggase ash and lime sludge on the geotechnical properties of the soil. Lime sludge and bagasse ash were added in increments of 4% upto 20% and 16% respectively. The experimental programme lead the researcher to conclude that the addition of bagasse ash and lime sludge both resulted in a decrease in the maximum dry density of the soil and increased the optimum moisture content. 8% bagasse ash with 16% lime sludge was found to be the optimal dosage as it produced the maximum CBR and unconfined compressive strength of the stabilized soil. An economic analysis of pavement constructed on the stabilized pavement resulted in a minimum savings of 13.9% in cost of the pavement when compared to the untreated soil.

Villamizar et al. [63] studied the effect of addition of coal ash and cassava peels on the strength of compressed stabilized soil blocks. The stabilized blocks were tested for flexure, compression and water absorption. The cassava peels were sun dried to remove excess moisture. The coal ash was used as an alternative stabilizer to reduce the linear shrinkage of the clay during drying. Coal ash and cassava peels were added by dry weight of soil. All were thoroughly and evenly mixed and then cast to sizes of 320mm x 80mm x 150mm. The cast bricks were cured for a period of 28 days in the sun. The results indicated that blocks stabilized with 5% coal ash produced the best compressive and flexural strength followed by the combination of 7.5% coal ash and 2.5% cassava peels. Addition of cassava peels without coal ash had an adverse effect on the compressed bricks.

In study carried out by Osinubi et al. [64], RHA was adopted as cementitious blend for stabilizing Recycled Asphalt Pavement (RAP). In this work, RAP blended with RHA was adopted for use in pavement subbase. A soaked CBR of 34% was achieved for the blend of 70% RAP and 30% RHA, which was recommended as the optimal blend for stabilizing RAP for use in subbase materials.

Ali et al. [65] studied the stabilization of expansive soil using combinations of bagasse ash and marble dust. An expansive soil was stabilized separately using upto 12% Bagasse ash and Marble dust in increments of 4%. It was found that the addition of marble dust and bagasse ash resulted in a reduction in plasticity, expansive index and swell pressure at 12% addition of either additive. However, 8% marble dust and 8% bagasse ash addition produced the maximum dry density.

Oyendiren and Fadamoro [66] studied two genetically different shale soils with rice husk ash and coconut husk ash varying from 2% to 20%. The test plan consisted of determination of plasticity characteristics, compaction characteristics, unconfined compression and CBR. It was found that the addition of 10% rice husk ash and coconut husk ash resulted in a reduction in the plasticity of soil 1. Further increase in the additive content resulted in an increase in the plasticity. For soil 2, a similar trend was observed till 6% addition of coconut husk ash, beyond which the plasticity increased, whereas it was 10% for rice husk ash with soil 2. Upto 10% addition of rice husk ash and coconut husk ash resulted in an increase in the maximum dry density of the soil and thereafter reduced. The optimum moisture content reduced till 10% addition of rice husk and coconut husk ash. The addition of rice husk and coconut husk ash resulted in a steady increase in the unconfined compressive strength of the stabilized soil. CBR on the other hand increased up till 10% addition of rice husk ash and coconut husk ash beyond which there is a reduction in CBR.

Amu et al. [67] investigated the potential of sugarcane straw ash in the stabilization of lateritic soil. The lateritic soil was stabilized with straw ash up to 8% in increments of 2% and the plasticity characteristics, compaction characteristics, unconfined compression and CBR of the stabilized soil were determined. It was found that the addition of sugarcane straw ash resulted in reduction in the plasticity, reduction in maximum dry density and increase in the optimum moisture content, unconfined compressive strength and CBR of the stabilized soil. It was found that 6% sugarcane straw ash produced the best improvement in soil properties.

Osinubi et al. [68] studied the compatibility of using municipal solid waste leachate and bagasse ash in the stabilization of lateritic soil for use as a waste containment barrier (liner). The lateritic soil was stabilized with bagasse ash upto 12% in increments of 4% with municipal solid waste leachate as liquid for moulding purposes. The samples were moulded at 2% wet of optimum and were fully saturated by immersing in distilled water for a period of 5 days before testing their hydraulic conductivities. The hydraulic conductivity of the stabilized soil was evaluated by permeating the specimens using distilled water until steady state was achieved followed by leachate until steady state was achieved. The tests were conducted for a total of 91 days and the conductivity measurements were taken daily. There was an increase in the hydraulic conductivity of the stabilized soil permeated with distilled water as well as municipal solid waste leachate, however, the order of increase in hydraulic conductivity reduced with the increase in bagasse ash content used for stabilization. In general, the hydraulic conductivities of all bagasse ash treated samples were lower than the regulatory standards and hence it was recommended that the bagasse ash treated soils were suitable for use in waste containment facilities.

Table 4 summarizes the improvements achieved by the use of agricultural wastes in soil stabilization. Just as in the case of industrial wastes, a majority of the researchers have concentrated on the strength aspect of the stabilized soil. The addition of agricultural wastes in soil stabilization also produces improvement in properties of the soil; however, the improvement achieved seems to be of a lesser order. The strength of the soil stabilized seems to be in the order of 200-600 kPa with the exception of stabilized earth blocks. The improvement in CBR of the stabilized soil is also of lesser order in the range of 10-50% with the exception of one case wherein stabilization with rice husk ash and coconut husk ash produced very high CBR values of the order of 200-300%, even higher than those produced by the industrial solid waste cement kiln dust. The studies involving swelling are also limited in the case of agricultural solid wastes. Investigations on compressibility and permeability properties are also very minimal.

5. Soil Stabilization using Solid Wastes from Miscellaneous Sources

A lot of other types of wastes coming from construction and demolition, quarry, sewage treatment plant, municipal solid waste sources have also been investigated in soil stabilization.

Sabat [69] adopted waste ceramic dust for stabilization of expansive soil. The expansive soil was treated with ceramic dust in increments of 5% upto a maximum of 30%. The amended soil showed reduced plasticity characteristics, increased strength and bearing, increased dry density and friction angle, reduced cohesion, optimum moisture and swell pressure. The amendment of the expansive soil with ceramic dust resulted in its classification changing from high plastic clay to low plastic clay (CH to CL). Economic analysis carried out by the author concluded that upto 30% ceramic dust can be used for strengthening of subgrade for flexible pavement with 15 to 24% savings in cost of construction.

Table 4 Comparison of Improvement Achieved by Agricultural Solid Waste Stabilization

Author	Soil- Optimum Waste Combination	Major Geotechnical Properties Tested	State before stabilization	Effect after Stabilization
Yadu et al. [59]	Black cotton soil + 12% Flyash	Unconfined Compression	118 kPa and 4%	345 kPa and ~11%
	Black cotton soil + 9-11% Rice husk ash	CBR		208 kPa and ~11%
Anupam et al. [60]	Clayey soil + 25% Flyash	CBR, Soaked	2%	8.5%
	Clayey soil + 25% Bagasse ash			7.8%
	Clayey soil +25% Rice straw ash			13%
	Clayey soil + 20% Rice husk ash			17.74%
Chittaranjan et al. [61]	Soil + Rice husk ash	CBR	7.66%	24.23%
	Soil + Bagasse ash			26.68%
	Soil + Groundnut shell ash			21.23%
Sabat [62]	Soil + 10% Rice husk ash + 15% Lime sludge	CBR	1.92%	8.71%
		Swell Pressure	130 kPa	4 kPa
		Compression Index	0.15	0.10
		Triaxial Compression Cohesion Friction angle	 13 kPa ~18^o	 26 kPa 21^o
Villamizar et al. [63]	Soil + 5% Coal ash	Compressive Strength, Flexural Strength & Water Absorption	1.97 MPa, 0.64 MPa & 30.12%	3.31 MPa, 0.76 MPa & 28.64%
	Soil + 7.5% Coal Ash + 2.5% Cassava Peels			2.53MPa, 0.48 MPa % 27.75%
Osinubi et al. [64]	70% Recycled asphalt pavement + 30% Rice husk ash	CBR, Soaked	23%	34%
		CBR, Unsoaked	35%	41%
Ali et al. [65]	Expansive soil + 8% Bagasse ash	Plasticity Expansive Index Swell Pressure	31%, 140 % & 9.02 psi	18%, 83% & 5.56 psi
	Expansive soil + 12% Marble dust			17%, 100% & 4.72psi

Oyediran and Fadamoro [66]	Shale soil 1 + 10% Rice husk ash	Unconfined Compression CBR	21.75-61 kPa 27-49%	~450-500 kPa ~200-300%
	Shale soil 2 + 10% Rice husk ash		70.7-100.2 kPa 32-45%	~250-290 kPa ~120-160%
	Shale soil 1 + 6-10% Coconut husk ash		21.75-61 kPa 27-49%	~250-300 kPa ~250-300%
	Shale soil 2 + 6-10% Coconut husk ash		70.7-100.2 kPa 32-45%	~270 kPa ~150-190%
Amu et al. [67]	Laterite soil + 6% sugarcane straw ash	Unconfined Compression	79.6 - 240.4 kPa	284.66-564.6 kPa
		CBR	6.24-6.31%	14.88-24.88%
Osinubi et al. [68]	Laterite soil + 12% Bagasse ash	Hydraulic conductivity	$1.32 \times 10^{-9} – 1.54 \times 10^{-10}$ m/s	$2.04 \times 10^{-10} – 1.51 \times 10^{-10}$ m/s

Ameta et al. [70] used crushed tile aggregate for stabilization of dune sand. In order to modify its properties to enhance its engineering characteristics, dune sand was blended with crushed tile aggregates with different particle sizes of 4.75mm, 2mm, 1.18mm and 0.425mm in increments of 5% upto 30%. The addition of tile waste to dune sand resulted in increase in the density of the blend with particle size and for same particle size with increase in the proportion of tile aggregate. The CBR values of the blends increased with the increase in the proportion of tile aggregate in the blend. Direct shear tests performed on the blends indicated an increase in the angle of internal friction with increase in particle size of the tile aggregate and proportion.

Baser [71] stabilized expansive soil using waste marble dust. Two types of marble dust were adopted for stabilizing the soil; Limestone dust and dolomitic marble dust. Both waste materials were used in increments of 5% upto 30% addition to the expansive soil. The stabilized blends were tested for plasticity and swell shrink characteristics. Baser concluded that the addition of marble dust reduced the liquid limit, plasticity and shrinkage index and increased the plastic and shrinkage limit. Marble dust amendment of expansive soils resulted in a considerable reduction in the swelling of the expansive soil, more for limestone dust compared to dolomitic dust. He concluded that both lime stone dust and dolomitic dust can be used for stabilization of expansive clay.

Osinubi et al. [72] delved into the stabilization of recycled asphalt pavement (RAP) with sawdust ash. An experimental investigation was carried out to assess the suitability of RAP stabilized with cementitious saw dust ash as pavement material. It was found that 90% RAP blended with 10% sawdust ash resulted in a soaked CBR value of 26% after 24 hours of soaking, which was recommended for use as subbase material for pavement construction.

Al-Sharif and Attom [12] explored the potential of burnt waste water sludge ash in the stabilization of clayey soil. Sludge ash was obtained by burning sludge from a local waste water treatment plant. Sludge ash was used to amend three different types of soil and the changes in their geotechnical properties were studied. It was established that 7.5% sewage sludge ash increased the unconfined compressive strength as well the maximum dry density and also reduced the swelling of the soil. Any higher percentage of sludge ash resulted in a reduction in the strength and the density of the soil. It was concluded that sewage sludge ash was a material of potential in soil stabilization.

Sabat and Nanda [73] researched the effect of marble dust on the stabilization of soil using another industrial waste viz. rice husk ash. To the optimal dosage of RHA determined from unconfined compressive strength tests, marble dust was added in increments of 5% upto 30% by weight. The stabilized soil was subject to a battery of tests including compaction tests, unconfined compressive strength tests, soaked CBR tests, swelling tests and durability tests after 7 days of curing. The experimental programme revealed that the addition of rice husk ash to soil results in an increase in the optimum moisture content and reduction in the maximu dry density. The addition of marble dust to optimal rice husk ash stabilized soil also showed similar trends in compaction characteristics. The unconfined compressive strength of the soil increased with the increase in marble dust content till a dosage of 20%. The soaked CBR values also showed s similar trend. The swelling pressure of rice husk stabilized soil decreased steadily with increase in the marble dust content in the stabilized soil. The soil samples were subjected to 12 cylces of wetting and drying to study the durability. The rice husk ash stabilized soil could not survive the durability test. However, the loss in strength due to alternate wetting and drying cycles was just 2% for 20% marble dust admixed rice husk ash stabilized soil.

Fauzi et al. [74] explored the potential of high density polyethylene and glass for stabilization of Kuantan clays. Cut and crushed PET bottles of mineral water and soda and crushed glass were used as the material stabilizers for stabilizing clayey soils from Kuantan, Malaysia. The soil samples were amended with upto 12% of the stabilizers in increments of 4%. The addition of the two stabilizers resulted in a general decrease in liquid limit, plasticity index and optimum moisture content and increase in the dry density and CBR of the blended specimens with increasing stabilizer content. The authors recommended that the two materials can be used as soil stabilizers for pavement subgrade stabilization from the point of view of the economy and the environment.

Okagbue [75] delved into the potential of wood ash in stabilization of expansive soil. The addition of wood ash to clayey soil resulted in a reduction in the plasticity and dry density of the soil and increase in the strength and CBR of the soil. However, the gain in strength could not be sustained beyond 14 days of curing as the strength reduced with increasing curing period. This led the author to conclude that though wood ash is able to modify the plasticity of soil due to the presence of lime in its chemical composition, it is not suitable for stabilization of soil for construction purposes.

Brooks et al. [76] evaluated the potential of lime stone dust and coal flyash in stabilizing problematic soils in the state of Southeastern Pennsylvania of the United States of America. Soil samples were treated with 15% and 25% flyash and 3, 6 and 9% limestone dust. The test results indicated a significant improvement in the geotechnical properties of the soil. Reduction in plasticity, increase in CBR and unconfined compressive strength, increase in optimum moisture content, reduction in maximum dry density and swell potential of the soil were the changes observed after stabilization. SEM images were used to analyse the changes at the microstructural level. It was concluded that the two soils stabilized using coal flyash and limestone dust could be used as road bases and bases for light traffic.

James and Pandian [77] investigated the effect of egg shell powder on the geotechnical properties of an expansive soil. The experimental program involved determination of index properties, strength and swell of the modified soil. It was found that addition of egg shell powder to soil resulted in reduction in plasticity characteristics, improvement in strength of the soil and reduction in swelling of the soil.

Sabat and Bose [78] investigated the combined effect of flyash-quarry dust mixes on the compaction characteristics, unconfined compressive strength, California bearing ratio (CBR), shear strength parameters and swelling pressure of an expansive soil. Fly ash and quarry dust in the proportion of 1:2 were added to an expansive soil up to 75% of its dry weight. Fly ash was added in increments of 5% from 0 to 25% whereas quarry dust was added in increments of 10% from 0 to 50% by dry weight of the soil. The investigation revealed that the addition of 45% flyash quarry dust mix resulted in the maximum unconfined compressive strength, increased CBR, increased angle of internal friction and reduced cohesion and swell pressure. The authors concluded that 45% flyash quarry dust mix was optimal for stabilization of soil to be used as subgrade of pavements. Ecomic analysis of the use of stabilized soil in pavement construction resulted in cost savings of upto 11.5%.

Saltan et al. [79] investigated the possibility of using pumice waste in stabilization of clayey subgrade for pavements. The clayey subgrade was stabilized with pumice waste upto 40% in increments of 10%. The stabilized soil was tested for its plasticity, CBR, resilient modulus and stress strain characteristics. It was found that the plasticity steadily decreased with the increase in the pumice waste content. The CBR of the subgrade clay steadily increased with the increase in the pumice waste content. The resilient modulus of the soil was found to be good at 10 and 20% addition of pumice waste whereas the values decreased on further increase in the pumice waste content.

Ene and Okagbue [80] investigated the potential of pyroclastic rock dust in the stabilization of expansive soil. The plasticity, linear shrinkage, compaction, California bearing ratio (CBR) and shear strength characteristics of the soil when mixed with varying proportions of pyroclastic rock dust were investigated. The results of the investigation revealed that the addition of pyroclastic rock dust, in general, reduced the plasticity and linear shrinkage of the soil. Its addition resulted in increased dry densities and optimum moisture contents. Pyroclastic rock dust modified expansive soil produced higher unconfined compressive strength and CBR. It was found that 8% pyroclastic dust was found to be the optimal dose for improving the properties. The authors also concluded that the stabilization using pyroclastic dust can be used instead of lime stabilization for pavements.

A comparison of the stabilization changes achieved by solid wastes from miscellaneous sources is tabulated in table 5. Unconfined compression and CBR have been frequent modes of investigation of the strength and bearing of the stabilized soil. The strength improvement achieved in most of the cases is of the order of around 300 kPa with the exception of one case of lime stone dust stabilization which produces strength of more than 1000 kPa. CBR improvements achieved are less than 30%. Investigations related to swell are meager whereas those related to permeability and compressibility is virtually non-existent.

6. Conclusions

Based on the review of the various works in literature, the following points can be concluded.

(i) Utilization of solid wastes in soil stabilization improves the geotechnical properties of the soil while also providing an opportunity for reuse of waste materials. Different industrial wastes provide different degrees of improvement and are suitable for improving soils of different types and are suited for different engineering requirements, thereby enhancing the range of stabilization that can be achieved. This also indicates that development of strength is influenced by soil type and type and nature of the industrial waste adopted. Stabilization with industrial wastes seems to produce the best improvements to strength and bearing in general with strengths as high as 6 MPa produced by cement kiln dust. Strength produced by agricultural wastes is generally in the order of 600 kPa and below. Other wastes like mineral wastes produce strengths of the order of 300 kPa and below. However, these are general trends with exceptional cases which produce results outside the specified ranges. There should be more investigations on the effectiveness of industrial wastes that produce good strength and bearing in other types of soils in order to establish their effectiveness as a universal stabilizer.

(ii) A wide range of index and engineering properties influenced by industrial waste stabilization have been studied. Plasticity, compaction, swell, strength and bearing are the most researched whereas consolidation, permeability and durability are comparatively less investigated. The effectiveness of solid wastes in improving compressibility characteristics need to be addressed especially in the case of soils that are known for their extreme volume change behavior. Effectiveness of solid wastes in order to stabilize soils for use as containment systems need to be delved into more detail, which will enable economical design of engineered landfill barriers and containment systems in developing countries. In order to achieve this goal, investigations need to concentrate on permeability characteristics of stabilized soils. Investigations related to durability of stabilized soils gain importance in light of the fact that lime stabilized soils lose their effectiveness in extreme conditions like wetting and drying, freeze thaw etc. Durability studies thus gain significance in areas with tropical climates and in cold regions wherein stabilized soils perform relatively poorly in extreme conditions.

Table 5 Comparison of Improvement Achieved by Solid Waste Stabilization from Miscellaneous Sources

Author	Soil- Optimum Waste Combination	Major Geotechnical Properties Tested	State before stabilization	Effect after Stabilization
Sabat [69]	Expansive soil + Ceramic dust	Unconfined Compression	55 kPa	98 kPa
		CBR	1.6%	4%
		Triaxial Strength Cohesion Friction Angle	 18 kPa 13^o	 13.5 kPa 39^o
		Swell Pressure	128 kPa	24 kPa
Ameta et al. [70]	Dune Sand + 30% Tile Waste	CBR, soaked	1.67%	3.45%
		CBR, Unsoaked	2.51%	6.59%
Baser [71]	Soil + 30% Lime stone dust Soil + 30% Dolomite dust	Swell Percentage	~38%	~15%
				~18%
Osinubi et al. [72]	90% Recycled asphalt pavement + 10% Sawdust ash	CBR, Soaked	23%	26%
		CBR, Unsoaked	20%	17%
Al-Sharif and Attom [12]	Soil + 7.5% burnt wastewater sludge	Unconfined Compression	~150-190 kPa	~170-210 kPa
		Swell Pressure	~290-460 kPa	~60-140 kPa
Sabat and Nanda [73]	Soil + 10% Rice husk ash + 20% Marble dust	Unconfined Compression	60 kPa	197 kPa
		CBR	2.6%	7.8%
		Swell Pressure	128 kPa	19 kPa
Okagbue [75]	Soil + 10% Wood ash	Unconfined Compression	65 kPa	110 kPa
		CBR	~5%	~18%
Brooks et al. [76]	Soil 1 + 9% Limestone dust Soil 2 + 9% Limestone dust	Unconfined Compression, CBR	610 kPa, 2.5%	1955 kPa, 6.8%
			540 kPa, 4%	1230 kPa, 9%
James and Pandian [77]	Expansive Soil + 30% Egg shell powder	Unconfined Compression	215 kPa	304 kPa
Sabat and Bose [78]	Expansive Soil + 45% Flash-quarry dust (1:2)	Unconfined Compression	55 kPa	~150 kPa
		CBR	1.82%	6%
		Triaxial Compression Cohesion Friction Angle	 17 kPa 13^o	 10 kPa 30^o
		Swell Pressure	132 kPa	12 kPa

Saltan et al. [79]	Clayey Soil + 40% Pumice waste	Plasticity	~35%	~20%
		Repeated Load Triaxial Resilient Modulus	~50 MPa	~240-250 MPa
		CBR	6.78%	~10%
Ene and Okagbue	Expansive soil + 8% Pyroclastic dust	CBR, Unsoaked	14%	18%
		CBR, Soaked	2%	4%
		Unconfined Compression	~74 kPa	~80 kPa

(iii) Some solid wastes have been extensively dealt with whereas others need more investigative works. Flyash, rice husk ash, blast furnace slag are few of the extensively researched solid wastes in soil stabilization. However, this should not stop researchers from investigating their effectiveness in a variety of soils and conditions. They do need more research in their utilization in soil stabilization due to the sheer volume of wastes produced every year. But, a thrust towards investigating new waste materials should begin now rather than later so that the problem of management of such wastes are within manageable proportions and made to stay within manageable extents by providing soil stabilization as an avenue for their resue.

(iv) Utilization of solid wastes in soil stabilization can provide similar or better results when compared to conventional stabilizers like lime. This will slowly enable the reduction of usage of the conventional stabilizers thereby reducing the carbon foot print of manufacture of such materials. Cement kiln dust used in soil stabilization producing strengths as high as 6 MPa can be an effective replacement for cement stabilization, whereas calcium carbide residue producing strengths as good as 2500 kPa can replace lime in soil stabilization. However, the suitability of these wastes for more types of soils and conditions need to be addressed before this can happen. However, it can be said with a fair amount of confidence that utilization of solid wastes can reduce the carbon footprint to an appreciable level in the near future with proper research and utilization levels.

(v) Solid wastes reuse in manufacture of stabilized soil blocks can provide cheaper alternatives to conventional construction materials. Stabilized earth blocks provide strengths that are comparable or higher than conventional bricks or blocks. Phosphogypsum stabilized adobe blocks produced strengths as high as 4.38 MPa whereas coal ash stabilized blocks produced strengths of 3.31MPa. However, utilization of only solid wastes in manufacture of stabilized blocks is limited. Even more limited is the research into the durability aspects of such stabilized blocks. Thus, more investigations are needed to establish the durability of such stabilized blocks when compared to fired bricks. The reason being that firing of bricks make them more resistant to water damage due to fusing of soil particles but in the case of stabilized blocks, its stability is due to reaction products of chemical stabilization which should be stable under water to prevent its degradation. Thus, more research with regard to the durability aspect of stabilized blocks need to be undertaken to ensure the acceptance and replacement of conventional brick by stabilized blocks in commercial construction.

(vi) Utilization of solid wastes results in soil stabilization provides opportunity for cost savings in pavement construction which will be of economic importance in under developed and developing countries. Utilization of flyash, rice husk ash, flyash quarry dust mixes and lime sludge and bagasse ash combinations have been reported to achieve cost savings of 20%, 14%, 11.5% and 13.9% respectively. However, economic evaluation should be done for not only pavement construction but also for other geotechnical applications and in more detail under a wide variety of conditions to improve the acceptance of utilization of solid waste in commercial geotechnical applications. Moreover, the economic analysis should not only be limited to in paper but pilot scale projects should be taken up and performance evaluated to ensure its commercial acceptance and success.

The authors conclude that more investigation on the less researched solid wastes and engineering properties can open up a wider avenue for utilization of solid wastes in soil stabilization resulting in effective waste management especially for developing countries.

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