Limestone ash waste as a substitute for lime in soil improvement for engineering construction

C.O. Okagbue · J.A. Yakubu

Abstract A by-product of the manufacture of cement at Nkalagu, Nigeria, is the waste material comprising 70% CaO and 30% undecomposed $CaCO_3$, referred to as limestone ash. The potential of this waste as a substitute for lime in the improvement of the engineering properties of laterite soils for construction purposes has been assessed. The geotechnical properties of lateritic soils when untreated and when treated with varying percentages of limestone ash have been established, including particle size analyses, Atterberg limits, Proctor compaction, California bearing ratio (CBR) and shear strength. The results confirmed those obtained by other workers on the use of lime stabilisation and indicate that limestone ash may form a substitute for lime in soil improvement for engineering construction.

Résumé Un sous-produit de fabrication du ciment à Nkalagu, au Nigeria, est constitué par un matériau comprenant 70% de CaO et 30% de $CaCO_3$ non dissocié, connu comme poussières de cimenterie. La possibilité d'utiliser ce déchet comme substitut à la chaux a été évalué pour l'amélioration des propriétés géotechniques des sols latéritiques destinés à la construction. Les propriétés géotechniques des sols latéritiques non traités et traités avec différents pourcentages de poussières de cimenterie ont été étudiées, en particulier: granulométries, limites d'Atterberg, essais de compactage Proctor, essai de portance CBR, résistance au cisaillement. Les résultats ont confirmé ceux obtenus par d'autres chercheurs pour la stabilisation à la chaux et indiquent que les poussières de cimenteries peuvent remplacer la chaux pour améliorer les propriétés des sols utilisés dans la construction.

Key words Laterites · Lime · Ash waste · Road construction · Stabilisation · Nigeria

Mots clés Latérites · Chaux · Poussières de cimenterie · Géotechnique routière · Stabilisation · Nigéria

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Introduction

Laterite soils are common in tropical latitudes and, being readily available at low cost, are used often for road construction. However, they frequently do not meet specification requirements, commonly having too high a fines percentage and hence being too plastic. The properties of such soils can be improved by the use of additives, including cement, lime or bitumen, although these are expensive.

Limestone ash is obtained from limestone as a by-product of cement manufacture. In Nigeria it is a waste product which at present is not used and hence remains in unsightly heaps at the cement manufacturing plants. This study assesses the possibility of using limestone ash in the improvement of lateritic soils.

Source and nature of limestone ash

The limestone ash used in this study was obtained from the Nigerian Cement Manufacturing Company (Nigercem) at Nkalagu in Enugu State, Nigeria. The company obtains its limestone raw material from a quarry in the Eze-aku Formation of Turonian age. According to Okeke (personal communication), two different grades of limestone are quarried, one with 85% $CaCO_3$ and one with only 70–71% $CaCO_3$. The two grades are mixed and crushed to produce a material of 78% $CaCO_3$. This mixture is then finely ground to pass the No. 172 British Standard sieve (0.089 mm) in a raw mill and combined with the necessary proportion of water to produce a slurry. The slurry is pumped into tall storage silos from which it is fed into large slurry basins where it is kept continuously agitated.

From these basins the slurry is pumped into the top of inclined rotary kilns which are fired by pulverised coal blown into the lower end (Fig. 1). As the slurry flows down the kiln, controlled by chain curtains, it is heated by the fired pulverised coal, the heat travelling in a counter direction and producing evaporation of the moisture from the slurry. Decomposition of the calcareous component into calcium oxide (quick lime) and carbon dioxide occurs. Finally, at a temperature of about 1000 °C in the burning zone, material that cannot withstand the pressure in the kiln is blown out as limestone ash, which simply accumulates around the chimney. The continuing chemical reaction between the decomposed materials results in the formation of roundish nodules referred to as Portland cement clinker. Limestone ash is a cement-like, grey powder which passes the British Standard 172 sieve.

Previous work

Extensive literature is available on soil improvement by the application of additives, notably cement and lime. The use of additives in construction began some 5000 years ago (Akoto and Singh 1981). In 1924 McCaustland reported on the use of hydrated lime for soil stabilisation in America (McCaustland 1924). In 1948, Aaron reported the first large-scale use of lime in pavement construction when 2% hydrated lime was used to reduce the plasticity index of a caliche gravel in Texas, USA. In Zambia, low-grade lateritic gravels were used as a road base after the addition of 2–3% lime (Clare and Crunchley 1957). Lund and Ramsey (1959) carried out experiments on lime stabilisation in Nebraska and reported that the addition of lime to plastic soils resulted in a reduction in the plasticity index with both the liquid and plastic limit of the soil affected by the additive. These findings were subsequently confirmed by authors working in various parts of the world, including Herrin and Mitchell (1961), Dumbleton (1962), Wang et al. (1963), Jan and Walker (1963), Mateos (1964), Peurifoy (1970), Levinson and Castel (1971), Ola (1975, 1977, 1978), Akpokodje (1985), Anifowose (1989), and Bell (1989, 1993).

Thompson (1965) indicated that the dry density decreased typically by 2–5% while the optimum moisture increased by 1–5% with a lime additive. Although Dumbleton et al. (1966) expressed some concern as to the use of lime with all soils, they supported lime stabilisation as an economic and appropriate method of road construction in Africa, because of the soil types available and the climate.

Research procedure

Bulk samples of laterite were obtained from a borrow pit at the town of Nsukka and taken to the laboratory where they were air dried for 2 weeks. Particle size analysis, Atterberg limit, compaction, California bearing ratio (CBR) and shear strength testing were undertaken generally in accordance with BS 1377 (1975, 1990; British Standards Institute 1975), some modifications being made to take account of the lateritic nature of the soil. In the case of the particle size analyses, for example, samples were washed through the sieve to ensure a complete segregation of the clasts. The clay mineralogy of the soil was obtained on samples passing the BS No. 200 sieve using X-ray diffraction and differential thermal analysis (DTA).

With the exception of the grain size and X-ray analyses, all the tests were repeated using varying percentages (by weight) of limestone ash and soil. Both soaked and unsoaked compaction tests were carried out using moulds in order that the CBR values could be determined at various moisture contents and compactions. Shear strength values were obtained by unconsolidated undrained triaxial testing. Table 1 indicates the standards used and the number of tests undertaken.

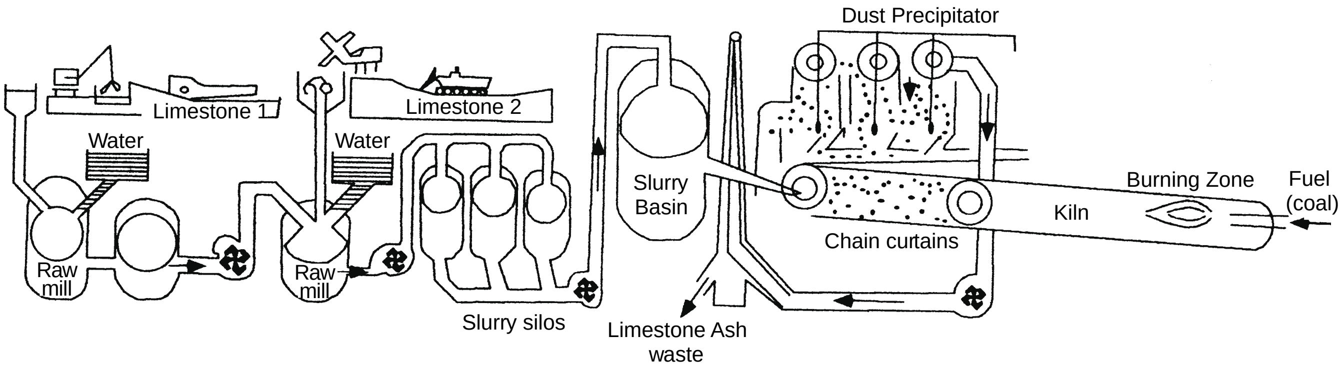

Fig. 1
Sketch showing production of limestone ash waste in the process of cement manufacture

Table 1
Compaction standards used in tests. BS British Standard; Mod BS Modified British Standard

Standard used	Type of test	No. of tests[a]	No. from unsoaked samples	No. from soaked samples	Soaking period (h)
BS	Compaction	36	36	–	–
BS	CBR	36	18	18	24
BS	Shear strength	36	18	18	24
Modified BS	Compaction	36	18	18	24
Modified BS	CBR	36	18	18	24
Modified BS	Shear strength	36	18	18	24

[a] Each test result represents a number of experiments

Table 2
Summary of Atterberg limit and linear shrinkage test results

Limestone ash (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index	Shrinkage limit
0	41.5	21.6	19.9	12.6
2	42.3	23.8	18.5	8.0
4	44.2	26.4	17.8	5.6
6	45.0	28.1	16.9	4.4
8	46.5	31.0	15.5	3.6
10	48.0	33.6	14.4	3.2

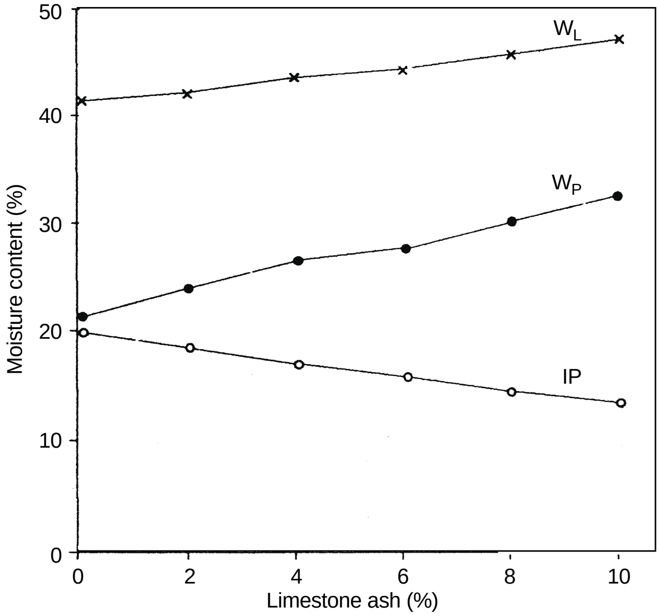

Fig. 2
Variation of liquid limit (W_L), plastic limit (W_P) and plasticity index (IP) of lateritic soil with different percentages of limestone ash

Results and discussion

Classification and Atterberg limits

The laterite used in the investigation comprised 25% gravel, 33% sand and 42% silt and clay fines. The fines plotted above the A line on the Casagrande plasticity chart, indicating the soil to be GW-GC material under the Unified Soil Classification system and A2–7 according to AASHTO.

The results of the liquid limit (w_L), plastic limit (w_p), plasticity index (I_p) and linear shrinkage tests on the treated and untreated soils are summarised in Table 2 and shown graphically in Figs. 2 and 3. It can be seen that both the liquid and plastic limits increased with the addition of limestone ash while the plasticity index and linear shrinkage decreased, supporting the findings of other workers in this field. The X-ray diffraction and differential thermal analyses confirmed that the predominant clay minerals were illite and kaolinite, with relatively small amounts of halloysite also present.

Thompson (1965) and Bell (1989, 1993) have suggested a number of mechanisms which may be responsible for the beneficial changes in the engineering properties of a soil when treated with lime. These include cation exchange, flocculation of the clay, agglomeration and pozzolanic reactions. According to these authors, the first two reactions take place rapidly and produce immediate changes in the plasticity and swelling properties of the treated soil. The calcium silicate gel produced as a result of the chemical reactions coats the clay clasts, binding them together and filling the pores. In this way, water absorption is reduced and hence swelling and shrinkage, leading to improved workability as the treated soil becomes more friable in character.

Compaction characteristics

Table 3 gives the compaction test results obtained using the British Standard and Modified British Standard compactive efforts. The results are also plotted in Figs. 4 and 5 from which it can be seen that while the dry density decreases with greater proportions of limestone ash, the optimum moisture content increases. Again, these results are consistent with those of other workers using lime admixtures with lateritic and other fine-grained soils in temperate zones. Ola (1977, 1978) proposed a two-fold explanation for the decrease in dry density, noting that the

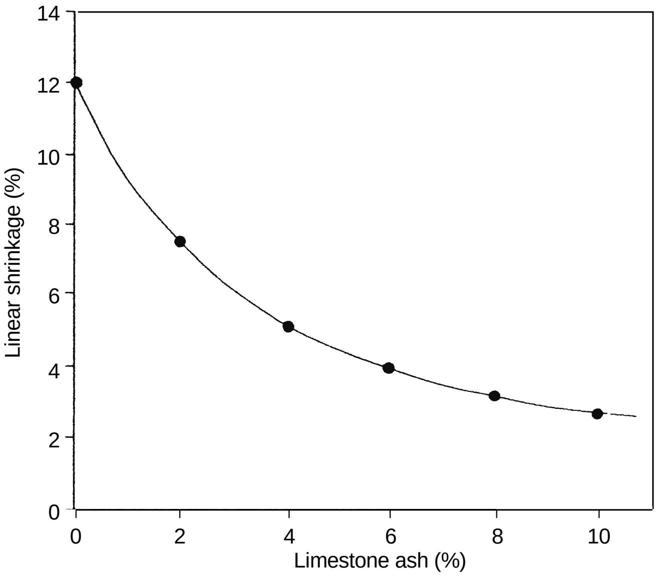

Fig. 3
Variation of linear shrinkage with different percentages of limestone ash

Table 3
Compaction test results following British Standard (BS) and Modified British Standard (Mod BS) procedures

Limestone ash (%)	Maximum dry density (kg/m^3)		Optimum moisture content (%)	
	BS	Mod BS	BS	Mod BS
0	1921	2033	15.5	14.0
2	1857	1985	16.0	14.2
4	1793	1971	18.2	14.5
6	1784	1953	18.7	14.7
8	1771	1938	19.0	14.8
10	1753	1923	19.5	15.0

lime causes agglomeration of the particles such that the effective particle size distribution is changed and that the specific gravity of lime is generally lower than that of most lateritic soils. Although Ola suggested that a pozzolanic reaction between the clay content and the lime was responsible for the increase in optimum moisture content, Akoto and Singh (1981) attributed this to the increase in fines content and the high affinity of lime for water. With increasing amounts of limestone ash, more water is required for the dissociation of the lime content into Ca^{2+} and OH^{-} ions in order to provide more Ca^{2+} ions for the cation exchange reaction. The present authors consider this to account for the increased optimum moisture content in samples with greater proportions of limestone ash.

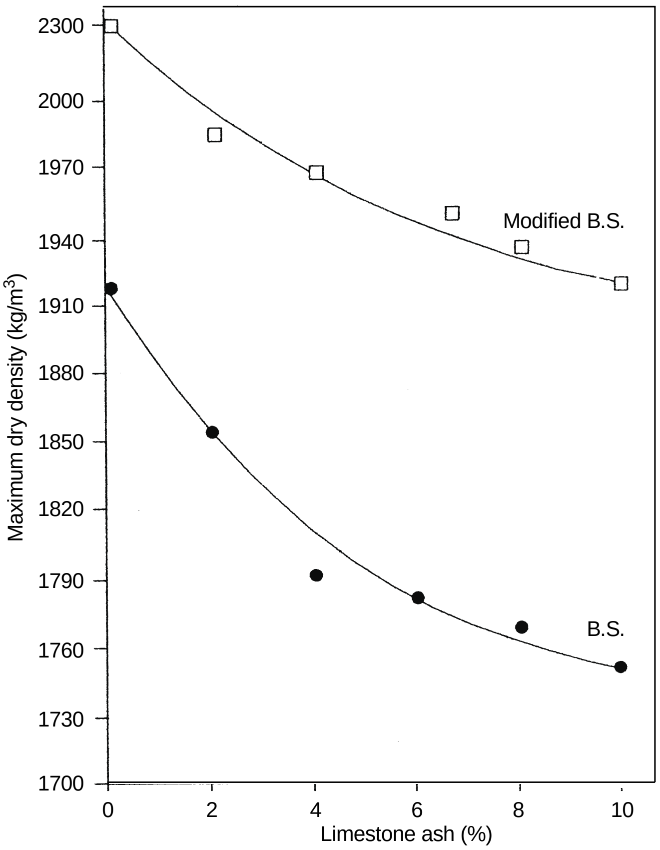

Fig. 4
Variation of maximum dry density with different percentages of limestone ash, tested following British Standard (BS) and Modified British Standard (Mod BS) procedures

It is interesting to note that there is a sharp initial drop in maximum dry density with increasing limestone ash content up to 6%, followed by a reduced rate of decrease with more than 6% additive. It is considered that the initial drop is due to the flocculation and agglomeration of the clay particles as a result of cation exchange reaction. The smaller drop in density with further amounts of limestone additive may be due to the replacement of the soil particles in a given volume by particles of limestone ash which has a comparatively low specific gravity of 2.2 compared with the 2.7 of the soil.

California bearing ratio (CBR)

Table 4 summarises the results of the CBR tests for the compacted soaked and unsoaked samples. The results are also shown graphically in Figs. 6 and 7, from which it can be seen that the CBR value increases as the percentage of limestone ash increases to an optimum level, after which a decrease in CBR is noted. For the soaked and unsoaked samples compacted at both BS and Modified BS compaction efforts, this optimum is reached at about 6% limestone ash – the limit at which the initial sharp decrease in maximum dry density slowed. Similar behaviour has been noted by other authors working on soil–lime mixtures and has been related to the lime fixation point. Thompson (1966), Anifowose (1989) and Osula (1991) report a 3% optimum for lime. If this is reliable, the present studies

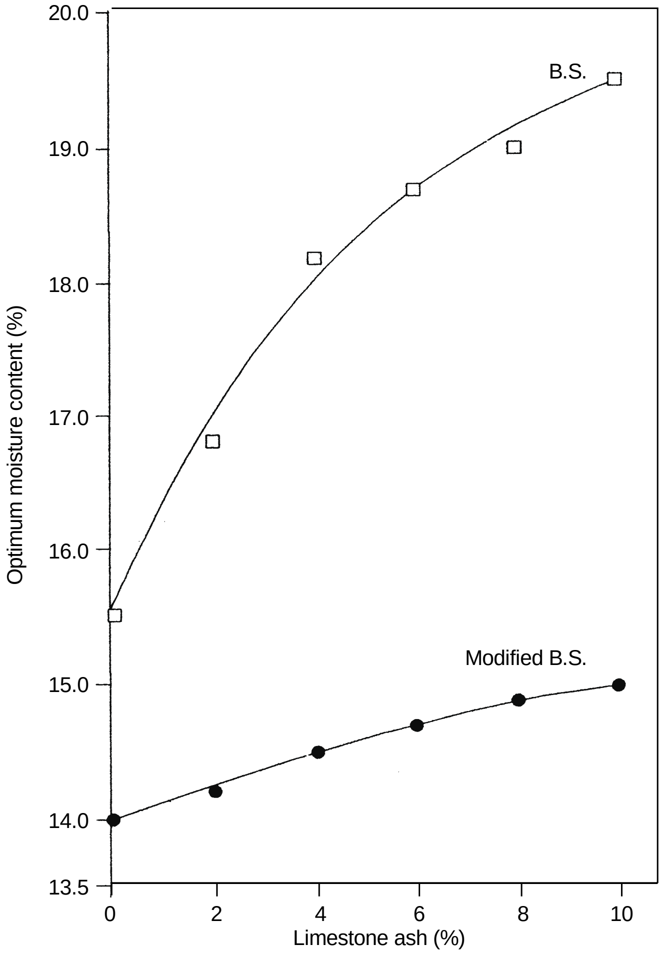

Fig. 5
Variation of optimum moisture content with different percentages of limestone ash, tested following British Standard and Modified British Standard procedures

Table 4
CBR test results for samples compacted following British Standard and Modified British Standard procedures

Limestone ash (%)	British Standard		Modified British Standard	
	Unsoaked	Soaked	Unsoaked	Soaked
0	66	25	70	26
2	70	42	73	40
4	75	55	82	65
6	85	60	90	75
8	70	50	78	65
10	45	34	71	41

suggest that double the amount of limestone ash may be required to achieve the same soil modification.

Various explanations have been put forward for the improvement of the CBR. Newbauer and Thompson (1972) attribute it to the immediate cation exchange and the flocculation and agglomeration reactions, while Diamond and

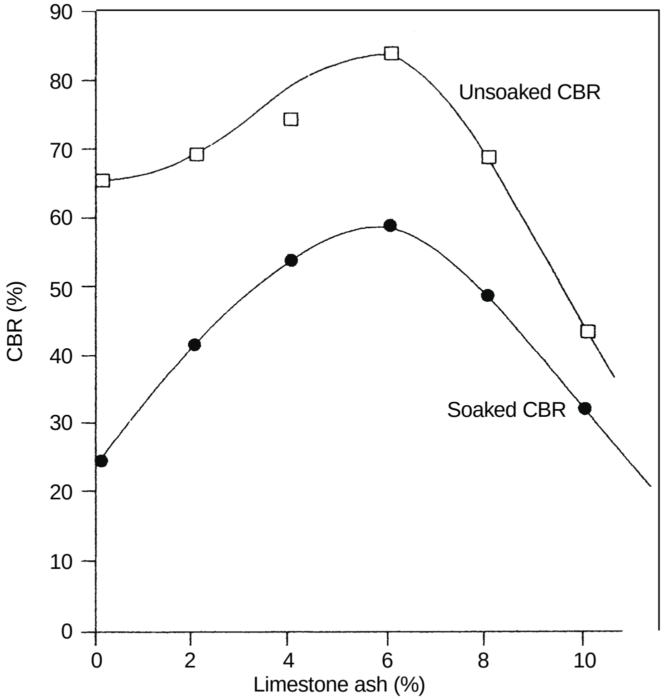

Fig. 6
Variation of California Bearing Ratio (CBR) with different percentages of limestone ash, tested following British Standard procedures

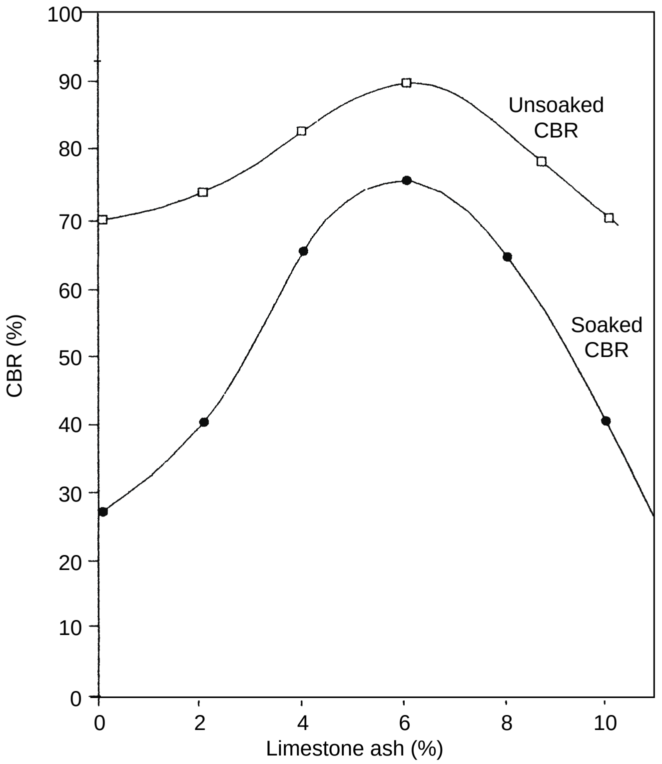

Fig. 7
Variation of California Bearing Ratio (CBR) with different percentages of limestone ash, tested following Modified British Standard procedures

Kinter (1965) postulated that the mechanism responsible is the formation of bonds of tetracalcium alumina hydrates and possibly silicate hydrates which may link the clay particles together. They suggest this is a result of an immediate reaction between the alumina-bearing edges of the clay particles and the lime absorbed on the faces of adjacent particles. Van Ganse (1974) considered the improvement to be due to the formation of "crumbs" of soils which retain their individuality when the lime–soil mixture is kneaded and compacted.

Shear strength

Unconsolidated undrained triaxial tests were conducted on treated and untreated samples compacted at maximum dry density and optimum moisture content. The results are given in Figs. 8 and 9 and summarised in Table 5. A decrease in friction angle and increase in cohesion values with increasing proportions of limestone ash are noted for all the samples.

Ola (1978) reported triaxial tests on lime-stabilised lateritic soil where there was a decrease in the angle of shearing resistance from 26.5 to 18.4° and an increase in cohesion from 24.1 to 45.5 kN/m^2, resulting in a general increase in the overall shear strength with increasing lime content. He considered this to be due to the bonding of particles into larger aggregates such that the soil behaved as a coarse-grained, strongly bonded, particulate material. Lees et al. (1982) and Bell (1989) also discuss cementation and pozzolanic reactions which occur over time.

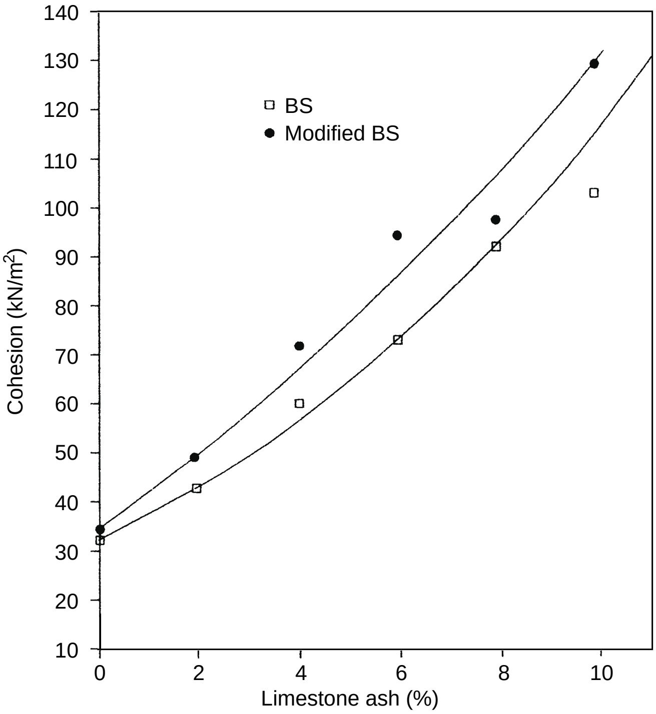

Fig. 8
Variation of cohesion with different percentages of limestone ash, tested following British Standard and Modified British Standard procedures

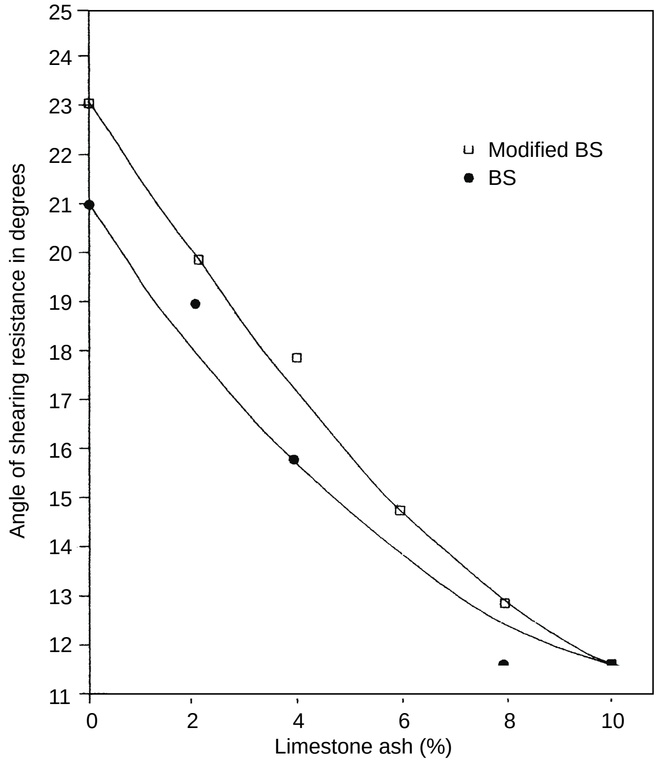

Fig. 9
Variation of angle of shearing resistance with different percentages of limestone ash, tested following British Standard and Modified British Standard procedures

Table 5
Triaxial test results for samples compacted following British Standard (BS) and Modified British Standard (Mod BS) procedures

Limestone ash (%)	Cohesion (kN/m^2)		Angle of shearing resistance (°)	
	BS	Mod BS	BS	Mod BS
0	33	35	21	23
2	50	50	19	20
4	60	72	16	18
6	73	95	15	15
8	92	97	12	13
10	103	126	12	12

Potential use of soils stabilised with limestone ash

Dumbleton (1962) observed that clayey gravels stabilised with hydrated lime could provide a suitable road base for highly trafficked roads. Mateos (1964) reported the successful use of properly compacted lime-stabilised clayey soils for road sub-base, while Thompson (1966) noted the extensive use of lime-stabilised soils for engineering construction and Ola (1977, 1978) found that lime stabilised lateritic soils were sufficiently improved to be used as road sub-base or base material. El-Rawi and Awad (1981) noted many soil types can be stabilised economically such that this process might be used in such works as airfields.

Low-grade lateritic gravels treated with 2–3% lime have been used in road bases in Zambia (Clare and Crunchley 1957) while a lime-stabilised caliche gravel was used in Texas as early as 1948 (Aaron 1948).

When considering potential uses of lime-stabilised materials, however, the effects of wetting cannot be overlooked. Soaked CBR values are regarded as critical when considering the use of limestone-ash-improved soil. Although this may provide an excellent road sub-base when a soaked CBR value of 20% is acceptable, unless waterproofed it would not generally be suitable for base material when a soaked CBR of 80% is usually required.

Conclusions

One of the major environmental problems facing the world today is the safe disposal of waste. The advantage is therefore two-fold when wastes are not simply disposed of but put to good use. This study has assessed the potential of limestone ash waste in stabilising lateritic soils. The tests carried out showed: (1) a decrease in plasticity index and shrinkage limit for treated soil with increased plastic and liquid limits and hence an overall improvement in the workability of the soil; (2) an increase in CBR with the addition of up to 6% limestone ash, the level at which the initial sharp decrease in maximum dry density begins to modify; and (3) the shear strength of the soil is improved with the addition of limestone ash. In general, the results indicate that the trends exhibited by lateritic soils treated with limestone ash are similar to those reported for soils treated with lime. Whilst they suggest limestone ash waste could be used as a substitute for lime, the results also indicate that double the quantity of limestone ash may be required to achieve the same level of soil modification as would be obtained by the use of lime.

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