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Use of Bottom Ash from a Thermal Power Plant and Lime to Improve Soils in Subgrades and Road Embankments

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Abstract: The present study has focused on stabilizing the soils of the embankments and improving the mechanical properties of gravel in subbases of pavements with different contents of bottom ash from thermal power plants and low percentages of lime. The density, humidity, simple resistance strength and bearing capacity of the new materials resulting from this combination have been studied. The results indicated that the optimal proportion of bottom ash added to the analyzed soil is 15%, while the optimal addition of lime is 1% for application in embankments and 2% for application in road subgrades. In clay soil that has a low simple resistance strength when 25% of bottom ash is added without lime, it can double the resistance. In the case of the gravel evaluated, it was found that the optimal ratio between the addition of bottom ash and lime is 6.5. In conclusion, it can be noted that soil that does not have any resistance when certain percentages of bottom ash are added, its properties are improved to be used in embankments.

Keywords: bottom ashes; lime; stabilized soils; embankments; functionalized materials

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1. Introduction

The current concept of the stabilization and improvement of construction materials is closely linked to the idea of mixing "marginal" soils with lime, or to a greater degree with cement in such a way that through hydration and pozzolanic reactions, the characteristics of the soils are improved. The use of industrial by-products in this type of work is not new, especially with fly ash and blast furnace ash; in contrast, the use of mineral-type ash from thermal power stations has not been widely studied.

Within the concept of "thermal power station ashes", there are two types of ash, on the one hand, fly ash and on the other, bottom ash. The pozzolanic character of thermal power station ash makes it especially suitable for mixing with additives containing high percentages of CO in their composition, such as lime or cement. Silicious-aluminous ash, such as those used in this study, can combine with the calcium oxide in lime or cement forming layers with high load-bearing capacity. However, the majority of studies focus on the use of cement and not on lime. This is mainly due to the number of concrete road pavements in the USA whose bases and sub-grades take advantage of the use of layers with the high stiffness modulus provided by stabilization with cement. The use of lime is focused primarily on highly plastic soils or for the construction of bases and sub-grades of flexible and semi-rigid roads, as is the case in Europe, and more specifically in Spain.

There are several studies on the addition of fly ash from thermoelectric power stations and lime to soils and gravels. Herrero demonstrated that the addition of lime to the soil/fly ash mixture increases the optimal water content of the mixture and reduces the maximum density obtained. Moreover, the load-bearing capacity of a soil sample depends on its lime content, with a clear increase being observed in its load-bearing capacity as the added lime content is augmented [1]. The use of ash from blast furnaces as an additive in granular layers for the construction of base layers is contemplated by important official bodies, such as the American Coal Ash Association (ACAA), which recommends the application of F-type fly ash along with a catalyst material such as lime or cement for treated granular layers. The dosage is between 10% and 15% of fly ash along with 2 to 8% of lime [2]. Arora and Aydilek concluded that the simple compression strength (SCS) in soil-ash and gravel-ash mixtures with added lime decreases with content greater than 4% of lime [3].

The Dept of Transport at the University Aristotle (Thessalonica) analyzed the application of fly ash from thermoelectric power stations in granular layers of sand and gravel and in the stabilization of soils. They carried out numerous characterization limit tests (Atterberg, Proctor and SCS) on samples with different contents of ash (5, 10 and 20% by weight) and for different curing times (7, 28 and 90 days). It was observed that the SCS values increased significantly as the ash proportion and curing periods increased, but less than was observed for stabilized soils. This was due to the higher number of gaps present in the granular layer. For this reason, they recommend a dosage of 10% given that the increased strength does not justify a larger proportion of material [4].

In the study of the evolution of simple compression strength over time for different percentages of fly ash and/or lime, a delay in the acquisition of strength is observed [5]. Another interesting study confirms this phenomenon, as well as analyzing how the strength always increases as the lime content does. However, this is not true for fly ash whose optimum value is between 10 and 15% for these soils. This is due to the decrease in the density of the mix, and thus, to the decrease in load-bearing capacity and SCS, with the addition of ash above a threshold value, which varies with the particle size distributions and plasticity of the type of soil [6]. Buhler and Cerato demonstrated another important characteristic of soils stabilized with fly ash and lime, namely, the improvement of plastic properties and the liquid and plastic limits, in such a way that the plastic index is reduced and the soil becomes less sensitive to changes in humidity [7]. Keulen et al. analyzed the performance of washed bottom ash from solid municipal waste incineration as a replacement for natural gravel in concrete. As a result, it was shown that the physical performance of fresh and hardened concrete (e.g., workability, strength, and freeze-thaw) of high-strength concrete mixes was maintained or improved compared to reference mixes, even after replacing up to 100% of the initial natural gravel [8].

A previous study analyzed the use of ashes from the thermoelectric power stations at Soto de Ribera and Aboño (both in Asturias, Spain), concluding that the soil-ash mixtures without lime were satisfactory for use in road sub-grades [9].

Continuing to develop new soil stabilizing products, Wang et al. study the potential application of ash and slag fly-based geopolymers as stabilizers for soft soils in sulfate erosion areas to promote environmental protection and waste recycling [10]. Finally, in 2023, Su et al. [11] conducted micromorphology, element composition and pore structure tests to compare and investigate the physical properties and micromechanism of solidified geopolymer-based on slag/fly ash, organic clay (GSO) and solidified cement organic clay (OCS).

In summary, these studies highlight the importance of soil stabilization and improvement of building materials using fly ash, lime and cement, and suggest specific dosages depending on soil characteristics and engineering requirements. They also show an ongoing interest in developing new technologies to address specific challenges in construction and promote environmental sustainability.

The aim of the research is for the analyzed material to be able to improve soils that can be used in road embankments and gravels used in the subbase of pavements. In addition to the effect that the bottom ash has together with lime, the research wants to know what the increase in the mechanical behavior of the soils and gravels is. On the other hand, based on these results, the environmental potential stands out, going from being a waste product that needs to be managed in landfills, to a product for effective use on roads, thus reducing environmental costs and reducing the use of natural materials.

2. Materials

Three types of soils were chosen, that on their own did not have optimum characteristics for use in sub-grades or road layers, but with the addition of ash and lime, could be stabilized for use in different layers of sub-grades or even in the set of road layers.

Table 1 shows the values of liquid limit, plasticity index, maximum dry density and optimum humidity, CBR index and simple compression strength. It can be observed that soil S3 has a good initial CBR, but even so we study whether it could be improved.

Table 1. Starting soil characteristics.

Soils	WL	IP	γ_d (KN/m^3)	Optimum Wet (%)	CBR	UCS(MPa)
S1	31.50	15.10	19.42	11.80	0	0.474
S2	27.32	11.95	22.12	6.90	2	0.852
S3	24.60	10.60	22.10	6.30	11	1.070

According to the Spanish classification, the three soils are considered tolerable; in contrast, according to the AASTHO and ASTM classifications, soils S1 and S2 are A-6 and CL type, respectively, and S3 is A-7-6 and SC type.

As for the gravels treated with bottom ash and lime, they fulfill all the requisites designated in the Spanish norm for gravel-cement (article 513 PG3). This starting gravel has a maximum particle size of 20 mm, a Los Angeles coefficient of 28, a SLAB index of 10 and a sand equivalent of 42, and its particle size distribution use is as indicated in the norm.

The bottom ash used in the study comes from the Soto de Ribera thermoelectric power station (Asturias, Spain). In contrast to the ash used in other soil stabilization studies, it is extracted from the precipitate of the pipes used for removing the gases from coal combustion. It has a maximum particle size between that of the slag stored in the ash collector of the furnace and the fly ash, which can remain in suspension due to its fine particle size.

The analysis of the peaks enables a reliable interpretation of the diffractogram (Figure 1). In this case, it can be observed that the predominant phases are siliceous and, to a lesser extent, calcite (calcium carbonate). There are also minority phases such as feldspars and clays or phyllosilicates, particularly, kaolin. The chemical composition of the ash, as can be observed in Table 2, has a high percentage of silicates and aluminates, and to a lesser extent iron and calcium oxides, the latter being responsible for providing the cementitious or pozzolanic characteristics.

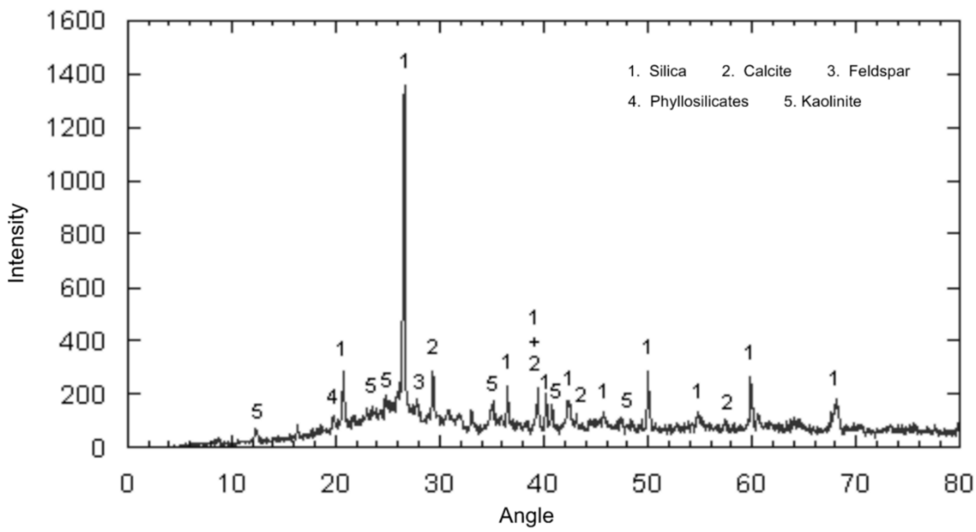


Figure 1. Diffractogram Bottom ash Soto de Ribera.

Table 2. Chemical composition Soto de Ribera ash and lime.

Component	Bottom Ash	Lime
Silica (SiO_2)%	38.8	
Alúmina (Al_2O_3)%	21.4	6.00
Ferric Oxide (Fe_2O_3)%	5.91	
Calcium Oxide (CaO)%	4.99	90.00
Potassium oxide (K_2O)%	2.33	-
Magnesia (MgO)%	1.16	-
Titanium oxide (TiO_2)%	0.87	-
Phosphorus pentoxide (P_2O_5)%	0.32	-
Strontium oxide (SrO)%	<0.1	-
Barium Oxide (BaO)%	<0.1	-
Carbon (C)%	23.3	-
Sulfur (S)%	0.48	-
Carbon Dioxide (CO_2)	-	4.00

The other ash components come from the "un-burnt" residues, which are negative for the pozzolanic character of the ash. According to the ASTM C 618 norm [12], the ash under study is Class F type (produced by calcinations of anthracite or bituminous coals; ashes that show pozzolanic properties). Comparing the bottom ashes and the fly ashes analyzed in other studies, the chemical composition is very similar [13,14].

After the chemical analysis of the Soto de Ribera ash, the pozzolanic character of the ash was studied [15]. The norm establishes that the test is positive (pozzolanic material) if after eight days the concentrations of hydroxyl and calcium ions are within the lower zone of the saturation concentration curve, which can be seen in the figure (zone 1). If the results obtained are observed (see Figure 2), the concentrations of [OH]- and [Ca O], (1.5 [●], and 1.47 [▲] m mol/L, respectively) after eight days can be found in the lower zone delimited by the saturation curve.

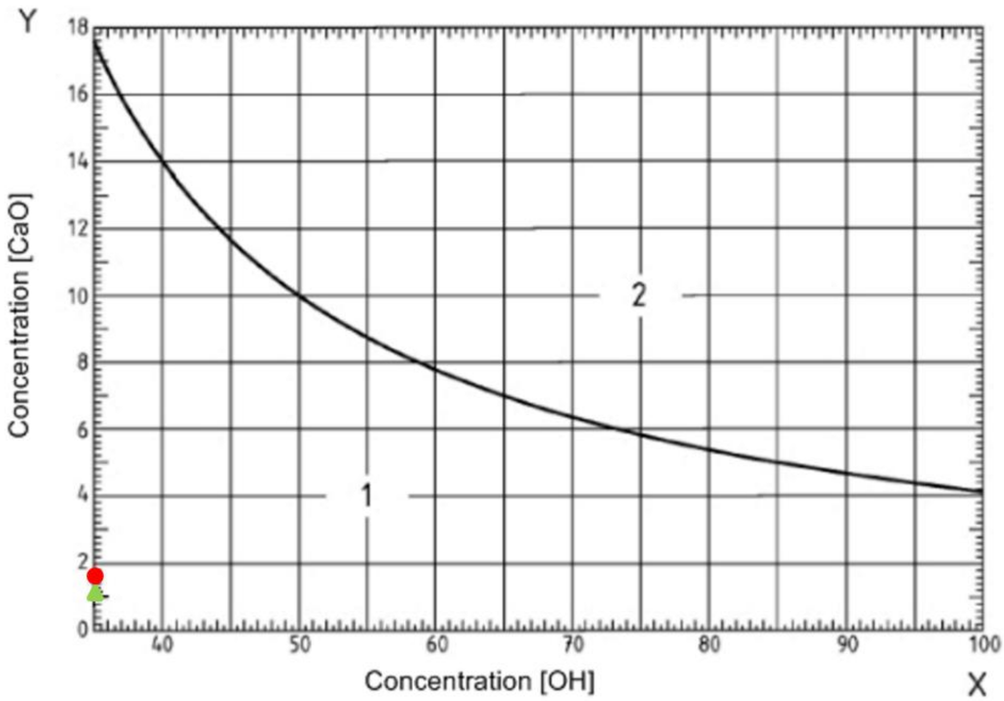


Figure 2. Pozzolanity.

Thus, the ash is considered to have a pozzolanic character mainly due to its chemical composition, having a high SiO_2 and Al_2O_3 content, and in the chemical analysis, the free non-hydrated lime percentage is much lower than the CaO value.

The lime used for stabilization of the soils and gravels is hydrated air lime CL90 [16], with the characteristics stipulated in the Spanish norm in article 200 of PG3.

3. Methods

Different percentages of ash and lime were added to the soils and gravels in the tests to study the variability and to discover the optimum percentages of added ash and lime.

The tests carried out to characterize and study the soils and gravels stabilized with bottom ash and lime were those included in the Spanish norms for the use of soils stabilized using lime or cement and those that refer to gravel-cement (articles 512 and 513 of PG3), namely Particle size analysis, Modified Proctor test, soil plasticity, CBR and simple compression strength (SCS).

Although the norm defines specific compaction times, several compaction times were tested for the CBR and SCS tests.

3.1. CBR Index

The CBR test is used to evaluate the bearing capacity of compacted soils such as embankments, pavement layers and esplanades, as well as in the classification of soils, it is based on the acronym CBR, which stands for Californian Bearing Ratio.

Soil CBR testing involves compacting a soil sample into standard molds, immersing them in water, and applying a point load to the soil surface using a standard piston.

The preparation of the soil sample is defined in the UNE 103502 [17]. Water is added gradually until the desired optimum humidity is reached. Once optimum humidity is achieved, the sample is placed in standardized CBR molds 15.24 cm in diameter and 17.78 cm in height.

Compaction is performed as defined in NLT-310 [18], which uses a vibratory hammer. In this case, the compaction times stipulated in the norm, namely 5, 10 and 20 s were varied because they do not provide sufficient compaction energy to achieve acceptable dry densities. For this reason, a specific study was carried out on the variation in density related to compaction time. The times necessary to obtain the acceptable strengths were found to be 20, 90 and 180 s, which were then used for the tests corresponding to the CBR index for the different soil-ash-lime mixes.

3.2. Simple Compression Strength Unconfined Compressive Strength (UCS)

The purpose of the unconfined compressive strength test [19] is to determine the strength of cohesive soil to unconfined compression. This procedure involves the application of an axial load with strain control on an undisturbed soil sample in the shape of a cylinder, with a height/diameter ratio equal to 2. In the simple compression test, the strain is kept constant while the applied load varies, resulting in a characteristic stress–strain curve. This is achieved by controlling the strain and accurately recording the data during the test.

For the simple compression strength tests, the same problem exists in obtaining densities as in the case of the CBR index. Moreover, as the sample sizes are very similar and the compaction method is identical to the previous case, the soil samples were compacted with a 180 s duration to guarantee that acceptable densities were obtained. The same happens in the case of gravels as for soils except that in this case, the compaction time necessary to obtain acceptable densities was 30 s.

3.3. Dynamic Tests

For the dynamic study, as there is no norm, in-house tests have been developed. A three-point static flexion test and dynamic loading test.

A sample of 305 mm × 305 mm × 100 mm was manufactured for both tests, compacted in a layer, with a compaction time permitting 100% of the reference Proctor density to be achieved.

To obtain the load to be applied in the dynamic test, a three-point flexion test was carried out on the sample and in this way, the reference load for the static flexion test was obtained.

The flexural strength σ_F in the interior fiber in the central section of the sample is:

$$\sigma_F = (25 \times Q)/(4 \times W)$$

where the W = 508.33 cm^3 and Q is the breaking load, depending on the characteristics of the sample.

As for the dynamic loading test, a 28 mm initial fissure was created on the underside of the central section of the sample across its complete width in order to monitor the propagation of cracks. The dynamic test was conducted on top of a 24 mm-thick rubber support simulating the situation of the material in the road layer, on an E1 type sub-grade. The test frequency was 10 Hz and the reference load was obtained from the flexion tests. The results obtained from the test were the different loading cycles, the horizontal deformation in the crack, (Figure 3), and the vertical displacement of the sample in the upper fiber.

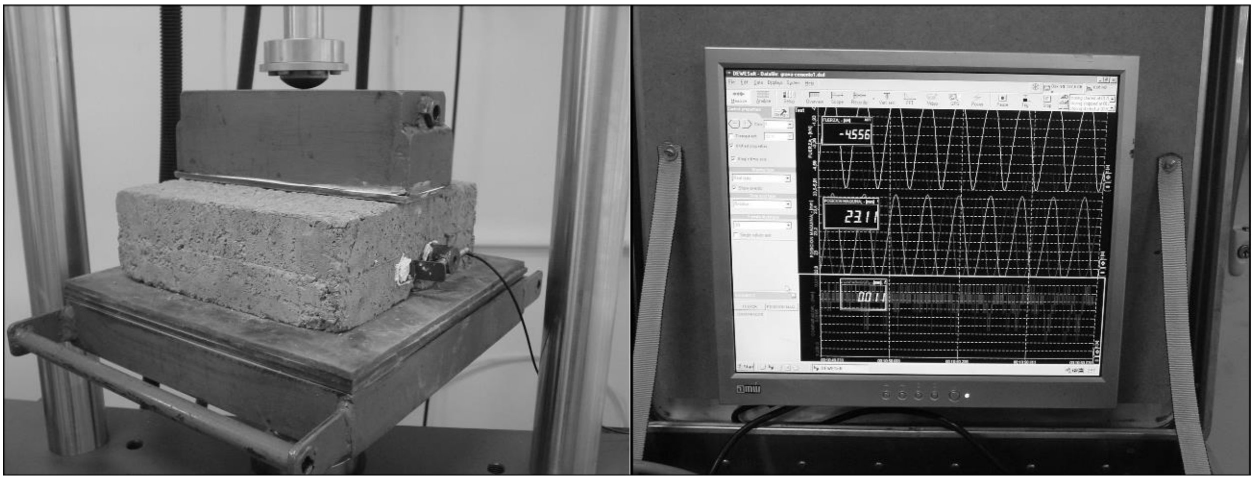


Figure 3. Dynamic test.

A three-point static flexion test was carried out in the fiber to obtain the reference value of the load to be applied. In the test, the breaking load for the soil-cement was 2.1 KN with a maximum stress of 0.246 MPa. These values are very low in comparison with the loads applied by traffic, so this line of analysis was abandoned for the case of stabilized soils.

4. Results

4.1. Soils Stabilized with Bottom Ash and Lime

The nomenclature used for the soils will be Sx – YYZ, where x: soil type (1, 2 or 3), YY: percentage of added ash to soil x, and Z: percentage of lime added to soil x.

4.1.1. Particle Size Analysis

Figure 4 shows the three groups of soils and the grading envelope of each soil subgroup S1, S2 and S3. Moreover, as the content of ash added to the soils increases, the percentage of fine particles decreases (less than 2 mm), given that part of the clay is replaced by the bottom ash.

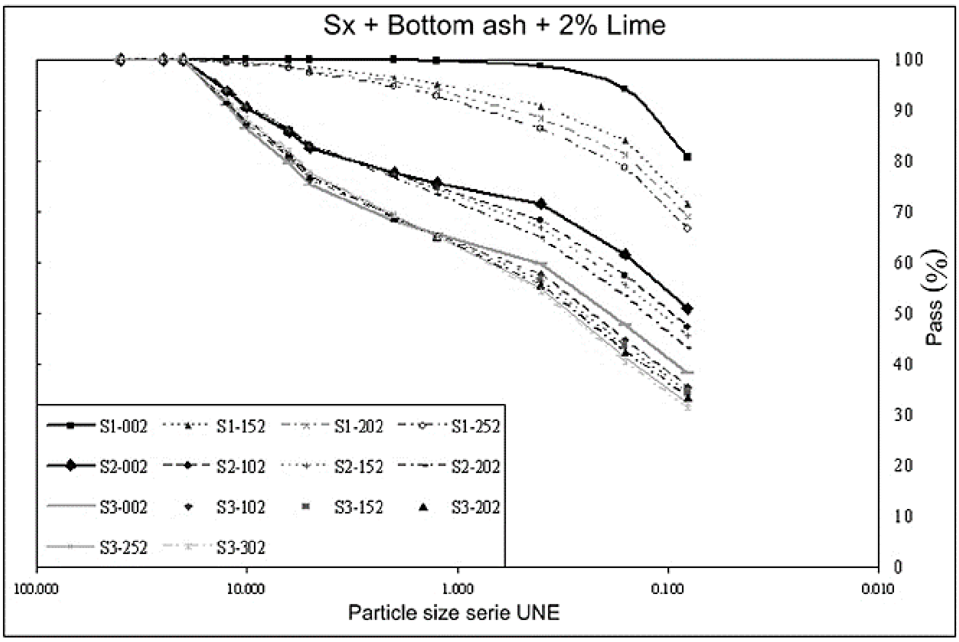


Figure 4. Particle size analysis for soils.

4.1.2. Variation of the Optimum Humidity and Maximum Dry Density

In the case of soil S1, the addition of ash decreases the optimum humidity. This is because the particle size of the bottom ash has a maximum size of 2 mm, and soil S1 (100% clay) has a clearly fine Particle size distribution.

In the case of soil S2, the variation in the particle size is much smaller. On increasing the ash content, the percentage of fine particles less than 2 mm also increases, so the optimum humidity increases. Soil S3 has a similar behavior to soil S2 in terms of the variation in the humidity with the addition of ash.

Soils S2 and S3 with added lime undergo an increase in optimum humidity due to the great fineness of lime. Soil S1 undergoes a different change when no ash is added. Given that it is made up of clay with a particle size equal to or less than the lime, the optimal humidity decreases as the specific surface decreases. However, if ash and lime are added, what happens is that the specific surface increases, as does the optimum humidity. A binder material with a very small particle size has a lot of specific surface area, and therefore, the optimal humidity increases. Even so, due to their characteristics, bottom-ash and lime soils increase the load-bearing capacity and decrease the maximum density of the Proctor test of the original soil.

As for the density, the same occurs in the case of all three soils and with the addition of ash and/or lime; the density decreases in all the cases, given that the density of the ash and of the lime is less than that of the starting soils (Table 3).

Table 3. Maximum densities and optimum wet. Soils Stabilized with Bottom Ash and Lime.

		Maximum Density (KN/m^3)					Optimum Wet			
		Lime Content					Lime Content			
Soil	**Bottom Ash**	**0%**	**1%**	**2%**	**3%**	**Bottom Ash**	**0%**	**1%**	**2%**	**3%**
S1 (100% clay)	0%	21.12	20.70	20.48	20.10	0%	11.80%	9.60%	10.30%	10.90%
	15%	19.60	19.30	19.22	-	15%	9.25%	10.50%	10.25%	-
	20%	19.20	19.20	18.75	18.60	20%	9.20%	9.30%	10.60%	10.70%
	25%	19.20	18.62	18.43	18.37	25%	9.80%	10.50%	11.10%	10.75%

Table 3. *Cont.*

		Maximum Density (KN/m^3)					Optimum Wet			
		Lime Content					Lime Content			
Soil	**Bottom Ash**	**0%**	**1%**	**2%**	**3%**	**Bottom Ash**	**0%**	**1%**	**2%**	**3%**
S2 (65% clay)	0%	22.12	21.35	21.12	21.00	0%	6.90%	8.00%	8.80%	9.00%
	10%	20.70	20.24	20.18	20.16	10%	7.80%	8.00%	8.70%	8.70%
	15%	20.14	20.00	19.75	19.83	15%	8.20%	8.20%	8.60%	8.75%
	20%	19.74	-	19.27	-	20%	7.70%	-	9.00%	-
S3 (50% clay)	0%	22.10	21.62	21.50	21.31	0%	6.30%	7.30%	7.75%	8.00%
	10%	-	-	20.60	20.44	10%	-	-	7.50%	8.00%
	15%	20.35	-	19.85	20.10	15%	7.90%	-	8.40%	8.30%
	20%	20.00	-	19.65	19.38	20%	7.25%	-	9.40%	8.40%

The results of the present Proctor test are similar to Herrero's results [1] on how the addition of lime increases the optimal water content and reduces the maximum density obtained.

4.1.3. Variation of the CBR Index

As has been explained, to obtain the CBR index and study compaction and load-bearing capacity, some modifications have been made to the test. Another characteristic that should be highlighted is the reduction in swelling, with this reduction being more notable on adding lime than on adding ash.

The densities obtained using the vibratory hammer in the case of soil S1 are insufficient in all cases, reaching percentages of 90–94% of the reference-modified Proctor density, even when the compaction times are increased. This occurs because soil S1 is clayey and it is impossible to reach the same values of compaction with vibratory methods as with mass impact ones. Nevertheless, the results obtained for load-bearing capacity are considered, given that as the density increases, the load-bearing capacity of the material increases. With soils S2 and S3, the problem of obtaining densities was not considered, in some cases reaching values of 99 and 100% of the modified Proctor density.

Table 4 shows the clear increase in load-bearing capacity both with added lime and with added ash, the effect being greater for added lime than for added ash. Other authors stabilized fly ash and GBFS, increasing the load capacity with the addition of cement [20]. Another characteristic that should be highlighted is the reduction in swelling, which is more notable with added lime than with added ash. Reductions of between 1 and 2% can be seen.

Table 4. CBR (180 s).

CBR												
Soil	**S1 (100% Clay)**				**S2 (65% Clay)**				**S3 (50% Clay)**			
% Bottom Ash / **% Lime**	**0%**	**15%**	**20%**	**25%**	**0%**	**10%**	**15%**	**20%**	**0%**	**10%**	**15%**	**20%**
0%	0	2	2	4	0	12	22	21	11	-	34	79
1%	11	12	14	22	50	50	75	63	71	-	-	-
2%	16	31	33	42	-	-	-	-	-	-	-	-

4.1.4. Variation in Unconfined Compressive Strength (UCS)

In the soils treated with ash and lime, the setting and curing times are much longer than for cement; therefore, the strengths obtained at 7 days are much lower than those for cement.

For soil 1, there is a clear tendency toward values of 25% added ash, which is the optimum value for this soil, given that with more added ash the strength values are smaller due to the lower density.

Moreover, the strength does not increase proportionally to the increasing percentage of added lime, but it can in fact decrease.

Soils S2 and S3 both obtain the greatest strengths with combinations of 15% ash and 2% lime for dry densities close to 100% of the modified Procter dry density (Table 5).

Table 5. Soils Stabilized with Bottom Ash and Lime UCS(MPa).

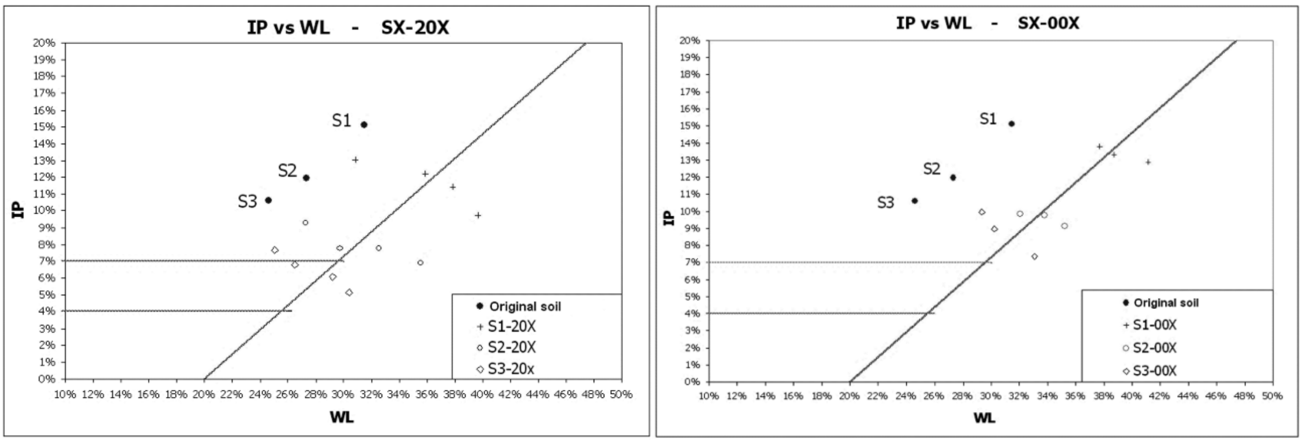
UCS (MPa)													
Soil	**S1 (100% Clay)**				**S2 (65% Clay)**				**S3 (50% Clay)**				
% Bottom Ash / **% Lime**	**0%**	**15%**	**20%**	**25%**	**0%**	**10%**	**15%**	**20%**	**0%**	**10%**	**15%**	**20%**	**30%**
0%	0.47	-	0.81	0.97	0.86	0.91	1.10	1.09	1.07	0.99	0.99	1.05	0.98
1%	0.52	-	0.86	1.00	-	-	-	-	-	-	-	-	-
2%	0.57	-	0.90	1.03	0.85	1.04	1.37	1.16	0.95	1.27	1.53	1.32	1.31
3%	0.88	-	0.97	1.10	1.07	0.87	0.91	0.91	1.16	1.00	1.17	1.17	-

The incorporation of bottom ash from thermal power plants and lime results in a significant increase in the bearing capacity and UCS of natural soils

4.1.5. Variation in Plasticity

The plasticity of soils depends on the proportion of clayey particles of a specific size that make up the soil structure. The normalized test to determine the limits of consistency requires the use of material that passes through a sieve of 0.4 mm aperture; therefore, the ash and the lime with the greatest proportion of particles passing through this aperture will tend to modify the plasticity of the mixes.

The addition of lime greatly increases the plastic limit value and maintains or slightly increases the liquid limit, so the plasticity index decreases. Depending on the existence of calcium (from the ash or lime) combined with the silicious and the alumina of the ash and clay, the pozzolanic reaction continues and the mechanical strength will increase: For this reason, the lime is converted into a catalyst in this reaction (Figure 5a,b).



(**a**) (**b**)

Figure 5. (**a**) Plasticity of soils with 20% bottom ash (**b**) Plasticity in soil without bottom ash.

Another effect produced by the pozzolanic reaction is the decrease in the permeability of the soil-ash-lime mix, which continues to decrease with the pozzolanic reactions, thus reducing the mix's susceptibility to water.

4.2. Gravel Treated with Ash and Lime

The nomenclature used for the gravels treated with ash and lime is G – YYZ, where YY: percentage of ash added to the gravel, and Z: percentage of lime added to the gravel.

The material used to carry out the study is silica-type gravel, which has been produced with a particle size of gravel cement with a maximum size of 20 mm (GC-20) required by PG3 for the construction of the base and sub-grade layers with gravel-cement.

4.2.1. Particle Size Analysis

The particle size used is as proposed in PG3 in article 513, for a GC-20 type gravel-cement.

The ash added to the gravel produces an effect on its particle size, making it more continuous. In contrast, the lime added produces an increase in filler (Figure 6).

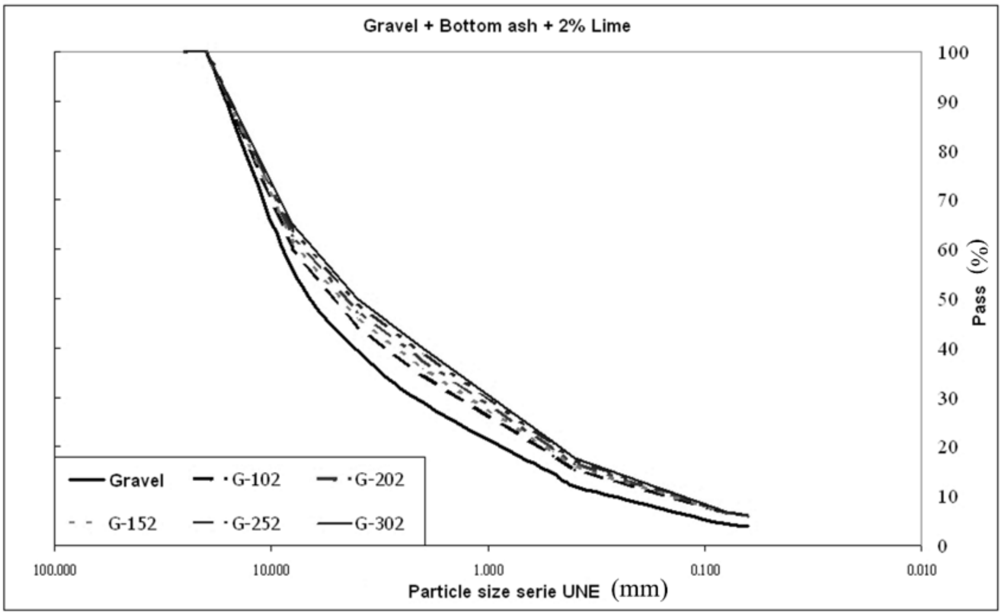


Figure 6. Particle size analysis for gravels.

4.2.2. Variation of the Optimum Humidity and Maximum Dry Density

As occurred with the soils, in the gravels treated with ash and lime, the dry density decreases with added ash and the optimum humidity increases (Table 6).

Table 6. Maximum densities and optimum wet. Gravel Treated with Ash and Lime.

	Maximum Density (KN/m^3)			Optimum Wet (%)		
	Lime Content			Lime Content		
Gravel	0%	2%	3%	0%	2%	3%
G-00%	22.20	22.05	21.93	6.00%	6.90%	7.50%
G-10%	21.03	21.32	20.71	7.65%	7.80%	8.15%
G-15%	20.80	20.50	20.49	8.60%	9.20%	8.75%
G-20%	20.04	19.99	19.98	9.72%	9.10%	9.10%

4.2.3. Variation in Unconfined Compressive Strength (UCS)

The unconfined compressive strength of gravels treated with different materials is a decisive factor in the dimensions of the different base and sub-grade layers.

The results in Table 7 show the special behavior of this ash and lime mix. For values of added ash of 15% and a 28-day curing period, simply by adding 3% lime, the maximum strength can be obtained. Moreover, it can be seen that simply adding lime does not increase the strengths, that is, the ash needs a specific proportion of lime, with respect to its own added value, to enable activation. Given that an increment of between 2 and 3% of added lime does not lead to a great variation in the compression strengths, and bearing in mind that for values of 4% of added lime the strengths start to decrease, the optimum value of added lime for a mix with 15% of added ash would be between 2 and 3% of lime. Even so, a slightly better compression value is found with mix G-152 than with G-153 for a curing period of 90 days. Moreover, the optimum value of added lime does not depend only on the bottom ash added, but also on the curing time. In fact, for curing periods of 90 days, the optimum is about 20% of added bottom ash and 3% of added lime. As we add more bottom ash, it is necessary to add more lime and the curing time must be increased to obtain the optimum value. Therefore, the optimum ratio of added bottom ash to lime is 6.5.

Table 7. Gravel Treated with Ash and Lime UCS (MPa).

UCS (MPa)									
	0% Lime			2% Lime			3% Lime		
Days	**7**	**28**	**90**	**7**	**28**	**90**	**7**	**28**	**90**
Gravel	0.161	-	-	0.359	0.485	0.586	0.24	0.392	0.528
G-10%	0.353	0.666	0.822	0.478	0.628	2.375	0.635	0.805	2.454
G-15%	0.456	0.653	0.561	0.567	1.091	2.753	0.623	1.301	2.680
G-20%	0.461	0.471	0.557	0.639	0.929	3.053	0.603	1.188	3.212
G-25%	-	-	-	-	-	2.932	-	-	-
G-30%	-	-	-	-	-	2.633	-	-	-

Analyzing the results, as well as the simple compression strength, the modulus of the material can be obtained, demonstrating the evolution of the modulus with the curing time of the mix (Table 8). The values of the modulus increase significantly after 28 days, obtaining an increase between 28 and 90 days of 300%, where the activation of the ash with the lime over an increasing curing time can be seen.

Table 8. Young's Module (MPa).

Young's Module (MPa)						
	2% Lime			3% Lime		
Days	**7**	**28**	**90**	**7**	**28**	**90**
G-10%	28	40	117	25	37	100
G-15%	26	46	123	26	48	120
G-20%	31	48	142	26	52	150

Comparing these results with the values obtained in two different studies for the case of fly ash, [21,22] similar values can be seen with respect to simple compression strength.

4.2.4. Dynamic Test

To carry out the dynamic study of these mixes of gravels with ash and lime, first a reference static flexion test was conducted and then the dynamic loading test was performed.

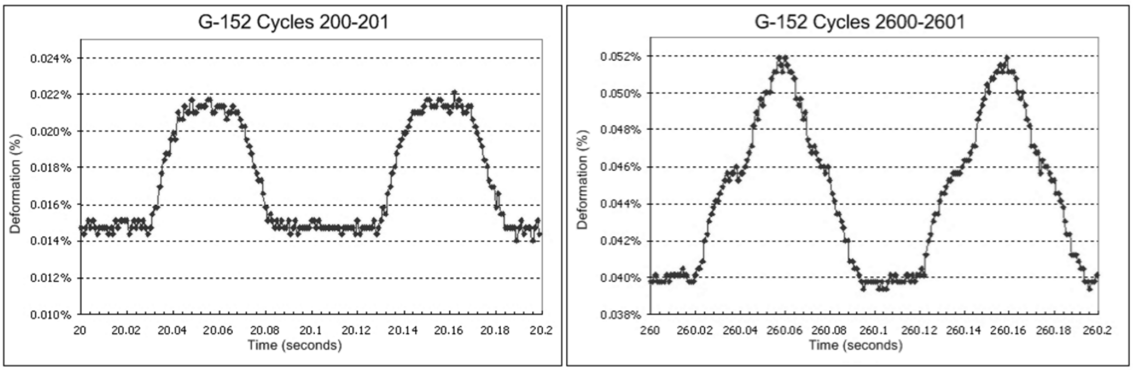
It should be mentioned that for the analysis of the behavior under dynamic loading, the mixes of gravel with ash and lime used were G-150, G-152 and G-153 due to the results obtained in the study of the simple compression strength at 28 days. The results of the static flexion test are shown in Table 9.

The gravels with added ash only do not acquire any strength at 90 days. In the case of mixes with added ash and lime, it was observed that at 28 days of curing, the flexion strengths were too low. Moreover, these samples were prepared for the dynamic test with a pre-fissure, but as they were incapable of resisting this process, the samples with 28 days' curing were rejected and only the 90-day cured samples were selected. In the samples with more than 15% added ash, a clear decrease in densities can be seen, which affects the flexion strengths, reducing them and making them null, which did not occur in the simple compression test. Another clear symptom is that these samples are not sufficiently strong to resist the process of pre-fissuring, even after 90 days of curing (Table 9).

Table 9. Static flexion test results.

% Lime		Gravel-Cement	G-15%
		28 Days	90 Days
0%	Breaking Load (KN)	10.00	0.00
	σ_F Stress (MPa)	1.23	0.00
2%	Breaking Load (KN)	-	3.00
	σ_F Stress (MPa)	-	0.37
3%	Breaking Load (KN)	-	3.50
	σ_F Stress (MPa)	-	0.43

After the static flexion test, the dynamic loading tests were carried out, starting with the gravel-ash-lime in order to compare results with the gravel-cement. The first dynamic test was with G-152, varying the load applied starting from a value a little less than the one used in the static flexion test (2 KN): It withstood 3000 cycles, which is a very low value indicating that the material does not resist sufficiently (Figure 7a,b).



(**a**) (**b**)

Figure 7. (**a**) Graphs of time vs. deformation cycles 200–201 (**b**) Graphs of time vs. deformation cycles 2600–2601.

The results show an excessively rapid growth of the crack, the deformations doubling in only 2400 cycles, even with relatively low loads. To analyze the behavior of the material under dynamic loading, very low loads must be used which do not correspond to those applied by traffic. Therefore, it can be concluded that the gravel-ash-lime mix does not have good behavior under the dynamic loads generated by traffic. This means that this material must not be used or must be used in lower layers where the traction forces are small.

The load corresponding to the flexion load was applied to the gravel-cement, leading to an excessive number of cycles for analysis; therefore, the load was increased up to 11.5 KN, producing breakage of the sample after 40,000 cycles.

5. Discussion

From the study of the results, it can be concluded that these ashes can be used in subgrades of pavements and embankments for roads to improve gravels and soils that on their own would not be suitable for use under normal conditions of traffic loads.

The ashes from coal-fired thermoelectric power stations are a residue that is difficult to deal with. The coal in its mineral state contains traces of heavy metals and other elements, and these substances are concentrated in the ash produced by combustion. This makes it necessary to build specific dumps for these sub-products, thus increasing the cost of dumping the material. As well as the costs, it is necessary to occupy an excessive surface of the tip, due to the large volume of the ash. Its current use in roads is practically non-existent, despite its cost being lower than natural aggregates, except for transport and spreading during placement, as with any gravel or soil. The percentage of added lime is low and does not significantly affect the cost of the material improved with ash and lime. Nowadays, diverse public administrations are allowing the use of this type of industrial residues (preferentially steel waste), due to the shortage of aggregate from quarries. Moreover, due to the social and environmental drawbacks of opening new aggregate quarries, there are practically no new ones.

The thermoelectric bottom ash without additives can be used in bases and sub-grades and as filler material. There are real examples in the north of Spain where they have been working correctly for several years [8,23]. This load-bearing capacity has led to them being used in this study for the improvement of soils and gravels which, through the effect of the lime, can be used in higher layers of roads to support the greater stresses and deformations induced by traffic loads.

The Aristotle University Department of Transportation's [4] recommendation of 10% ash dosing also relates to the findings of the current study regarding the optimal proportion of ash added to the soil.

The research is aligned with the results of Arora and Aydilek [3] on how increasing lime content can negatively affect simple compressive strength in soil-ash and gravel-ash mixtures. The research carried out coincides with the recommendations of the American Coal Ash Association (ACAA) regarding the dosage of bottom ash and lime for treated granular layers [2].

6. Conclusions

The main conclusions of this study are:

1. It is possible to avoid dumping "marginal" soils and bottom ash residues from thermoelectric power stations so that under specific conditions they can be used for building roads. The use of bottom ashes improves the mechanical properties of pavement subbases and embankments, achieving an infrastructure of greater ecological value and cost savings of sub-industrial materials that are often taken to landfills.
2. The stabilization of soils and gravels with thermoelectric bottom ash and lime gives rise to a modification of the particle size of the original material. Moreover, it implies a reduction in the maximum Proctor dry density compared with the initial reference of the soil, along with an increase in its optimum humidity.
3. From the soils, when using soils S1 and S2, which initially were "tolerable" soils, if 15% of ash, and also 1% of lime in the case of S1 is added, a CBR index permitting them to be used in bases and sub-grades can be achieved. Soil S3 can achieve the characteristics of stabilized soil for 15% of ash and 2% of lime, making it suitable for use in sub-grades of road layers. A soil that has no resistance by adding 25% bottom ash becomes a tolerable soil and it can be used in embankments. Very clayey soil, if combined with 15% bottom ash and 1% lime is a high-performance soil.
4. In some cases, the addition of lime appears to have a positive effect on CBR. For example, for soil S1 with 0% lower ash, it is observed that the CBR increases from 0% to 2% lime. However, in other cases, such as for S3 soil, it appears that the lime content does not have a significant effect on the CBR. For soil S1 with 0% ash, it is observed that the UCS increases with an increasing percentage of lime.
5. The effect of the ash and lime enables the conclusion to be drawn that although the soil liquid limit increases, the plastic limit increases even more, which leads to a reduction in the index of plasticity.
6. These improved soils achieve high levels of compaction for 180 s of compaction with a vibratory hammer in the laboratory. From the viewpoint of placement, given that the dry density of the ash is low, it is recommendable that higher compaction is applied than would be applied to natural soil in normal conditions, although this would not require a long time or great cost.
7. For the gravels, the values of the modulus increase significantly after 28 days, showing a rise of 300% between 28 and 90 days, indicating the activation of the ash with lime over an extended curing period. The values of the modulus increase significantly after

28 days, showing a rise of 300% between 28 and 90 days, indicating the activation of the ash with lime over an extended curing period.

8. In general, it is observed that increasing the bottom ash content can increase strength, although this effect may vary depending on the specific percentage and curing time. For the G-20% mix, it is observed that the strength increases with the bottom ash content, but this increase is more pronounced for the 90-day curing period.
9. The gravel treated with bottom ash from a thermoelectric plant and lime needs longer curing times than the gravel-cement in order to reach acceptable strengths. The gravel-cement has a high strength under dynamic loading, while the gravel treated with ash and lime demonstrates poor behavior under this loading produced by traffic; therefore, its usage is not recommendable either in layers in which the stresses undergone by the material are of this type or where there are high traction stresses.

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