El Cezeri
Journal of Science and Engineering
ISSN: 2148-3736

Research Article

Experimental Study on Clay Stabilization Using Waste Pumice, Waste Marble Dust, and Lime

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DOI : 10.31202/ecjse.1506870
Received: 28.06.2024 Accepted: 03.09.2024
How to cite this article:
Ömür Çimen, S. Nilay Keskin, Engin Kalay, " Experimental Study on Clay Stabilization Using Waste Pumice, Waste Marble Dust, and Lime", El-Cezeri Journal of Science and Engineering, Vol: 11, Iss: 3, (2024), pp.(317-326).
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Abstract : In high-plasticity clays, low unconfined compressive strength and high swelling pressure cause problems in engineering structures. In this study; pumice, marble dust, and lime were mixed with high-plasticity clay to investigate their effects on the engineering properties of clay. Atterberg's limits, standard compaction, unconfined compression test, and swelling experiments were performed by adding pumice, marble dust, and lime to clay in pre-defined ratios. After determining the optimum dosages for each additive, samples prepared at maximum dry density and optimum water contents were cured for 7, 28, and 90 days. Unconfined compression tests, triaxial compression tests, and CBR tests were performed on those samples. SEM, X-ray, and chemical analysis were also performed. It was observed that the additives used improved the engineering properties of high-plasticity clay.

Keywords : Soil Stabilization, Clay, Waste Material, Geotechnical Properties.

1 Introduction

Large quantities of domestic, industrial, and mining wastes are produced yearly. Recycling, incineration, and burial are procedures for the disposal of these waste materials. Many countries use landfills to eliminate waste materials that cannot be recycled or processed [1]. Mine wastes or by-products offer a great potential to meet the demand for large-volume low-cost mineral resources for road construction [2]. Bruder-Hubscher et al. [3] stated that the incineration of municipal solid wastes is a management option that can achieve up to 80% and 90% reduction in waste mass and volume, respectively. Puma et al. [4] reported that the most commonly used methods for processing non-recyclable solid wastes (about 426 kg per capita-1 year-1) in Italy are landfilling (60%) and incineration (18%).

Recent projects show that successful waste usage significantly saves construction costs [5]. One of the methods applied to improve the engineering properties of clay soil is to mix some waste additives with clay soil. Clay soils with a high expansion, high moisture capacity, low bearing value, and high shrinkage potential can cause problems in various engineering structures. Waste materials can be evaluated as a potential additive for structural fills such as roads, slopes, and dams. There are numerous studies on the various wastes used in fillings in the literature and many of these studies are on the stabilization of clayey soils.

Naganathan et al. [6] showed that kaolin addition delayed the initial setting time of controlled low-strength material mixtures, reduced bleeding, lowered compressive strength, and increased the values of water absorption, sorption, and initial surface absorption. Babu and Chouksey [7], and Peddaiah et al. [5] observed that plastic wastes increase soil resistance and significantly reduce compressibility.

Kamon and Nontananandh [8] examined the potential for burning various industrial wastes with lime to produce a by-product having cementing characteristics similar to those of ordinary Portland cement in stabilizing loam soil. They obtained that the percentages of the main cementitious compounds in this new cement-like stabilizer are comparable to those of cement for subgrade purposes. Attom and Al-Sharif [9] evaluated burned olive waste for usage as a soil stabilizer. They found that the 2.5% addition by weight of burned olive waste increases the Unconfined Compressive Strength (UCS) and maximum dry density (MDD) and the 7.5% addition by weight of olive ash minimizes the swelling pressure of the soil. Igwe and Adepehin [10] reported using granite and dolerite dust for clay stabilization. They found that a noticeable reduction in shrinkage and plasticity, as well as an increase in California Bearing Ratio (CBR), were observed in the treated soil samples. Cokca and Yilmaz [11] evaluated the feasibility of utilizing fly ash, rubber, and bentonite as a low hydraulic conductivity liner material. They implied that the rubber and bentonite with added fly ash showed good promise as a candidate for the construction of a liner based on hydraulic conductivity, leachate analysis, unconfined compression, split tensile strength, one-dimensional consolidation, swell, and freeze/thaw cycle tests.

Forteza et al. [12] reported that bottom ash is an adequate soil for embankments and landfills and an excellent material for granular layers (bases and subbases). Baykal et al. [2] suggested a new technique for adding water to fly ash samples to enhance the conditions for cementitious mineral formation without sacrificing compressibility. They reported that the snow addition to fly ash noticeably increased the UCS and splitting tensile strength beginning from 14 days of curing, new technology will allow the construction of highway embankments, bases, and subbases during the wintertime in cold regions. Tonoz et al. [13] investigated the performance of lime in powder form in laboratory-scaled models to improve the physical, swelling, and strength characteristics of Ankara clay in Turkey. They implied that the UCS increased by approximately 84% after 28 days and that if the curing period is less than 28 days, the UCS values of the lime-treated samples are higher than those of natural samples.

Senol et al. [14] presented the results of research that considered self-cementing fly ashes for stabilizing four different types of soft subgrades from various road sites in Wisconsin, USA. They reported that the fly ash stabilization substantially increased both the UCS and CBR values for the mixtures tested, and it has the potential to offer an alternative for the soft subgrade improvement of highway construction. Pahanikumar and Shankar [15] investigated the heave studies on fly ash-stabilized expansive clay liners. Hossain et al. [16] presented the characteristics of Papua New Guinea clayey soils stabilized with various percentages of volcanic ash, finely ground natural lime, cement, and their combinations. They reported that the stabilized soils exhibit enhanced mechanical properties, such as compressive and tensile strength, modulus of elasticity and CBR, and durability regarding water resistance, sorptivity, and shrinkage. They proposed that suitable stabilized soil mixtures using volcanic ash, lime, and cement and their combinations can be used to set up road pavements, airfields, earth dams, and low-cost housing. Sengupta et al. [17] investigated the improvement of the bearing ratio of clayey subgrade using a compacted fly ash layer. They determined the improvement of clayey soil when a compacted fly ash layer was placed on it with the different values of thickness ratio, placement moisture content, and compaction energy.

Dubois et al. [18] investigated the potential of using dredged marine sediments in road construction, and they reported the efficiency of lime in improving the mechanical characteristics of the mixtures. Brooks et al. [19] presented the results of a laboratory experimental program to evaluate the potential of limestone dust and coal fly ash to stabilize some problem soils in south-eastern Pennsylvania, showing that the plasticity and swell were reduced by 40% and between 40 and 70%, respectively. The results further showed a marked increase in the strength of the soils for CBR and UCS when stabilized with the additives.

Al-Mukhtar et al. [20] investigated the lime consumption by 10% of the lime treatment of five soils containing different major clay minerals. They assessed the short-term reaction (cation exchange and flocculation) and the long-term reaction (pozzolanic reaction) due to the highly alkaline medium induced by the dissolution of lime in the water contained in the soil. Zorluer and Gucek [21] investigated the reuse of marble dust and fly ash in soil stabilization finding that their addition to clay soil increased the UCS, CBR, and freeze-thaw strength but decreased the swelling potential and grain loss after freeze-thaw. Guney et al. [22] reported that sepiolite is the dominant material affecting both the geo-mechanical and geo-environmental properties of liners of kaolinite, zeolite and their mixtures. Modarres and Nosoudy [23] evaluated the environmental and technical impacts of coal waste usage at stabilization of the hydrated lime-additive medium-plastic clay. They implied that a coal waste powder addition and its ash with lime extent enhanced the soil-bearing capacity. Jamsawang et al. [24] determined the free swell potential of expansive clays stabilized with the shallow bottom ash mixing method. They show the free swell potential values of the stabilized expansive samples decreased with increasing bottom ash content.

The effect of pumice material on high-plasticity and low-plasticity clay soils was evaluated. It has been shown that pumice can be used as a stabilization material in high-plasticity clays [25]. Cimen et al. [26] examined waste pumice's use to stabilize the high-plasticity clayey subgrade, which is inappropriate for road construction. It improved the mechanical properties and reduced the swelling potential.

In the present study, waste pumice, waste marble dust, and lime as the soil stabilizer were added to high-plasticity clay soil to investigate their effects on the engineering properties of clay. Liquid limit, plastic limit, standard compaction test, unconfined compression test, and swelling test were performed by adding these additives according to the weight ratios of the additives. The optimum dosages for pumice, marble dust, and lime were first determined. Then triple mixture samples were prepared using those optimum dosages. For these mixture samples, first CBR tests and then 7, 28, and 90-day cured unconfined compression tests were performed. The change in engineering properties of high plasticity clay was investigated by using different percentages of waste materials. It is aimed to obtain a cheap, effective and sustainable improvement by using waste materials in clay soil stabilization.

2 Material and Experimental Study

In this study, the materials used for soil stabilization are supplied from pumice, marble, and lime factories in Isparta, Turkey, and the high-plasticity clay is taken from the construction field of the Fethiye – Esen 1 hydroelectric power plant in Türkiye. The samples used are presented in Figure 1 below.

The chemical properties of the high-plasticity clay, pumice (P), marble dust (M), and lime (L) are determined with XRF test equipment. The chemical test results are given in Table 1. X-ray analyses were performed for the mineral properties of the samples. The minerals obtained are shown in Table 2.

(a) Clay **(b)** Lime

(c) Pumice **(d)** Marble Dust

Figure 1: Images of the samples used

Table 1: Results of Chemical Analysis for Used Materials [27]

Sample	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3	L.I.
Clay (C)	<0.1	17.4	4.3	47.1	<0.1	0.3	2.8	0.2	0.1	16.6	9.85
Pumice (P)	5.3	1.1	17.1	60.9	0.2	5.0	3.0	0.3	0.1	3.2	2.80
Marble Dust (M)	<0.1	0.3	<0.1	0.2	<0.1	<0.1	57.0	<0.1	<0.1	0.1	42.35
Lime (L)	<0.1	0.4	<0.1	0.1	<0.1	<0.1	79.3	<0.1	<0.1	0.1	19.85

L.I: Loss of ignition

Table 2: Results of Mineralogical Analysis for Used Materials [27]

Materials	Minerals
Clay	Simectite group, serpentine group, quartz, calcite, amorphous silica, amphibole group (very few), feldspar (very very few), chlorite (very very few).
Pumice	Feldspar, opal-CT, quartz, mica group, amphibole group.
Marble Dust	Calcite
Lime	Portlandite, aragonite (few), calcite (few), illite (very very few)

For engineering properties of samples, liquid limit tests, plastic limit tests (as described in the ASTM D4318-05), standard compaction tests (as described in the ASTM D698-00), unconfined compression tests (as described in the ASTM D2166-00) and free volume swelling tests (as described in the ASTM D4546 method A) are conducted [28], [29], [30], [31]. Those tests were carried out to determine the geotechnical properties of clay both in its natural state and when mixed with varying percentages at weight (5, 10, 15, 20, 25, 30, 35% of passed No40 sieve pumice for 2, 4, 5, 6, 10, 15, 20, 25, 30% of passed No40 sieve marble dust for 1, 2, 3, 4, 5, 6, 7% of passed No40 sieve lime). After determining the optimum dosages of clay-pumice, clay-marble dust, and clay-lime, triple-mixed samples were prepared. Then, the same experiments were made. Images of some samples after unconfined compression tests are shown in Figure 2.

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

Figure 2: Images of some samples after unconfined compression tests

Unconfined compression tests are conducted for dry curing periods of 7, 28 and 90 days on the samples determined optimum additive ratios according to the ASTM D2166-00 standard test method [30]. The samples are compacted in a right circular cylinder with a diameter of 3.5 cm and a height of 7 cm according to the ASTM D 698-00 Standard Test method, and they are kept in a desiccator by covering with a stretch film during curing [29]. The shear characteristics of the samples are measured by triaxial compression tests using 50, 100, and 200 kPa cell pressures under undrained conditions according to the ASTM D4767-95 standard test method [32]. The California bearing ratio (CBR) test is implemented to evaluate the potential strength of the samples for use in the design of roads according to the ASTM D1883-07e2 standard test method [33]. The swelling percentage is determined after the samples are soaked underwater for 4 days. Scanning Electron Microscopy (SEM) images of used samples were taken using FEI Quanta 400 equipment.

3 Results and Discussions

Liquid limit (WL), plastic limit (WP), plasticity index (PI), maximum dry density (γ_{dmax}), optimum water content (W_{opt}), Unconfined compressive strength (q_u), free volume swelling potential (SP), and swelling pressure (P_s) were shown in Table 3.

These results presented that the liquid limit, plastic limit, and plasticity index of clay have decreased with the pumice additive. It was observed the maximum dry density and unconfined compressive strength of clay were increased and optimum water content, swelling potential, and swelling pressure were decreased with the addition of pumice. An ideal pumice mixing ratio was determined as 25-30%.

With the addition of marble dust, the liquid limit, plastic limit, and plasticity index of clay were decreased by 20% marble dust additive. However, there is an increase of over 20% in the liquid limit of marble powder. Therefore, the plasticity index increased. By increasing the amount of marble dust, it was seen that the maximum dry unit weight and the unconfined compressive strength of clay were increased and optimum water content, swelling potential, and swelling pressure were decreased. An ideal marble dust mixing ratio was determined as 5%. With the addition of lime, the liquid limit, plastic limit, and plasticity index of clay decreased rapidly. When the lime ratio increases, maximum dry unit weight and unconfined compressive strength increase, optimum water content, swelling potential, and swelling pressure decrease. An ideal lime mixing ratio was determined as 6%. The effects of pumice, marble dust, and lime on the unconfined compressive strength, swelling potential, and swelling pressure of the clay used are shown in Figure 3.

As seen in Figure 3a; Increasing the amount of additive increases the unconfined compressive strength. This increase is different for pumice, marble dust and lime. After a certain amount of additive, the unconfined compressive strength decreases. As seen in Figure 3a and 3b; Increasing the amount of additive generally decreases swelling potential and swelling pressure. This decrease is different for pumice, marble dust and lime.

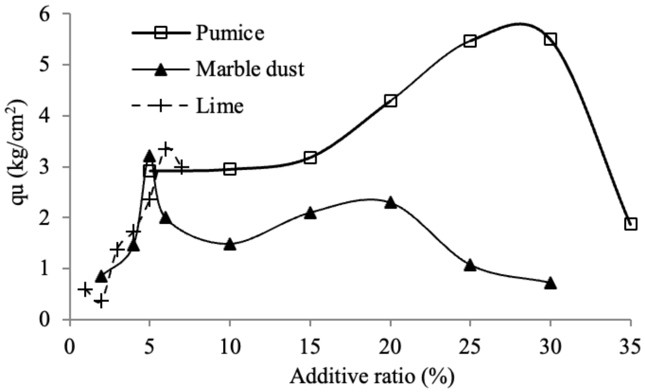
It can be seen in Table 3 that the results of the triple mixture (pumice-lime-clay, pumice-marble dust-clay, lime-marble dust-clay) are quite different from the results of the binary mixture (pumice-clay, marble dust-clay, lime-clay). When 30% pumice additive is kept constant and the amount of lime additive is increased, the liquid limit, plastic limit, plasticity index, optimum water content, swelling potential, and swelling pressure of the mixture are decreased. Maximum unconfined compressive strength at these mixtures is obtained at 30% pumice and 3%lime. When 30% pumice additive is kept constant and the amount of marble dust additive is increased, the liquid limit, plastic limit, plasticity index, optimum water content, swelling potential, and swelling pressure of the mixture are decreased. Maximum unconfined compressive strength at these mixtures is obtained at 30% pumice and 6% marble dust.

Table 3: Results of liquid limit tests, plastic limit tests, standard compaction tests, unconfined strength tests, and free volume swelling tests for samples [25], [27]

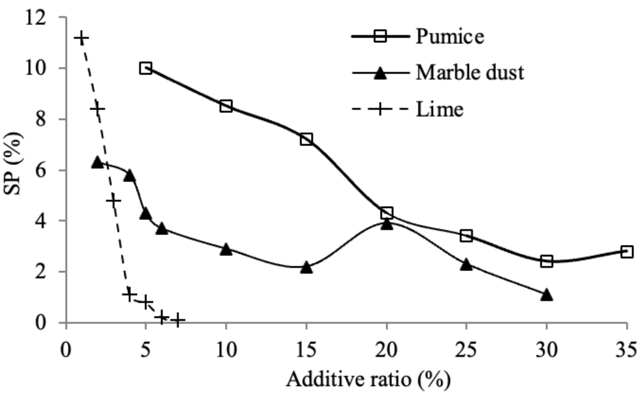
Samples Properties	WL (%)	WP (%)	PI (%)	γ_{dmax} (gr/cm^3)	W_{opt} (%)	q_u (kg/cm^2)	SP (%)	P_s (kg/cm^2)
100% C	108	38	70	1.16	38	1.96	12.0	1.50
100% P	-	-	-	1.18	29	0.45	-	-
100% M	-	21.5	-	1.63	20	2.16	-	-
5% P + 95% C	100	34.5	65.5	1.20	34	2.92	10.0	0.75
10% P + 90% C	95	32.5	62.5	1.16	29	2.95	8.5	0.40
15% P + 85% C	90	30	60	1.21	35	3.18	7.2	0.33
20% P + 80% C	89	27	62	1.23	35	4.29	4.3	0.37
25% P + 75% C	88	27	61	1.30	32	5.47	3.4	0.20
30% P + 70% C	80	27	53	1.30	32	5.50	2.4	0.25
35% P + 65% C	77	26	51	1.31	28	1.87	2.8	0.10
2% M + 98% C	115	34	81	1.16	37	0.86	6.3	1.32
4% M + 96% C	102	34	68	1.20	33	1.46	5.8	1.17
5% M + 95% C	112	38	74	1.19	37	3.22	4.3	1.05
6% M + 94% C	98	32	66	1.21	26	2.00	3.7	1.08
10% M + 90% C	100	34	66	1.16	36	1.49	2.9	1.02
15% M + 85% C	84	33	51	1.23	30	2.10	2.2	1.25
20% M + 80% C	80	32	48	1.31	29	2.30	3.9	1.03
25% M + 75% C	90.5	28	62.5	1.30	31	1.08	2.3	1.41
30% M + 70% C	90	26	64	1.34	29	0.73	1.1	0.93
1% L + 99% C	96	32	64	1.16	37	0.60	11.2	1.46
2% L + 98% C	84	53	31	1.14	35	0.36	8.4	1.41
3% L + 97% C	81	58	23	1.12	42	1.38	4.8	1.03
4% L + 96% C	78	56	22	1.24	37	1.73	1.1	0.77
5% L + 95% C	80	61	19	1.24	34	2.35	0.8	0.75
6% L + 94% C	73	59	14	1.26	34	3.35	0.2	0.65
7% L + 93% C	72	-	-	1.21	36	3.00	0.1	0.60
30% P + 1% L + 69% C	80	36	44	1.24	27	2.84	1.0	0.80
30% P + 2% L + 68% C	73	51	22	1.26	34	2.21	0.8	0.05
30% P + 3% L + 67% C	71	53	18	1.29	20	4.18	0.6	0.05
30% P + 4% L + 66% C	71	51	20	1.27	22	2.39	0.5	0.04
30% P + 5% L + 65% C	65	52	13	1.23	29	2.78	0.2	0.02
30% P + 6% L + 64% C	65	-	-	1.28	26	3.39	0.1	0.02
30% P + 7% L + 63% C	69	-	-	1.32	25	2.20	0.1	0.01
30% P + 4% M + 66% C	78	27	51	1.34	33	1.43	0.8	0.52
30% P + 5% M + 65% C	77	23	54	1.33	18	2.01	0.6	0.50
30% P + 6% M + 64% C	80	23	57	1.34	23	4.02	0.8	0.34
30% P + 7% M + 63% C	76	28	48	1.21	36	0.93	0.7	0.15
6% L + 10% P + 84% C	85	64	21	1.31	31	3.52	0.6	0.81
6% L + 20% P + 74% C	78	63	15	1.31	24	3.84	0.4	0.49
6% L + 4% M + 90% C	80	63	17	1.32	31	2.04	0.9	0.15
6% L + 5% M + 89% C	80	66	14	1.30	32	4.36	0.5	0.04
6% L + 6% M + 88% C	79	62	17	1.31	36	3.08	0.4	0.04
5% M + 10% P + 85% C	96	63	10	1.31	36	1.92	6.5	1.03
5% M + 20% P + 75% C	90	36	54	1.31	36	1.51	3.5	0.53
5% M + 5% L + 90% C	80	61	19	1.28	38	3.10	0.3	0.40
5% M + 7% L + 88% C	83	63	20	1.26	37	3.38	0.2	0.10
5% M + 8% L + 87% C	72	55	17	1.25	37	2.44	0.1	0.08
30% M + 3% L + 67% C	66	40	26	1.42	19	2.50	1.0	0.80

Then, 6% lime was kept constant, and pumice and marble dust were mixed in different ratios. In this case, the amount of pumice increased while the liquid limit, plastic limit, plasticity index, optimum water content, swelling potential, and swelling pressure of the mixture decreased. Maximum unconfined compressive strength in this mixture is obtained by 20% pumice. When 6% lime was kept constant and the amount of marble dust was increased, the liquid limit, plastic limit, plasticity index, optimum water content, swelling potential and swelling pressure of the mixture did not change much. Maximum unconfined compressive strength in this mixture is obtained at 5% marble dust.

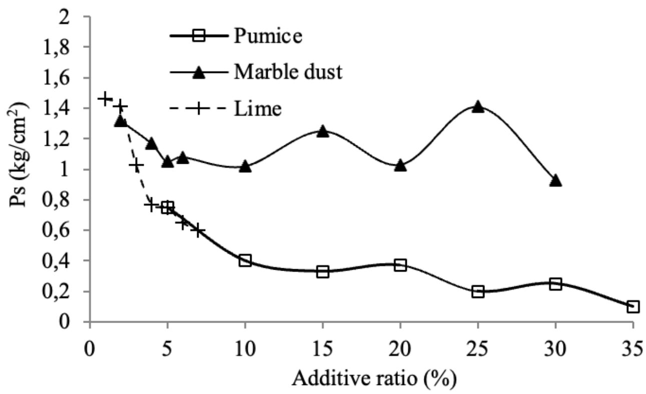
The last, 5% marble dust was kept constant, and pumice and lime were mixed in different ratios. When 5% marble dust was kept constant and the amount of pumice was increased, liquid limit, unconfined compressive strength, swelling potential, and



(a) Relationship between unconfined compressive strength and additive ratio



(b) Relationship between swelling potential and additive ratio



(c) Relationship between swelling pressure and additive ratio

Figure 3: Effects of additive ratio on high plasticity clay

swelling pressure decreased, but plastic limit, maximum dry unit weight and optimum water content were unchanged. When 5% marble dust was kept constant and the amount of lime was increased, the liquid limit, plastic limit, plasticity index, swelling potential, and swelling pressure of the mixture were decreased and unconfined compressive strength and maximum dry unit weight were increased. Maximum unconfined compressive strength in this mixture is obtained at 6% lime.

All mixture ratios were evaluated among themselves and the optimum proportions of each mixture were determined. The optimum values for mixing a single additive into clay and mixing two different additives are given in Table 4. In general, it is found that with an increase in the amounts of marble dust, pumice, and lime in the clay sample, the maximum dry unit weight (γ_{dmax}) of the clayey mixture increases, the optimum water content (W_{opt}) decreases, and the unconfined compressive strength (q_u) increases. As a result, it is determined that the optimum addition to the clayey mixture with the marble dust is 5%, and those of the crushed pumice and quick-lime are 30% and 6%, respectively. In the mixing with the marble dust additive, the liquid limit (*WL*) is determined to be 112%, higher than the 108% of the clay; the plastic limit (*WP*) is obtained as 38%, equal to that of the clay; and the plasticity index (*PI*) is obtained as 74%, higher than the 70% of the clay. In the mixing with the crushed pumice additive, Atterberg's limits are determined to be lower than those of clay. In the mixture with lime, lower values of the liquid limit and plasticity index are obtained, while a higher value of the plastic limit is obtained. When these three additives are compared, pumice is more effective in the increase of the maximum dry unit weight and reduction of the optimum water content however lime is more effective in the plasticity index reduction.

When two additives (M + P, M + L and P + L) at the optimum ratios are added to the clay, the highest maximum dry unit weight and the lowest optimum water content are obtained from sample #9 (30% M + 3%L + 67% C) and the lowest plasticity index is obtained from sample #8 (5%M + 6%L + 89%C).

The results of the unconfined compression tests (7, 28, and 90-day curing), triaxial compression tests, and CBR tests are shown in Table 4. The strengths of the mixture samples are determined to be higher than that (1.96 kg/cm^2) of clay. After a 7-day curing time, there is an increase in the strengths of mixture samples, except for samples # 4, #5, and #7 with M and P, while the strength values of all of the mixtures increase after 28- and 90-day curing times. According to the test results, the additives affecting the UCS of the clay can be ordered by impact as lime, pumice, and marble dust. The mixtures can also be ordered as samples #10, #6, and #8 (20%P + 6%L+74%C, 6%L +94%C, and 5%M + 6%L+89%C). This effect can also be seen in Fig. 1. It is determined that the strengths of samples #10, #6, and #8 are, respectively, 13.4, 12.8, and 11.4 higher than those of the high-plasticity clay after 90 days of curing. It is known that the lime-clay reactions continue for quite a long time and that the water content, temperature, and curing time influence the reactions [34], [35], [36], [37]. Consoli et al. [38] reported for Botucatu residual soil (12.5% fly ash) - lime mixtures that the percentage increase in the UCS over the curing time is approximately 62% higher for specimens molded after 60 days of curing compared to 28 days of curing, and there is a further 38% increase in strength in the specimens molded after 90 days of curing compared to the results obtained at 60 days of curing. This implied that the crushed pumice–clay and marble dust–clay reactions also proceed over a long period. Ural et al. [39] have shown that the unconfined compressive strength of high plasticity clay increases when waste PVC is used, through 28-day curing experiments. Yılmaz and Duman [40] showed that when waste Midyat stone and 6% lime were added to low plasticity clay, the 28-day cured unconfined compressive strength increased.

The shear characteristics of the samples are measured by the triaxial compression tests using 50, 100, and 200 kPa cell pressures under undrained conditions according to the ASTM D4767-95 standard test method [31]. The values of the cohesion (C), which is equal to the shear strength when the compressive stress is equal to zero, and the angle of internal friction ($\emptyset$), which is the angle of shear resistance, of the samples are given in Table 4. The highest cohesion is obtained as 1.0 kg/cm^2 for sample #10 (20%P + 6%L+74%C), while that of the clay is 0.2 kg/cm^2. The next highest mixtures are #11 (0.75 kg/cm^2) and #8 (0.7 kg/cm^2). The highest angle of internal friction is determined to be $\emptyset = 36.4°$ for sample #6 (6%L+94%C), followed by $\emptyset = 32.3°$ and $\emptyset = 30.9°$ for samples #11 (30%P+ 3%L+67%C) and #7 (30%P + 6%M +64%C), compared to a value for the clay of $\emptyset = 6°$. Changes of the unconfined compressive strengths of samples at various curing times are given in Figure 4. It is observed that as the curing time increases, the unconfined compressive strength also increases.

Table 4: Results of the unconfined compression, triaxial compression, swelling, and CBR tests [27]

#	Sample properties	q_u (kg/cm^2)	q_u (kg/cm^2)			C (kg/cm^2)	ϕ (°)	Swelling (%)	CBR (%)
			7-days	28-days	90-days				
1	100% C	1.96	-	-	-	0.20	6.0	5.78	0.9
2	100% M	-	-	-	-	-	-	-	-
3	100% P	-	-	-	-	-	-	-	-
4	5%M + 95%C	3.22	1.94	4.62	5.40	0.50	13.4	2.98	2.1
5	30%P + 70%C	5.50	2.42	5.51	7.14	0.35	11.8	1.84	4.1
6	6%L + 94%C	3.35	7.37	17.91	25.18	0.60	36.4	0.76	15.2
7	30%P + 6%M + 64%C	4.02	3.98	6.61	7.85	0.60	30.9	0.94	2.0
8	6%L + 5%M + 89%C	4.36	8.85	16.15	22.33	0.70	16.7	0.31	25.1
9	3%L + 30%M + 67%C	2.50	8.50	8.62	12.13	0.15	18.4	0.21	30.1
10	6%L + 20%P + 74%C	3.84	8.63	10.50	26.35	1.00	26.5	0.26	22.1
11	3%L + 30%P + 67%C	4.18	6.65	8.69	19.61	0.75	32.3	0.26	34.3

The California bearing ratio (CBR) test is implemented to evaluate the potential strength of the samples for use in the design of roads according to the ASTM D1883-07e2 standard test method [33]. The samples are soaked under water for 4 days and the swelling percentage is calculated. The CBR values are also determined from the load–penetration curves. Table 4 shows the results of the swelling percentage and CBR for the mixtures. The General Directorate of Highways in Türkiye recommends that subgrade soils have a swelling percentage of ≤ 3 and CBR > 10. As seen in Table 4, all of the mixtures have values of swelling percentage less than 3, and except for samples #4, #5, and #7, all of the mixtures have CBR values greater than 10. According to these results, it is clear that the mixtures with quick-lime can be used as a stabilization material. The highest CBR ratios are obtained from sample #11 (30%P+ 3%L+67%C), 34.3; sample #9 (30%M + 3%L+67%C), 30.1; and sample #8 (5%M + 6%L+89%C), 25.1. It is significant that the CBR values of samples #11 and #9, with 3% L, are greater than those of samples #6 and #8, with 6% L, resulting in a lower cost for the subgrade. The reasons that sample #11, containing P, has the highest CBR value may include the flocculation, accumulation, and pozzolanic reactions, together with the cation exchange capacity.

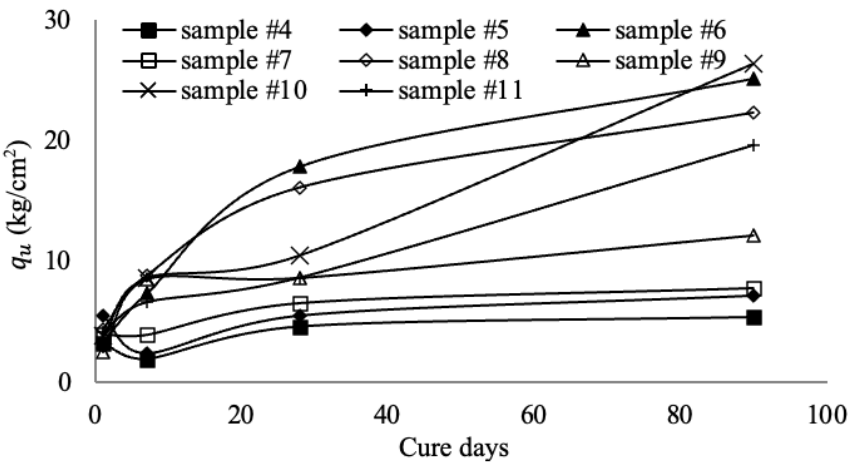


Figure 4: Unconfined compressive strengths of samples at various curing times

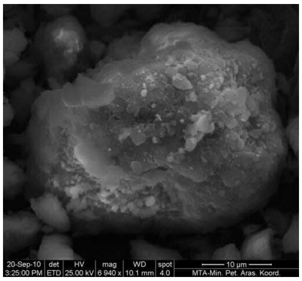
Morphological analyses of samples were carried out using SEM. SEM images are shown in Figure 5. Comparing SEM images at stabilized with additives clays and pure clay, showed very different morphological structures. It has occurred that open pores of pumice are filled with lime and clay from Figures 5e and 5h. It is thought that portlandite crystals in lime can fill the pore structures and give strength-increasing properties.

It has been shown that the change in engineering properties of high plasticity clay is also possible by mixing waste materials. The use of waste materials in soil stabilization will reduce the storage areas of these materials. In this way, more environmentally appropriate solutions can be produced.

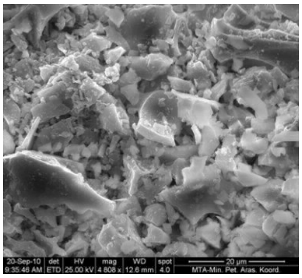
4 Conclusions

The effects of pumice, marble dust, and quick-lime additives in high-plasticity clay are evaluated in the study. The in situ test fillings are prepared according to the optimum mixture ratios obtained from test results in the laboratory. The conclusions obtained from this study are listed below:

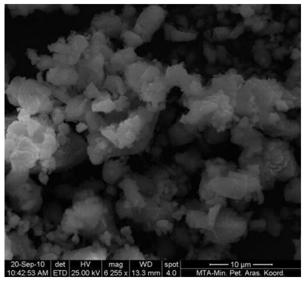
1) With the addition of crushed pumice, marble dust, and lime into high plasticity clay, it is observed that the values of the dry unit weight, unconfined compressive strength, cohesion, angle of internal friction, and CBR increase, while those of the optimum water content, liquid limit, plasticity index and percentage of swelling decrease. Evaluating these results, the changes in the consistency limits, optimum water content, and maximum dry unit weight stem from short-term reactions while those in the unconfined compressive strength, CBR, percentage of swelling, cohesion, and internal friction angle are from long-term ones.
2) It is seen that the curing duration has a greater effect on the unconfined compressive strength of the lime-supplemented mixtures in laboratory tests with 7, 28, and 90-day curing. Among the samples at 90 days' curing, the highest unconfined compressive strength value is obtained from the mixture of 20%P + 6%L + 74%C as 26.35 kg/cm^2 (13.4 times more than that of clay), and the others are in the order of 6%L +94%C (25.18 kg/cm^2) and 5%M + 6%L+ 89%C (22.33 kg/cm^2).
3) It is determined from the triaxial compression tests that the highest cohesion is found in the mixture of 20%P + 6%L + 74%C (1.0 kg/cm^2, 5 times more than that of clay), followed by 30%P + 3%L + 67%C (0.75 kg/cm^2) and 5%M + 6%L + 89%C (0.7 kg/cm^2). Also, the highest angle of internal friction is found in the mixture of 6%L + 94%C (36.4°, 6 times more than that of clay), followed by 30%P + 3%L+ 67%C (32.3°) and 30%P + 6%M + 64%C (30.9°).
4) It is determined that all of the mixtures have values of percentage of swelling less than 3 and that the highest CBR ratios are obtained from the mixtures of 30%P + 3%L + 67%C (34.3), 30%M + 3%L +67%C (30.1), and 5%M + 6%L + 89%C (25.1). The highest values of CBR are obtained from the mixtures with 3% lime.
5) From the overall results, it is seen that mixtures of crushed pumice and marble dust with little lime can be effectively used for stabilization for high plasticity clay soil.



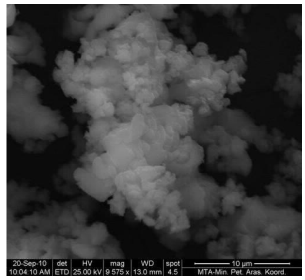
(**a**) 100% Clay (C)



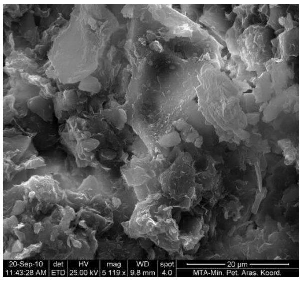
(**b**) 100% Pumice (P)



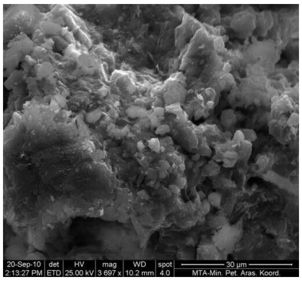
(**c**) 100% Marble dust (M)



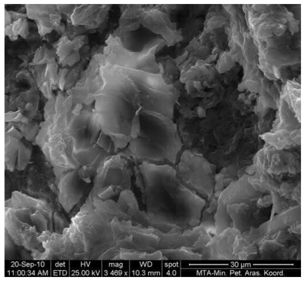
(**d**) 100% Lime (L)



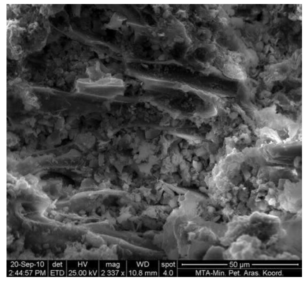
(**e**) 30% P + 70% C



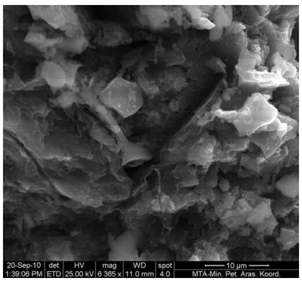
(**f**) 5% M + 95% C



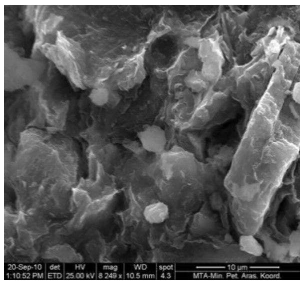
(**g**) 6% L + 94% C



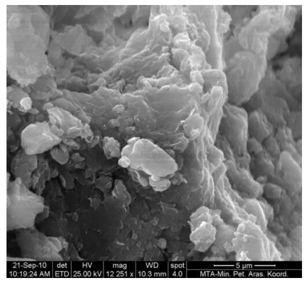
(**h**) 30% P + 3% L + 67% C



(**i**) 30% P + 6% M + 64% C



(**j**) 6% L + 5% M + 89% C



(**k**) 3% L + 30% M + 67% C

Figure 5: SEM images of pure and mixed samples

Acknowledgments

This study was supported by the Scientific and Technological Research Council of Turkey [grant number 109M344]; and the Scientific Research Project Management Unit of Süleyman Demirel University [grant number 98-DES-10]. The authors thank both institutions for their support.

Authors' Contributions

In this study, all authors wrote up the article.

Competing Interests

The authors declare that they have no conflict of interest.

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