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*Original Article*

# Geotechnical and Economic Analysis of Cantilever Walls on Clayey Sand with Gravel Stabilised with Drywall Gypsum, Glass, Brick, and Recycled Marble

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***Abstract*** *- In civil engineering, the clay soils in urban areas of Junín have low bearing capacity and high deformability, which increases the cost of constructing retaining walls. This research analysed the structural design of cantilever walls stabilising soils with recycled waste such as plaster, glass, marble, and brick to improve their properties and optimise structural and economic performance. The specific weight, cohesion, angle of internal friction, and bearing capacity were evaluated, determining the optimal doses for each addition. Based on the experimental results, the walls were designed, and a comparative analysis of costs and dimensions was carried out. Glass powder at 15% was the most efficient and economical alternative, increasing the bearing capacity and allowing the wall base width and total cost to be reduced by more than 20%. Recycled gypsum at 12.5% showed the best technical balance, increasing cohesion and bearing capacity, as well as reducing footing thickness and optimising structural expenditure.*

*In contrast, marble powder generated moderate improvements with less economic impact, while brick powder showed no benefits and reduced these properties. Overall, the stabilisation of clay soils with recycled waste proved to be a technically, economically, and environmentally viable alternative, improving soil properties, reducing structural dimensions, and lowering costs. In contrast, marble dust produced moderate improvements with less economic impact, while brick dust showed no benefits and reduced these properties. Overall, the stabilisation of clay soils with recycled waste proved to be a technically, economically, and environmentally viable alternative, improving soil properties, reducing structural dimensions, and lowering construction costs. The results consolidate glass powder and recycled gypsum as high-value sustainable additions to civil infrastructure.*

***Keywords*** *- Retaining Cantilever Walls, Soils, Stabilisation, Recycled Waste, Bearing Capacity, Cohesion, Angle Of Internal Friction.*

## 1. Introduction

In Peru, the urban population reached 78.9% in 2023, compared with approximately 46.8% in 1960, representing an increase of more than 32 percentage points over six decades [1, 2] This sustained urban growth drove the progressive expansion of cities into peripheral areas commonly characterized by unfavorable geotechnical conditions, including steep slopes, ravines, and soils with low bearing capacity [3, 4]. A representative case was the city of Huancayo, where 92.3% of the provincial population resided in urban areas, and districts such as Huancán were rapidly incorporated into the metropolitan continuum. This process accelerated the occupation of terrain with irregular topography and mechanically unstable soils, increasing population exposure to significant geotechnical hazards [5, 6].

As a consequence of this expansion, numerous residential settlements developed without adequate earth-retaining systems, leaving them exposed to lateral soil pressures and progressive instability mechanisms. The absence or deficient design of retaining walls increased the likelihood of landslides, differential settlements, structural cracking, and partial or total collapse, particularly during periods of intense rainfall or seismic excitation [7, 8]. These deficiencies manifested critically in several regions of the country. In Retamas (La Libertad), a large-scale landslide in March 2022 buried dozens of dwellings, caused missing persons, and forced the evacuation of the population [9, 10]. In Huaraz, slope failures resulted in fatalities and extensive damage to housing and infrastructure, while in Huancayo, emergency retaining walls were required to prevent the collapse of buildings affected by ground movements and active erosion processes [11]. These events demonstrated that inadequate geotechnical planning not only endangered public safety but also generated high repair and reconstruction costs, limiting safe and sustainable urban development [12, 13].

In this context, traditional soil improvement methods based on the addition of cement or lime proved technically effective in increasing strength and stiffness; however, their large-scale application entailed high economic costs and a significant environmental impact, including carbon emissions [14, 15]. In response to these limitations, alternatives aligned with circular economy principles were promoted, prioritizing the reuse of construction and demolition waste as soil stabilizing agents [16]. Several international studies reported that the incorporation of recycled materials improved bearing capacity and shear strength of fine-grained soils, enhancing the performance of shallow foundations and, in some cases, earth-retaining structures [17-19].

Nevertheless, most of these investigations focused on road applications, where soil response was primarily evaluated under vertical loading and expressed through indices such as CBR or unconfined compressive strength. In the specific case of cantilever retaining walls, soil behavior was more complex, as structural stability depended mainly on active earth pressure, governed by unit weight, internal friction angle, and effective cohesion, together with foundation bearing capacity and sliding resistance. Increases in cohesion or internal friction angle could reduce the active earth pressure coefficient and improve global stability, allowing optimization of wall dimensions and a reduction in concrete and steel demand [20, 21]. Conversely, interventions that did not simultaneously consider these parameters could maintain or even aggravate failure risks, compromising the safety of buildings and urban infrastructure [22].

Based on this assessment, a relevant research gap was identified: the available literature provided limited integrated evidence linking soil stabilization with recycled materials to the simultaneous modification of $c$–$\varphi$–$\gamma$ parameters, their effect on active earth pressure, and the resulting geometric and economic optimization of cantilever retaining walls. To address this gap, the present study evaluated the geotechnical behavior of a clayey sand with gravel stabilized using recycled drywall gypsum, recycled glass powder, marble dust, and brick dust. Optimal addition percentages were determined from experimental results of unit weight, cohesion, and internal friction angle, and these parameters were incorporated into the structural design of cantilever retaining walls, considering stability and cost criteria. The novelty of the study lay in establishing a direct relationship between recycled-material soil stabilization and the effective reduction of structural dimensions and construction costs, providing a technical and economic basis for decision-making in urban earth-retaining works.

## 2. Literature Review

### *2.1. Soil Stabilization with Recycled Gypsum: Evidence and Limitations for Cantilever Retaining Walls*

In Peru, recycled drywall gypsum was applied as a stabilizing agent for subgrade soils using dosages of 2.5 %, 5.0 %, 7.5 % and 10.0 %, and its response was evaluated through modified Proctor compaction and CBR testing. The most favorable performance was obtained with a 7.5 % gypsum content combined with 1.5 % fiber, achieving CBR increases of up to 173 %, which confirmed its effectiveness in improving bearing capacity for unpaved road applications [23].

Under high moisture conditions, recycled gypsum was incorporated at 7.5 %, 15 % and 22.5 % and combined with Type B cement or lime, with curing periods of 3, 7, and 28 days and subsequent water immersion for up to 60 days. The inclusion of binders significantly reduced degradation associated with calcium sulfate solubility, with volumetric deformations remaining below 0.15 %, which proved critical for saturated environments [24]. A technical review further reported that recycled gypsum contents between 7 % and 15 % increased unconfined compressive strength and CBR, reduced swelling potential by up to 70 %, and modified plasticity through cation exchange and hydration products. Improved durability under wet–dry cycles was attributed to reduced leaching and microstructural stabilization when lime or cement was used [25].

The available evidence focused primarily on pavement indicators and material durability [23–25]. Changes in shear strength parameters obtained from direct shear testing, particularly cohesion and internal friction angle, were not systematically reported, nor was their influence on active earth pressure, lateral thrust, or global wall stability. In addition, the geotechnical improvements were not integrated with wall re-dimensioning or with the total cost of the wall–foundation system.

### *2.2. Recycled Glass Powder: Mechanical Performance and Activation Dependency*

In Tarma, soil stabilization with crushed glass was evaluated over a wide range from 0 % to 60 %, with an optimal content identified at 20 %. At this dosage, a maximum dry density of 1.987 g/cm³ and a CBR of 17.8 % were obtained, together with a progressive reduction in optimum moisture content that facilitated field compaction [26]. A systematic review of glass powder passing sieve No. 200 reported optimal contents around 15 %, with significant strength improvements and reductions in swelling index from 5.5 % to 1.65 % under specific conditions, indicating enhanced soil stability [27].

When alkaline activation was applied, finely ground glass smaller than 0.075 mm acted as a Geopolymer Precursor. Under this approach, an optimal content of 5 % was reported, yielding higher strength gains than other additives and demonstrating that the dominant mechanism depended on chemical activation and curing [28]. In expansive CL soils, glass powder contents between 2.5 % and 25 % showed an optimum at 15 %, increasing unconfined compressive strength from 205 kPa to 360 kPa and CBR from 4.5 % to 12.2 %, while reducing free swell and plasticity index by more than 70 % [29]. Durability studies further demonstrated that systems with 15 % recycled glass activated with Calcium Carbide ($CaC_2$) residue exhibited very high strength and stability in aggressive environments, maintaining performance in water, wastewater, seawater, gasoline, and acidic media under controlled Geopolymerization conditions [30].

Although substantial strength and bearing improvements were documented, the studies remained focused on pavements, expansive soils, or geopolymer systems [26–30]. The direct linkage between changes in unit weight, cohesion, and internal friction angle and their impact on active earth pressure, sliding, overturning, bearing capacity, and structural material demand in Cantilever Retaining Walls was not established.

### *2.3. Marble Powder: Filler-Controlled Behavior and Binder-Dependent Gains*

In soil–cement mixtures, partial replacement of cement with marble powder at 10 % and 20 % resulted in reduced early strength followed by strength gains at later ages, together with increased stiffness. This behavior was associated with the filler effect of marble powder and the progressive development of cementitious products during curing [31]. In low- and high-plasticity clays, marble powder contents between 5 % and 20 % increased strength, with optimal values ranging from 10 % to 15 % depending on mineralogy and plasticity, while also increasing dry density and reducing optimum moisture content, thereby improving compaction conditions [32].

In expansive soils, marble powder reduced plasticity and swelling and improved strength up to an optimal content of 20 %, whereas higher dosages reduced cohesion and strength due to dilution of the load-bearing soil matrix [33].In Peru, low-percentage marble powder additions combined with other fines improved subgrade performance by reducing plasticity index and increasing dry density and CBR, leading to improved geotechnical classification for pavement design [34].

Most studies prioritized subgrade performance or binder-assisted systems [31–34]. Evidence directly applicable to retaining wall design remained limited, particularly regarding direct shear parameters, their translation into active earth pressure coefficients, and their effect on wall dimensions and total construction cost.

### *2.4. Brick Powder: Heterogeneous Performance and Strong Dependence on Cementitious Environments*

In ceramic product applications, brick waste incorporation improved mechanical and thermal properties within controlled ranges, confirming its recycling potential, although its objective differed from soil support for retaining structures [35]. In mortars, recycled brick powder used as fine aggregate replacement enhanced strength and reduced porosity up to an optimal substitution of 50 %, while higher contents degraded performance due to increased porosity and water demand, in systems governed by cementitious matrices [36].

In rural subgrades, brick powder contents of 10 %, 15 % and 20 % reduced consistency limits and increased dry density and CBR, with an optimum at 20 % yielding CBR increases of up to 85 % [37]. In expansive soils, combinations with lime and ash produced even higher CBR gains, confirming the decisive role of chemical activation in performance [38].

The most consistent evidence corresponded to cementitious matrices or pavement stabilization with activators [36–38]. The behavior of brick powder as a single additive in foundation soils for cantilever retaining walls remained insufficiently explored, particularly regarding shear strength parameters, active earth pressure response, structural dimensioning, and total system cost.

### *2.5. Critical Synthesis and Contribution of the Present Study*

The reviewed literature confirmed that recycled gypsum, glass, marble, and brick improved classical mechanical indicators such as CBR, compressive strength, plasticity, and swelling, with a predominant focus on pavements and expansive soils [23–34]. It was also evident that the highest strength and durability gains frequently depended on cement, lime, or alkaline activation and controlled curing, conditions that do not always reflect typical field scenarios for shallow foundations in urban works [24, 28, 30, 31].

For cantilever retaining walls, three recurring limitations were identified. The combined variation of unit weight, cohesion, and internal friction angle obtained from shear testing was rarely reported or linked to active earth pressure and lateral thrust. Soil improvements were seldom translated into verifiable changes in foundation width, toe–heel proportions, footing thickness, or reinforcement demand under a unified design framework. In addition, economic assessments remained partial, as alternatives were not compared based on the total cost of the wall–foundation system under homogeneous design assumptions.

To address these gaps, the present study experimentally quantified unit weight, cohesion, and internal friction angle for soils stabilized with recycled materials and incorporated these parameters into cantilever retaining wall design, including stability verification and cost estimation. This integrated approach enabled simultaneous assessment of geotechnical response, structural implications, and economic performance, providing direct evidence for selecting recycled stabilizers for urban retaining structures.

## 3. Materials and Methods

This section describes recycled additives incorporated into soil and their direct application in the design of Cantilever Retaining Walls. Recycled gypsum, glass powder, marble powder, and brick powder were processed, mixed with the soil in situ, and tested to determine the unit weight, cohesion, angle of internal friction, and allowable bearing capacity. These parameters were then used to calculate the active earth pressure and to dimension the cantilever retaining walls in accordance with uniform design criteria. Subsequently, the geometries of the resulting walls and the quantities of material were evaluated to assess the technical and economic feasibility of each recycled additive.

### *3.1. Study Area*

The study area was located in the El Porvenir neighbourhood, Huancán district, Huancayo province, Junín region, selected for its representative soils with low bearing capacity and topographical conditions that reflect the geotechnical challenges of the region [39, 40]. Figure 1 shows, on the left, a satellite view of the study area outlined in red, and on the right, a contour map highlighting the significant altimetric variations present in the sector.

This graphic representation clearly shows the site's geographical and topographical conditions that justify the site selection and the relevance of the proposed solutions, ensuring that the results apply to similar situations in the local environment.

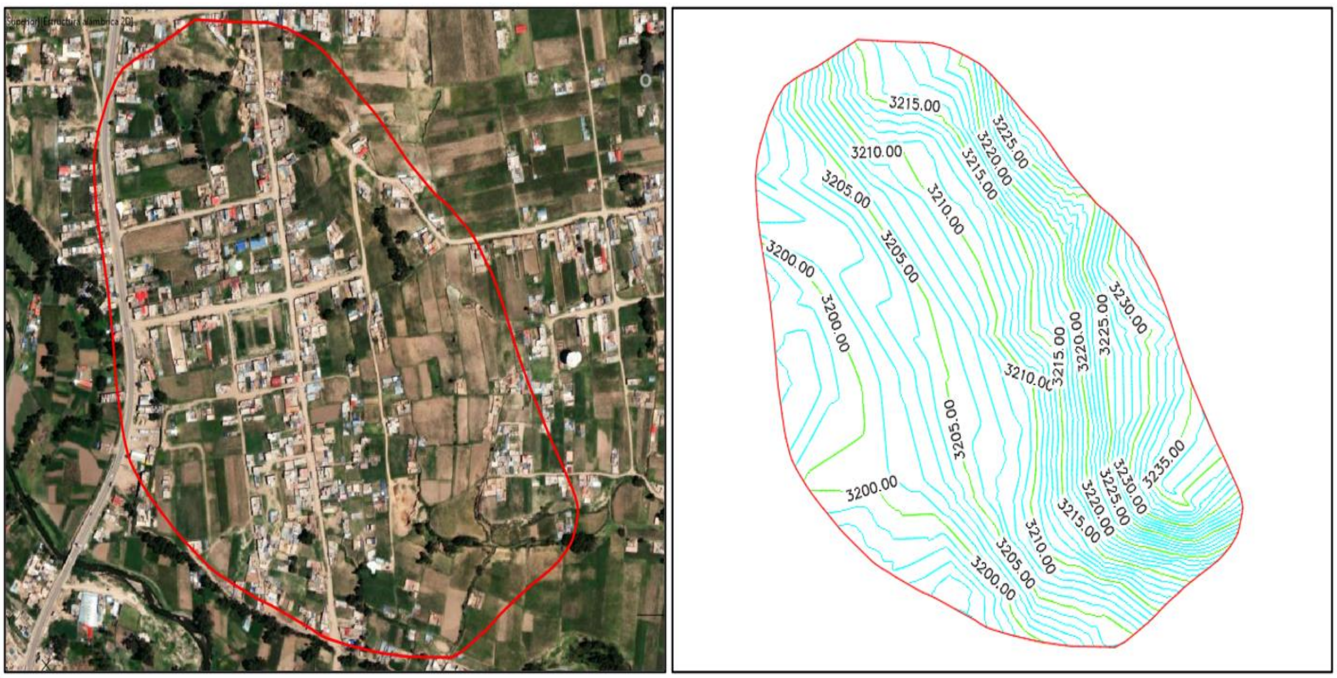


**Fig. 1 Topographical conditions of huancán**

#### *3.1.1. Soil Sample Extraction*

Soil sample extraction is the process by which soil is collected from a specific site for laboratory analysis, allowing its physical, chemical, and mechanical properties to be characterised under controlled conditions [41, 42]. The sample was extracted in accordance with the MTC E 101 Materials Testing Manual [43].

The material collected corresponds to Zone II, identified in Figure 2, as it is the most representative and frequent in the study area, in addition to having the typical geotechnical characteristics of local soils [39].

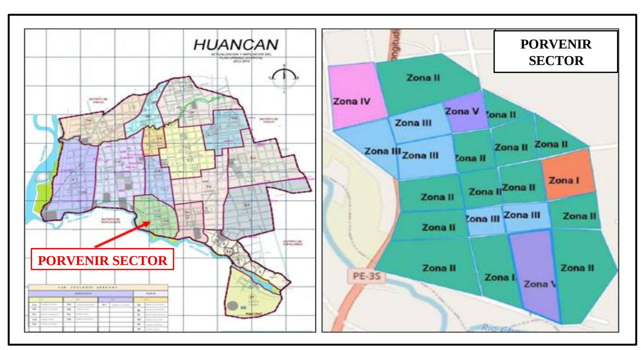


**Fig. 2 Sampling Zoning**

### *3.2. Study Area*

Soil testing involves experimental procedures carried out in the laboratory or in the field to determine the physical and mechanical properties of soils [43, 44]. This section describes the tests carried out on soil in its natural state and on samples stabilised with drywall plaster, brick dust, recycled glass, and marble dust. For the in situ soil, its classification was evaluated by means of Granulometric analysis and plasticity limits, while for the mixtures with additives, the allowable capacity, internal friction angle, cohesion, and lateral thrust exerted on cantilever retaining walls were determined.

#### *3.2.1. Particle Size Distribution*

The Granulometric test is a laboratory test designed to determine the distribution of particle sizes present in soil, allowing it to be classified according to its Granulometric Composition [45, 46]. Soil samples collected from Zone II were analyzed through sieve-based particle size testing following the procedures specified in ASTM D422 [47]. This analysis, shown in Figure 3, made it possible to determine the particle size distribution and classify the soils according to their granulometric composition. The granulometric analysis indicated that the gravel fraction constituted 37.8% of the total sample, while sand accounted for 58.3%, confirming the predominance of coarse particles in the soil matrix. In contrast, only 3.9% of the material passed the No. 200 sieve, evidencing a very low fines content. As a result of this particle size distribution, the granulometric curve exhibited a continuous gradation, with a uniformity coefficient of 37.28 and a curvature coefficient of 0.5. These values are characteristic of a well-graded granular soil.

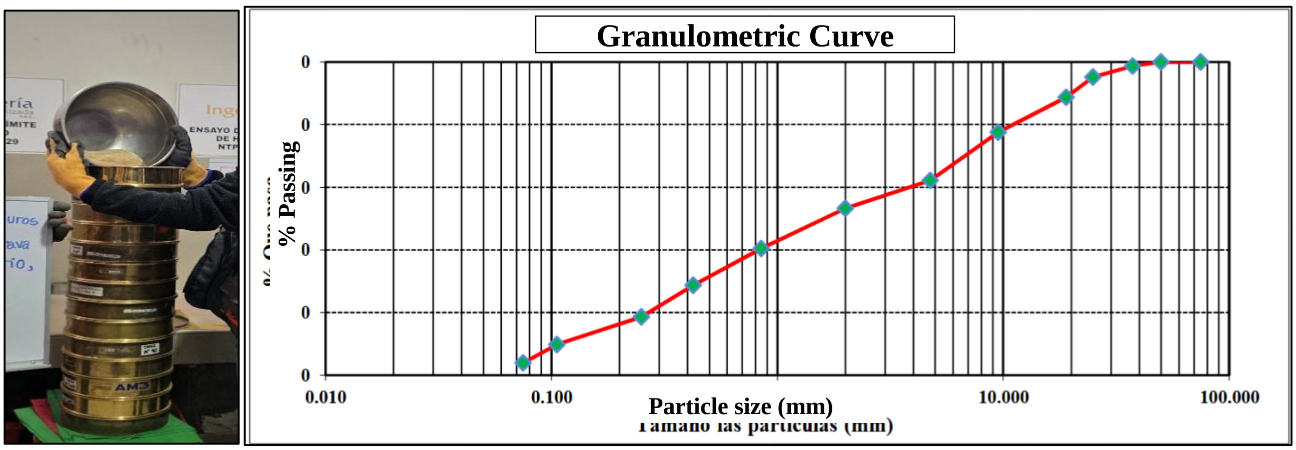


**Fig. 3 Granulometry test and granulometric curve**

#### *3.2.2. Soil Classification*

The soil classification was based on the results of granulometry and consistency limit tests, allowing its mechanical behavior and response to loads to be identified. This characterization was used as the basis for selecting the Geotechnical Parameters used in the bearing capacity analysis and in the design of the retaining walls [48, 49]. International Systems (AASHTO and SUCS) were used to express their characteristics [50, 51] concisely Haga clic o pulse aquí para escribir texto.. Likewise, the necessary tests were carried out to characterise the soil, such as determining its moisture content and consistency limits [52]. Figure 4 shows the execution of the aforementioned tests.

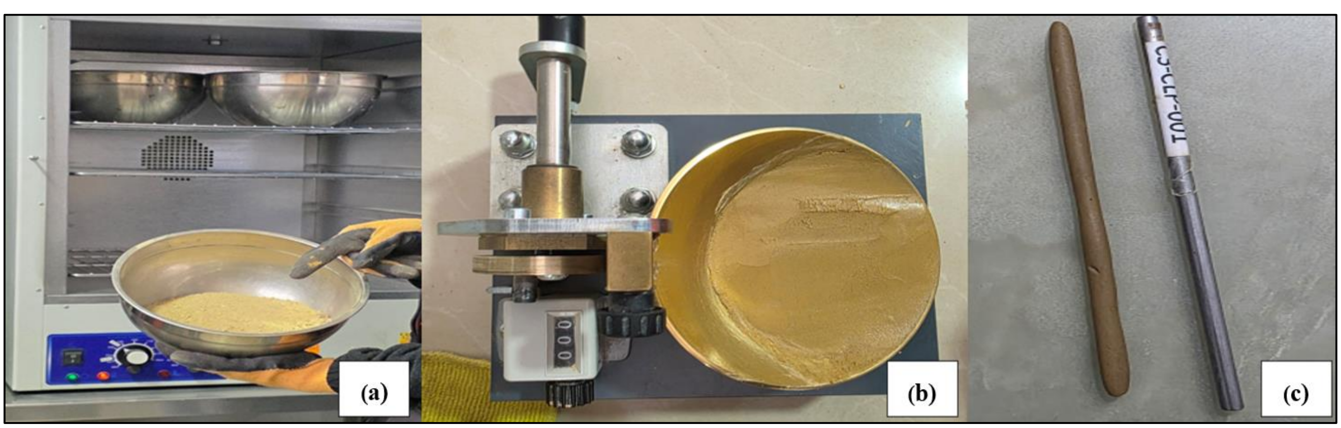


**Fig. 4 Moisture content test and atterberg limits**

Table 5 shows the results of the tests carried out. The moisture content was low (3.1%), indicating that the soil is relatively dry and stable. The Atterberg limit results showed a liquid limit of 17% and the absence of both a plastic limit and a plasticity index, classifying the soil as non-plastic. According to the SUCS classification, the soil corresponds to poorly graded sand with Gravel (SP), while the AASHTO classification places it in group A-1-b (0), i.e., sand or gravel with some fines.

**Table 1. In situ soil properties**

| Property | Value |
|---|---|
| Geotechnical Zone | Zone II |
| Moisture Content (%) | 3.1 |
| Liquid Limit (LL%) | 17 |
| Plastic Limit (LP%) | No presenta |
| Plasticity Index (PI%) | No presenta |
| SUCS Classification | SP - Poorly Graded Sand with Gravel |
| AASHTO Classification | A-1-b (0) |

*3.2.3. Volumetric Weight*

The volumetric weight test is a fundamental procedure in soil characterisation, used to determine the relationship between the weight and volume of a representative sample. A representative volume of soil was extracted and its mass measured in situ to determine the natural specific gravity, which was obtained as the ratio of weight to volume [53]. The procedure resulted in a natural specific gravity of 1.986 g/cm³, as shown in Figure 5.

*3.2.4. Direct Shear*

The shear strength of the soil was determined using the direct shear test in accordance with the MTC E 123 standard [52]. Controlled everyday stresses were applied to the specimen confined in the shear box, followed by horizontal displacement at a constant rate until failure developed along the predefined shear plane, allowing the determination of peak shear resistance parameters [54, 55].

**Fig. 5 Volumetric weight test**

*Direct Shear Test Procedure*

Figure 6 illustrates the direct shear testing procedure adopted in this study. The soil was conditioned by washing through a No. 200 sieve to remove loose fines, after which the specimen was prepared in a shear box with internal dimensions of 100 × 100 × 100 mm under controlled density and moisture conditions. Everyday stresses were applied incrementally, and shear displacement was imposed at a constant rate of 1.5 mm per minute until peak shear resistance was mobilised. The resulting failure surface along the predefined shear plane was subsequently examined to verify the shear mechanism. This procedure was applied uniformly to natural soil and mixtures stabilised with drywall gypsum, glass powder, brick powder, and marble powder, which allowed comparable results to be obtained for all materials tested.

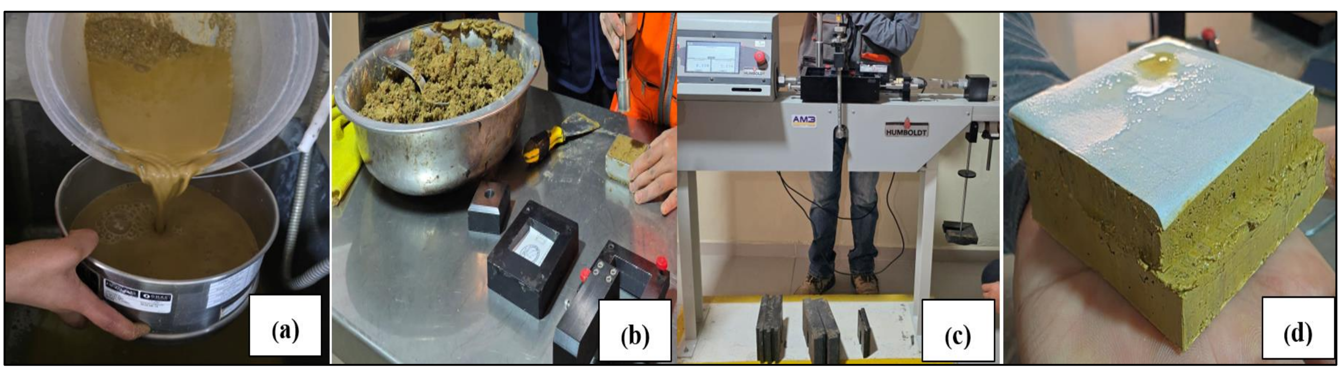


**Fig. 6 Volumetric weight test**

The values obtained using this protocol are presented in Table 2. For natural soil, a specific weight of 1,986 g/cm³, a cohesion of 0.011 kg/cm², and an internal friction angle of 22.807° were determined, parameters that reflect the typical behaviour of soils with a predominance of sandy fraction and moderate acceptable content. Based on these values, the allowable bearing capacity of the soil was estimated at 1,988 kg/cm², constituting the baseline against which the effect of recycled additives on improving geotechnical properties and optimising the design of cantilever retaining walls was subsequently evaluated.

**Table 2. Direct shear test of soil In Situ**

| Property | Value |
|---|---|
| Natural Specific Weight (gr/cm³) | 1.986 |
| Cohesion (c, kg/cm²) | 0.011 |
| Angle of Friction (φ, °) | 22.807 |
| Permissible Bearing Capacity (kg/cm²) | 1.988 |

### 3.3. Additions of Recycled Materials

This section presents the additions that were incorporated into the soil in situ, including recycled gypsum, brick dust, recycled glass, and marble dust.

The origin and main characteristics of each material are detailed, as well as the processing to achieve effective integration into the soil mixtures, seeking to optimise their physical and mechanical properties.

#### *3.3.1. Recycled Plaster Powder*

Recycled plaster is a powdered material obtained from the processing of Plasterboard or Drywall Waste [56, 57]. It consists mainly of Calcium Sulphate Dihydrate ($CaSO_4 \cdot 2H_2O$), which maintains a fine particle size after crushing and grinding. It has a low density of approximately 700 kg/m³, a pH close to neutral (6.5), and a high water retention capacity. Its setting time is usually longer than that of commercial gypsum and, depending on the purity and recycling process, it can achieve compressive strengths suitable for construction and soil stabilisation applications [58, 59]. Table 3 summarises its main properties.

**Table 3. Properties of recycled gypsum [58, 59]**

| Property | Description |
|---|---|
| Particle size | Fine (<0.3 mm after grinding) |
| Chemical composition | 85% $CaSO_4 \cdot 2H_2O$ (calcium sulphate dihydrate) |
| Density | 700 kg/m³ |
| pH | Neutral (6.5) |

The waste used consisted of plasterboard conventionally used in buildings, with standard dimensions of 1.20 m × 2.40 m and thicknesses between 12.5 and 15 mm. These values coincide with those most commonly used in the construction industry. The collected material was visually inspected to remove contaminants such as cardboard, fibres, metals, plastics, and paint residues. Subsequently, the cardboard layer was manually removed, leaving only the gypsum core.

The fragments were dried in the open air for 24 hours and then subjected to primary crushing, followed by fine grinding in a ball mill. The product obtained was sieved with a No. 200 mesh, ensuring a uniform particle size suitable for mixing with soil. The final recycled gypsum powder is shown in Figure 7.

**Fig. 7 Recycled plaster powder**

In this research, percentages of 10%, 12.5%, 15%, 17.5% and 20% of the dry weight of the soil were used, selected based on the literature, which reports that the optimum addition value is around 12.5% [23].

#### *3.3.2. Recycled Glass Powder*

Glass powder is a particulate material obtained by crushing and grinding glass waste (bottles, containers, windows, and flat construction glass) to an excellent size. This by-product is characterised by its high Amorphous Silica ($SiO_2$) content and large specific surface area, which gives it high pozzolanic reactivity in alkaline media [30, 60, 61].

Table 4 shows its properties, which include a particle size of less than 75 µm (200 mesh), a density of 2.6 g/cm³, and a chemical composition dominated by Silica (69%), accompanied by $Na_2O$ (12%) and CaO (10%), as well as minor oxides such as $Al_2O_3$ and $Fe_2O_3$ [62]. This characteristic favours the formation of cementitious compounds (C-S-H and C-A-H) when combined with soils and activators such as lime or cement.

**Table 4. Properties of glass powder [62]**

| Property | Description |
|---|---|
| Particle size | 75 µm (mesh No. 200) |
| Chemical composition | $SiO_2$: 69%, $Na_2O$: 12%, CaO: 10%, $Al_2O_3$ and $Fe_2O_3$ |
| Density | 2.6 g/cm³ |
| Puzzolanic reactivity | High, especially after calcination or fine grinding |

To obtain it, waste from containers, bottles, and flat glass from urban landfills and demolition sites was collected. The selected fragments, with thicknesses of 3 to 6 mm, were visually inspected to rule out contaminants, washed, and dried in the open air. They were then crushed and ground in a ball mill until particles smaller than 75 µm were obtained. In Figure 8, item (a) shows the grinding process, and item (b) shows the powder already processed and ready for incorporation into soil stabilisation mixtures.

**Fig. 8 Recycled glass powder**

In this study, percentages of 10%, 12.5%, 15%, 17.5% and 20% of the dry weight of the soil were used, selected based on the literature, which reports an optimal content of around 15% [63].

### *3.3.3. Recycled Marble Powder*

Marble dust is an acceptable by-product generated during the cutting, polishing, and manufacturing processes of pieces intended for construction, decoration, and furniture. Its composition is dominated by Calcium Carbonate ($CaCO_3$) in concentrations exceeding ninety per cent, accompanied by minor fractions of Silica ($SiO_2$), Magnesium Oxide ($MgO$), Iron Oxide ($Fe_2O_3$), and Alumina ($Al_2O_3$) [64, 65].

Although it is generally considered to be difficult to dispose of as environmental waste, this material has characteristics that make it suitable for soil stabilisation. Its high proportion of Calcium Carbonate promotes particle interaction and acts as a filler, increasing the maximum dry density and reducing the optimum moisture content required for compaction. Similarly, when incorporated into clayey or expansive soils, it helps to decrease the plasticity index, reduce the potential for swelling, and improve workability [66].

The physical and chemical properties of marble powder are presented in Table 5. This material has a density of 2.8 g/cm³, a slightly alkaline pH close to eight, a particle size of less than seventy-five micrometres (200 mesh), and very low Pozzolanic reactivity, so its performance is mainly associated with its physical filling effect and the limited chemical interaction of Calcium Carbonate [67].

**Table 4. Properties of marble powder [67]**

| Property | Description |
|---|---|
| Particle size | 75 µm (mesh N°200) |
| Chemical composition | $aCO_3$: 95%, traces of $SiO_2$, $MgO$, $Fe_2O_3$, $Al_2O_3$ |
| Density | 2.8 g/cm³ |
| pH | Slightly alkaline (8) |
| Puzzolanic reactivity | Very low; mainly filling behaviour |

For this research, waste was collected from marble cutting and polishing workshops, as well as from construction and demolition projects. The selected fragments were free of visible impurities such as metal debris, cementitious materials, coatings, or organic matter. They were then washed and brushed to remove adhering particles and dried in the open air for twenty-four hours. Once conditioned, they underwent a primary crushing process and ball mill grinding until particles smaller than seventy-five micrometres were obtained. Finally, sieving with a No. 200 mesh was performed to ensure uniform particle size. The product obtained is shown in Figure 9 as recycled marble powder ready for incorporation into soil mixtures.

**Fig. 9 Recycled marble powder**

The research used percentages of 10%, 12.5%, 15%, 17.5% and 20% relative to the dry weight of the soil, defined on the basis of previous studies reporting an optimum addition content of around 15% [32]. This range allowed the effect of different proportions on the strength and plasticity properties to be evaluated, in order to identify the most appropriate dosage for improving soils intended to support Cantilevered Retaining Walls.

### *3.3.4. Brick Dust*

Brick dust is an acceptable by-product obtained by crushing and grinding fired ceramic bricks from demolition sites, kiln rejects, and construction debris, particularly from Artisanal Tambourine and industrial tubular bricks, which are the most common types of waste in local masonry [68, 69]. Its mineralogical composition is dominated by Silica ($SiO_2$) and Alumina ($Al_2O_3$), with lower contents of iron and calcium oxides; however, as it is a material already fired at temperatures above 900 °C, its clay phases are transformed into stable glassy structures, which limit its chemical reactivity. Consequently, and given that no lime or cement was added in this research to activate possible Pozzolanic Reactions, brick dust does not act as a cementing agent, but rather as a physical stabiliser. Its effect on the soil is due to its physical and microstructural properties: angular and rough particles that increase internal friction, a specific surface area that promotes interconnection between grains, and a fine fraction that fills voids, reducing plasticity and swelling potential, as well as improving compaction and shear strength [70]. Table 6 summarises its main characteristics, including a specific gravity of 2.67 g/cm³, absorption of 2.77% and controlled particle size with a No. 140 mesh, which ensures its performance as a stabilising additive.

**Table 6. Properties of brick dust [70].**

| Property | Description |
|---|---|
| Particle size | (mesh N°140) |
| Colour | Orange |
| Specific gravity | 2.67 g/cm³ |
| % Absorption | 2.77% |
| Appearance | Dry powder |

The conditioning process applied included the selection of contaminant-free fragments, their cleaning and natural drying for 24 hours, followed by primary crushing and grinding in a ball mill. The product was sieved with a No. 140 mesh to ensure a homogeneous and stable particle size, obtaining a fine powder with a characteristic orange colour, as shown in Figure 10.

**Fig. 10 Recycled brick powder**

In this research, proportions of 10%, 12.5%, 15%, 17.5% and 20% of brick dust were incorporated in relation to the dry weight of the soil. This range was defined considering that previous studies have identified an optimal content close to 20%, at which significant improvements in compaction and reduction of plasticity of clay soils are achieved [37, 38]. Selecting these percentages allowed the experimental plan to be structured, facilitating the systematic evaluation of the effect of brick dust on the physical and mechanical properties of the clayey soil with gravel in the study area.

### 3.4. Cantilever Retaining Wall

A Cantilever Retaining Wall is a reinforced concrete structure consisting of a vertical screen and a horizontal footing, designed to support and stabilise uneven soil masses, transmitting lateral thrusts from the ground to the foundation through the screen's resistance to bending [71, 72], as shown in Figure 11.

The dimensions of this type of wall depend mainly on the height to be contained, the properties of the soil (such as its bearing capacity, angle of internal friction and specific weight), the earth pressures calculated using methods such as Coulomb or Rankine, the presence of additional loads (overloads and seismic loads), and the stability conditions required to prevent overturning, sliding and failure of the ground under the footing, also considering regulatory requirements and the need for an adequate drainage system to prevent water accumulation behind the wall [73, 74].

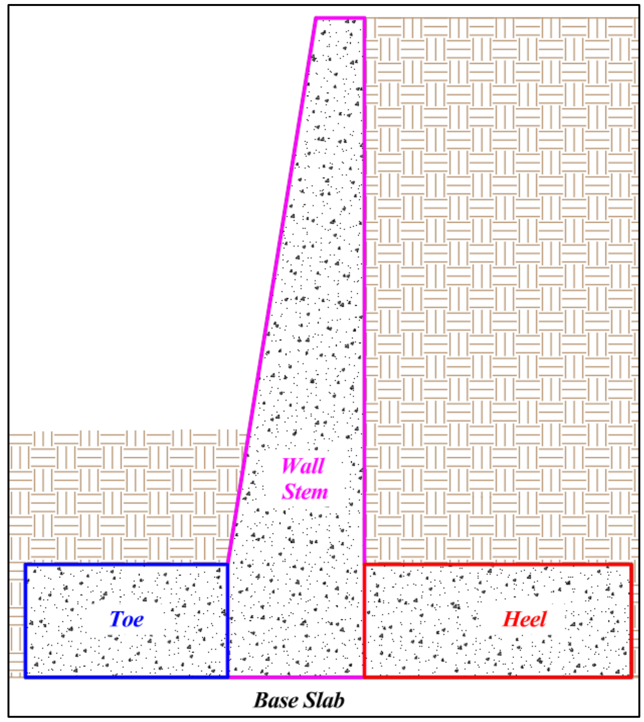


**Fig. 11 Cantilever retaining wall**

#### 3.4.1. Characteristics and Design Criteria of the Cantilever Retaining Wall

For the design of the Cantilever Retaining Wall, reinforced concrete with a compressive strength of 210 kg/cm² and reinforcing steel with a yield strength of 4200 kg/cm² were considered, values widely used in structural engineering due to their performance and availability [75]. The concrete was adopted with a specific weight of 2400 kg/m³, while a uniform overload of 0.5 kN/m² was applied to the fill, representative of urban loads such as pedestrian traffic, light vehicles, or temporary storage of materials [76, 77]. Haga clic o pulse aquí para escribir texto.. The lateral thrust analysis was performed according to Rankine's theory, in which the pressure exerted by the soil depends on the active coefficient Ka, a direct function of the internal friction angle of the material (φ).

The triangular thrust associated with the soil's own weight was expressed as $\gamma t \cdot H \cdot Ka \cdot 1$ m, where $\gamma t$ is the natural specific weight, and H is the fill height. In comparison, the surface surcharge was represented by a rectangular thrust equivalent to $Sc \cdot Ka \cdot 1$ m, where Sc corresponds to the applied surcharge. Figure 12 illustrates the load scheme used in the design.

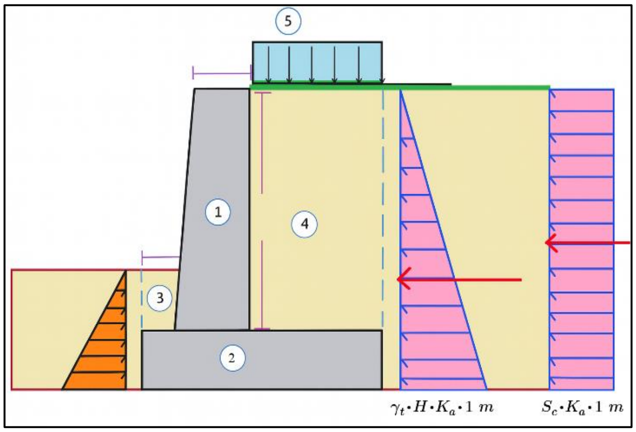


**Fig. 12 Cantilever retaining wall**

It is important to note that soil cohesion contributes to shear strength and, therefore, to the reduction of effective lateral thrust. At the same time, the active coefficient Ka decreases as the angle of internal friction increases, generating lower pressures on the wall. Consequently, any variation in these parameters resulting from the addition of recycled materials directly affects the dimensioning and stability of the retaining wall, which is why they were reconsidered for each soil mixture evaluated.

## 4. Results

This section details the results obtained from optimising Cantilever Walls on clay soils using recycled drywall plaster, brick dust, glass, and marble. Soil samples extracted from the district of Huancán, in the province of Huancayo, were subjected to stabilisation treatments using these recycled materials.

### *4.1. Specific Weight*

The results of the specific weight test obtained after adding the additives to the soil in situ are presented below. Table 7 shows the behaviour of the soil's specific weight when incorporating different additives: recycled gypsum, glass powder, marble powder, and brick powder, compared to the soil in situ, whose initial value was 1.988 g/cm³.The incorporation of recycled additives led to higher specific weight values than those measured in the natural soil for all dosages evaluated. Recycled gypsum exhibited the most pronounced effect, attaining a maximum specific weight of 2.196 g/cm³ at 12.5%, which reflects a more compact granular arrangement and reduced void ratio. Recycled glass reached 2.140 g/cm³ at 15.0%, indicating effective densification associated with its higher particle density. Marble powder produced a peak value of 2.125 g/cm³ at 12.5%, consistent with a filler-controlled densification mechanism. Brick dust showed the lowest response, with a maximum of 2.079 g/cm³ at 15.0%, attributable to its higher porosity and limited packing efficiency. At dosages exceeding 15%, no further gains were observed, confirming an optimal addition range for densification.

**Table 7. Specific weight**

| Description | Addition | Specific Weight (gr/cm³) |
|---|---|---|
| In situ soil | 0.0% | 1.988 |
| Recycled Gypsum Powder | 10.0% | 2.166 |
| | 12.5% | 2.196 |
| | 15.0% | 2.172 |
| | 17.5% | 2.153 |
| | 20.0% | 2.126 |
| Recycled Glass Powder | 10.0% | 2.120 |
| | 12.5% | 2.134 |
| | 15.0% | 2.140 |
| | 17.5% | 2.099 |
| | 20.0% | 2.080 |
| Recycled Marble Powder | 10.0% | 2.093 |
| | 12.5% | 2.125 |
| | 15.0% | 2.102 |
| | 17.5% | 2.078 |
| | 20.0% | 2.065 |
| Recycled Brick Powder | 10.0% | 2.044 |
| | 12.5% | 2.064 |
| | 15.0% | 2.079 |
| | 17.5% | 2.052 |
| | 20.0% | 2.042 |

Figure 13 illustrates the improvement in specific weight in relation to the in situ soil for each type of addition and dose applied. As the additions increased, the specific weight increased significantly in all cases in relation to the base value, with recycled gypsum clearly standing out achieving the most with 10.47% improvement at 12.5% addition. Glass powder combined to achieve 7.65% with 15.0% addition, marble powder combined for a 6.89% at 12.5% addition, and brick powder combined for improvement of 4.57% at 15.0% addition. The results reflect that soil density increased with the waste, particularly so with gypsum and glass, which are denser and less porous. The other additions to the engineered waste percentages improved the soil density and should be lower in design. A 15% addition should be the maximum in terms of engineering waste for ideal soil compaction.

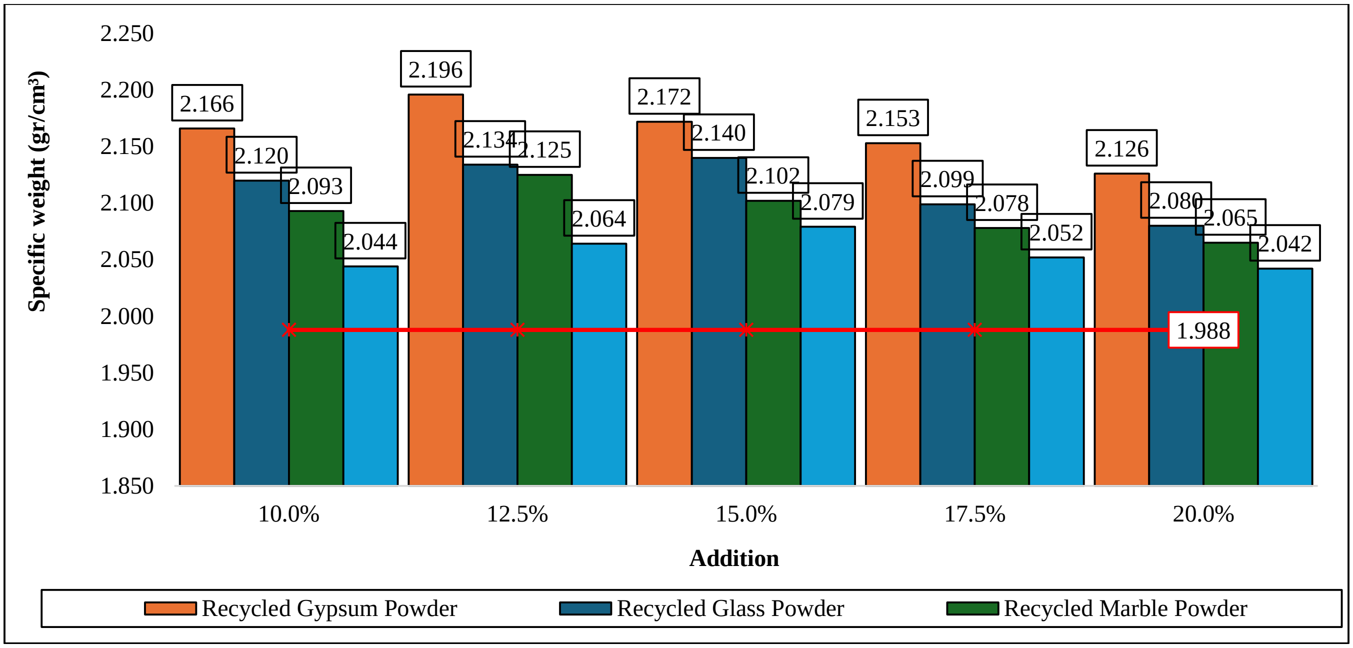


**Fig. 13 Specific weight**

### *4.2. Cohesion*

Table 8 summarizes the cohesion values obtained from direct shear testing of the in situ soil and the mixtures stabilized with recycled materials. The natural soil exhibited an initial cohesion of 0.011 kg/cm². The incorporation of recycled gypsum produced the highest increase, reaching 0.153 kg/cm² at 12.5%, attributed to the formation of cementitious bonds that enhanced interparticle contact and shear resistance. Glass powder achieved a maximum cohesion of 0.142 kg/cm² at 15.0%, associated with particle angularity and improved mechanical interlocking within the soil matrix. Marble powder showed a moderate increase, with a peak cohesion of 0.130 kg/cm² at 12.5%, mainly due to its filler effect and surface adhesion between fine particles. Brick dust presented the lowest improvement, reaching 0.064 kg/cm² at 15.0%, reflecting its porous structure and limited bonding capacity. For all materials, dosages above 15% resulted in a reduction of cohesion, indicating mixture saturation and a deterioration of effective stress transfer mechanisms.

Figure 14 shows that all additives caused increases in cohesion, up to an optimum dose. Recycled gypsum increased cohesion the most, with an increase of 1,290.9% compared to the in situ soil at 12.5% addition. This increase was followed by glass powder with 1,190.9% at 15% addition, then marble powder with 1,081.8% at 12.5% addition, and finally brick powder with 481.8% at 15% addition. However, at higher doses, cohesion decreased dramatically, showing that an excess of fine particles tends to disrupt the internal structure of the soil and weaken its resistance. In summary, the results showed that the increase in cohesion depends directly on the physicochemical properties of each additive: recycled gypsum acted as the most efficient, thanks to its cementing effect, glass and marble functioned mainly as densifiers and filling agents, while brick, due to its high porosity and low density, showed more limited behaviour. These results made it possible to establish that the positive effect of the additions is only maintained within an optimal dosage range, with excessive use of the material being counterproductive.

**Table 8. Cohesion**

| Description | Addition | Cohesion (kg/cm2) |
|---|---|---|
| In situ soil | 0.0% | 0.011 |
| Recycled Gypsum Powder | 10.0% | 0.074 |
| | 12.5% | 0.153 |
| | 15.0% | 0.106 |
| | 17.5% | 0.049 |
| | 20.0% | 0.010 |
| Recycled Glass Powder | 10.0% | 0.094 |
| | 12.5% | 0.119 |
| | 15.0% | 0.142 |
| | 17.5% | 0.060 |
| | 20.0% | 0.025 |
| Recycled Marble Powder | 10.0% | 0.070 |
| | 12.5% | 0.130 |
| | 15.0% | 0.080 |
| | 17.5% | 0.033 |
| | 20.0% | 0.017 |
| Recycled Brick Powder | 10.0% | 0.017 |
| | 12.5% | 0.029 |
| | 15.0% | 0.064 |
| | 17.5% | 0.022 |
| | 20.0% | 0.009 |

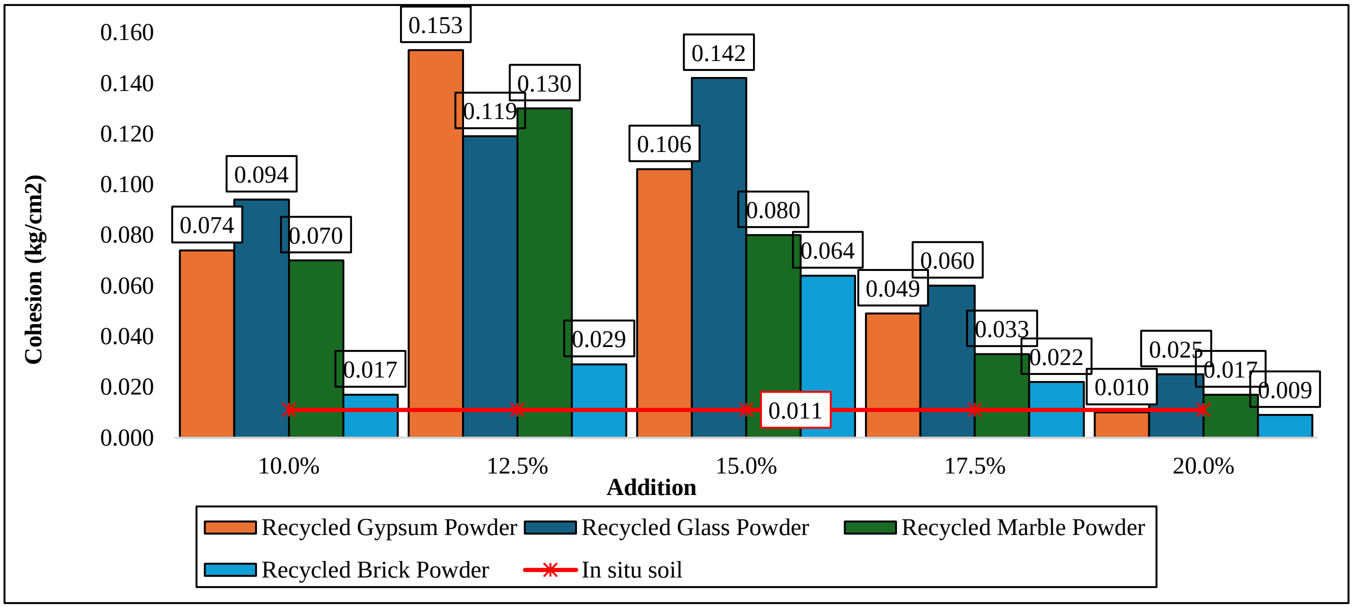


**Fig. 14 Cohesion**

### *4.3. Angle of Friction (φ, °)*

Table 9 and Figure 15 show that the angle of internal friction of the soil in situ, with an initial value of 22.807°, presented different variations after the incorporation of the different recycled waste materials. In the case of recycled gypsum, the friction angle showed a progressive decrease in the first additions, reaching a minimum value of 14.681° at 12.5%, and recovering to 22.807° at 20.0%, which shows unstable behaviour. This trend was associated with the formation of a more plastic microstructure at intermediate doses, which temporarily reduced particle-particle friction, and then stabilised with higher addition percentages. Glass powder showed a more consistent response, with a minimum value of 15.096° at 15.0% and a subsequent increase to 20.782° at 20.0%, showing that moderate doses reduce friction due to excess fine material. In contrast, high doses restore the granular structure. Similarly, marble powder reached its lowest value of 16.106° at 12.5%, gradually increasing to 20.065° at 20.0%, which is attributed to the filling effect of fine particles that initially softens contacts but then improves compaction. Of all the stabilizing materials assessed, brick dust showed the most consistent internal friction angle response, achieving a peak of 20.128° at 20.0% addition with only slight changes throughout the range evaluated. The reason for this is the behavioral attributes of the material. Due to the material's angular and rough particle morphology, there is a formation of mechanical interlocking without surpassing the frictional capacity of the native soil.

In comparison, Recycled gypsum, glass powder, and marble powder, at intermediate levels, particularly between 10% and 15%, caused the most friction angle reduction due to the increased quantity of fines and subsequent decrease in particle-to-particle friction. Therefore, none of the stabilized mixtures exceeded the in-situ soils' friction angle from a geotechnical perspective. Such a reduction represents an increase in the coefficient of active earth pressure, and therefore a rise in lateral thrust on earth retaining structures. It implies that in stability work, the use of such materials must focus on their cohesion and stiffness, and that the increase in cementation must counterbalance the loss in frictional resistance.

**Table. 9 Angle of friction (φ, °)**

| Description | Addition | Angle of Friction (φ, °) |
|---|---|---|
| In situ soil | 0.0% | 22.807 |
| Recycled Gypsum Powder | 10.0% | 17.939 |
| | 12.5% | 14.681 |
| | 15.0% | 16.739 |
| | 17.5% | 18.894 |
| | 20.0% | 22.807 |
| Recycled Glass Powder | 10.0% | 17.210 |
| | 12.5% | 15.589 |
| | 15.0% | 15.096 |
| | 17.5% | 18.996 |
| | 20.0% | 20.782 |
| Recycled Marble Powder | 10.0% | 18.108 |
| | 12.5% | 16.106 |
| | 15.0% | 18.662 |
| | 17.5% | 19.481 |
| | 20.0% | 20.065 |
| Recycled Brick Powder | 10.0% | 20.065 |
| | 12.5% | 19.621 |
| | 15.0% | 17.875 |
| | 17.5% | 19.647 |
| | 20.0% | 20.128 |

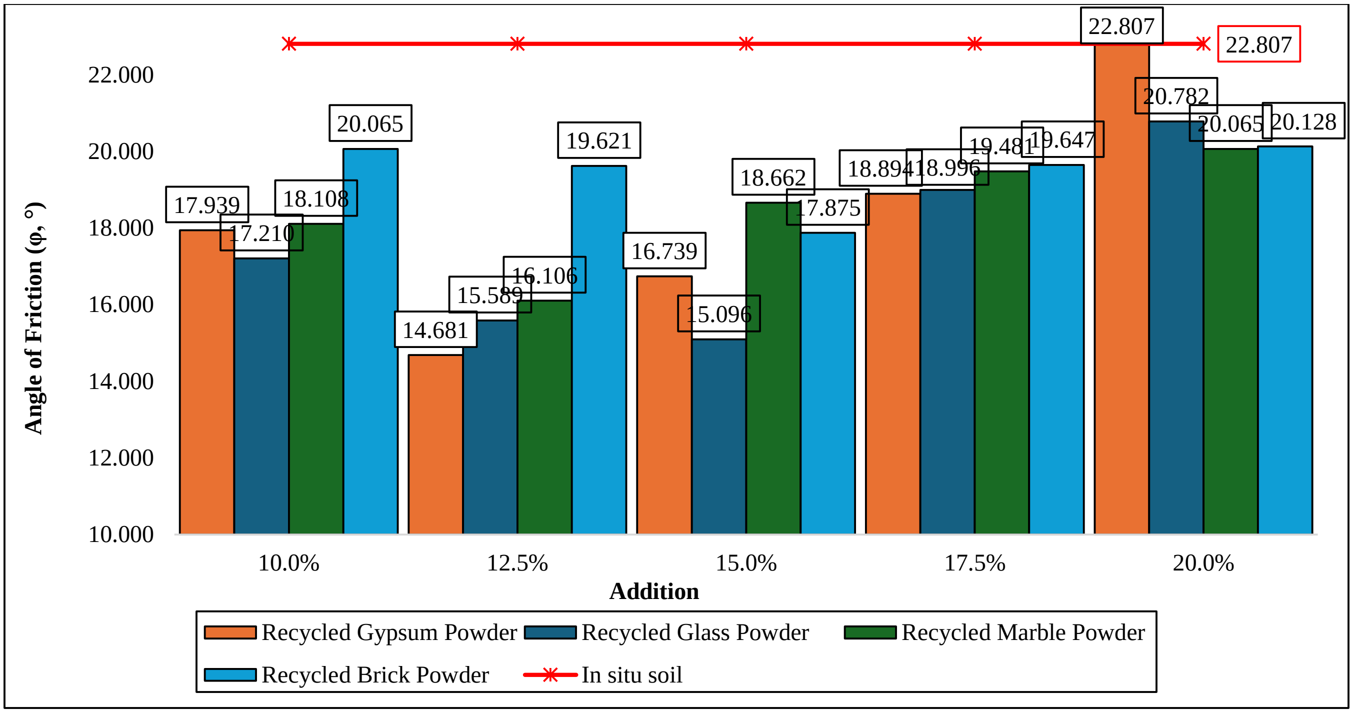


**Fig. 15 Angle of Friction (φ, °)**

### *4.4. Permissible Load-Bearing Capacity (kg/cm²)*

Table 10 and Figure 16 indicate that the permissible bearing capacity of the in situ soil (1.988 kg/cm²) changed markedly with the incorporation of recycled additions. Recycled gypsum yielded the highest value, reaching 2.108 kg/cm² at 20%, consistent with the formation of particle bonding and increased apparent cementation associated with calcium sulphate, which enhanced stiffness and reduced compressibility under foundation stress. Glass powder achieved a maximum of 2.016 kg/cm² at 15%, where its high hardness and density promoted a filler-driven densification, improving packing efficiency and stress transfer within the granular skeleton. Marble powder reached 2.075 kg/cm² at 12.5%, attributable to the microfiller effect of $CaCO_3$ that reduced the void ratio and improved contact between particles, thereby increasing the load-bearing response. Brick dust showed the least improvement, peaking at 1.714 kg/cm² at 15%, which is consistent with its higher porosity and lower intrinsic density, limiting densification and producing a less efficient load-transfer fabric. Overall, the strongest gains were concentrated between 12.5% and 15%, whereas higher contents tended to reduce performance, suggesting overfilling and loss of structural continuity due to excess fines. From a design standpoint, increases in permissible bearing capacity directly support reductions in footing width and thickness, lower concrete and reinforcement demand, and reduced differential settlement risk, improving both stability margins and structural cost-efficiency. On the other hand, a reduction in bearing capacity at high doses is unfavourable, as it requires a larger foundation size and higher construction costs. In conclusion, recycled gypsum proved to be the most effective material for improving soil bearing capacity, followed by marble powder and glass powder. In contrast, brick powder had a more limited effect.

**Table 10. Allowable bearing capacity (kg/cm²)**

| Description | Addition | Allowable Bearing Capacity (kg/cm²) |
|---|---|---|
| In situ soil | 0.0% | 1.988 |
| Recycled Gypsum Powder | 10.0% | 1.870 |
| | 12.5% | 2.060 |
| | 15.0% | 1.992 |
| | 17.5% | 1.783 |
| | 20.0% | 2.108 |
| Recycled Glass Powder | 10.0% | 1.926 |
| | 12.5% | 1.900 |
| | 15.0% | 2.016 |
| | 17.5% | 1.892 |
| | 20.0% | 1.824 |
| Recycled Marble Powder | 10.0% | 1.817 |
| | 12.5% | 2.075 |
| | 15.0% | 2.035 |
| | 17.5% | 1.670 |
| | 20.0% | 1.580 |
| Recycled Brick Powder | 10.0% | 1.559 |
| | 12.5% | 1.643 |
| | 15.0% | 1.714 |
| | 17.5% | 1.568 |
| | 20.0% | 1.490 |

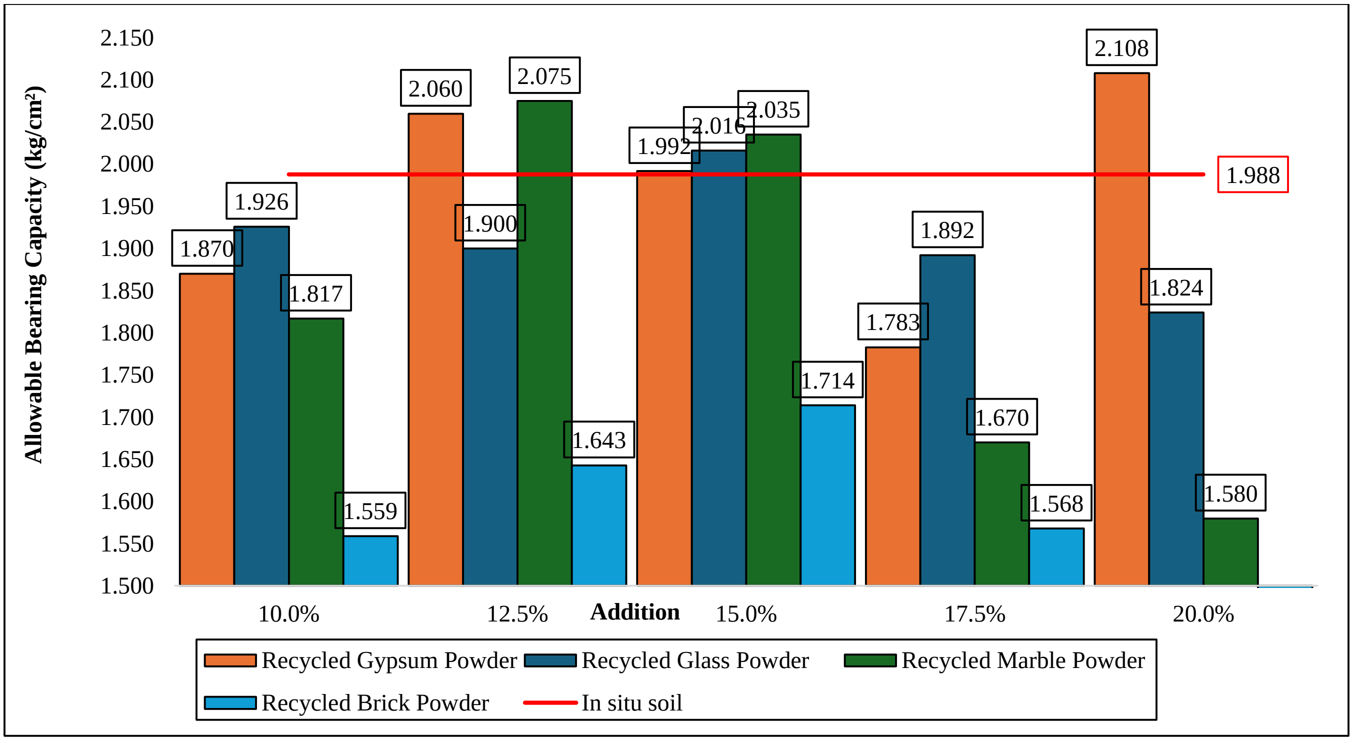


**Fig. 16 Allowable bearing capacity (kg/cm²)**

### *4.5. Optimal Additions*

The optimal doses for each type of recycled waste were determined based on the overall behaviour of the soil's geotechnical properties. Table 11 shows that recycled gypsum achieved its best performance at 12.5%, glass powder at 15%, marble powder at 12.5% and brick powder at 15%. These percentages represent the point at which each addition maximised the balance between densification, cohesion, and bearing capacity, before higher doses generated saturation or compaction reduction effects. Overall, it is evident that proportions between 12.5% and 15% constitute the optimal range for obtaining an adequate and stable improvement in the mechanical properties of soil treated with recycled materials.

**Table 11. Optimal additions of inputs**

| Description | In situ soil | Recycled Gypsum Powder | Recycled Glass Powder | Recycled Marble Powder | Recycled Brick Powder |
|---|---|---|---|---|---|
| Optimal dose (%) | 0 | 12.5 | 15 | 12.5 | 15 |
| Natural Specific Weight (gr/cm³) | 1.988 | 2.196 | 2.14 | 2.125 | 2.079 |
| Cohesion (c, kg/cm²) | 0.011 | 0.153 | 0.142 | 0.13 | 0.064 |
| Angle of friction (φ, °) | 22.807 | 18.894 | 18.996 | 19.481 | 20.128 |
| Admissible bearing capacity (kg/cm²) | 1.988 | 2.108 | 2.016 | 2.075 | 1.714 |

Figure 17 shows the allowable bearing capacity of the in situ soil and the soil treated with different additions at their respective optimum doses. It can be seen that recycled gypsum, at a dosage of 12.5%, achieved the highest bearing capacity, with a value of 2,108 kg/cm², showing a significant improvement over the base soil. Marble powder at 12.5% achieved a permissible bearing capacity of 2.075 kg/cm², followed by glass powder at 15% with 2.016 kg/cm²; in both cases, the gains are consistent with improved packing and a lower void ratio, which enhances contact efficiency and stress transmission through the soil skeleton. Brick dust at 15% reached 1.714 kg/cm², reflecting the least favorable response, compatible with its higher porosity and reduced densification potential; moreover, this value is lower than the in situ soil baseline (1.988 kg/cm²), indicating that its contribution is not technically advantageous for foundation demand. In design terms, the observed increases with marble and glass directly translate into higher bearing safety margins and allow reductions in footing dimensions and associated concrete and reinforcement quantities. In contrast, brick dust would tend to penalize stability checks by requiring larger bases to meet bearing and serviceability criteria.

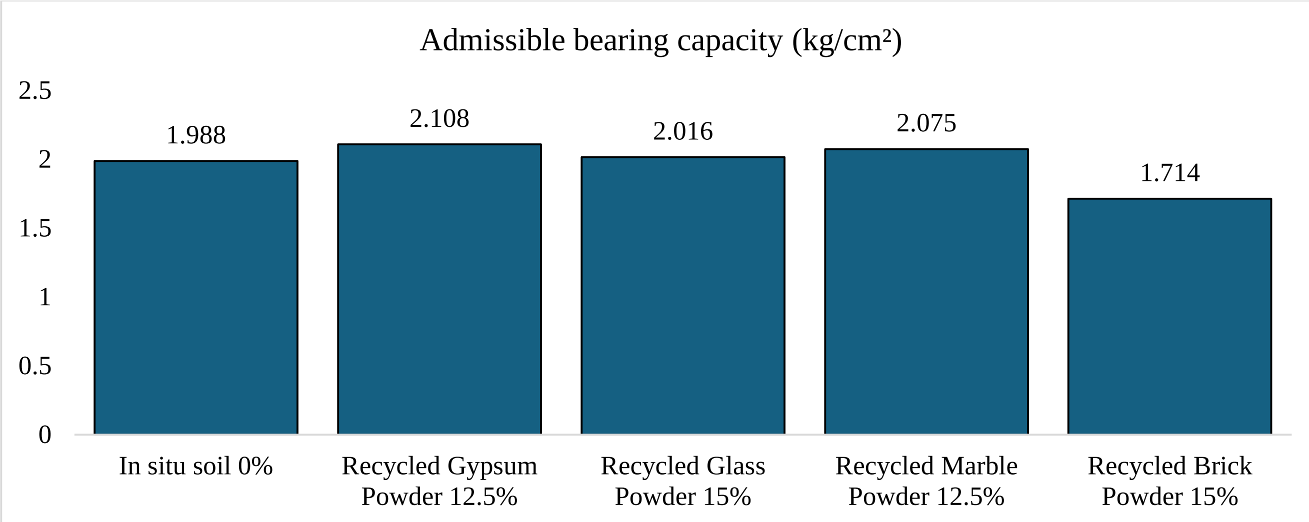


**Fig. 17 Bearing capacity according to optimum dosage**

### *4.6. Cantilever Wall Design*

The design of the Cantilevered Retaining Walls, developed for both the in-situ soil and the stabilised mixtures with the optimum doses of recycled gypsum, glass powder, marble powder, and brick powder, is presented below. The procedure was based on the criteria set out in section 2.8.1, considering the active lateral earth pressure calculated using Rankine theory, where the thrust depends on the active Coefficient (Ka), defined as a function of the angle of Internal Friction (φ) of each mix, as well as the Specific Weight (γ) and The Height Of The Wall (H). To these variables were added the Cohesion (c), which contributes to the partial reduction of the thrust, and the uniform overload q applied at the surface, which was transmitted to the wall as an additional pressure. The factors of safety against overturning, sliding, and bearing capacity were verified in accordance with the regulations, ensuring that the proposed dimensions complied with the stability conditions.

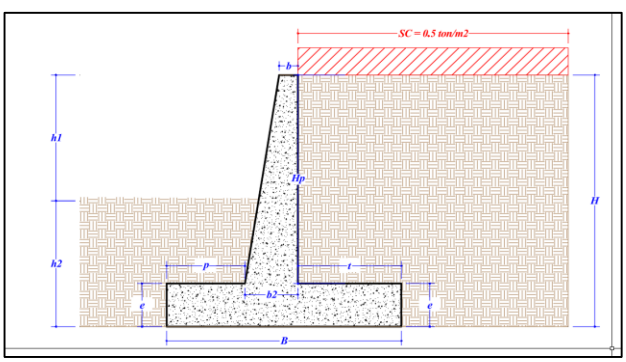


**Fig. 18 Cantilever wall dimensions variables**

#### *4.6.1. Dimensions of Cantilevered Walls*

Figure 18 shows schematically the geometric variables adopted for the design, such as total Height (H), Base Width (B), Heel (t), Toe (p), Footing Thickness (e), and Crown (b). These dimensions were calculated based on the geotechnical parameters obtained experimentally (Table 11), which allowed differentiated designs to be established for each soil alternative treated.

The results presented in Table 12 show that while the overall wall height (6.00 m) and height above ground (5.00 m) remained constant for all cases, the structural dimensions of the footing and footing varied significantly depending on the material used. For in-situ soil, a total base width of 6.50 m and a footing thickness of 0.80 m were required, reflecting a more robust design due to the lower strength of the original material. By incorporating recycled gypsum, the base width was reduced to 6.00 m and the thickness to 0.60 m, evidencing an improvement in bearing capacity and a decrease in active thrust due to the increased cohesion and stiffness of the treated soil.

Similarly, glass powder presented the most efficient behaviour, with a base of 5.50 m and a footing thickness of 0.60 m, which represents the most significant reduction in dimensions and, therefore, a lower consumption of concrete and steel in the wall design. Marble powder maintained a base width of 6.00 m and a thickness of 0.60 m, showing an intermediate and stable performance, suitable for moderate loading conditions. In contrast, the brick powder required a base width of 7.00 m, the largest among all cases, despite maintaining the same footing thickness (0.60 m), due to its lower bearing capacity and higher deformability, which demanded a broader foundation to guarantee the stability of the system. Overall, these results show that the improvement of soil properties by means of recycled additions can considerably reduce the design dimensions of the wall, achieving more efficient, sustainable, and economically favourable structures, especially in the cases of recycled gypsum and glass powder.

**Table 12. Dimensions of cantilevered walls**

| Description | In situ soil | Recycled Gypsum Powder | Recycled Glass Powder | Recycled Marble Powder | Recycled Brick Powder |
|---|---|---|---|---|---|
| Total height of wall (H) | 6.00 | 6.00 | 6.00 | 6.00 | 6.00 |
| Height above ground (h1) | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| Height below ground (h2) | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Height of the screen (Hp) | 5.20 | 5.40 | 5.40 | 5.40 | 5.40 |
| **Total width of base (B)** | **6.50** | **6.00** | **5.50** | **6.00** | **7.00** |
| Screen width (b2) | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Heel (t) | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| Toe (p) | 2.00 | 1.50 | 1.00 | 1.20 | 2.50 |
| **Shoe thickness (e)** | **0.80** | **0.60** | **0.60** | **0.60** | **0.60** |
| Crown (b) | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |

Table 13 shows that the steel arrangement in the Cantilever Retaining Walls was adjusted according to the Geotechnical Properties obtained for each type of stabilised soil. In the screen, both vertical and inclined reinforcement were arranged with rods Ø 3/4" @ 20 cm in the case of in-situ soil. In comparison, a closer spacing of Ø 3/4" @ 15 cm was used in the mixtures with recycled gypsum, glass dust, marble dust, and brick dust, in order to maintain adequate structural stiffness against lateral thrust and to compensate for the moderate reduction of the friction angle. The horizontal steel of the screen, consisting of Ø 1/2" rods, had variable spacings: 20 cm for in-situ soil, glass powder, and marble powder, while it was extended to 25 cm for recycled gypsum and brick powder, reflecting a lower active pressure on the wall and a more uniform stress distribution.

In the foundation, both at the heel and toe, the steel arrangement was directly related to the allowable bearing capacity (qa) of each soil type. In the in-situ soil, rebars Ø 3/4" @ 17.5 cm were used in both directions (longitudinal and transverse), forming a dense mesh to resist the higher contact stresses. In the recycled gypsum, the longitudinal reinforcement was extended to 20 cm and the transverse reinforcement to 25 cm. At the same time, in the glass powder and marble powder soils, the spacings increased to 22.5 cm and 25 cm, respectively, reflecting a significant improvement in soil stiffness and lower structural demand. Brick dust presented an intermediate behaviour, with longitudinal steel of Ø 3/4" @ 20 cm and transverse steel of Ø 3/4" @ 25 cm, showing an increase in capacity with respect to natural soil, although lower than that obtained with gypsum or glass.

**Table 13. Cantilever wall steel**

| Description | In situ soil | Recycled Gypsum Powder | Recycled Glass Powder | Recycled Marble Powder | Recycled Brick Powder |
|---|---|---|---|---|---|
| **Wall Panel** | | | | | |
| Vertical Reinforcement | Ø 3/4" @ 20 cm | Ø 3/4" @ 15 cm | Ø 3/4" @ 15 cm | Ø 3/4" @ 15 cm | Ø 3/4" @ 15 cm |
| Inclined Reinforcement | Ø 3/4" @ 20 cm | Ø 3/4" @ 15 cm | Ø 3/4" @ 15 cm | Ø 3/4" @ 15 cm | Ø 3/4" @ 15 cm |
| Horizontal Reinforcement | Ø 1/2" @ 20 cm | Ø 1/2" @ 25 cm | Ø 1/2" @ 20 cm | Ø 1/2" @ 20 cm | Ø 1/2" @ 25 cm |
| **Heel** | | | | | |
| Longitudinal Reinforcement | Ø 3/4" @ 17.5 cm | Ø 3/4" @ 20 cm | Ø 3/4" @ 22.5 cm | Ø 3/4" @ 22.5 cm | Ø 3/4" @ 20 cm |
| Transverse Reinforcement | Ø 3/4" @ 17.5 cm | Ø 3/4" @ 25 cm | Ø 3/4" @ 25 cm | Ø 3/4" @ 25 cm | Ø 3/4" @ 25 cm |
| **Toe** | | | | | |
| Longitudinal Reinforcement | Ø 3/4" @ 17.5 cm | Ø 3/4" @ 20 cm | Ø 3/4" @ 22.5 cm | Ø 3/4" @ 22.5 cm | Ø 3/4" @ 20 cm |
| Transverse Reinforcement | Ø 3/4" @ 17.5 cm | Ø 3/4" @ 25 cm | Ø 3/4" @ 25 cm | Ø 3/4" @ 25 cm | Ø 3/4" @ 25 cm |

Figure 19 shows how the most effective additions, recycled gypsum and glass powder, not only reduced the dimensions of the base and the thickness of the footing, but also decreased the amount of steel required in both the screen and the foundation. This result confirms that the improvement in cohesion and internal friction angle directly reduces the stresses on the screen. At the same time, the increase in bearing capacity optimises the performance of the footing. Overall, stabilisation with recycled materials resulted in a more efficient and sustainable design, with lower concrete and steel consumption without compromising structural safety.

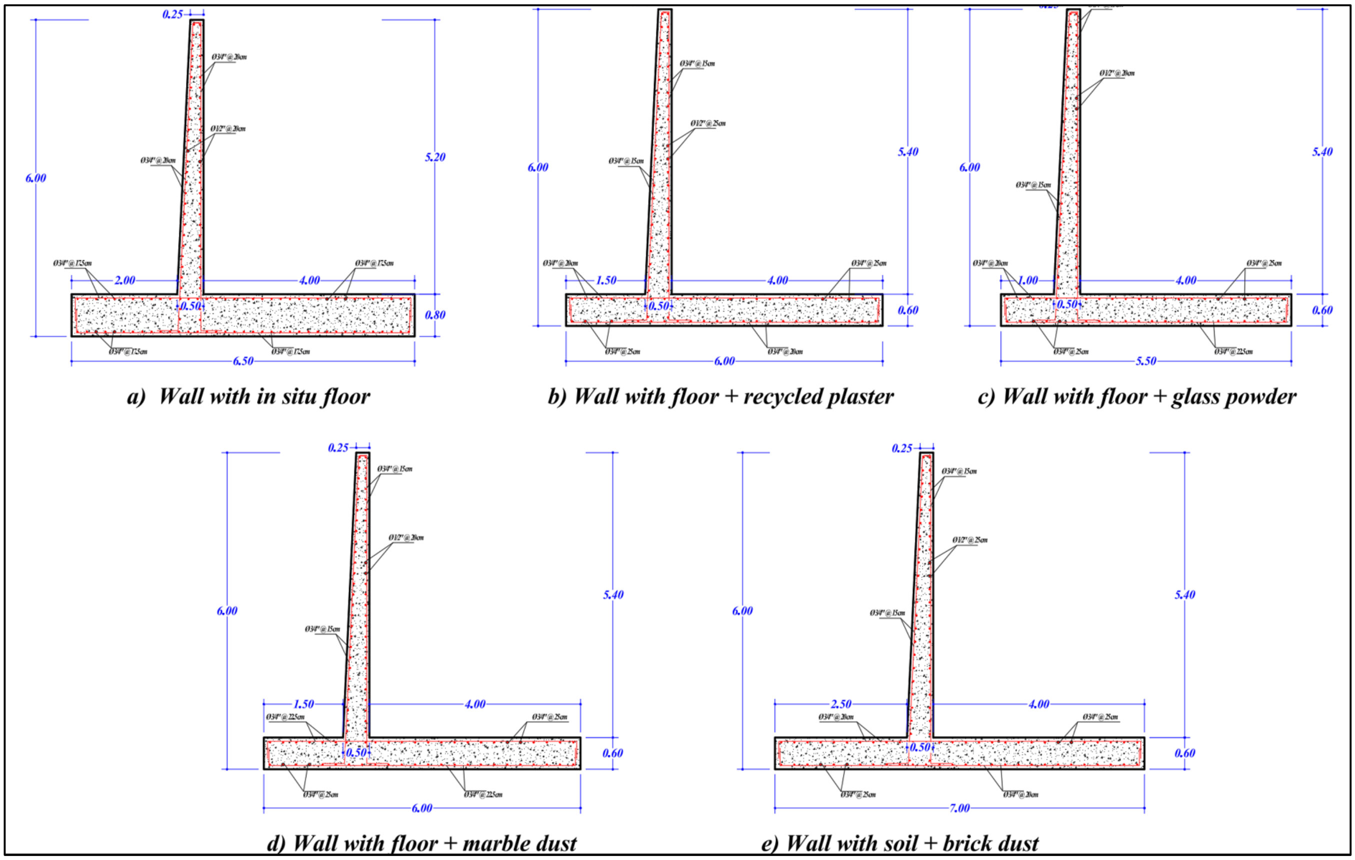


**Fig. 19 Detailing of cantilevered walls**

*4.6.2. Cost Analysis of Cantilever Walls*

Table 14 presents a comparison of construction costs for cantilever retaining walls designed with soils stabilised using different recycled additives. The results show the direct effect of geotechnical improvement on the structural and economic efficiency of the system. In the case of in-situ soil, the highest consumption of materials was recorded, with 7.15 m³ of concrete and 644.05 kg of steel, reaching a total cost of S/ 6,561.85, due to the need for wider foundations and denser reinforcements to compensate for its lower bearing capacity. By incorporating recycled gypsum, material consumption was reduced to 5.62 m³ of concrete and 567.92 kg of steel, with a total cost of S/ 5,437.61, representing an approximate saving of 17% compared to natural soil. This outcome is consistent with the combined increase in cohesion and global stiffness of the backfill–foundation system, which reduced the design active thrust and improved sliding and bearing verifications, thereby enabling a narrower base and lower structural demand. Under the glass-powder condition, the wall reached the minimum total cost (S/ 5,178.53), with material quantities limited to 5.33 m³ of concrete and 543.91 kg of reinforcement, evidencing the highest efficiency among the alternatives through direct reductions in footing geometry and flexural reinforcement requirements. In the case of marble dust, the total cost was S/ 5,543.07, with 5.63 m³ of concrete and 590.60 kg of steel, showing favourable technical performance, although with a slight increase in material compared to gypsum and glass. Brick dust yielded a total cost of S/ 6,231.52, with 6.23 m³ of concrete and 675.02 kg of reinforcement, remaining close to the in situ configuration and therefore showing limited economic leverage. This response is consistent with its lower contribution to densification and load transfer efficiency, which constrained gains in bearing verification and overturning/sliding resistance, ultimately requiring a wider footing and higher steel demand to satisfy stability and serviceability checks. Overall, recycled gypsum and glass powder delivered the most favorable soil–structure interaction, translating measurable improvements in strength/stiffness into smaller wall geometries and a marked reduction in concrete and reinforcement consumption, positioning both as the most efficient and sustainable alternatives for cantilever retaining wall design.

**Table. 14 Measurement and costs of cantilevered walls**

| Description | In situ soil | Recycled Gypsum Powder | Recycled Glass Powder | Recycled Marble Powder | Recycled Brick Powder |
|---|---|---|---|---|---|
| Concrete metreage (m3) | 7.15 | 5.62 | 5.33 | 5.63 | 6.23 |
| Concrete price (x m3) | 509.03 | 509.03 | 509.03 | 509.03 | 509.03 |
| Total cost of concrete (S/.) | S/ 3,639.58 | S/ 2,860.76 | S/ 2,710.60 | S/ 2,863.31 | S/ 3,168.73 |
| Measurement Steel (kg) | 644.05 | 567.92 | 543.91 | 590.60 | 675.02 |
| Steel Price (x Kg) | 4.54 | 4.54 | 4.54 | 4.54 | 4.54 |
| Total cost of steel (S/.) | S/ 2,922.27 | S/ 2,576.85 | S/ 2,467.93 | S/ 2,679.76 | S/ 3,062.79 |
| Total Cost | **S/ 6,561.85** | **S/ 5,437.61** | **S/ 5,178.53** | **S/ 5,543.07** | **S/ 6,231.52** |

*4.6.3. Analysis of the Costs of Obtaining Additions*

Table 15 shows the processing costs for the various additives, and from this, we can see that the glass powder costs the most (S/ 0.70 per kg), because of the fine grinding and particle size classification stages, followed closely by the marble powder (S/ 0.67 per kg). On the other hand, processed recycled gypsum is cheaper (S/ 0.62 per kg), because the production stages demand less energy with simpler steps for separation and grinding. Taking into account the costs per cubic meter of soil treated, which includes the specific weight of each addition and the optimum dose that was determined experimentally, glass powder costs the most (S/ 269.96 per m³), as it requires higher quantities (15%) plus costs more to process. Recycled gypsum is the most economical (S/ 162.87 per m³). Marble powder and brick powder were in the middle range, with costs of S/ 214.07 and S/ 225.90 per m³, respectively. This analysis showed that the choice of additive depends not only on geotechnical performance, but also on the economics of processing, with recycled gypsum being the material with the best balance between technical efficiency and cost of procurement.

**Table 15. Cost of procurement of additions**

| Description | Recycled Gypsum Powder | Recycled Glass Powder | Recycled Marble Powder | Recycled Brick Powder |
|---|---|---|---|---|
| Collection (S/./kg) | S/ 0.15 | S/ 0.10 | S/ 0.10 | S/ 0.10 |
| Transport (S/./kg) | S/ 0.10 | S/ 0.15 | S/ 0.15 | S/ 0.12 |
| Cleaning/Pretrat. (S/./kg) | S/ 0.05 | S/ 0.08 | S/ 0.08 | S/ 0.08 |
| Crushing/Milling (S/./kg) | S/ 0.30 | S/ 0.35 | S/ 0.32 | S/ 0.28 |
| Storage (S/./kg) | S/ 0.02 | S/ 0.02 | S/ 0.02 | S/ 0.02 |
| **Processing Cost (S/./kg)** | **S/ 0.62** | **S/ 0.70** | **S/ 0.67** | **S/ 0.60** |
| Natural Specific Gravity (gr/cm³) | 2627 | 2571 | 2556 | 2510 |
| Optimum percentage | 0.1 | 0.15 | 0.125 | 0.15 |
| Necessary addition (kg) | 262.7 | 385.65 | 319.5 | 376.5 |
| **Cost (kg/m3)** | **S/ 162.87** | **S/ 269.96** | **S/ 214.07** | **S/ 225.90** |

*4.6.4. Cost Analysis of Implementing Additions to Cantilever Walls*

Table 16 shows the costs of implementing the additions, allowing for a comparison of the economic impact of each alternative in the design of cantilever walls. The most economical option was found to be the incorporation of glass powder, with a total cost of S/S/5,448.48, followed by recycled plaster, with S/S/5,600.49, and marble powder, with S/ 5,757.13. In contrast, brick powder had a total cost of S/S/6,457.42, slightly lower than that of in situ soil (S/ 6,561.85), confirming its lower economic efficiency compared to the other additives. These results demonstrated that the appropriate selection of the type of additive has a direct impact on reducing the overall costs of the project. In particular, the use of glass powder and recycled plaster optimised structural and economic efficiency, significantly reducing material consumption and improving the overall sustainability of the Cantilever Wall Design.

**Table 16. Implementation costs of additives and cantilever walls**

| Description | Cost of Application of Additions |
|---|---|
| Insitu Flooring | S/ 6,561.85 |
| Recycled Gypsum | S/ 5,600.49 |
| Glass Dust | S/ 5,448.48 |
| Marble Dust | S/ 5,757.13 |
| Brick Dust | S/ 6,457.42 |

Figure 20 shows the differences in total application costs for each type of additive and for the in situ soil. It can be seen that the glass powder alternative had the lowest total cost (S/ 5,448.48), establishing itself as the most economical option among all those analysed.

It was followed by recycled gypsum at S/ 5,600.49 and marble powder at S/ 5,757.13, both with notable reductions compared to natural soil. In contrast, brick dust had a high cost of S/S/6,457.42, although slightly lower than in situ soil (S/ 6,561.85).

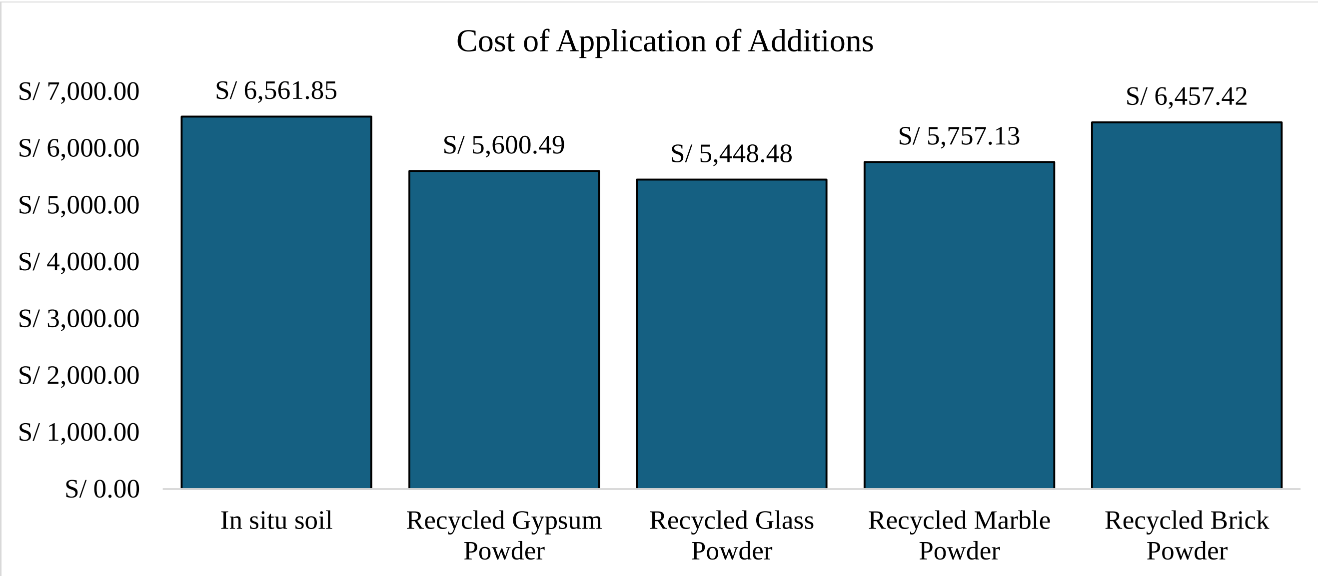


**Fig. 20 Final costs of cantilever walls plus additions**

The results obtained in this research showed a significant reduction in the total construction costs of Cantilever Retaining Walls when using clay soils stabilised with recycled waste, achieving savings of up to 21.23% compared to the design on in situ soil. This maximum saving corresponded to the use of glass powder, followed by recycled gypsum and marble powder, which also showed notable economic improvements by optimising the consumption of concrete and structural steel. However, it is important to note that the economic analysis did not consider the cost associated with the compaction process, as the optimum moisture content of the mixtures was not determined. Optimum moisture content directly controls field densification, mobilised strength, and in situ soil response, and therefore conditions both structural performance and construction cost. This parameter is commonly established through compaction and CBR testing, which quantify bearing response under controlled moisture states. Future studies should incorporate optimum moisture and compaction cost analysis to enable a field-representative evaluation of stability, bearing capacity, and economic efficiency of the proposed stabilisation alternatives.

## 5. Discussion

Application of recycled gypsum and phosphogypsum in geotechnical engineering, e.g., in China International Reviews, shows isolated improvements in compaction, shear strength, and reduces the expansivity of soils. However, authors note the high (wet) Solubility Of Calcium Sulfate, recommending gypsum and phosphogypsum mixed with lime or cement to reduce leaching and mitigate environmental impact. Likewise, their review notes that clay soils and gypsum can increase the unconfined compressive strength up to 150%, depending on the optimum proportion and moisture control during curing [78]. Stabilising clay soil with Recycled Drywall Gypsum in this study increased cohesion from 0.011 kg/cm² (natural soil) to 0.153 kg/cm², and increased the allowable bearing capacity from 1.988 kg/cm² to 2.108 kg/cm² with 12.5% optimum dosage. Also, specific weight increased to 2.196 g/cm³, demonstrating soil densification and increased stiffness. This behaviour showed that recycled gypsum acted as an effective cementing agent, improving the interconnection between particles and reducing voids, which resulted in a more stable and shear-resistant structure. The two studies differ primarily because of the kind of gypsum used and the conditions of the experiments. In China, mixtures with phosphogypsum and industrial gypsum were evaluated in saturated environments and under prolonged curing, where the solubility of calcium sulphate affected the durability of the material. In contrast, the present study used recycled gypsum from drywall, with lower impurity content and controlled humidity conditions, which reduced the dissolution of the material and favoured the formation of stable cementitious bonds in a shorter period. Furthermore, while conducted in China, it recommends combining it with lime or cement to achieve stability. The results of this research demonstrated that recycled gypsum, even without additional additives, can significantly improve cohesion and bearing capacity when applied in optimal proportions and under adequate drainage conditions.

According to the experimental study conducted by Rajaee in Iran, the use of different particle sizes of recycled glass powder in the stabilisation of alkali-activated clay soils allowed the identification that hybrid gradations significantly improve geotechnical properties compared to mixtures of uniform particles. The authors reported an increase in Unconfined Compressive Strength (UCS) of up to 271% compared to soil without additives, reaching values close to 2 MPa in samples with 20% glass and 2 M NaOH activator. They also observed that the HC hybrid mixture (60% fine particles, 40% coarse particles) presented the best balance between cohesion (220 kPa) and internal friction angle (38°), generating a dense microstructure with lower porosity [79]. In this research, the incorporation of recycled glass powder as a stabilising material in clay soils intended for cantilever wall foundations resulted in a progressive improvement in the bearing capacity and maximum dry density of the soil. The optimal addition of 15% produced an increase in cohesion from 0.011 kg/cm² to 0.142 kg/cm² and an allowable bearing capacity from 1.988 kg/cm² to 2.016 kg/cm², accompanied by a densification of the dry specific weight (2.140 g/cm³). This behaviour is attributed to the pozzolanic action of the amorphous silicate present in the glass, which promotes the formation of C-S-H bonds and the reduction of intergranular voids, improving stiffness and adhesion between particles. The two studies differ in the type of activation used and the scale of the experiments. Rajaee (2024) used a geopolymerised system with alkaline (NaOH 2 M-6 M) and gradation control, activated dissolution reactions that achieved higher strength in the 28-day curing period. Conversely, for this research, glass powder was used without any external alkaline activation; therefore, reactions were restricted to the compaction-induced physical and chemical interaction between the glass and clay fraction.

In a study conducted in Turkey, the use of marble powder was evaluated as a partial replacement for cement in the stabilisation of alluvial clays. This was aimed at reducing the environmental footprint of the use of traditional materials. The results indicated that replacing 10% of the cement with marble powder produced a slight decrease (8.3%) in Unconfined Compressive Strength (UCS) at 7 days, attributed to the low initial pozzolanic reactivity of calcium carbonate. However, after 60 days of curing, the strength increased by up to 20%, reaching values of 7200 kPa with 13% cement and 10% marble powder. Likewise, the initial shear Modulus ($G_0$) increased by up to 32% in densified samples (1.8 g/cm³), and SEM micrographs showed the progressive formation of secondary C-S-H and C-A-H gels that filled microcracks and improved the cohesion of the matrix [31]. In this research, the addition of recycled marble powder to local clay soil showed a significant stabilising effect on bearing capacity and dry specific weight, with an optimum proportion of 12.5%. An increase in cohesion from 0.011 kg/cm² (natural soil) to 0.130 kg/cm² was obtained, and an increase in the allowable bearing capacity from 1.988 kg/cm² to 2.075 kg/cm². The dry specific weight reached 2.125 g/cm³, showing a reduction in porosity and denser packing. These results were associated with the high concentration of $CaCO_3$ in the marble powder, which acts as a microfiller and nucleating agent for the formation of cementitious products, improving soil compaction and stiffness without requiring prolonged curing processes. The differences observed between the two studies lie in the nature of the soil, the compaction density, and the activation mechanism of the marble. Hanafi (2025) worked with highly plastic alluvial clay and chemically activated cement mixtures, where the gain in strength manifested itself at later ages (60 days) due to the slow reaction of $CaCO_3$ with the $Ca(OH)_2$ in the cement. In contrast, the present study used less plastic clay soils without added cement, so the effect of marble powder was mainly physical structural, acting as a filler and densification enhancer in a short stabilisation period.

In a study conducted in Peru, where the addition of recycled brick powder to clay soils was evaluated, it significantly improved simple compressive strength, cohesion and maximum dry density, demonstrating a progressive stabilising effect up to an optimum proportion of 15%. At this dosage, cohesion increased by 118% compared to natural soil, and unconfined strength increased to 2.41 kg/cm², attributed to the pozzolanic reaction between the silicon and aluminium oxides in the ceramic material and the calcium hydroxide in the soil [80]. In this study, the incorporation of recycled brick dust into clay soil for the construction of Cantilever Retaining Walls achieved a cohesion of 0.064 kg/cm² and an allowable bearing capacity of 1.714 kg/cm² with an optimum content of 15%. The void ratio decreased, and the granular structure became more settled, resulting in a dry unit weight of 2.079 g/cm³. This phenomenon is attributed to the silicoaluminous nature of the brick dust, which exhibits a low pozzolanic activity and, more dominantly, a fine filler effect that improves packing and contact efficiency between particles. The divergence with Villalta (2023) is attributed to soil type and activation condition differences: that study used a medium plasticity clay with partial lime activation, which promotes greater chemical bonding and increases strength. In the current study, the clayey sand without activators primarily invoked a physical densification mechanism and, more so, improved stress transmission than chemically driven strength development.

## 6. Conclusion

The results confirmed that the stabilization of clay soils using recycled gypsum, glass powder, marble powder, and brick powder produced a measurable improvement in key geotechnical parameters. Increases in dry unit weight and cohesion were consistently observed, together with controlled variations in internal friction angle, leading to an overall enhancement of load-bearing capacity and mechanical response under structural loading conditions. Secondly, recycled gypsum demonstrated the greatest stabilising effect, achieving an optimal dosage of 12.5%, a specific weight of 2,196 g/cm³, a cohesion of 0.153 kg/cm², a friction angle of 18.894°, and an admissible bearing capacity of 2,108 kg/cm². These improvements can be explained by the secondary cementing action of Calcium Sulphate Dihydrate ($CaSO_4 \cdot 2H_2O$), which promoted the formation of bonds between fine particles and a more rigid and dense structure. From a structural point of view, these properties made it possible to reduce the width of the wall base from 6.50 m to 6.00 m and the thickness of the footing from 0.80 m to 0.60 m, decreasing the volume of concrete and the amount of steel required. In economic terms, the recycled gypsum had a total cost of S/S/5,600.49, making it a highly competitive and sustainable option.

Thirdly, recycled glass powder, with a dosage of 15%, showed the best economic performance and technical performance very close to gypsum, registering a specific weight of 2,140 g/cm³, a cohesion of 0.142 kg/cm², a friction angle of 18.996°, and a bearing capacity of 2,016 kg/cm². Its high amorphous silica content and fine grain size favoured more efficient packing and greater interconnection between particles. These effects made it possible to reduce the base of the wall to 5.50 m and maintain a footing thickness of 0.60 m, while also achieving the lowest total cost for the assembly (S/S/5,448.48), demonstrating its excellent cost benefit ratio for foundation applications.

Fourthly, marble powder, at a dosage of 12.5%, achieved a specific weight of 2.125 g/cm³, a cohesion of 0.130 kg/cm², a friction angle of 19.481°, and a bearing capacity of 2.075 kg/cm². Its effect is mainly related to the filling character of Calcium Carbonate ($CaCO_3$), which decreased the plasticity of the soil and improved contact between particles. Although its performance was intermediate compared to gypsum and glass, it allowed a base of 6.00 m to be maintained and total costs to be reduced to S/ 5,757.13, positioning it as a technically and environmentally viable alternative, especially in areas where this waste is easily accessible.

Fifthly, recycled brick dust, with an optimal dosage of 15%, showed a specific weight of 2,079 g/cm³, a cohesion of 0.064 kg/cm², a friction angle of 20.128°, and a bearing capacity of 1,714 kg/cm². Although it doubled the capacity of natural soil, its performance was more limited due to its high porosity and low intrinsic density, which reduces the stiffness of the mixture. In terms of design, it required a 7.00 m base and maintained the footing thickness at 0.60 m, reaching a total cost of S/ 6,457.42, very close to that of the unimproved soil (S/ 6,561.85). Therefore, its use is recommended only in projects with high local availability or low structural demand, such as fillings or lower height walls.

Sixthly, the applicability of the identified mechanisms to other types of soil is highlighted, specifying their direct impact on cohesion, internal friction angle, and specific weight, which control the active thrust Coefficient (Ka) and the permissible bearing capacity. In sandy soils, where the initial cohesion is negligible, the incorporation of recycled gypsum and glass powder can generate apparent cohesion and moderately increase the internal friction angle through improved particle interlocking and surface roughness. These mechanisms reduce the active earth pressure coefficient Ka and increase the dry unit weight by enhancing packing efficiency, allowing narrower foundations and a lower reinforcement demand in the retaining wall stem. In silty soils, which are very sensitive to moisture, glass powder and marble powder tend to decrease plasticity and increase internal friction, while gypsum can provide secondary cementation that increases cohesion. These improvements reduce lateral thrust and delayed settlement, promoting the stability of the retaining wall.

In coarse granular soils, such as well-graded gravel, the expected benefit is mainly physical due to the filler effect: discrete increases in internal friction and specific weight are obtained, with limited impact on reducing wall dimensions, but useful for optimising compaction and maximum dry density. In expansive soils, the combined action of gypsum (by reducing expansivity through ion exchange) and glass (by improving packing and internal friction) can increase cohesion and internal friction and reduce swelling, providing clear advantages in terms of the durability of the fill and the reduction of stresses transmitted to the wall. However, its behaviour in wet and dry cycles needs to be validated.

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Finally, the results presented established a solid basis for future research and practical applications in geotechnical engineering, especially in urban and rural areas with low-bearing-capacity soils. The replicability of this methodology and its technical, economic, and environmental benefits position recycled additives, especially recycled gypsum, as high-value-added alternatives, promoting innovative solutions for civil infrastructure projects.

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