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Stabilization of clayey subgrade with waste pumice for road infrastructure

Abstract: High-plasticity clayey subgrade, which is unsuitable for road construction, may sometimes occur along highway routes. In such cases, engineers need to change the route of a highway project, resulting in an increase in road length and project costs. In this study, waste pumice was examined for stabilization of high-plasticity clayey subgrade, which is inappropriate for road construction. For this purpose, the physical and index properties of clay and pumice were determined. Then, the pumice was mixed with high plasticity clay at different ratios by weight. By performing standard Proctor compaction tests on the mixtures, the effects of adding pumice on compaction were also studied. Unconfined compression tests and California bearing ratio (CBR) tests were performed on all pumice-clay mixtures, and the test results and the CBR ratios were compared for each sample, respectively. The results showed that pumice stabilization improved the mechanical properties and reduced the swelling potential of high plasticity clayey subgrade.

Keywords: pumice; road infrastructure; stabilization; waste material.

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1 Introduction

Road pavements are layered systems with better quality materials on top where the intensity of stress is high and inferior materials at the bottom where the intensity is low. Typical bituminous pavements are composed of wearing course, base course, subbase, and subgrade layers, as seen in Figure 1 [1]. The road base or the ground on which the road lies is called the subgrade. Performance of roads depends on many factors that include the subgrade soil type, the density of traffic, and even the weather conditions the road is subjected to. The subgrade must be able to support loads transmitted from the pavement structure. This load-bearing capacity is often affected by the degree of compaction, moisture content, and especially soil type. Some clay-type soils shrink and swell depending on their moisture content, whereas soils with excessive fines may be susceptible to frost heave in freezing areas [2]. Types of pavement subgrade soil affect the selection of road project routes in view of problematic characteristics. In such cases, either the highway route is changed or the layer that has problematic soil is replaced with a new layer that has the proper soil type. Sometimes, these kinds of problems necessitate increasing the route length of a road construction project and hence project costs. Selection of an appropriate subgrade stabilization process to improve subgrade resistance to permanent deformation is very important for overall pavement performance [3].

The method of stabilization is well known and has been used throughout the world for many decades in improving some soil properties [4]. Some of the materials used for soil stabilization are sea peel, pumice, froth concrete, thermic power station ash, fly ash, volcanic ash, lime, cement, auto tire pieces, industrial churn, marble powder, gravel, and rubber [4–19].

Stabilization and solidification refer to treatment processes that are designed to accomplish one or more of the following objectives [20]: a) improve the handling and physical characteristics of the waste, b) limit the mobility of toxic constituents of the waste, and c) render the waste as a usable material in construction.

Pumice is an amorphous foam produced during volcanic eruptions. It is composed mostly of silica and alumina in relative amounts according to the geological area of origin, and it also includes other chemical elements, such as different oxides and water [21]. Pumice is a volcanic rock of which the porous structure is formed by dissolved gases being precipitated during cooling as the lava hurtles through the air. Connectivity of the pore structure may range from completely closed to completely open [22].

There is plenty of pumice formed during explosive volcanic eruptions in Turkey, especially in Isparta. Turkey has seven billion m^3 total pumice reserve [23]. Pumice is used in the fields of construction, chemical industry, agriculture, and dentistry. Particles larger than 3 mm are used in these sectors but smaller pumice particles are stocked in the field.

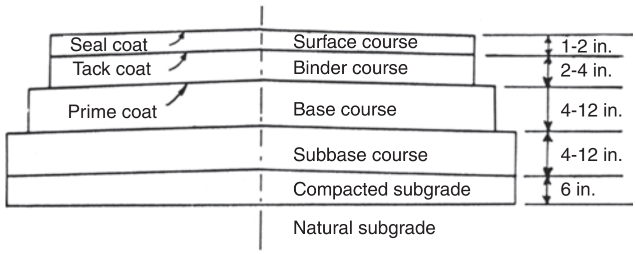

Figure 1 Typical cross-section of a conventional flexible pavement [1].

The objectives of soil stabilization with additives are to improve volume stability, strength and stress-strain properties, permeability, and durability. The development of high strength and stiffness is achieved by reduction of the void space, by bonding particles and aggregates together, by maintenance of flocculent structures, and by prevention of swelling. Uniform mixing process is the most important factor affecting the quality of results [24].

In the western part of the Netherlands, the subgrade consists of clayey materials. In the construction of major roads in this area, the subgrade is replaced to a depth of at least 50 cm by sand material. The sand is either dredged from river estuaries or produced on land in sand pits [25]. Soil stabilization is an efficient technique that has been used for many years in solving soil problems in civil engineering projects [26]. When stabilized materials that meet all gradation, durability, and strength requirements are utilized in pavement structures, soils that have been mixed with a stabilizing material are considered modified. Stabilization of high plasticity clayey subgrade with pumice may prevent the pavement from swelling.

Tremblay et al. [27] reported the results of a laboratory study in which 13 different organic compounds were added separately into two different soils, which were then treated with 10% cement. They found that oils and hydrocarbons, which are insoluble in water, delayed cement hydration but did not affect the final strength. Cimen [28] stated that pumice is a suitable additive material for stabilization of high plasticity clay. Kavlak [29] suggested that the Isparta-Gelincik pumice can be used for mechanic stabilization of problematic highway subgrades because he observed that the strength of these subgrades increased with pumice stabilization. In another study, Cimen [30] blended clay with marble dust, pumice, and lime. After the optimum dosages for each additive were determined, the samples were prepared at maximum dry density and the optimum water contents were cured for between 7 and 28 days. Unconfined pressure tests, triaxial pressure tests, and California bearing ratio (CBR) tests were performed on the samples. By evaluating the results obtained *in situ* and from laboratory experiments, the feasibility of using waste materials in soil improvement and their applicability in the field was investigated.

Bin-Shafique et al. [31] investigated the long-term performance of fly ash-stabilized low-plasticity clay and high-plasticity expansive clay soil subbases. Plasticity index tests, unconfined compression tests, and vertical swell tests were performed on the specimens for 7-day curing, wet-dry cycles (with tap water and saline water), and freeze-thaw cycles. These implied that stabilized soils were at least three times higher than unstabilized soils. Seco et al. [32] used six different waste additives, lime, and Portland cement for expansive soils. Of the waste materials, the most notable was the behavior of rice-husk fly ash, which was found to be highly effective in stabilizing expansive soils. Cetin et al. [33] conducted CBR and resilient modulus tests on sample mixtures of fly ash and lime kiln dust. These sample mixtures showed lower base thicknesses. The authors suggested that construction costs can be reduced by stabilizing road surface materials with high carbon fly ash.

In the present study, stabilizing fine-grained subgrade soils with high clay content using the Isparta-Karakaya pumice waste was investigated. Pumice waste in different ratios was blended with problematic clay to improve the mechanical properties of the soil.

2 Materials and methods

During the Paleocene and Quaternary periods, pumice deposits in Isparta and its neighboring regions were formed after eruptions of the Gölcük volcano, which is located southwest of Isparta, Turkey. There are four sources of pumice in Isparta, namely, the Karakaya, Gölcük, Gelincik and Aliköy zones, and the pumice from each source exhibits different properties. In the present study, pumice was obtained from the Isparta-Karakaya region, which spans an area of 1940 hectares. Its apparent reserve is about 0.8 billion m^3, with a possible reserve of 1.2 billion m^3, and a total reserve of about 2 billion m^3 [34].

Isparta-Karakaya pumice is generally used for lightweight briquette production. Particles that can pass through a No. 40 sieve are not used in the production process. This group of pumice is called pumice waste. The amount of the Isparta-Karakaya pumice waste is estimated to be about 20,000 tonnes.

The pore structure of the Isparta-Karakaya pumice is shown in Figure 2. The pore perimeter is surrounded by ferrous material. In Figure 3, there are black opaque minerals, such as pyrite, magnetite, chalcopyrite, and hematite, among others. Amorphous materials surround the opaque minerals. Pyroxene and feldspar crystals within the pumice are shown in Figures 4 and 5, respectively.

There are very few studies on the use of pumice in the construction of highway pavements. To date, some lightweight aggregates, with the exception of pumice, have been used for various purposes. Bottom ashes were applied in wearing courses, surface treatments, base courses, road bases, and subbase layers after being crushed as granular material [35]. Coal products were integrated in subbase layers as a stabilization material [36]. These products were utilized as fill in embankments, in subbase and base courses, and as aggregate in concrete and hot mix asphalt mixtures [36, 37]. Lime-pulverized fly ash slurry that is injected under pressure was employed to stabilize embankments and levees. Increases in strength by 15%–30% were reported [38].

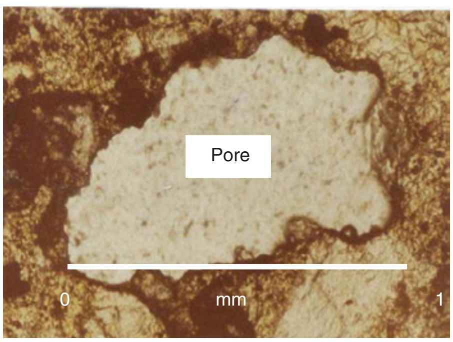

Figure 2 The pore structure of the Isparta-Karakaya pumice.

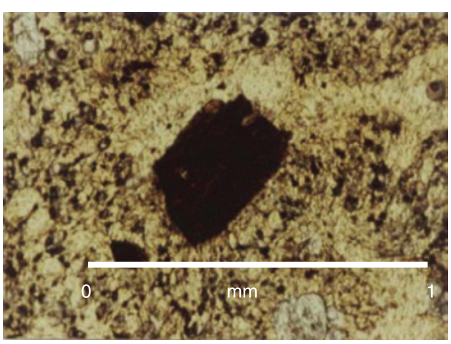

Figure 3 Opaque minerals within the Isparta-Karakaya pumice.

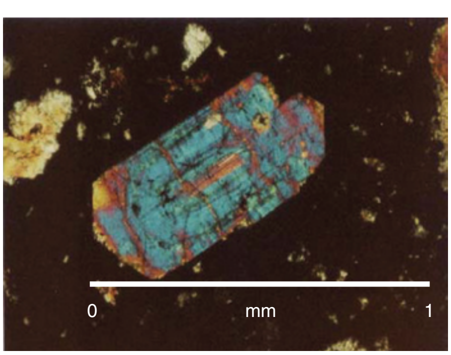

Figure 4 Pyroxene feno crystals within the Isparta-Karakaya pumice.

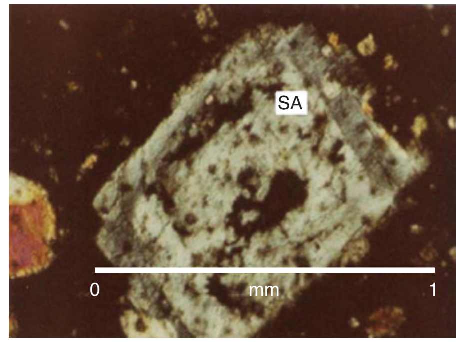

Figure 5 Zoned feldspar crystal within the Isparta-Karakaya pumice.

2.1 Experiments conducted on pumice

The present study is the first of such that deals with the utilization of pumice for stabilization of highway subgrades. For this purpose, chemical analyses and sieve tests were performed. Porosity, pore ratio, saturated degree, natural water content, natural unit weight, liquid limit, plastic limit, durability, abrasion, and permeability coefficient values were determined. These experiments were conducted in accordance with the ASTM standards to identify the engineering properties of pumice waste and examine the effects of these properties on problematic clayey subgrade soils. Waste pumice in different ratios by weight was mixed with high-plasticity clayey soil to modify the aforementioned engineering properties.

Chemical characterization of the pumice involved chemical analysis to determine its concentration of major, minor, and some trace elements. The Isparta pumice is composed of silica and aluminum (Table 1). The high SiO_2 ratio of the aggregate is what gives the pumice its abrasion property, whereas the high Al_2O_3 ratio bestow the pumice durability to fire and heat.

Table 1 Chemical composition of the Isparta pumice [28].

Major element	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO
Isparta Pumice (%)	63.40	16.70	6.50	2.50	3.40	5.35	2.15

The physical characteristics of the Isparta-Karakaya pumice aggregate are shown in Table 2. Porosity is the ratio of the volume of void to the total volume of material [39]. The porosity of pumice is higher than that of other materials because pumice has abundant voids at the micro and macro scale. For this reason, its water absorption capability is higher. With increasing grain size, the void ratio, porosity, and water absorption properties of pumice also increase. The waste fraction of pumice in industrial processes is 0–3 mm. In this study, pumice that could pass through a No. 40 sieve (0.425 mm) was used for mixing with expansive clay.

The physical characteristics of the Isparta pumice aggregate are given in Table 2 [40]. The water content, porosity, and saturation degree increase with decreasing particle size. The results of the Durability (Na_2SO_4), Los Angeles abrasion, and CBR tests on the Isparta-Karakaya pumice were 26%, 37.33%, and 29.36%, respectively [41]. The index properties of the Isparta pumice are given in Table 3. The natural unit weight of pumice is extremely low, but its permeability coefficient is high. Because of these properties of pumice, it is considered as a lightweight aggregate.

2.2 Experiments conducted on clay and pumice

Classification and standard compaction tests were conducted on the clay samples. The hydrometer results show that the pumice is composed of 58% clay and 42% silt. The liquid limit is 126%, plastic limit is 47%, and plasticity index is 79%. Therefore, the soil sample is high-plasticity clay (CH) based on the Unified Soil Classification System. X-ray analysis was performed to determine the mineralogical factors of the soil sample at the Laboratory of General Directorate of Mineral Research and Exploration. A sample was subjected to normal inflection at 2.5–70°C and to inflection with saturated ethylene glycol at 2.5–40°C. Excessive clay minerals were determined. The results show that the dominant clay minerals in order of high presence ratio are montmorillonite, kaolin, a few illit, quartz, feldspar, and a few mixed-layer clay minerals.

Table 2 Physical characteristics of the Isparta pumice aggregate [41].

Sieve (mm)	8–16	4–8	2–4
γ_{dmin} (kg/m^3)	650	738	893
γ_{dmax} (kg/m^3)	683	742	912
Water absorption	11.72	19.33	42.4
Void ratio	28.47	29.92	32.34
Porosity	28.47	70.08	67.66
Degree of saturation	15.22	22.42	28.67

Table 3 Index properties of the Isparta pumice.

Properties	Isparta-Karakaya pumice test results
Liquid limit (%)	35
Plastic limit	Non-plastic
Shrinkage limit (%)	7
Natural water content (%)	28
Natural Unit weight (g/cm^3)	0.7
Permeability coefficient (cm/sn)	0.4
Specific gravity, Gs	1.22

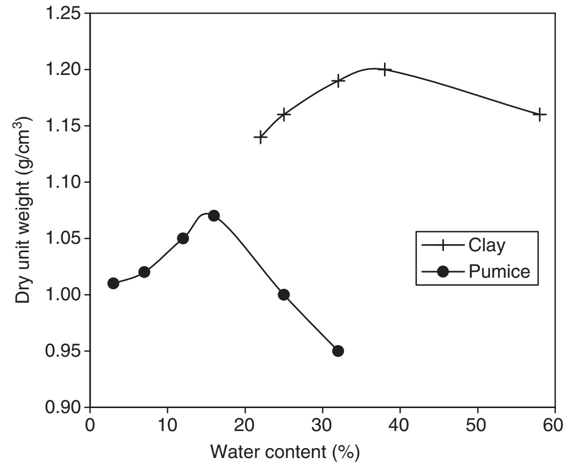

Figure 6 Results of standard compaction tests on the clay and pumice samples.

Standard compaction tests were done on the clay and pumice samples according to the ASTM standards. The dry unit weight and water content relations are shown in Figure 6. The maximum dry density and optimum water content of the clay samples are 1.19 g/cm^3 and 38%, respectively, whereas the maximum dry density and optimum water content of the pumice samples are 1.07 g/cm^3 and 16%, respectively. The optimum water content of pumice is lower than that of clay. These measurements suggest that the possible optimum water content value of clay-pumice mixtures is less than that of natural clay.

2.3 Experiments conducted on the pumice-clay mixture

Coarse-grained soil has greater pore structure than does fine-grained soil. For this reason, vibroflotation, dynamic compaction, and compaction piles are methods suitable for stabilization. The compaction characteristics of fine-grained soil are largely governed by its moisture content. Compared with those of coarse-grained fills, the properties of cohesive fills depend to a greater extent on the placement conditions [42].

Standard compaction, unconfined compression, and swelling pressure tests were conducted to determine the effects of pumice. In the standard compaction tests, clay samples that could pass through a No. 4 sieve and pumice samples that could pass through a No. 40 sieve were used. In the unconfined compression and swelling pressure tests, clay and pumice samples that could pass through a No. 40 sieve were used. Pumice was mixed into the clay samples in ratios of 10%, 15%, 20%, 30%, 40%, and 50% by weight in the tests. Atterberg limits tests were performed on the pumice-clay mixture samples. From these tests, the shrinkage limit, liquid limit, and plastic limit of the mixture samples were determined [43]. The results are given in Table 4.

Each sample for the unconfined compression and swelling pressure tests was prepared according to its own maximum unit weight and maximum water content values. For the unconfined compression test, the clay sample and the pumice-clay mixture samples were compacted in a standard compaction mold. The clay-pumice mixture samples were prepared in a ring 5 cm in diameter and 10 cm in height. Vertical load was applied on the soil samples until they could no longer support any additional load. The highest vertical stress is defined as the unconfined compressive strength of soil (q_u). For the swelling pressure test, the clay sample and the pumice-clay mixture samples were compacted in a standard compaction mold and were taken using an oedometer ring 71.4 mm in diameter and 16.3 mm in height. Swelling pressure was determined by constant volume tests according to the ASTM standards on the use of one-dimensional oedometer apparatus. The procedure for the swelling pressure test involved inundating the sample in the oedometer while preventing the sample from swelling. The swell pressure is reported as the maximum applied stress required in maintaining constant volume. Table 4 shows the maximum dry unit weight and the optimum water content values for which the samples were prepared and the values for the unconfined compressive strength.

The unit weight of the compacted sample was calculated using Equation 1:

$$\gamma_{comp} = \gamma_{d\,max}(1 + w_{opt}) \quad (1)$$

where $\gamma_{d\ max}$ and w_{opt} are maximum dry density and optimum water content respectively.

In addition, CBR tests were performed on the clay-pumice mixture samples. The results are shown in Table 5. The CBR degree increased when the pumice ratio was increased to 40%. However, the CBR degree decreased when the pumice ratio was increased further to 50%.

The relationship among the amount of pumice in the mixture, compacted unit weight, unconfined compressive strength, swelling pressure, and CBR is shown in Figure 7. With the increasing amount of pumice in the mixture, a higher dry unit weight was obtained for lower water contents, whereas decreased liquid and plastic limits were observed. As q_u increased, low unconfined compressive strength was observed only on pure pumice sample, whereas increased unconfined compressive strength was recorded for the pumice-clay mixture samples. However, the unconfined compressive strength decreased for the pumice-clay mixtures for pumice ratios 40% and above. The swelling pressure values decreased with increasing pumice ratios. The CBR values increased with increasing pumice ratios above 40%.

The stabilization process is due to the mechanical performance of the clay-pumice mixture. Puzzolanic reaction

Table 4 Standard compaction conditions and results of unconfined compressive strength, swelling pressure, and Atterberg limits tests [44].

Tests Samples	LL (%)	PL (%)	SL	γ_{dmax} (g/cm^3)	W_{opt} (%)	q_u (kg/cm^2)	P_s (kg/cm^2)
Clay	126	47	37	1.19	38	2.06	3.10
Pumice	35	–	7	1.07	16	0.54	–
%10 pumice+%90 clay	102	38	25	1.23	34	3.00	2.85
%15 pumice+%85 clay	96	35	21	1.24	32	3.60	2.75
%20 pumice+%80 clay	82	34	17	1.26	31	3.70	2.50
%30 pumice+%70 clay	72	28	13	1.36	28	4.44	2.25
%40 pumice+%60 clay	72	28	12	1.42	25	4.00	2.25
%50 pumice+%50 clay	66	27	8	1.46	27	3.50	2.00

LL, liquid limit; PL, plastic limit; SL, shrinkage limit; γ_{dmax}, maximum dry density; w_{opt}, optimum water content; q_u, unconfined compressive strength; P_s, swelling pressure.

Table 5 CBR tests results.

Tests samples	CBR (%)
Clay	0.95
%10 pumice+%90 clay	1.10
%20 pumice+%80 clay	2.50
%30 pumice+%70 clay	3.80
%40 pumice+%60 clay	4.00
%50 pumice+%50 clay	3.50

was not observed for these mixtures. The changes in the plasticity index are due to the addition of a non-cohesive fraction to the material. A chemical change in the clay was not observed. In this study, the pumice from the Isparta-Karakaya region was used. It was found that the Karakaya pumice has no puzzolanic effect, whereas the volcanic slag aggregates have puzzolanic effects.

3 Conclusions

In this study, stabilization of high-plasticity clayey subgrade of road pavements using the Isparta-Karakaya pumice waste was investigated. Once the index properties were determined, standard compaction, constant volume swelling, unconfined compression, shrinkage, and liquid and plastic limit tests were conducted to examine the effects of pumice on the compaction properties and the unconfined compressive strength of compacted clay. The Isparta-Karakaya pumice is composed of silica and aluminum. The natural unit weight of the pumice is extremely low. However, its permeability coefficient is high. The durability value against freezing of the pumice is 26. The Los Angeles abrasion and CBR values prove the limit values of Turkish Standards.

The shrinkage, liquid limit, and plastic limit values decreased with increasing pumice ratio because pumice is a non-plastic material. Standard compaction tests were performed by adding varying amounts of pumice to clay. With increasing pumice ratio in the mixture, it was observed that the maximum unit weight increased, whereas the optimum water content decreased. Moreover, the swelling pressure decreased with increasing amounts of pumice in the mixture. The unconfined compressive strength increased with pumice additive ratios of up to 30%. In contrast, the unconfined compressive strength decreased with pumice additive ratios of 40%–50%. The CBR degree increased as the pumice ratio was increased

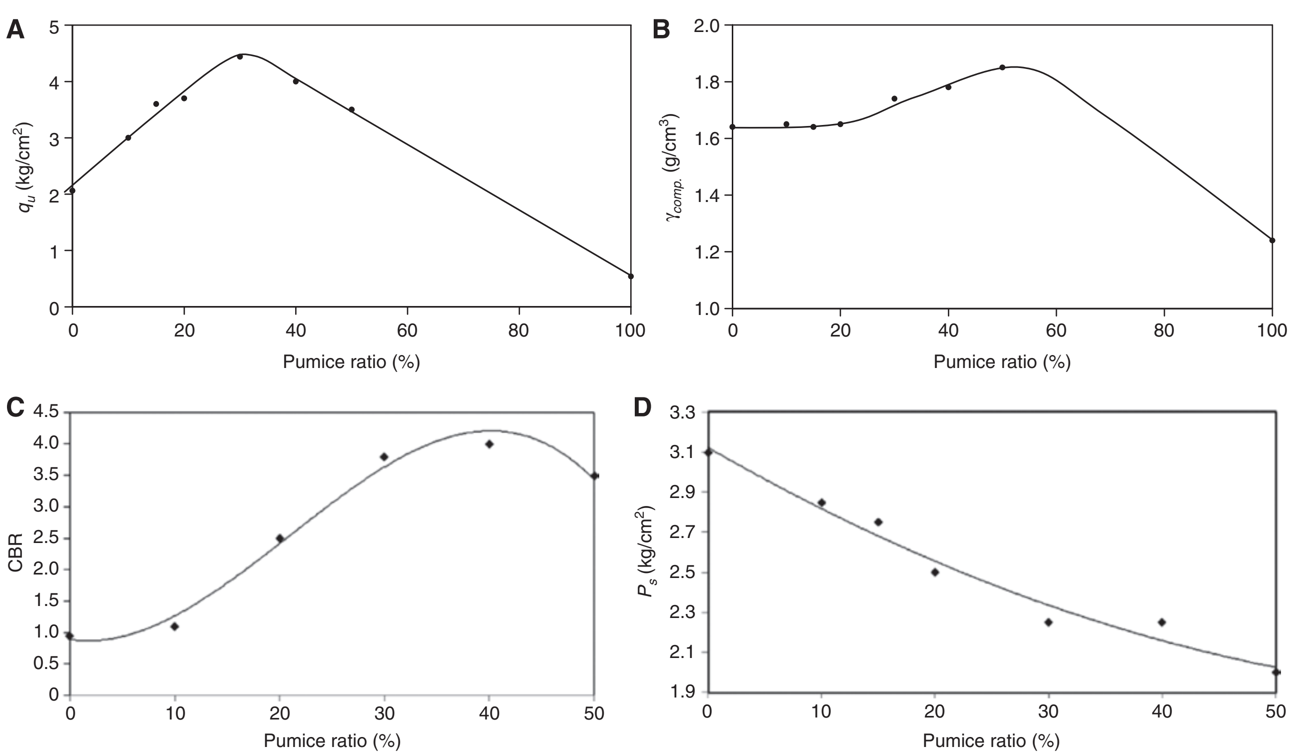

Figure 7 Effect of pumice ratio at the mixtures.
(A) q_u, unconfined compressive strength. (B) γ_{comp}, compacted unit weight. (C) CBR. (D) P_s, swelling pressure.

up to 40%, but it decreased as the pumice ratio reached 50%. Therefore, the ideal amount of the Isparta-Karakaya pumice additive to use for clayey subgrades is 30% by weight.

The use of pumice for stabilization of clayey subgrades has economic, environmental, and engineering benefits. Locally available pumice has little commercial value. Because it is readily available, the transportation costs involved in using this resource is minimal.

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