

## Research Article

# Sustainable Use of Tepetate Composite in Earthen Structure

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One of the best indicators for construction sustainability is the use of earthy local materials which are completely recyclable and savers of energy during their life cycle. Tepetate is an underestimated earth-natural material, vast and economic, used only in a compacted form in backfills for layers of low resistance in pavements and platforms of buildings. This volcanic soil, named in different ways in several countries, is found in the central region of Mexico. Its resistance as compacted material is very low, of the order of 0.08 MPa. In this work, an improved sustainable-tepetate composite, using CaOH, is presented. This research includes the determination of mechanical properties as well as the physicochemical characterization of the sustainable-tepetate composite behavior. It can be concluded that the strength of the proposed composite increases significantly, immediately after treatment and with time. X-Ray Diffraction shows that all the mineralogical phases prevail in the natural tepetate and only a new phase appeared (calcite), which increases with time. This and the reaction of CaOH with clay content are very likely associated with the continuous strength increase of the composite.

## 1. Introduction

Construction based on earthy materials is the most important, since these are natural, sustainable, and plenty in any region of the world. Unfortunately, the applications of an earthy material, in general, depend on their mechanical properties in their pure natural form. This fact makes them of limited applications, which leads to be used only as fills in platforms. One example of this kind of materials is the *tepetate*. However, there is a potential of being used as a composite via the use of other economical and sustainable materials for constructions such as the CaOH. Indeed, CaOH is a material being used from ancient times. There are several antique constructions as bridges, castles, and aqueducts built with stones and CaOH as joining material. These constructions have lasted for centuries and they still can be seen nowadays. The previous shows their long useful life.

Moreover, CaOH has a wide field of applications, both, in industry (paper, paints, etc.) and construction (it decreases soils expansion and increases strength on pavements). It is also used as fertilizer, metallurgy, water treatment, glass manufacture, and so forth.

In this work, CaOH was used to improve the mechanical properties of natural *tepetate*. This is an economic and vast volcanic soil used in construction only as backfill material.

## 2. Background

The use of earth on site as a building material saves manufacturing cost, time, energy, environmental pollution, and transportation cost. Earth can also be used in the construction of low cost sustainable houses which is significantly cheaper than using conventional bricks. Selected soil (sand and clay) is mixed with water to the correct proportions and then placed in a hydraulic or hand operated compressing machine to produce compressed blocks, which, after curing, is used for building walls [1, 2].

Tepetates have been reported in several countries, mainly in Latin America. They have been denoted with different names such as silcrete in the USA; talpetate in Nicaragua; hardpan, duripan, and cangahua in Colombia and Ecuador; cangagua, moromoro, tosca, and ñadis in Chile; hardpan in Perú; and kora and masa in Japan [3].

Tepetate is a word derived from the Nahuatl *tepetlatl*, whose root *tel* means stone and *pétlatl*, petate. Literally it has been translated as “stone-petate,” “stone-like,” or “soft-rock.” For the aztecs, this word was included within their classification of materials of a type of soil for agriculture, hard to work [4]. However, when the Spaniards arrived to Mexico, the word tepetate was synonymous of agriculture-useless because of its low quality [5].

In Mexico there exists a great amount of materials denoted as tepetates. These occupy approximately 30% of the surface of the whole country [6, 7], either on the surface or in the first meter deep [8]. Tepetates are interstratified volcanic banks, including paleosoils of different nature characterized by horizontal boundaries and well defined between the layers. Tepetates of the Mexican central plateau have been described as massive, compacted and hard, natural formations, and cemented for several chemical agents, including clays and silicates [3]. Tepetates classification has been based on the type of cementing substance. When the cementing substance is mainly silica ( $\text{SiO}_2$ ), the tepetates are denoted “duripan”; when is calcium carbonate ( $\text{CaCO}_3$ ), the tepetates are denoted “petrocalcic” type; when is calcium sulfate ( $\text{CaSO}_4$ ), they are denoted “petrogypsic” type; when are salts, they are denoted “petrosalt” type; when is iron, they are denoted “petroferric” type and when is clay, they are denoted “fragipan” type. Tepetates are originated basically from volcanic materials that have been cemented or compacted, as consequence of three main processes: (1) consolidation of mineral particles provoking compaction; (2) nature of the pyroclastic materials consolidated at the instant of being deposited; (3) hardening by pedologic (sedimentary) processes which produce cementing substances in solution [6, 7].

Several works on Mexican tepetates have been reported in the literature. Most of them have been based in their physical and chemical characterization [9–11]. In most of those it reports is assessed that tepetate is a matrix composed of sand, lime, and small percentages of clays. However, once in a while they can exhibit high content of clays. This variability leads to a problem for work-rehabilitation of tepetates for each textural type generates an independent physical and mechanical behavior. Clearly, this fact requires a specific investigation. Some of their reports were based on micromorphological characteristics [12] which have a distribution related to gross and fine particles, simple porphyritic, and morphology of peds in subangular blocks suggesting a reorganization of the basal mass. There are also reports focused on the cementing substance identification, the use of soil, and its ecological significance [6, 7].

Some authors have made reference to the relief, climate, and pedologic origin of tepetates [13, 14]. As a matter of fact, it has been determined that the secondary hardening happens under template or semiarid conditions, this climate condition allows the liberation of compounds. The liberated compounds are lixiviated and deposited and then, they act as cementing substance (free silica, calcium carbonate) in the soil. These are particularly efficient if in the matrix of the horizon where they are deposited, are absorbed by clay. Tepetates are formed, preferably, in subhumid climates (annual precipitation less than 800 mm), characterized for a

dry season lasting from four to six months [14], where, in general, evapotranspiration is greater than the precipitation.

There are also a great amount of studies about its agricultural properties (important for agronomy). Indeed, since the pre-Hispanic age there have been some attempts for using them in agriculture, by breaking them up and fertilizing them [15]. This is so because they have a very low content of organic matter, nitrogen, and phosphorous, which makes it difficult for using them in agricultural production [16]. Some studies have been on tepetate taxonomy; for example, [17] reported that in the lower level, known as generic, there were kinds of soils that can be located in the group of work soils as well as in the nonwork soils. This double inclusion is exemplified with the materials named as tepetates. About its classification and geological origin [6, 18], tepetates are originated from old deposits of volcanic ashes, deposited *in situ* or reworked, which were subjected to both processes, namely, diagenesis (hydroconsolidation) and pedogenesis that contributed to its compaction and/or cementation.

On the other hand, tepetates below soils produce lithological discontinuity that block the water infiltration and favor the lateral leakage, marking a surface where slides are prone. As well, tepetate could favor erosion and prevent aquifers reloading [19].

In 1996, while the III International Symposium of Hardened Volcanic Soils was celebrated at Quito, Ecuador, it was proposed to characterize tepetates as a hardened horizon, of volcanic origin, whose material is basically composed of pyroclastic materials, or fluids, or else as degraded volcanic soils.

Based on research done for several authors [9–11], it is possible to infer that, independently of its origin, tepetates always show common physical, mechanical, and chemical properties among them. Its compaction or cementation should be highlighted, which are reflected in high apparent densities ( $16.67\text{--}18.63\text{ KN/m}^3$ ), low porosity (from 13% to 24%), and its hydraulic conductivities and holding low humidity. These characteristics limit significantly the fast incorporation of primary plants, and generate a constant soil erosion.

Llerena [20] and García [21] considered tepetates of the Mexican Valley as pumite fragments of the Terciary or Cenozoic in process of weathering. Valdés [22] mentioned that tepetates of the Mexico were formed due to the alluvial sediments that lately were consolidated. Rodríguez et al. [23] noticed that the results reported by the aforementioned author lack sufficient precision and left questions about the hardened layers, concluding that tepetates may have diverse origins.

Zebrowski [3] states two geological processes for explaining the horizons hardening, as follows.

(A) Simple consolidation-compaction or by the hydroconsolidation of volcanic materials transported by the water. In both cases, there always exists an increase of the apparent density material, a greater hardness, and consequently, a decrease of porosity.

(B) Hardening of volcanic materials at the instant of their deposit and posterior cooling (pyroclastic flows) is another.

These natural deposits, called tepetate in Mexico, have very low permeability and the overlying soil erodes rapidly when cultivated. Unconfined compression varied from 0.29 to 15.7 MPa, and the mean was 2.42 MPa. The strongest, most indurated tepetate appears to occur when disseminated carbonates combine with silica as cementing substances [24]. The reported properties are circumstantial and depend on the geological consolidation and type of cementing substance.

As construction material, the properties of tepetates show a wide range of values, thus making it less reliable as homogeneous material for construction. Adding, it has a very low strength as construction material [25]. The properties of Tepetate depend on the volcanic origin of this material, mainly through phreatomagmatic eruptions. As construction material, 80% of the tepetates are classified as silty sand according to the Unified System of Soil Classification with no plasticity [26].

About problematic soils used in embankments for sustainable pavements, there is a study for bituminous sand materials where their high bitumen content makes oil sand materials problematic for field operations [27]. Then, about expansive soils there is a study on their engineering properties as subgrade when stabilized by using different percentage of hydrated lime on thickness of pavement structural system. The results suggest that the highly strength, lowest swelling and small thickness of pavement were determined with an optimum percentage of lime content of 6% [28].

CaOH is a natural linking material in the preparation of mortars for construction. Indeed their usage goes back to ancient times. Developed countries specify for construction in seismic zones the compulsory use of CaOH in mortars because of their unique features of adherence and strength for sustaining diagonal tensions.

Up to the industrial revolution and the cement discovery in 1824 at Portland, UK, CaOH had been the main link for construction in mortars, stuccos, and paints. Due to the limited facility of transportation, constructors applied the local material but they knew a wide spectrum of tricks for correcting the effects of each of the found CaOH and producing the mortars with the required quality in each application case, such as the control of speed for solidification, hardness, and the degree of waterproofing [29].

Lime treatment in clay soils can be explained by two types of chemical reactions that occur when lime is added to a wet soil: short-term reactions known as soil improvement or modification consisting of cation exchange and flocculation and the long-term reaction known as stabilization/solidification: the pozzolanic activity. During the cation exchange, the highly alkaline environment produced by the addition of lime causes silica and alumina to be dissolved out of the structure of the clay minerals and to combine with the calcium to produce new cementitious compounds: calcium silicate hydrates, calcium aluminate hydrates, and calcium aluminosilicate hydrates. The calcium hydrosilicates contribute substantially to the strength of the stabilized soil material and are of varying composition. These reactions contribute to flocculation by bonding adjacent soil particles together and strengthen the soil with curing time [30, 31].

### 3. Experimental Methodology

**3.1. Soils Samplings.** Tepetate was taken from one of the large active banks of Queretaro, QRO, Mexico. It should be pointed out that this location was selected because tepetate was being used for backfills in residential areas and also as layers for base or subbase of pavements. The place is known as "Mompani," having geographical coordinates: latitude  $20^{\circ}39'6.90''N$ , longitude  $100^{\circ}28'29.61''W$ , and a height of 1905 m above sea level. The CaOH used was of the commercial type.

**3.2. Procedure.** After extracting the material from "Mompani," the index and mechanical properties were determined, following the procedure set by the American Society for Testing and Materials (ASTM):

- (i) gradation (size of aggregates) [32];
- (ii) liquid limit, plastic limit, and index limit (material plasticity) [33];
- (iii) classification by the Unified System for Soil Classification (it defines soil type) [34];
- (iv) proctor Standard Compaction (it determines the maximum dry density and optimum humidity of the material for obtaining the greater strength) [35];
- (v) unconfined compressive strength (material strength) [36].

Then, the physicommechanical behavior of the sustainable-tepetate composite using CaOH was studied, by performing the tests listed as follows:

- (i) proctor Standard Compaction [35];
- (ii) unconfined compressive strength at different ages [36].

Finally the physicochemical characterization of natural tepetate and the sustainable-tepetate composite was done via X-Ray Diffraction.

### 4. Results

**4.1. Index and Mechanical Properties of the Natural Tepetate under Study.** Gradation was made by the dry mechanical method. It was determined using sieve analysis. With this method, the particles distribution can be quantified starting from the larger ones (75 microns, retained in sieve N°200) [32]. The results of soil gradation were gravel (23.22%), sands (42.55%), and fines (34.23%).

The plasticity properties (Liquid Limit, LL, Plastic Limit, PL, and Plastic Index, PI) were determined for the bank of selected material [33]. The values obtained were LL = 32.45%, PL = 31.38%, and PI = 1.07%. The soil classification was obtained by the plasticity chart. From this, one had that the fines are limes of low plasticity (ML). Then, with the plasticity properties and the gradation (45.5% sands and 32.36% of fines) the soil can be classified as a silty sand (SM) [34]. Since tepetate is a material placed and compacted in the construction site, its ideal compaction was determined via

TABLE 1: Materials standard compaction.

Material	Maximum dry unit weight (KN/m <sup>3</sup> )	Optimum moisture (%)
Natural tepetate	12.67	28.5
Tepetate-CaOH 2%	12.47	27.5
Tepetate-CaOH 4%	12.55	28
Tepetate-CaOH 6%	12.73	27.8
Tepetate-CaOH 8%	12.94	26.5
Tepetate-CaOH 10%	12.79	27.5
Tepetate-CaOH 12%	12.81	28.5
Tepetate-CaOH 15%	13.09	26.5
Tepetate-CaOH 20%	13.19	25.5

Proctor Standard test [35]. The maximum specific dry weight was 12.67 KN/m<sup>3</sup> with an optimum humidity of 28.5%. The strength of natural tepetate was measured to 0 days and was 0.082 MPa [36].

#### 4.2. Properties of the Sustainable-Tepetate Composite

**4.2.1. Proctor Standard Compaction.** The Proctor Standard test [35] was made for the sustainable-tepetate composite with different percentages of CaOH (2%, 4%, 6%, 8%, 10%, 12%, 15%, and 20%, with respect to the soil dry weight). These are shown in Table 1. From that table, it can be seen that, in general with the increase of CaOH, the optimum humidity tends to decrease and its maximum specific-dry weight increases slowly. Moreover, it can be seen that the increment of CaOH disintegrates tepetate, easing and increasing the compaction. The optimum moisture of most of the composites is between 26–28.5%, and from 12.47 to 13.18 KN/m<sup>3</sup> of maximum dry unit weight.

**4.2.2. Unconfined Compression Strength of Sustainable-Tepetate Composite.** The Unconfined Compression Strength Standard test [36] was made for the sustainable-tepetate composite with different percentages of CaOH. Probes of sustainable-tepetate composites were compacted for different CaOH percentages. For this, their dry unit weight and optimum humidity, obtained by the Proctor standard, were applied. Probes were prepared for several periods of time, namely, for 0, 7, 14, 28, 42, 56, 70, 112, and 126 days, as shown in Table 2 and Figure 1. Tepetate strength test was made only to 0 days and the result was 0.08 MPa.

From Figure 1, it is apparent that the strength increases when the amount of CaOH in the composite also increases. The increase of strength with time is also noticeable, and the same happens with clays [37]. However, there is an optimum amount (10%) of CaOH leading to the maximum strength. As time goes on, the composite strength increases significantly, reaching to 2.94 MPa at 28 days and up to 4.21 MPa at 56 days, stabilization time. The increase of resistance of the tepetate is very likely for its clay content. The treatment of clay with lime increases its resistance with the time due to the formation of calcium silicate hydrates, calcium aluminate hydrates, and

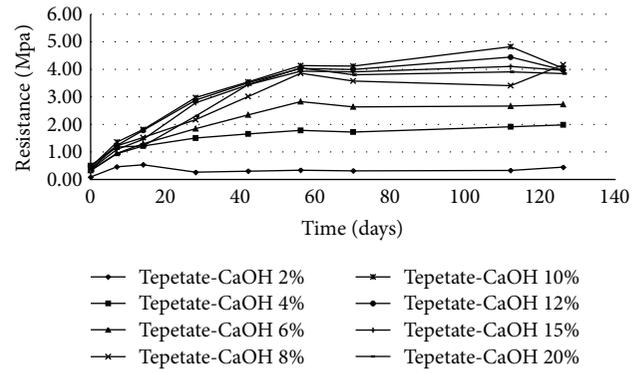


FIGURE 1: Strength time variation of the sustainable-tepetate composite.

calcium aluminosilicate hydrates. These reactions contribute to flocculation by bonding adjacent soil particles together and strengthen the soil with curing time.

**4.3. X-Ray Diffraction (XRD).** X-Ray Diffraction was done with a diffractometer Bruker D8-Advance at 30 KV and 30 mA. Samples of natural tepetate and the sustainable-tepetate composite at 15 and 30 days were analyzed for identifying minerals at the outset and those formed after some time.

**Natural Tepetate.** X-Ray Diffraction to natural tepetate was done. The study shows that several minerals as the halloysite, hematite, and quartz can be identified. The halloysite is a type of clay with plasticity much greater than the kaolinite. Hematite is a product of contact metamorphism and iron formations and is a common cementing substance in sedimentary rocks, frequently abundant in weathered iron minerals. This is an outcome of the goethite decomposition, which was found in the composite.

Quartz was another mineral found. Actually, this is the main component of sands [6] and was also identified at the tepetate XRD.

**Sustainable-Tepetate Composite at 15 Days.** The diffractogram of better sustainable-tepetate composite (10% CaOH) at 15 days shows that all the phases of the natural tepetate are present, among them, quartz, hematite, and halloysite (from white to light gray), but a new phase (calcite) appeared as result of the reaction of the CaOH with water.

The use of CaOH with expansive-clay soils, a treatment applied generally to inhibit volumetric instability, showed an increase of strength. Additionally, it is known that such a mixture generates calcite formation, which increases with time [37]. Therefore, it is very likely that the calcite is responsible of the strength composite.

The light gray and white colors of the tepetate seem to be originated by the absence of weathering of the original rock of gray and white colors, deposits of CaCO<sub>3</sub>, arising from salts or as result of iron removal, leaving great amount of minerals rich in SiO<sub>2</sub> as quartz, feldspar, and kaolinite [6, 7].

TABLE 2: Resistance of sustainable-tepetate composite in time.

Resistance material (MPa)	Time (days)								
	0	7	14	28	42	56	70	112	126
Tepetate-CaOH 2%	0.09	0.46	0.53	0.27	0.30	0.34	0.31	0.33	0.45
Tepetate-CaOH 4%	0.50	1.18	1.21	1.50	1.66	1.78	1.72	1.92	1.98
Tepetate-CaOH 6%	0.33	0.95	1.29	1.85	2.35	2.83	2.64	2.66	2.73
Tepetate-CaOH 8%	0.38	1.22	1.52	2.17	3.02	3.86	3.58	3.41	4.17
Tepetate-CaOH 10%	0.44	1.36	1.82	2.97	3.54	4.14	4.12	4.83	4.04
Tepetate-CaOH 12%	0.47	1.24	1.78	2.88	3.51	4.03	4.00	4.44	3.97
Tepetate-CaOH 15%	0.36	1.09	1.46	2.79	3.44	3.93	3.91	4.10	3.96
Tepetate-CaOH 20%	0.32	0.93	1.22	2.30	3.45	4.05	3.80	3.91	3.85

*Sustainable-Tepetate Composite at 30 Days.* The diffractogram of the sustainable-tepetate composite (10% CaOH) at 30 days shows that all the phases of the natural tepetate are present, but the calcite shows an increment with respect to 15 days, because the deflection or peak of the calcite grows in the diffractogram [37].

## 5. Conclusions

The strength of the natural tepetate was 0.08 MPa. It was constituted by graves (23.22%), sands (42.55%), and fines (34.23%).

The mechanical behavior of the sustainable-tepetate composite was improved with a maximum 10% of CaOH. Indeed with this percentage of CaOH, the maximum strength was obtained. After this percentage the strength showed no improvement. Additionally, a significant increase of strength was recorded as time went on. In fact, at 28 days the strength was 2.94 MPa whereas at 56 days, time for stabilization, the strength was 4.21 MPa. Thus, it is apparent that the inclusion of CaOH produced an optimum strength of the tepetate, by improving their mechanical properties in structures of compacted soils. This methodology creates a new sustainable composite using tepetate.

From the X-Ray Diffraction it was inferred that the natural tepetate was constituted mainly by halloysite, quartz, and hematite. These correspond to the gradation of soil with a better definition (weathered sands and halloysite clay). Since there was presence of iron minerals (hematite) and clay (halloysite), the tepetate could be classified as of the petroferic type with some halloysite clay. In the sustainable-tepetate composite with CaOH, all the phases of natural tepetate appeared. However, a new phase formed (calcite), which increased with time, could be associated very likely with the increase of strength of the composite with time. At the same time, the reactions of CaOH with clay content contribute to flocculation by bonding adjacent soil particles together and strengthen the soil with curing time.

The sustainable-composite tepetate offers an alternative construction material because of local construction material, being lasting, resistant, and economical, of low consumption energy in its preparation. Moreover, it is one hundred percent recyclable and thus can be used for reinforced platforms or for block elements.

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