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Influence of Tile Waste on the Mechanical and Microstructural Properties of Clay-Bentonitic Soil

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ABSTRACT

Expansive soils constitute a significant problem in geotechnical engineering, as their volume variations cause major structural damage and considerable economic costs. This work aims to evaluate the effectiveness of incorporating crushed tile waste to improve the physical and mechanical properties of a reconstituted swelling soil containing 75% clay and 25% bentonite, in order to reduce its plasticity and swelling potential. Geotechnical laboratory tests were carried out on mixtures containing 0%, 5%, 10%, 20%, and 30% tile waste, including methylene blue Index (MBI), Atterberg limits, normal Proctor test, direct shear, uniaxial compression strength (UCS), and oedometer test. Microstructural analyses (XRD, XRF, EDX, and SEM) were also conducted to characterize the samples. Results show a decrease in MBI from 8.16 to 4.0 and a decrease in Atterberg limits with increasing waste content. The maximum dry density (MDD) reached 1.62 g/cm³ at 5%, and the optimum moisture content (OMC) increased to 25.8% at 10%. The uniaxial compressive strength (UCS) and shear strength are highest at 30%, while the friction angle and cohesion increase with curing time. The addition of 20 to 30% tile waste reduces the swelling index. These findings indicate that the use of tile waste is a promising and sustainable solution for stabilizing expansive soils.

1. INTRODUCTION

Expansive soils constitute a major challenge in geotechnical engineering. Their swelling and shrinkage over the seasons cause significant structural damage in building structures and underground infrastructure, such as cracks in walls and foundations, differential settlement, and landslides, resulting in considerable economic costs [1].

Subgrade bearing capacity represents a critical geotechnical parameter in site selection for engineering projects. When subgrade conditions are inadequate, remediation can be achieved through excavation of poor material and substitution by high-performance backfill materials [2]. Soil stabilization is a widely used technique for enhancing the geotechnical and physical properties of expansive soils [3, 4]. In fact, cement, lime, fly ash, and recycled construction materials are the main binders used in improving bearing capacity and reducing soil compressibility [5, 6]. However, despite their proven effectiveness, these materials present growing environmental concerns due to their energy-intensive production and high carbon footprint [7].

Meanwhile, the construction and civil engineering sector generates significant volumes of waste, mainly from construction, renovation, and demolition sites [8].

Their recovery in civil engineering applications, particularly as soil stabilization additives, is currently a growing area of research [9]. Tiles and ceramics are known for their mechanical strength, durability, and aesthetic qualities. They are produced in large quantities, and scrap or defective products become a significant source of waste [10]. In Algeria, waste production is continuing to increase due to rapid urbanization, population growth, and socio-economic changes [11].

Several studies have highlighted the potential of various recycled materials to improve the geotechnical properties of swelling clay soils.

Tile waste is an abundant material that is readily available in the construction sector. The use of crushed tile waste to stabilize expansive soils enhances their geotechnical properties through several physical and chemical mechanisms. The addition of tile particles to clay soil reduces the plasticity index (PI) and liquid limit (LL) of the mixture. This reduction means that the soil has a lower water retention capacity, thus reducing its potential for swelling and shrinkage [12].

In addition, tile particles are denser and larger than clay particles allowing them to fill the voids between fine particles, improving the overall compactness of the mixture. This process leads to an increase in maximum dry density (MDD) and a decrease in optimal moisture content (OMC) during compaction [13].

Given their high silica and alumina content, tile waste reacts with an activator such as lime. This pozzolanic reaction produces hydrated cementitious compounds (C-S-H and C-A-S-H). These new hydrates bind soil particles together and increase its overall mechanical strength. The combined action of these mechanisms leads to significant improvements in the geotechnical properties of the treated soil, such as a reduction in free swelling and an increase in unconfined compressive strength and bearing capacity [14].

Previous studies on soil stabilization have mostly used tile waste in the form of fine powder. However, this study involves the use of tile waste that has been coarsely crushed to a particle size similar to that of sand, which could influence mechanical behavior and interaction with the soil matrix differently than finer particles.

Sabat [15] studied the expansive soils mixed with different proportions of ceramic dust and noted an inverse relationship between the addition of ceramic dust and parameters such as Atterberg limits, optimal moisture content (OMC), cohesion, and swelling pressure. However, geotechnical properties, particularly maximum dry density (MDD), uniaxial compressive strength (UCS), and California bearing ratio (CBR), revealed an improvement. Chen and Idusuyi [16] have improved the liquidity index and OMC of expansive soils by adding ceramic powder from 0 to 30%. However, an increase in MDD and CBR value has been observed.

Al-Bared et al. [17] studied the stabilization of marine clays using ceramic tile waste and highlighted positive changes, notably a reduction in the plasticity index (PI) and OMC values, associated with an improvement in UCS.

Moreover, Rathor et al. [18] demonstrated that the addition of ceramic tile waste modified the physical and mechanical properties of expansive soils and decreased the swelling phenomenon.

Zaini et al. [19] found that the use of columns of crushed ceramic tile waste as granular columns increased the shear strength of the soil by up to 52% and the lateral load resistance of kaolinitic clay soils. However, the strength enhancement is less significant in the absence of confining pressure. Without adequate confinement, the soil is more prone to settlement, which diminishes the effectiveness of the stabilization.

Rani et al. [20] observed that the incorporation of ceramic tile waste in the treatment of expansive soils led to a reduction in consistency limits, OMC, and swelling pressure. Meanwhile, MDD and CBR values showed a progressive increase with higher ceramic tile waste content.

Md Isa et al. [21] found that the incorporation of tile waste reduced the OMC of the soil while adding powdered tile waste in excess of 15% led to a reduction in unconfined compressive strength (UCS).

Anil et al. [22] found that adding 30% tile waste degraded the overall geotechnical properties of the soil. An excessive amount of tile aggregate disrupts the native soil structure and impairs particle bonding, which leads to a loss of shear strength.

As regards soil stabilization studies, the use of soil reconstituted from a mixture of clay and bentonite is mainly intended to create a standardized reference material with controlled and predictable properties, to guarantee the reliability and reproducibility of scientific research. This method makes it possible to create a reference soil representing particularly difficult geotechnical conditions (very high swelling, low bearing capacity) in the laboratory, which may be rare or difficult to find consistently in nature. This allows the effectiveness of stabilization methods to be tested in the worst-case scenario [23].

Bentonite is a clay mineral composed mainly of montmorillonite and has a very high swelling capacity. Mixing it in precise proportions with a less active clay creates an artificial soil with a specific and known level of swelling. This allows to simulate different degrees of soil expansivity in a controlled laboratory environment [24].

This study investigates the influence of crushed tile waste on the behavior of a reconstituted soil composed of 75% clay and 25% bentonite. Previous studies on the stabilization of expansive soils have utilized tile waste sourced directly from the local tile manufacturing industry. In contrast, the tile waste used in this study was recovered from structures undergoing renovation or demolition, and consequently contains adhered residues from cement or mortar screeds.

The main objective of this study is to assess the effect of incorporating different percentages of crushed tile waste at levels of 0%, 5%, 10%, 20%, and 30% on the physical properties of reconstituted expansive soil. The characterization includes the determination of the methylene blue value and Atterberg limits, as well as its compaction characteristics, including maximum dry density and optimum moisture content. In addition, the study evaluates the evolution of shear strength and unconfined compressive strength parameters over curing periods of 1, 7, and 28 days. Furthermore, the study analyse the impact on soil compressibility and swelling potential in order to determine the optimal tile waste content that provides the most significant improvement in soil geotechnical properties.

The microstructural analyses were performed using X-ray diffraction (XRD), X-ray fluorescence (XRF), energy dispersive X-ray analysis (EDX), and scanning electron microscopy (SEM) on samples of clay, bentonite, and tile waste in order to characterize their mineralogical and morphological properties. Then, the physical and geotechnical properties of reconstituted soils containing crushed tile waste were characterized in depth, including MDD, OMC, UCS, Proctor test, Atterberg limits, oedometer test, compression test, and swelling test.

2. MATERIALS AND METHODS

2.1 Materials

The materials used in this study consist of a soil reconstituted of 75% clay and 25% bentonite, along with crushed tile waste (Figure 1). The clayey soil was obtained from a construction site in Skikda, Algeria. The recovered clayey soil was oven-dried at a temperature of 70°C for 24 hours, then sieved using a 1 mm sieve. Different geotechnical properties of the clay soil, such as grain size distribution, MBI, liquid limit, plastic limit, maximum dry density, and optimum moisture content, were determined in accordance with standard procedures as indicated in Table 1. XRD, XRF, EDX, and SEM microstructure tests were performed on the clay soil. Table 2 presents the results of the XRF test of the clay soil.

X-Ray Diffraction analysis was performed using a D2 Phaser X-ray diffractometer (Bruker) equipped with a Cu-Kα

X-ray tube (wavelength λ = 1.54 Å). The analysis aimed to investigate the crystalline structure of raw materials, notably the clay soil, bentonite and tile waste. Scans were conducted over a 2θ angular range of 5° to 45°, with a step size of 0.02° and a scan time of 0.1 s per step. The diffraction patterns obtained were analyzed using DIFFRAC. EVATM software, which leverages the International Centre for Diffraction Data (ICDD) PFD4 database for phase identification and semi-quantitative analysis.

a) b) c)

Figure 1. Materials used a) clay; b) bentonite; c) tile waste

According to the XRD (Figure 2), the clay soil is mainly composed of kaolinite (K), indicated by the peak at around 11.5°. Quartz (Q) is clearly indicated by the very intense peak around 26.5-26.7°. Illite (I) appears at the peak around 20-21°, and there is also a small amount of feldspars (F), shown by the secondary peaks around 24-25° and within the range of 35-45°. The peak at 2θ = 35° corresponds to hematite (α-Fe_2O_3) [25].

Table 1. Geotechnical properties of clay soil

Parameters	Values	Standard Used
Apparent density (g/cm^3)	1.47	NF P 94-053
Absolute density (g/cm^3)	2.20	NF P 94-050
W (%)	25.6	NF P 94-050
Sr (%)	82.7	
LL (%)	65.58	NF P 94-051
PL (%)	32.12	
PI (%)	33.46	
MBI	6.33	NF P 94-068
MDD (kN/m^3)	15.47	NF P 94-093
OMC %	25	
Element <80 µm (%)	96.10	

The X-ray fluorescence spectrometer used was an S2 Ranger (Bruker) model, which includes an XFlash SDD (Silicon Drift Detector) and an X-ray emitter. The samples analyzed were pellets made by pressing a mixture of 2 g of wax and 10 g of the product to be analyzed at 0.6 MPa.

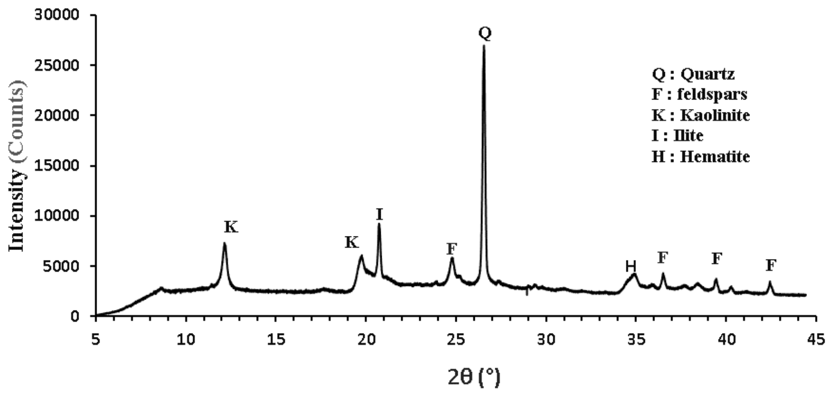


Figure 2. XRD Pattern of clay soil

According to Table 2, the very high chemical proportion of quartz (SiO_2) strongly confirms the major presence of quartz (SiO_2) identified by XRD. The high content of Al_2O_3 provides solid evidence for the presence of kaolinite. A proportion of 23.06% Al_2O_3 in the total sample, combined with the XRD peak, confirms kaolinite as a major component alongside quartz. The significant presence of Fe_2O_3 indicates the presence of ferrous minerals. In clays, this can correspond to iron oxides and hydroxides such as hematite (Fe_2O_3), which are very common in clays.

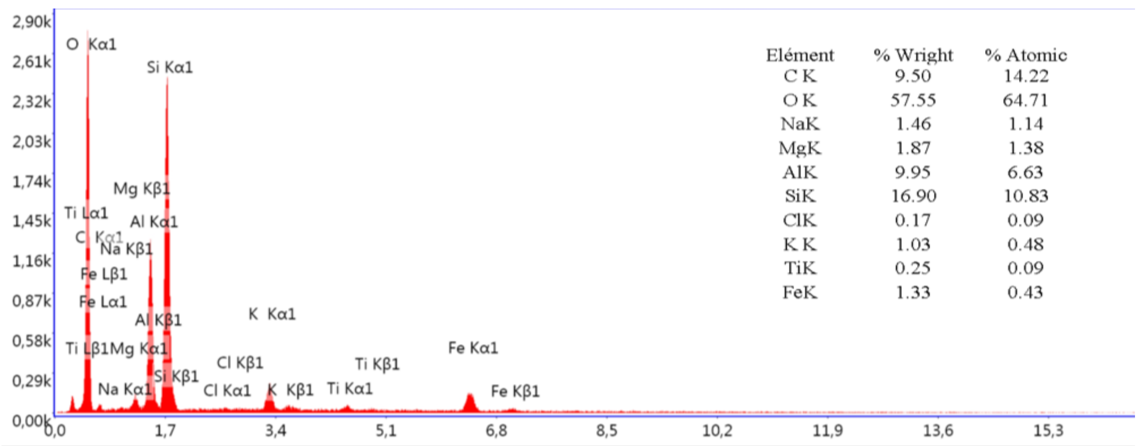
Table 2. Chemical composition of the clay soil

Oxyde	MgO	Al_2O_3	SiO_2	P2O5	SO_3	Cl
%	3.1	23.06	57.74	0.21	0.68	0.27
Oxyde	**K_2O**	**CaO**	**TiO_2**	**Fe_2O_3**	**ZrO**	
%	3.95	1.37	1.49	7.62	0.07	

SEM imaging was performed using an FEI Quanta 250 FEG electron source and a large field detector (LFD) for secondary electrons (SE). The device was operated at a voltage of 20 kV and a water vapor pressure of 1.5 mbar. The advantage of this technique is that it does not require any sample preparation before testing, which could alter its morphology, and allows it to be preserved from damage. EDX provides the elemental chemical composition (EDX spectra) using EDAX/Gemini, a lithium-doped silicon semiconductor detector (Si:Li).

According to Figure 3(a), the EDX spectrum of the clay soil shows prominent peaks for Oxygen (O) and Silicon (Si), indicating a significant presence of silicates, which are the primary components of clay minerals. The substantial presence of Al, Mg, Fe, K, and Na suggests the presence of various types of clay minerals (illite, kaolinite). The SEM image (Figure 3(b)) of the clay soil visually confirms the fine and lamellar morphology as well as the typical aggregated structure of clay soils. These microscopic characteristics are fundamental for understanding the macroscopic geotechnical behavior of clay [26].

The bentonite used in this study is supplied from the Bental Unit - Mostaganem, Algeria. The main physical characteristics of the bentonite are: MBI: 25, LL = 175 and PH = 9. The bentonite was analyzed by XRD, XRF, EDX and SEM tests.



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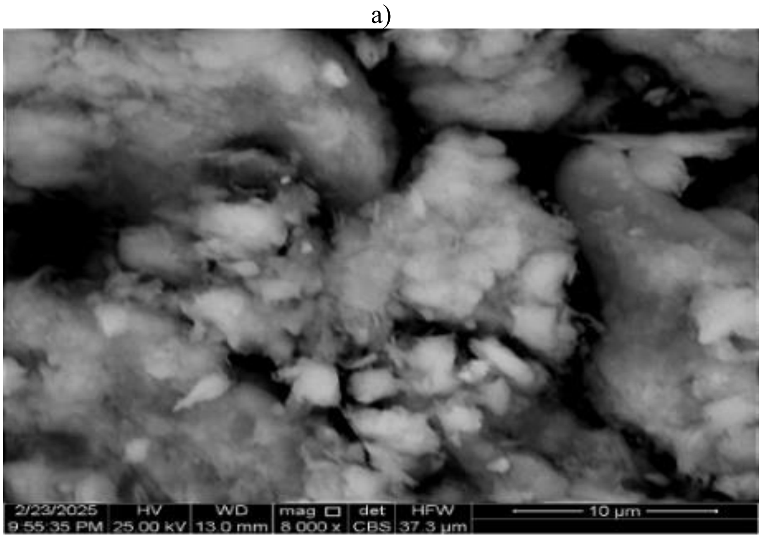

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Figure 3. EDX and SEM images of clayly soil: a) EDX b) SEM at 8000 magnifications

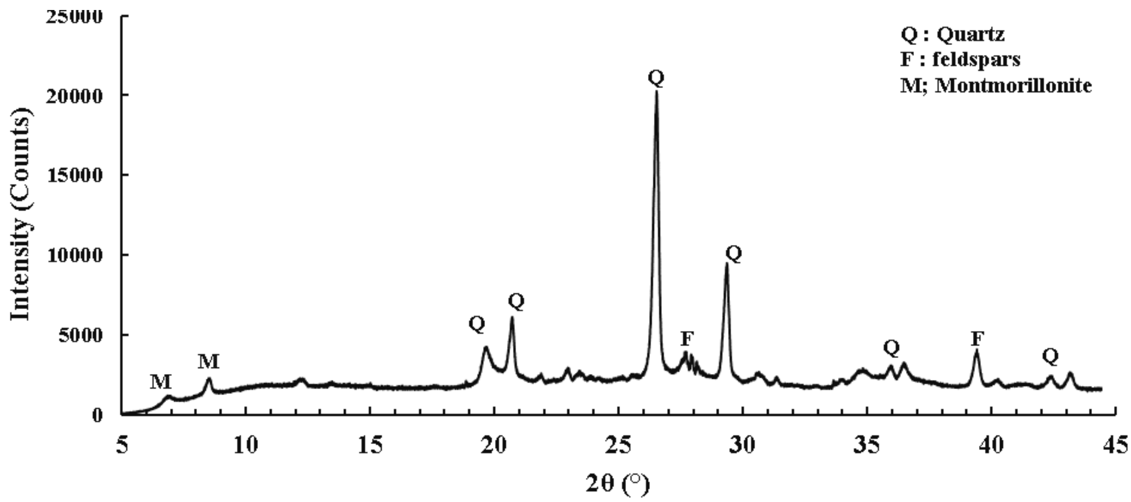


Figure 4. XRD pattern of bentonite

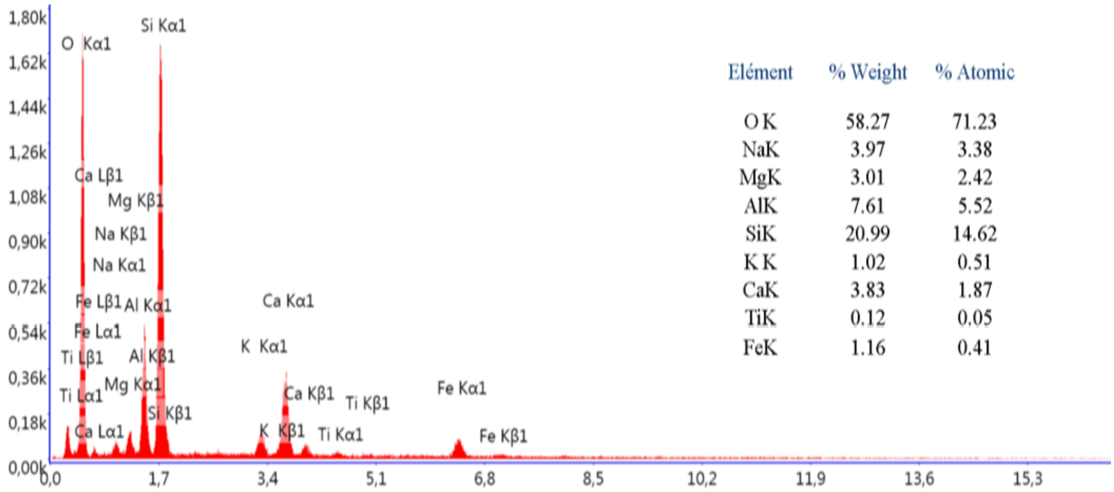
According to Figure 4, the DRX curve identified the minerals at the following positions (2θ angles), corresponding to the intensity peaks: Montmorillonite at the peak extending approximately from 2θ = 6° to 8°. Quartz (SiO_2) at the peak centered around 2θ = 20.8°. The two most intense peaks, the sharpest in the diffractogram, at the peak 2θ = 26.6° and the second peak centered around 2θ = 29.5°. Feldspar(s) at the peak located approximately at 2θ = 28.3°. The XRF results of bentonite presented in Table 3 show that bentonite is composed of a large amount of SiO_2 (silica) and a minimal percentage of calcium and magnesium, aluminum and sulfuric anhydride.

The EDX spectrum (Figure 5(a)) and the associated elemental composition table provide information on the chemical composition of bentonite. The major elements are Oxygen (O) and Silicon (Si). This high proportion of oxygen and silicon is fundamental for silicate minerals, of which montmorillonite is a part. The simultaneous presence of (Si) and (Al) in high quantities is the signature of aluminosilicates, which are the basic constituents of clays. Sodium (Na) (3.97% by mass, 3.38% atomic) and Calcium (Ca) (3.83% by mass, 1.87% atomic) are typical exchangeable cations present in the interlayer spaces of montmorillonite. The predominance of sodium suggests that this is a sodium bentonite, known for its swelling properties compared to those of calcium bentonites.

Scanning electron microscope (SEM) analysis of the bentonite sample (Figure 5(b)) reveals a typically lamellar and aggregated particle morphology, with thin, irregular sheets that stack to form micrometer-sized aggregates under the influence of interparticle forces. This sheet-like structure is a distinctive feature of smectite clay minerals, such as montmorillonite, the main constituent of bentonite [27].

Table 3. Chemical composition of bentonite relative to XRF test

Oxyde	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl
%	2.6	4.4	14.65	54.32	0.11	0.77	0.21
Oxyde	**K_2O**	**CaO**	**TiO_2**	**Fe_2O_3**	**SrO**	**BaO**	
%	3.20	12.97	0.75	5.63	0.06	0.05	



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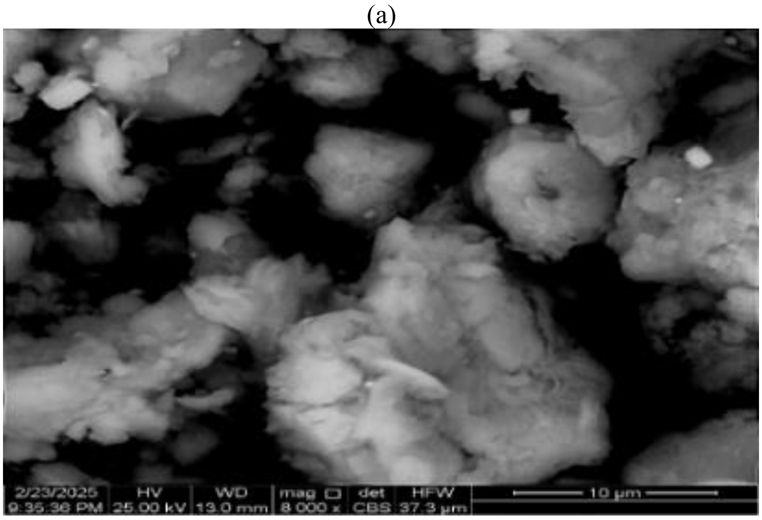


(b)

Figure 5. EDX and SEM images of tile bentonite: (a) EDX (b) SEM at 8000 magnifications

Table 4. Geotechnical properties of tile waste

Parameters	Value	Standard
Apparent density (g/cm^3)	1.11	NF P 94-053
Absolute density (g/cm^3)	2.20	NF P 94-050
D10	0.125	NF 18-304
D30	0.151	
Cu	1.784	
Cc	0.818	
MBI	0.0016	NF P 94-068

The tile waste originates from buildings undergoing renovation. This waste is crushed before being incorporated into reconstituted clay soil. The geotechnical properties of crushed tile waste are presented in Table 4. Figure 6 shows the particle size analysis of crushed tiles carried out according to the standard (NF 18-304).

Based on the chemical composition Table 5 of tile waste obtained through XRF analysis, the main components are: CaO (77.70%) Calcium oxide represents more than three-quarters of the composition, indicating that the tile waste is primarily composed of calcareous materials. This high content suggests the presence of limestone, Portland cement, or other calcareous binders used in tile manufacturing. SiO_2 (12.69%) Silica represents the second most important component. This moderate proportion is typical of ceramic materials and indicates the presence of sand, feldspar, or other silicate minerals used as fillers in the ceramic paste. Al_2O_3 (3.18%) Alumina generally comes from clays used in tile manufacturing.

Table 5. Chemical composition of tile waste

Oxyde	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O
%	1.5	3.18	12.69	0.11	1.13	0.05	0.65
Oxyde	**CaO**	**TiO_2**	**Mn0**	**Fe_2O_3**	**SrO**	**BaO**	
%	77.70	0.21	0.14	2.43	0.06	0.15	

From Figure 7, the XRD of the crushed tile waste shows sharp and intense peaks. Calcite ($CaCO_3$) dominant Peak at 29.4° (2θ) with Intensity 35,000 counts. Quartz (SiO_2) at 26.6° (2θ), 20.8° (2θ) and 23.1° (2θ). Hematite (Fe_2O_3) Peak at 36.1° (2θ). Periclase (MgO peak at 43.0° (2θ). This is in good agreement with XRF test [28, 29].

Figure 8(a) presents the EDX spectrum and the elemental composition of the crushed tile waste. The predominant presence of oxygen (O), calcium (Ca) and silicon (Si) is particularly significant. This is typical of ceramic materials, indicating that the tile was mainly composed of calcium silicates (characteristic of hydrated Portland cement compounds) and/or silica in crystalline and amorphous form (SiO_2). The presence of Carbon (C) is also a major element in association with the high calcium content, indicates the probable presence of calcium carbonate ($CaCO_3$), a raw material in the manufacture of the tile. Magnesium (Mg), Aluminum (Al), Sulfur (S) and Iron (Fe) further confirm the origin of the construction materials and the XRD of the crushed tile. SEM (Figure 8(b)) reveals a heterogeneous distribution with particles ranging from a few microns to approximately 30-40 µm. The majority of particles exhibit angular and irregular contours, typical of mechanical grinding. Particles present textured surfaces with marked asperities. Several particles reveal surface micro porosity, typical of porous ceramic materials. The general homogeneous appearance of particles is consistent with the chemical composition dominated by Ca, O, and Si. The angular morphology increases specific surface area compared to spherical particles. Rough surfaces offer more potential sites for chemical.

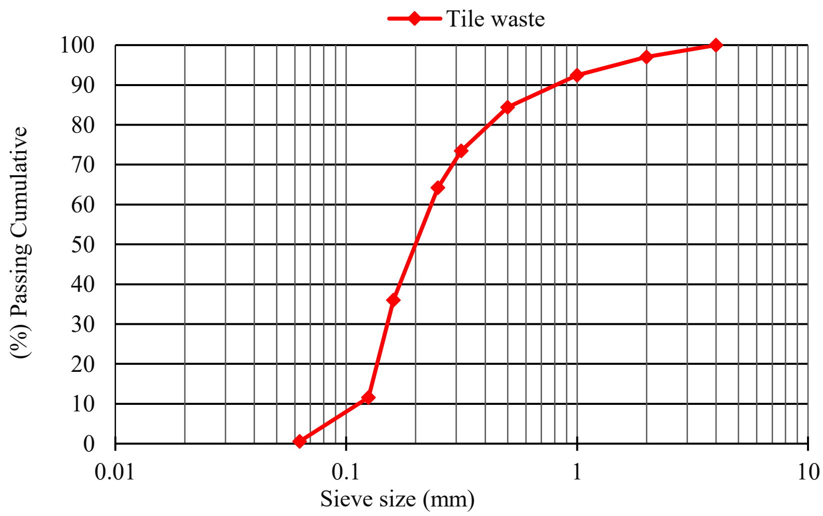


Figure 6. Grain size distribution of tile waste

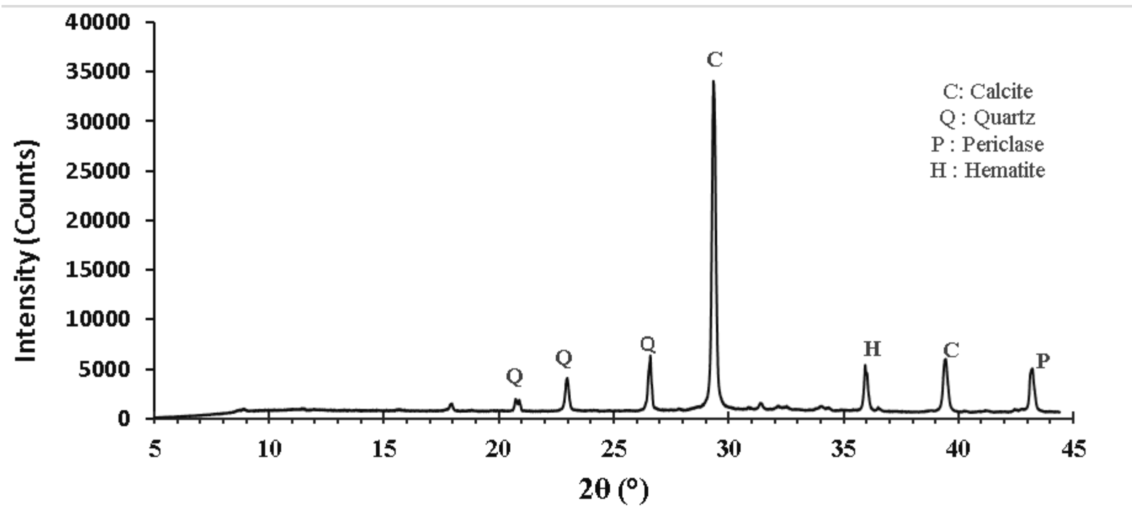
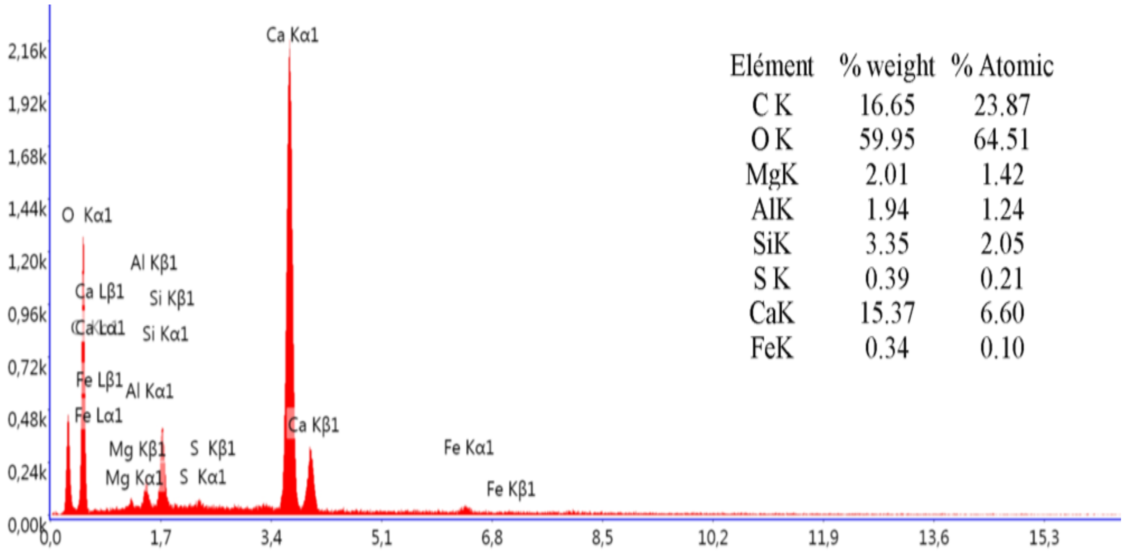


Figure 7. XRD of tile waste



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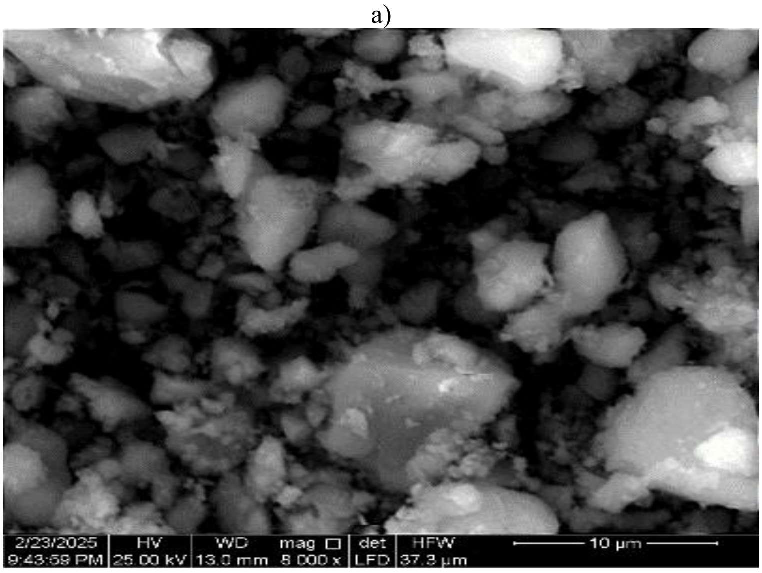


b)

Figure 8. EDX and SEM images of tile waste: a) EDX b) SEM at 8000 magnifications

2.2 Methods

A series of laboratory geotechnical tests were conducted to evaluate the impact of different percentages (5%, 10%, 20% and 30%) of crushed tile waste (TW) on the geotechnical behavior of a reconstituted soil composed of 75% clay and 25% bentonite. The experimental program included: methylene blue Index (MBI), Atterberg limits, standard Proctor compaction, direct shear box under consolidated drained conditions (CD), unconfined compressive strength (UCS) and oedometer consolidation tests.

2.2.1 Methylene blue test

The methylene blue test constitutes a fundamental geotechnical test defined by NF P 94-068 standard [30], allowing measurement of the methylene blue adsorption capacity of a soil. This method, also called the "spot test", aims to determine the methylene blue Index (MBI) which characterizes the clay content of the tested material. According to the test procedure, a 60-gram sample of reconstituted clay soil containing different proportions of crushed ceramic tiles (0%, 5%, 10%, 20%, and 30%) is suspended in 500 ml of demineralized water under continuous agitation at 400 rpm. The progressive addition of methylene blue solution in 5 ml doses is followed by a spot test on filter paper, allowing detection of excess dye through the appearance of a persistent light blue halo (Figure 9).

Figure 9. Methylene blue test

2.2.2 Atterberg limit test

To determine the liquid limit (LL) and plastic limit (PL), Atterberg limits tests were performed on various combinations of clay and crushed tile waste (TW) (Figure 10). These tests were carried out strictly following the standard procedure described in the study [31]. This allowed for an accurate assessment of the changes in the consistency characteristics of the mixtures with varying TW content. For different reconstituted clay soil mixtures and proportions of tile waste (0%, 5%, 10%, 20% and 30%), this procedure allows observing the effect of the addition of TW waste on the plasticity of the mixtures.

Figure 10. Atterberg limit test

2.2.3 Standard Proctor test

The standard Proctor test defined by the NF-P 94-093 standard [32] is performed to determine the optimum water content (OMC) and maximum dry density (MDD) of a mixture of reconstituted clayey soil with various percentages of crushed tile waste (0%, 5%; 10%, 20%, and 30%). This method involves compacting the soil in a cylindrical mold 101.5 mm in diameter and 116.5 mm high in successive 3 layers, each layer receives 25 blows from a 2.5 kg hammer falling from a height of 300 mm respectively (Figure 11). For mixtures containing reconstituted soil and varying proportions of tile waste, the Proctor test assesses the effect of added waste on compaction characteristics, thus helping to optimize the mixture for use in construction and foundation layers.

Figure 11. Standard Proctor test

2.2.4 Direct shear test

The direct shear test was used to evaluate the shear strength parameters of the reconstituted soil and mixtures using the direct shear test apparatus in accordance with the study [33]. Consolidated-drained (CD) direct shear tests were carried out on the basic composition of the reconstituted soil as well as on the mixtures of the reconstituted soil and crushed tile waste at different proportions (0%, 5%, 10%, 20% and 30%) of the dry weight of the reconstituted soil. Shear tests were carried out on 6 cm diameter specimens, prepared at the Proctor optimum of each mixture (Figure 12). These tests are carried out with a direct shear apparatus employing a systematic loading protocol with three distinct normal stress levels: 100 kPa, 200 kPa, and 300 kPa applied vertically. All tests were conducted at a controlled displacement rate of 1 mm/min in order to determine the shear stress of the different mixtures.

Figure 12. Direct shear test

2.2.5 Unconfined compressive strength test

The unconfined compression test is a commonly used laboratory procedure to determine the mechanical strength of cohesive soils, such as clay, without the application of lateral confining pressure, carried out according to the standard [34]. The maximum axial stress sustained by the specimen is recorded as the unconfined compressive strength (UCS) of the soil. The reconstituted soil samples and soil mixtures treated with crushed tile waste in the proportions (0%, 5%, 10%, 20% and 30%) were molded to the maximum dry density (MDD) and optimum moisture content (OMC), determined by the standard Proctor test. After preparation, they were sealed in plastic bags and cured for 24 hours, 7 and 28 days. For testing, the specimens were placed vertically between the platens of the unconfined compression testing machine and loaded at a constant strain rate of 0.5 mm per minute until failure (Figure 13).

Figure 13. Unconfined compression strength test (UCS)

Figure 14. Oedometric test

2.2.6 Oedometric test

The oedometric test, described by standard [35] is a laboratory procedure used to determine the compressibility characteristics of reconstituted soil and soil mixtures treated with crushed tile waste in the proportions (0%, 5%, 10%, 20% and 30%). The samples are subjected to a series of progressive vertical loads. For each loading stage, the resulting vertical deformation (settlement) is measured after dissipation of excess pore pressure and complete primary consolidation (Figure 14). This procedure produces a consolidation curve, from which parameters such as the compression index (Cc), swelling index (Cs), and preconsolidation pressure (σ'_p) are deduced, these are essential for predicting settlement under future loads.

3. RESULTS AND DISCUSSION

From Figure 15, the MBI value recorded a significant decrease with the increase in the percentage of crushed tile waste (TW). A MBI of 8.16 for the reconstituted soil decreased to 4 for the reconstituted soil + 30% TW mixture. The addition of crushed tile particles decreases the relative amount of clay minerals that adsorb methylene blue [36].

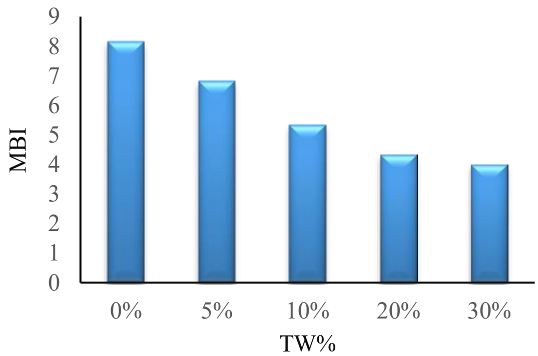


Figure 15. MBI values as a function of TW %

As shown in Figure 16, the percentage of tile waste increases from 0% to 30%, there is a general decrease in all three Atterberg limits: liquid limit (LL), plastic limit (PL), and plasticity index (PI). The liquid limit value decreases gradually as the percentage of crushed tile waste increases. It drops from 73.48% at 0% tile waste to 53.25% at 30% tile waste. This is in agreement with the results of the research [37].

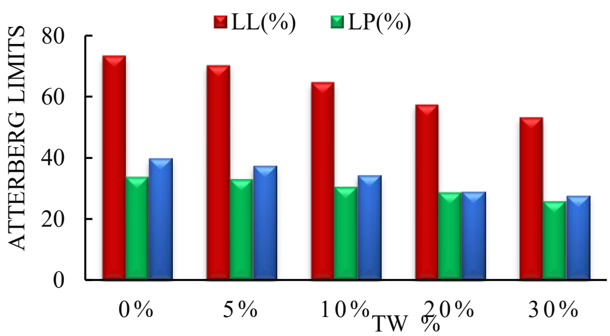


Figure 16. Atterberg limits versus tile waste percentage

The plastic limit (PL) shows a slight decrease as the percentage of tile waste increases. It drops from approximately 33.72% at 0% waste to approximately 25.72% at 30% waste. The plasticity index (PI), which is the difference between the liquid limit and the plastic limit (LL - PL), also decreases significantly with increasing percentage of tile waste. It drops from 39.76% at 0% (TW) to 27.53% at 30% (TW). This reduction in plasticity index indicates an improvement in the workability of the reconstituted soil. An addition of 10% (TW) is sufficient to enhance soil workability by reducing the plasticity index from 33.72% to 30.42%. This is in agreement with the results of the studies [38, 39].

Figure 17 illustrates the relationship between maximum density (MDD) in g/cm³ and optimum moisture content (OMC) for reconstituted soil samples mixed with different percentages of tile waste (TW). Each curve represents a different TW content: 0%, 5%, 10%, 20%, and 30%. With 5% (TW), the MDD is the highest among all samples, reaching approximately 1.62 g/cm³. This suggests that a small amount of tile waste can improve the dry density of the soil. The MDD for 10% (TW) is around 1.54 g/cm³, which is slightly lower than pure reconstituted soil. The MDD for 10% TW is around 1.54 g/cm³, which is slightly lower than pure soil. The highest MDD is observed at 5% TW. Beyond 5%, the MDD generally decreases, although 20% and 30% TW still have slightly higher MDD than 0% and 10% TW.

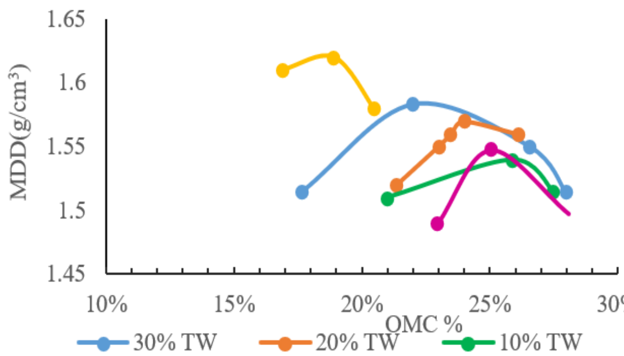
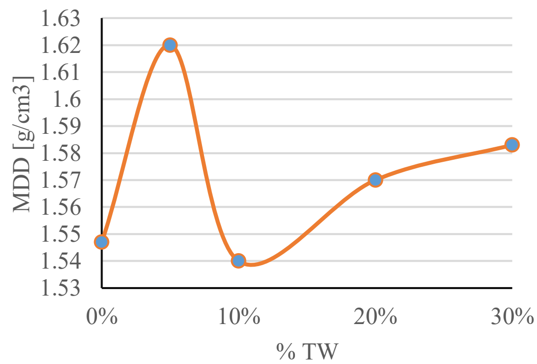
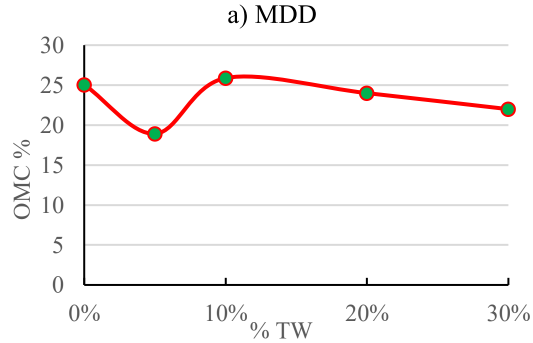


Figure 17. Proctor curve for different percentages of tile waste



a) MDD



b) OMC

Figure 18. a) MDD and b) OMC as a function of tile waste percentages

Figure 18(a) shows an initial increase in MDD, approximately 1.62 g/cm³, followed by a sharp drop at 10% (TW), and then a gradual recovery for 20% and 30% (TW). The peak MDD is clearly observed at 5% TW. As shown in

Figure 18(b), the OMC significantly decreases to its lowest point, approximately 18;9%, at 5% (TW). This indicates that adding a small amount of tile waste makes the reconstituted soil-TW mixture easier to compact with less water. The OMC increases to approximately 25.8% at 10% TW and continues to decrease slightly to approximately 21,9% at 30% (TW). The results are in good agreement with those of the study [40].

As shown in Figure 19, the curve 30% TW presents the highest shear stress values across the entire range of normal stresses. however, the curves 20% TW and 10% TW display lowest shear resistances. The slope of the lines reveals that the 30% TW mixture develops the highest friction angle.

The 30% TW mixture presents the highest cohesion, confirming previous results on the development of cementitious bonds due to pozzolanic reactions between calcium oxides (77.7% CaO) and the clay matrix [17, 41].

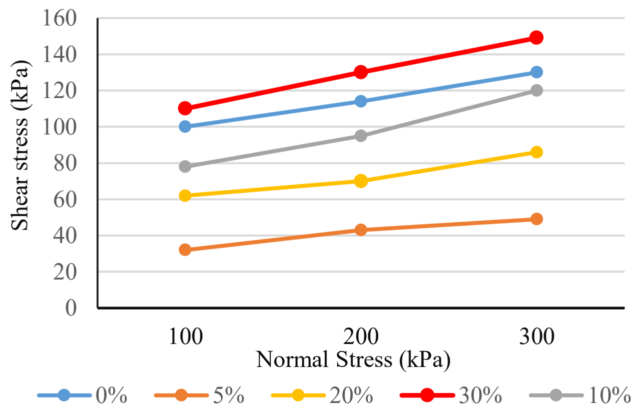


Figure 19. Intrinsic curves of reconstituted soil and tile waste mixtures

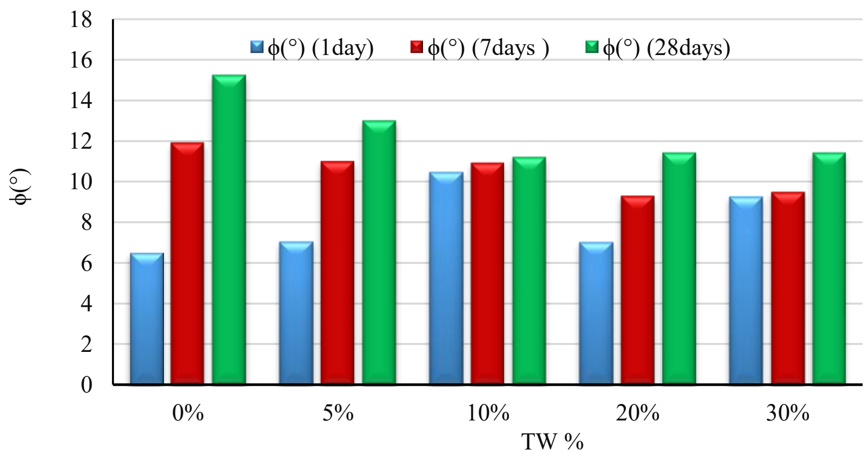
From Figure 20, for all percentages of crushed tile waste, the friction angle generally increases with curing time. The 28-day cured samples show the highest friction angles, followed by 7-day cured samples, and then 1-day cured samples. This suggests that the addition of crushed tiles waste contributes to a gradual improvement of internal friction angle over time, due to pozzolanic reactions or other long-term binding effects.

From Figure 20(a), at 0% TW (Control Sample) the friction angle increases significantly from approximately 6.5° at 1 day to about 12° at 7 days, and further to about 15.5° at 28 days. This indicates the inherent ability of the reconstituted soil to gain strength over time. 10% TW shows the most promising results in terms of initial (1 day) friction angle improvement. At higher percentages, such as 20% and 30% TW, result in lower friction angles than with 10% TW or even the control, especially at shorter curing times. EDX of crushed tiles shows higher (Ca) and (O) contents, confirming the silico-calcareous nature of the waste, (Ca) can strengthen the structure through pozzolanic reactions in the presence of water and silica, contributing to the observed increase in shear strength and friction angle.

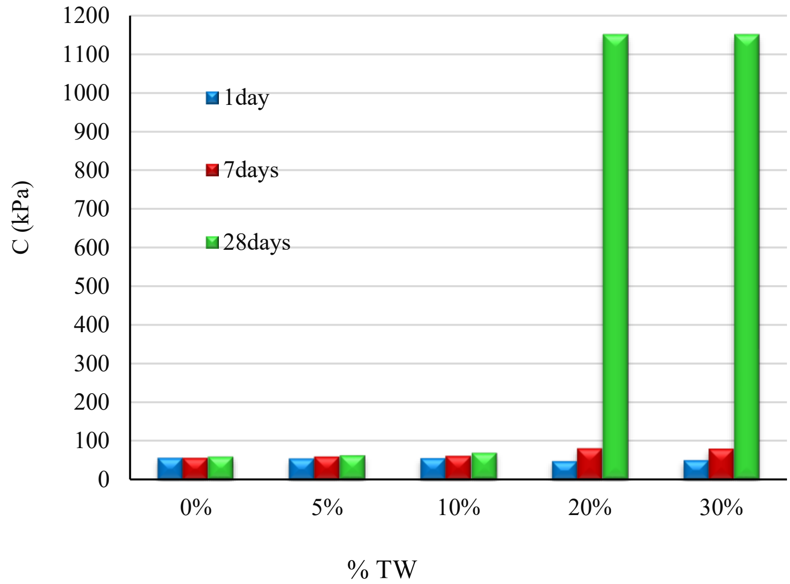
SEM observations reveal that the reconstituted clayey soil is composed of dense but porous fine particles, whereas the tile waste consists of coarser, angular grains. Mixing these materials improves the soil's microstructure by reducing porosity, increasing density, and promoting mechanical interlocking. These findings are consistent with results of the researches [23, 42].

According to Figure 20(b), for moderate tile waste (TW) contents (up to 20%), cohesion recorded an increase especially after 28 days of curing. This indicates that the addition of angular tile waste particles provides mechanical reinforcement, improving particle interlocking and the overall density of the reconstituted clay soil. Beyond 20% TW, cohesion stabilize. This suggests a saturation effect where excessive inclusions disrupt the clay matrix structure. These results are supported by studies [19, 42].

As shown in Figure 21, at medium additive content (around 10-20%), the compression curve shows a progressive increase in unconfined compressive strength (UCS). The maximum compressive strength value of 711.46 kPa was recorded for a percentage of 30% [43]. This improvement results from better compaction, increased density, and mechanical reinforcement due to interlocking of angular particles from the additive. The compressive strength of clayey soil mixtures rises with the addition of crushed tile waste up to an optimal percentage, driven by microstructural densification and chemical interactions confirmed by EDX and SEM. The presence of Ca enhances potential pozzolanic reactions when mixed with the silica-rich reconstituted clay soil, forming additional binding compounds that contribute to increased strength [44].



a) Friction angle



b) Cohesion

Figure 20. a) Friction angle and b) cohesion of reconstituted soil and tile waste mixtures at curing time of 1 day, 7 days and 28 days

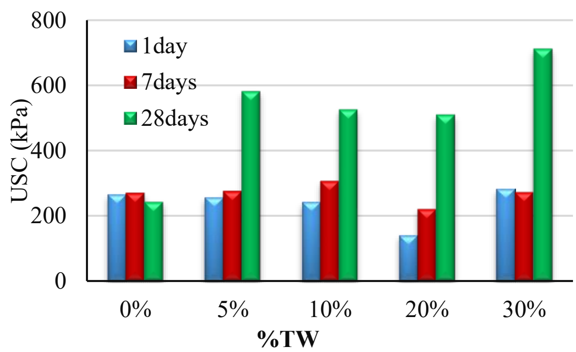


Figure 21. UCS of reconstituted soil and tile waste mixtures at curing time of 1 day, 7 days and 28 days

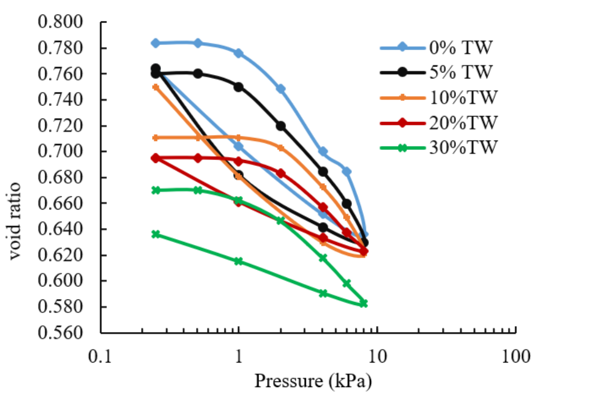
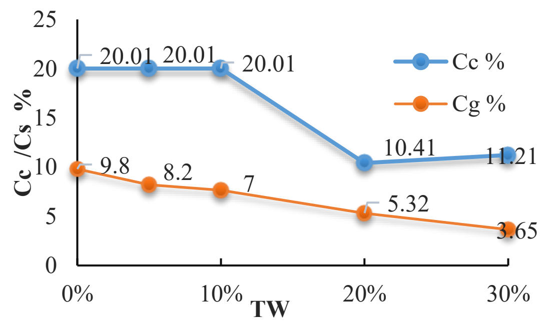
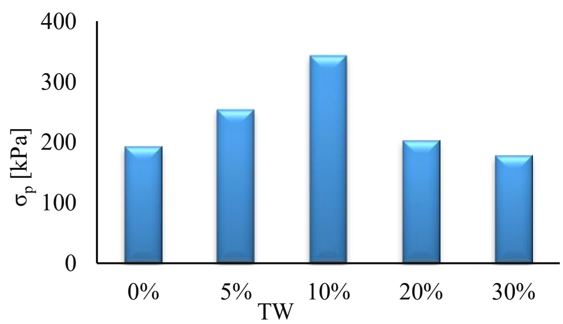


Figure 22. Oedometric compressibility curve of reconstituted soil and tile waste mixtures

Figure 22 shows the evolution of the void ratio (e) as a function of the applied pressure for mixtures of clay soils treated with 0%, 5%, 10%, 20% and 30% tile waste. The incorporation of crushed tile waste significantly reduces the compression index (Cc) and the recompression index (Cs) of the soil. The addition of 20 to 30% TW significantly decreases the value of Cc, indicating a significant reduction in the primary compressibility compared to the untreated reconstituted soil. These results agree well with the study of [40].



a) Compression and swelling index

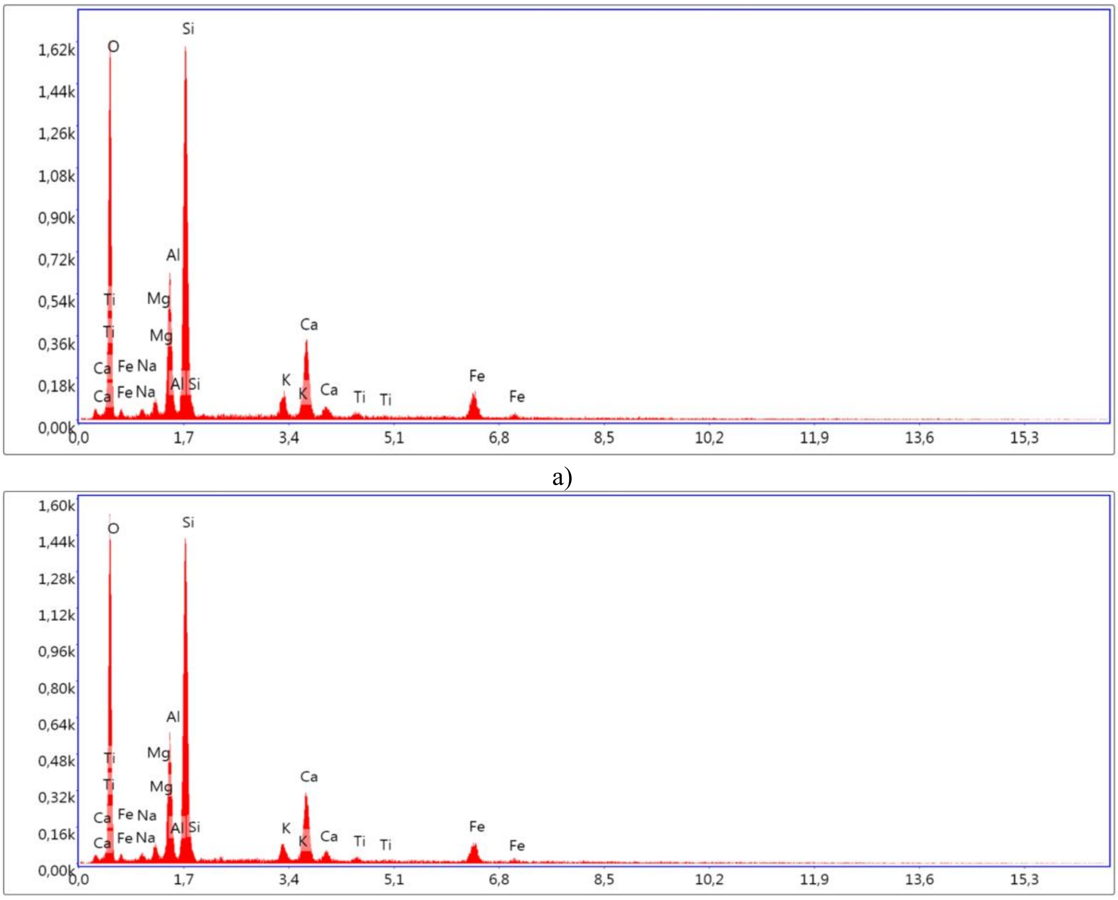


b) Preconsolidation Stress

Figure 23. Preconsolidation stress of reconstituted soil and tile waste mixtures

Figure 23(a) shows the evolution of the compression index (Cc%) and the swelling index (Cs%) of a reconstituted clayey soil treated with proportions of crushed tile waste (TW), from 0% to 30%. The compression index remains high and stable (around 20%) up to 10% TW. Beyond this point, there is a sharp drop to 10.41% at 20% TW, followed by a slight increase to 11.21% at 30% TW. Cs (swell/recompression index) decreases steadily from 9.8% (0% TW) to 3.65% (30%). The gradual addition of tile waste systematically decreases the swelling and recompression potential of the reconstituted clay soil, recent studies show that incorporating 20-30% ceramic waste leads to a strong reduction in both compressibility (Cc) and swelling (Cs) indices [21, 45].

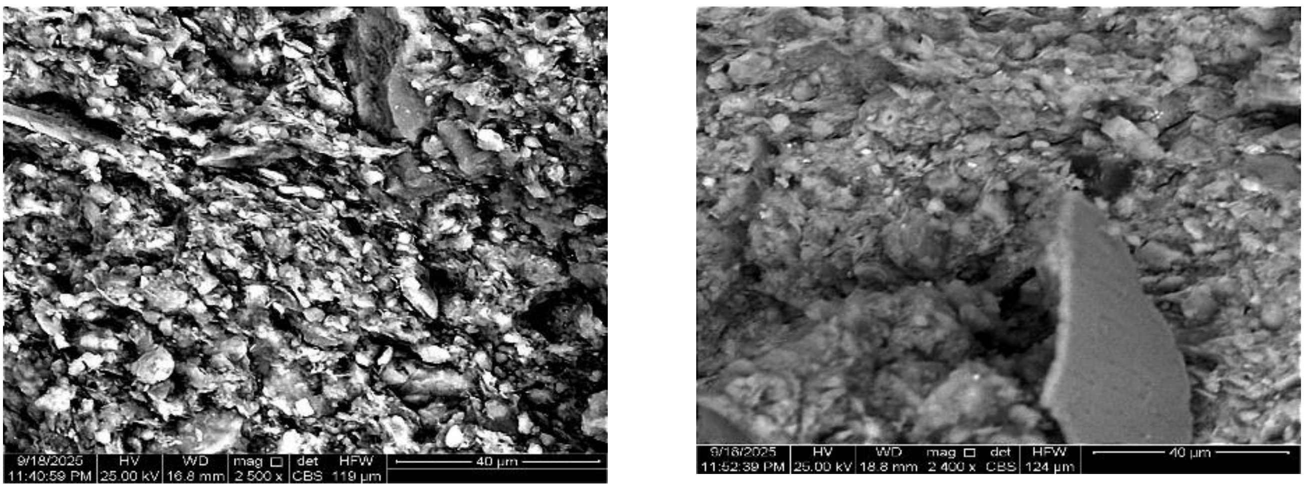
As shown in Figure 23(b), adding 5% crushed tile waste significantly increases the preconsolidation stress to approximately 250 kPa. This suggests that even a small amount of crushed tile waste contributes to improving the effective stiffness of the mixture. Adding tile waste gradually increases the preconsolidation pressure up to an optimum at 10%. At 30% crushed tile waste, the preconsolidation stress further decreases to approximately 180 kPa. This is the lowest preconsolidation stress observed in the experiment, even lower than the untreated sample. An excessive amount of poorly integrated tile waste could lead to an overall higher void ratio in the mixture, resulting in a more compressible and weaker material.



a)

b)

Figure 24. EDX of clay-bentonite mixture at a) 0%TW and b) 5%TW



a)

b)

Figure 25. SEM of clay-bentonite mixture: a) at 0% TW and b) at 5% TW

According to Figure 24, the addition of 5% tile waste (TW) to the clay-bentonite mixture primarily enriches it with calcium. This observation strongly suggests that the tile waste used is rich in calcium-based compounds, such as calcium carbonate ($CaCO_3$) or other calcium oxides, which are common in the manufacturing of ceramic tiles. This increase in calcium content is a critical finding, as calcium can play a key role in soil stabilization reactions. In the presence of silica and alumina (from the clay), the additional calcium can promote the formation of new cementitious compounds, such as Calcium Silicate Hydrates (C-S-H) and Calcium Aluminate Hydrates (C-A-H). This pozzolanic reaction could explain a potential improvement in the mechanical properties of the treated soil.

Figure 25 provide detailed views of the material's surface morphology and microstructure. They compare the structure of the clay-bentonite mixture before and after the addition of 5% TW.

SEM of untreated sample (Figure 25(a)) exhibits an open and porous fabric. In contrast, the treated sample with 5% TW (Figure 25(b)) shows a much more compact and homogeneous matrix. This indicates that the tile waste does not act as an inert filler; it has reacted with the clay and bentonite components. This observation, combined with the previous EDX analysis showing an increase in calcium, strongly suggests the formation of new cementitious compounds (such as Calcium Silicate Hydrates, C-S-H). These new binders coat the soil and waste particles, fill the voids, and create a stronger, more coherent matrix. This change in microstructure is the direct cause of the improvement in the mechanical properties (such as strength and bearing capacity) of the treated soil [45].

4. CONCLUSIONS

An experimental study was conducted to evaluate the geotechnical improvement potential of crushed tile waste as a stabilizing additive for expansive clay soil. The investigation focused on a reconstituted soil mixture composed of 75% clay and 25% bentonite, exhibiting significant swelling characteristics with a Methylene Blue Value (MBI) of 8.16, a plasticity index (PI) of 36.77%, a compression index (Cc) of 20.01%, and a swelling index (Cs) of 9.8%. These parameters indicate a highly plastic and expansive soil with substantial swelling potential, making it problematic for construction applications.

The primary objective was to assess the effectiveness of crushed tile waste in enhancing multiple geotechnical properties, including plasticity characteristics and workability, soil density and compaction behavior, shear strength parameters, unconfined compressive strength (UCS) and compression and swelling index. The obtained results reveal several important conclusions that contribute to the advancement of knowledge in the field of sustainable soil stabilization.

(1) The incorporation of crushed tile waste results in a significant reduction in methylene blue Index, MBI decreased from 8.16 (untreated soil) to 4.0 (30% TW) and Atterberg limits, indicating a decrease in clay activity and water sensitivity of the mixture. This favorable modification translates into a notable improvement in soil workability, facilitating its implementation in geotechnical applications.

(2) Proctor tests revealed that the addition of 5% crushed tile waste achieves the optimal maximum dry density (MDD) (1.62 g/cm³), which is higher than that of the control soil. Simultaneously, the optimum moisture content (OMC) decreases with the incorporation of the additive, presenting considerable economic and technical advantages for earthwork construction.

(3) Direct shear tests conducted under consolidated drained conditions show that adding crushed tile waste substantially improves the soil's shear strength. With an optimal 10% tile-waste dosage, the peak friction angle climbed from about 6.5° after 1 day of curing to roughly 12° at 7 days, and then to around 15.5° at 28 days. This steady rise highlights the ability of the reconstituted mixture (75% clay and 25% bentonite) to develop strength over time, as consolidation and pozzolanic interactions between the clay matrix and tile waste fines progressively reinforce the soil skeleton.

(4) At dosages up to 10% crushed-tile waste, cohesion stays low roughly 50-80 kPa throughout the 28-day curing period showing virtually no gain with time. Once the tile content exceeds 20%, cohesion rises sharply: values climb from the initial 50-80 kPa to more than 1150 kPa after 28 days, a fifteen-fold increase. A similar jump is observed at 30% tile waste, which also reaches about 1,150 kPa at 28 days. This evolution suggests that the high CaO level (77.7%) activates pozzolanic reactions only beyond a critical dosage and after extended curing, ultimately forging strong inter-granular bonds that dramatically boost the soil.

(5) The evaluation of the unconfined compressive strength at different curing periods (1, 7 and 28 days) shows a progressive improvement, particularly for contents of 5% and 30% of crushed tile waste.

(6) Oedometric tests indicate a progressive increase in preconsolidation pressure with the addition of crushed tile waste, reaching an optimum at 10%. The compression index of the reconstituted soil decreases beyond 10% TW, with values dropping from 20.01% to 10.41% at 20% TW. At the maximum tested concentration of 30% of total mass, the compression index partially recovers to 11.21%, indicating a nonlinear relationship between additive content and consolidation behavior. The swelling index decreases from 9.8% at 0% TW to 3.65% at 30% crushed tile waste.

(7) Oedometric tests indicate a progressive increase in preconsolidation pressure with the addition of crushed tile waste, reaching an optimum at 10%. The compression index of the reconstituted soil decreases beyond 10% TW, with values dropping from 20.01% to 10.41% at 20% TW. At the maximum tested concentration of 30% of total mass, the compression index partially recovers to 11.21%, indicating a nonlinear relationship between additive content and consolidation behavior. The swelling index decreases from 9.8% at 0% TW to 3.65% at 30% crushed tile waste.

(8) The EDX analysis of clay-bentonite mixture reveals that the bentonite is a sodium-calcium bentonite, rich in exchangeable cations (Na+, Ca2+), which is the source of its swelling properties. clay is a more classic aluminosilicate with a much lower content of exchangeable cations. The additional reactive silica and calcium introduced by the tile waste participate in pozzolanic reactions, forming cementitious compounds that bind the soil particles together.

(9) The SEM analysis visually confirms the effectiveness of tile waste as a stabilizing agent. The addition of tile waste introduces reactive silica and alumina, which react to form cementitious compounds that fill voids and bind soil particles, thereby enhancing the overall geotechnical properties of the clay-bentonite mixture.

The results obtained demonstrate the technical and environmental feasibility of using tile waste as a stabilizing material for clay soils. This approach is part of a circular economy approach, simultaneously reducing the landfilling of ceramic waste and the consumption of traditional natural resources.

Based on the experimental results, it is recommended to use crushed tile waste within an optimal range of 5 to 10% to maximize geotechnical benefits. This research opens promising perspectives for the development of ecological stabilization techniques that are economically viable, contributing to the evolution toward more sustainable practices in geotechnical engineering.

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