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Original Article

Influence of Sodium Persulfate, Sodium Percarbonate, and Magnesium Phosphate Cement on the Stabilization of Peat Soils

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Abstract *- In the high Andean regions of Peru, peat soils exhibit high compressibility, low bearing capacity, and a high organic matter content, conditions that compromise the stability of roads and foundations. In Caylloma, Arequipa, these materials have caused subsidence along the road to Colca Canyon, posing risks to transport infrastructure. Given the limited effectiveness of Portland cement, this study proposed an alternative approach based on solid oxidants and Magnesium Phosphate Cement (MPC) to improve the thermal and mechanical behaviour of the soil. The thermal and mechanical behaviour of peat treated with sodium persulphate or sodium percarbonate, each combined with MPC, was evaluated under controlled laboratory conditions. Peat soil collected from the Chimpa sector was treated using different oxidant dosages combined with MPC modified with volcanic ash. Thermogravimetric (TG–DTG), direct shear, and unconfined compressive strength tests were conducted. The results showed that the formulations combining each oxidant with MPC exhibited lower total mass losses during heating and improved the mechanical strength of the treated peat compared with untreated soil. The most favourable formulations contained 3% sodium percarbonate or 3% sodium persulphate, each combined with 15% MPC, with the latter formulation achieving the best overall mechanical performance in terms of unconfined compressive strength, cohesion, internal friction angle, and allowable bearing capacity. These findings demonstrated that the combined stabilisation formulations constitute a promising alternative for improving the thermal and mechanical behaviour of organic peat soils under controlled laboratory conditions.*

Keywords *- Magnesium phosphate cement, Peat soil, Soil stabilisation, Solid oxidation, Thermogravimetric analysis.*

1. Introduction

Organic soils are materials consisting mainly of plant remains at various stages of decomposition, formed in environments characterised by high moisture content, prolonged saturation and limited aeration [1, 2]. Globally, they cover around 3% of the Earth's land surface; therefore, although their distribution is relatively limited, they play a significant role in biogeochemical cycles and in the stability of sensitive ecosystems [3].

In Peru, these soils are found in 19 regions and cover approximately 1 051 134 ha, equivalent to 0.8% of the national territory [4]. Their presence is due to the interaction of climatic, altitudinal and geological factors that favour the accumulation and slow decomposition of organic matter [5]. In Arequipa, approximately 133 434.8 ha of organic soils have been identified, equivalent to 2.11% of the region's total area, with a particularly high concentration in high-Andean areas such as the province of Caylloma, home to the Colca Valley, a region renowned for the Colca Canyon and its pre-Inca agricultural terraces, which are still in use where environmental, cultural and economic values of national significance converge [6-8].

From a geotechnical perspective, organic soils are characterised by high porosity, low bulk density, high organic carbon content and high water retention capacity [9-11]. Although these properties favour ecological functions such as water storage and natural fertility, they are unfavourable for civil engineering, as they reduce structural stiffness, increase compressibility and decrease shear strength [12-14]. Within this group, Peat soils (PT) represent a critical condition, characterised by organic matter contents exceeding 75 per cent, a highly deformable fibrous structure and low bearing capacity [15, 16]. These characteristics can lead to differential settlement, slow consolidation, progressive loss of strength and non-linear behaviour under static or dynamic loads, compromising the safety of foundations, roads and infrastructure built on this type of deposit [17-19].

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This problem came to light on 3 June 2023, when a 5.2-magnitude earthquake exacerbated the instability of the ground in the Colca Valley and caused severe damage in the area [20]. This event occurred against a backdrop of recurring damage since 2022, a period during which 80 homes were reported to be uninhabitable, and 158 homes were affected, highlighting the vulnerability of the population and the infrastructure built on soil with low bearing capacity [21]. In view of these conditions, experts recommended the relocation of residents due to the low bearing capacity and high instability of the ground [20].

Subsequently, on 17 August 2025, a subsidence occurred on the AR-109 road, near the Chimpa sector in the town of Pinchollo, close to the Mirador de la Cruz del Cóndor viewpoint in the district of Cabanaconde, which disrupted traffic and affected the daily journeys of between 800 and 1,000 domestic and foreign tourists [22, 23]. These events show that patching and high-Andean organic soils are a risk factor for connectivity, public safety and the local tourism economy due to their low bearing capacity, slow consolidation, volumetric variations and progressive loss of shear strength [15, 16, 18].

In response to these challenges, various studies have evaluated stabilisation techniques aimed at increasing the bearing capacity and reducing the compressibility of organic soils. Among these, chemical treatments using sodium persulphate, sodium percarbonate and potassium ferrate have been investigated; these are capable of improving strength by partially degrading the organic matter and enhancing the action of the cementing agents [24].

Mixtures of carbide lime, granulated blast furnace slag and small proportions of Portland cement have also been proposed, in conjunction with processes of flocculation, crystallisation and cohesion gain [25]. Furthermore, the incorporation of vinyl acetate-ethylene copolymers has made it possible to increase unconfined compressive strength through polymeric bonds between the fine particles and the organic fraction of the soil [26].

In this context, a research gap remains concerning the limited experimental evidence on the thermal and mechanical behaviour of natural high-Andean peat soils treated with sodium persulphate or sodium percarbonate, each separately combined with volcanic-ash-modified Magnesium Phosphate Cement (MPC). Although previous investigations have evaluated different chemical treatments for improving organic soils, further investigation is required to determine the response of highly organic peat to these stabilisation systems, particularly in terms of mass loss during heating, shear strength and unconfined compressive strength. To address this limitation, the present study aimed to evaluate and compare the thermal and mechanical behaviour of peat samples collected from the Chimpa sector, Caylloma, Arequipa, using both oxidants, evaluated separately and combined with volcanic-ash-modified MPC, under controlled laboratory conditions. Accordingly, the investigation sought to identify the treatment formulations exhibiting the most favourable responses and to provide comparative experimental evidence for the assessment of alternative stabilisation methods for high-Andean peat soils.

2. Literature Review

2.1. Geotechnical Problems Associated with Organic and Peat Soils Area

A literature review focusing on organic soils was carried out; Figure 1 summarises the main geotechnical problems identified in various regions of the world. This evidence demonstrates the characteristic unstable mechanical behaviour of such soils and the significant structural damage they cause to buildings, roads and other civil engineering works.

Item a shows an area of peat swamps in Kuala, Malaysia, characterised by organic deposits up to 20 m deep, high acidity (pH > 3.9) and organic matter content exceeding 70 per cent, conditions which led to differential settlement, subsidence and cracking in homes, rural roads and power lines, due to the low bearing capacity and high compressibility of the ground [27]; in item b, a soft peat soil area in Thailand is shown, where the lack of deep treatment and increased loads on a saturated organic layer led to progressive settlement and foundation subsidence, evident in the partial collapse of structures and uneven road surfaces [28]; in item c, a large area of peat soils is identified in Sibu, East Malaysia, with organic matter content of up to 98 per cent, considered one of the most critical areas in the country.

In this area, subsidence of up to 1 m was recorded on urban roads and post-construction settlement of 750 mm in buildings, caused by prolonged consolidation and poor drainage of the organic soil [29]; finally, in item d, critical structural failures are documented in infrastructure built on organic soils in various regions of the world and in north-eastern India, where low shear strength, high compressibility and non-linear dynamic behaviour led to differential settlement, cracking and structural collapse, such as the settlement of industrial containers in Amsterdam and undulations caused by long-term settlement on roads in Japan [30].

In light of this issue, recent research has explored the use of chemical oxidants capable of partially degrading organic matter and improving the efficiency of cementation processes. Notable among these agents are Sodium Persulphate ($Na_2S_2O_8$) and Sodium Percarbonate ($2Na_2CO_3 \cdot 3H_2O_2$), due to their potential to increase the strength, stiffness and stability of soils with a high organic content. The following paragraphs summarise the main experimental findings associated with their application.

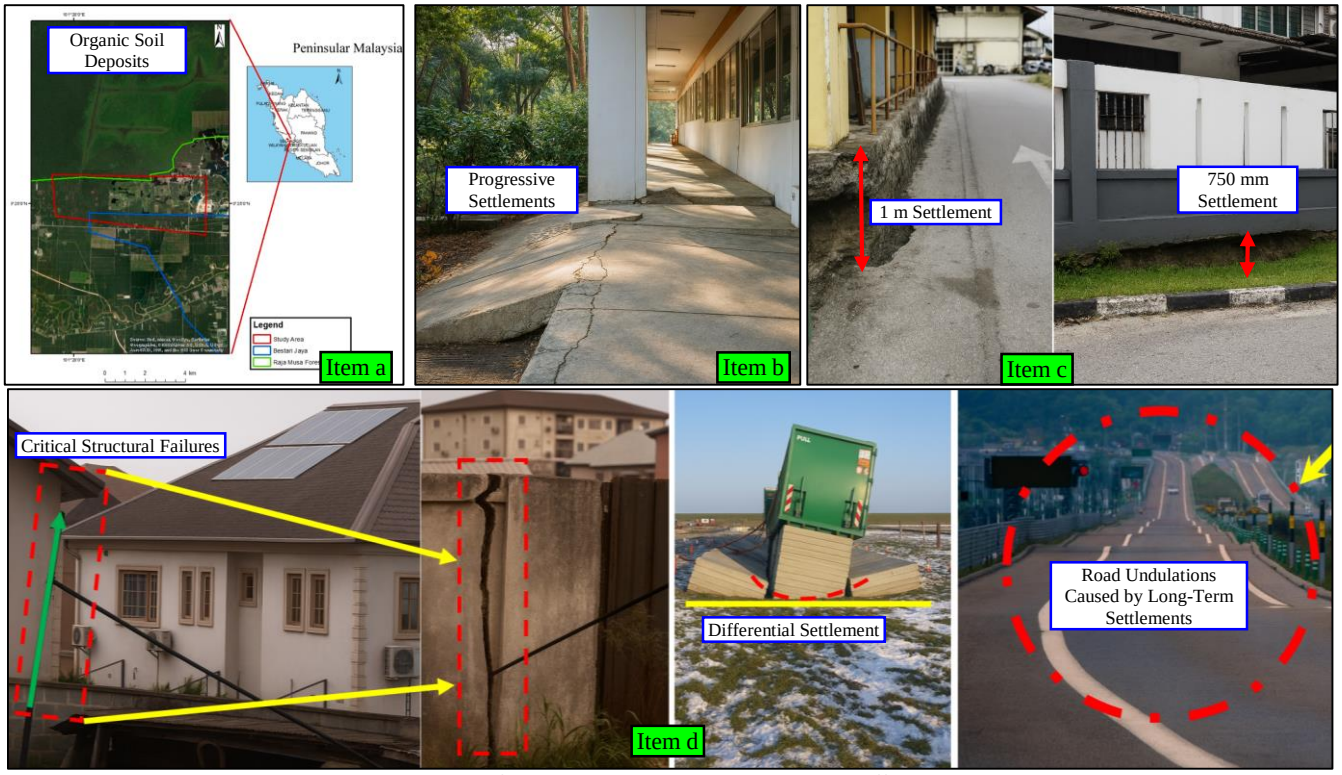

Fig 1. Structural failures associated with organic soils in different regions

2.2. Sodium Percarbonate in Organic Soil Treatment

In China, researchers at the State Key Laboratory of Geomechanics and Geotechnical Engineering evaluated a combined oxidation and solidification method to improve dredged soils with a high organic content; the study used sodium persulphate, sodium percarbonate and potassium ferrate, incorporated together with Portland cement at dosages of 5%, 10% and 15%, in order to degrade the organic matter and promote cement hydration; after 60 days, the treatments with persulphate and percarbonate, combined with 15% cement, increased the unconfined compressive strength by almost four times compared with the soil without an oxidant, whilst the ferrate treatment achieved a 1.5-fold increase; these findings verified that pre-oxidation may enhance the microstructure and bond density of the soil, consequently improving the stabilisation efficiency of organic matrices [24]. At the same time, an overview of the application of sodium percarbonate as a relatively safe substitute oxidant for H_2O_2 in water and soil advanced oxidation processes was provided by top scholars from College of Resources and Environment. The review included studies on homogeneous and heterogeneous activation by metal catalysis, ultraviolet irradiation, plasma, zero-valent iron and nanocomposites. Results indicated that percarbonate gave rise to reactive species including ·OH, $O_2^{\cdot-}$ and carbonate radicals while preserving slightly alkaline conditions. Additionally, PC/Fe^{2+}, PC/Fe^{3+} and PC/UV systems had almost 99% degradation efficiencies against organic contaminants (benzene, aniline, antibiotics, polycyclic aromatic hydrocarbons and azo dyes). The authors conclude that percarbonate represents an environmentally friendly, cost and energy-efficient oxygen source for use in advanced oxidation and sustainable environmental remediation efforts [31].

In Brazil, researchers at the Federal University of São Paulo reviewed the use of sodium percarbonate in soil and groundwater remediation through in situ chemical oxidation. The study analysed its performance as an alternative to H_2O_2, taking into account reaction mechanisms, metal activators, chelating agents and operating conditions. The review reported that percarbonate, either on its own or activated with Fe(II), Fe(III), citric acid or oxalic acid, can degrade aromatic hydrocarbons, chlorinated solvents and polycyclic compounds through the generation of ·OH, $HO_2^{\cdot}$ and $O_2^{\cdot-}$ radicals. In Fe(III)/PC/contaminant systems, removal rates of up to 100 per cent were achieved in less than 60 minutes for benzene, tetrachloroethylene and trichloroethylene. Furthermore, its greater stability, near-neutral pH and sustained release of oxygen were highlighted, conditions which favour complementary bioremediation processes [32]. Similarly, researchers at the Federal University of Pernambuco assessed the effectiveness of sodium percarbonate in degrading polycyclic aromatic hydrocarbons present in soil contaminated with diesel from the RNEST refinery. The study employed a photo-Fenton system using PC, Fe^{2+} and different irradiation conditions, applied for 6 hours at a pH of 4 to soil samples containing 300 $g \cdot kg^{-1}$ of diesel. The results showed a 55% reduction in total organic carbon and a 76% reduction in

total PAHs, which fell from 85,753 to 20,715 mg·kg⁻¹ [33]. These results corroborated that percarbonate serves as a stable, highly efficient and easy to handle oxidant which can represent an eco-sustainable alternative to traditional oxidation procedures.

2.3. Sodium Persulfate in Organic Soil Stabilization

In China, people from Suzhou University investigated the use of sodium persulphate as an additional oxidant for solidification of dredged sludge with a high organic matter content, using Portland cement. Soil was amended with fulvic acid, cement and persulphate at the following concentrations; 0-4 per cent FA, 10-25 per cent cement and 0–8 per cent ps (w/w) at a moisture content of 50 per cent, then characterised using UCS, XRD, TG, FTIR and SEM-EDS after curing for 7 days and upon test completion at day28. Results indicated that persulphate was indeed activated by the alkaline environment of cement during hydration, thereby reducing organic matter interference and facilitate the synthesis of hardened cementation products including C-S-H and ettringite. The optimal mixture, comprising 4% fulvic acid, 20% cement and 6% persulphate, reached 1212.7 kPa at 28 days, equivalent to 15.1 times the strength of the soil without an oxidant. The study demonstrated that the cement-persulphate system improves the stabilisation of organic sludge by integrating oxidative degradation, cementitious hydration and microstructural densification [34].

The activation of $SO_4^{\cdot -}$ radicals by the mixture 15% SAC and its optimal amounts of $Ca(OH)_2$ (0.14%) and persulphate (1%), intensified the degradation reactions of proteins, lignins and aliphatic fractions in this study. In addition, the release of Ca^{2+} and SO_4^{2-} facilitated the precipitation of acicular ettringite, which increased cohesion. Consequently, the organic matter content reduced to 10.9 % to 4.8 %, and with that compressive strength is attained at 3.2 MPa, which meets the standards for materials implantation [35].

In Chengdu, researchers reviewed the use of sodium persulphate in the remediation of soil contaminated with organic compounds has been reviewed by researchers from Chengdz University, who focused particularly on its underground oxidation mechanisms of hazardous solutes and formation of soil gas; the study is an extensive review of over 60 research articles covering thermal, ferric, alkaline and electrokinetic activation including the analysis of contaminants such as TPHs, PAHs, PCBs, pesticides, pharmaceuticals and phthalates; the results showed sodium persulphate was the most frequently used oxidant due to its low cost and high solubility, long persistence in the subsoil that achieved degradation efficiencies of 80% to 100% of soil contaminated with TCE, PAHs and diesel; moreover, it was found that thermal activation and an alkaline pH could promote the production of oxidising radicals, which is an indication of their stability and flexibility for in-situ treatment of polluted soil [36]. They also examined the remediation of soil contaminated with petroleum hydrocarbons by ultrasonically activated sodium persulphate and metallic iron. Different concentration of oxidant, ultrasonic power and pH were used in treatment so that the optimum generation of oxidising radicals could be obtained. In the best conditions, around 82% of hydrocarbons were removed, and mineralisation of organic carbon reached approximately 54% within 3 days using the combined system. Light compounds, such as alcohols and esters, degraded more rapidly, whilst long-chain alkanes showed greater resistance [36].

Global research into the use of alternative oxidising and cementing agents in the stabilisation of organic soils has demonstrated significant progress in improving their strength, stiffness and durability. Solid oxidising agents such as sodium persulphate and sodium percarbonate have been extensively studied for their ability to degrade organic matter and promote the formation of cementing products, whilst Magnesium Phosphate Cement (MPC) has established itself as a fast-setting inorganic binder with high chemical compatibility with difficult soils. However, much of this research has focused on environmental remediation contexts or dredged soils, without comprehensively evaluating the combined performance between controlled solid oxidation and MPC cementation when applied to highly organic natural soils. Consequently, a scientific gap remains regarding the thermal and mechanical characterisation of peat-type soils treated using this combined approach. In this context, this research aims to provide an innovative approach by applying, for the first time, the technique of controlled solid oxidation using persulphate and sodium percarbonate, together with cementation using magnesium phosphate modified with volcanic ash, to improve the strength and durability of organic soils in the Arequipa region, thereby proposing an efficient, sustainable and replicable alternative for the improvement of soils with low bearing capacity.

3. Materials and Methods

This section describes the materials, tests and procedures used to improve organic Peat-Type (PT) soils from the Chimpa area, Caylloma, Arequipa. The experimental programme comprised soil extraction, conditioning and characterisation, followed by the preparation of stabilised mixtures through the combined incorporation of sodium persulphate or sodium percarbonate with Magnesium Phosphate Cement (MPC) modified with volcanic ash. The procedures for specimen preparation, curing and thermal and mechanical testing are also described.

3.1. Study Area

The province of Caylloma, situated in the Arequipa region, forms part of the southern fringe of the Western Cordillera of the Andes, characterised by its rugged terrain, altitudes exceeding 3,100 metres above sea level, and the presence of deep ravines and volcanic formations [37]. The province has a cold, humid climate, with marked variations

between the cold season and the rainy season, and the high-Andean vegetation consists mainly of cacti, grasses and ichu; whilst the local economy is based on the rearing of camelids and sheep [38, 39]. In this study, the Chimpa sector of the Pinchollo settlement, in the district of Cabanaconde, shown in Figure 2, was selected as the sampling point. In this figure, the red outline represents the provincial boundaries of Caylloma, whilst the pink box indicates the detailed study area corresponding to the Pinchollo sector, where the geographical location of the sampling point can be seen. This area was selected due to the presence of subsidence and deformations on the road [23], which indicated unstable geotechnical behaviour associated with saturated organic strata.

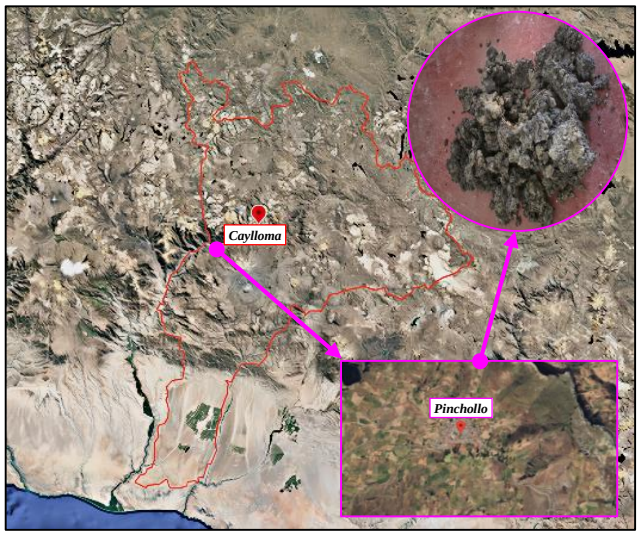

Fig. 2 Study area

3.2. Organic Soils

Organic soils contain a significant proportion of material derived from recent plant remains, which significantly alters their strength, compressibility and consolidation behaviour [40]. From a geotechnical perspective, when the organic content exceeds approximately 20 per cent, the soil ceases to behave like a conventional mineral material, whilst values above 75 per cent are usually associated with peat [41, 42]. Depending on their composition and degree of decomposition, these soils can be classified as organic when they contain between 5% and 20% organic matter, and as highly organic when they exceed this range [14]. In the SUCS system, they are mainly identified as OL, OH and Pt, corresponding to organic silts, organic clays and peats, respectively [1]. Within this framework, chemical oxidants may contribute to the modification of the organic matrix when combined with cementitious agents, potentially improving the response to stabilisation treatment [43].

3.3. Soil Oxidation

The oxidation of organic soils is defined as the process by which the organic matter present in the soil reacts with oxygen, leading to its degradation, the release of gases (CO_2, CH_4), a reduction in solid volume and an alteration of the material's internal structure, as shown in Figure 3 [44]. This mechanism, which tends to intensify when the land is drained, exposed to air or the water table drops, results in a progressive loss of solid matter and an increase in porosity, which in turn increases compressibility and leads to structural collapse or surface subsidence [24, 45]. In the context of this research, this principle was applied to the organic soil in the study area in Arequipa through the controlled incorporation of solid oxidising agents such as sodium persulphate and sodium percarbonate under laboratory conditions.

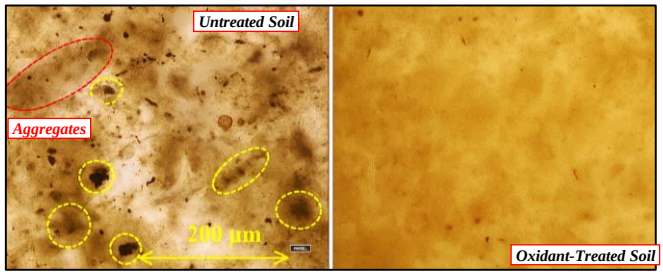

Fig. 3 Soil before and after oxidation treatment [24]

3.3.1. Sodium Percarbonate (PC)

Sodium Percarbonate, whose microscopic morphology is shown in Figure 4, has the characteristic chemical formula $2Na_2CO_3 \cdot 3H_2O_2$ and acts as a solid oxidant which, upon dissolution, releases hydrogen peroxide, sodium carbonate and reactive species capable of partially degrading soil organic matter [31, 33]. In organic soils, this action promotes the decomposition of humic compounds and lignocellulosic fibres, potentially reducing their interference with hydration and cementation reactions [46, 47]. For this reason, Sodium Percarbonate (PC) was selected as an oxidising agent to evaluate its influence on the behaviour of organic soils. Unlike conventional stabilisers such as lime or slag, which primarily act through cementitious or pozzolanic reactions, PC was selected for its oxidising capacity and its potential to modify organic compounds that may interfere with soil stabilisation processes.

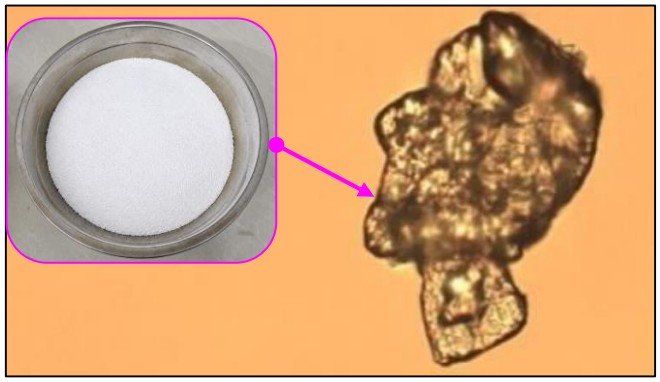

Fig. 4 Microscopic view of Sodium Percarbonate [48]

Sodium percarbonate is a solid, sustained-release oxidant that generates reactive oxygen species, such as (OH) and

($O_2^{\cdot-}$), capable of partially degrading organic matter in soils with a high organic carbon content [31]. Experimental studies have reported that dosages of around 3 per cent by dry weight of the soil reduce the organic fraction and improve compressive strength by reducing the interference of organic compounds with the hydration and cementation processes [24, 31]. In this study, doses of 1%, 2%, 3%, 4% and 5% sodium percarbonate were evaluated to identify the most effective concentration for the mechanical stabilisation of peat.

3.3.2. Sodium Persulphate (PS)

Sodium Persulphate ($Na_2S_2O_8$) is a highly stable solid oxidant, the microscopic morphology of which is shown in Figure 5. Its oxidising capacity is activated by thermal, alkaline, metallic or catalytic stimuli, generating sulphate ($SO_4^{\bullet-}$) and hydroxyl (•OH) radicals, which are capable of degrading complex organic compounds present in the soil [31] [49]. In organic matrices, this reaction may partially reduce the interference of organic matter with hydration and cementation processes, promoting better interaction between the soil and the cementing agent [50]. For this reason, Sodium Persulphate (PS) was selected as an oxidising agent to evaluate its influence on the behaviour of organic soils. Unlike conventional stabilisers such as lime or slag, which primarily act through cementitious or pozzolanic reactions, PS was selected for its oxidising capacity and its potential to modify humic compounds that may interfere with soil stabilisation processes.

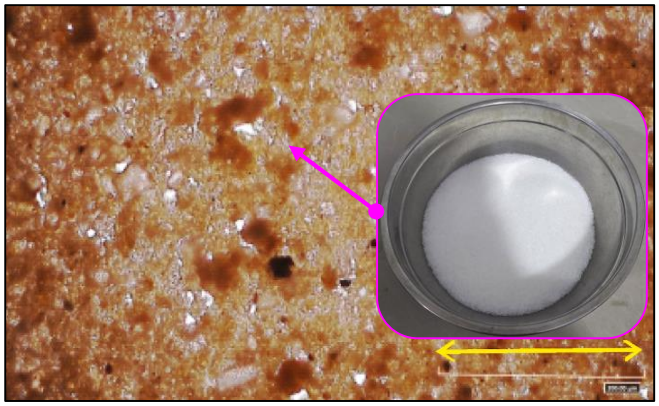

Fig. 5 Microscopic view of Sodium Persulfate [34]

Sodium persulphate has a high oxidising capacity and performs well in alkaline media, where it can generate sulphate radicals ($SO_4^{\cdot-}$) capable of partially degrading organic matter and reducing its interference with cementation reactions [51]. Previous studies reported that dosages of around 3% by dry weight of the soil led to significant increases in strength, particularly when the oxidising agent was combined with cementing agents [24, 34, 35]. Based on this background, doses of 1%, 2%, 3%, 4% and 5% sodium persulphate were evaluated in order to identify the most effective concentration for the mechanical stabilisation of peat.

3.4. Magnesium Phosphate Cement (MPC)

Magnesium Phosphate Cement (MPC) is a fast-setting inorganic binder, formed by the acid-base reaction between Magnesium Oxide (MgO) and a soluble phosphate salt, usually monopotassium phosphate (KH_2PO_4) [52, 53]. As depicted in Figure 6, its microstructure is characterised by a compact and homogeneous matrix, their principal composition being struvite crystals ($MgKPO_4 \cdot 6H_2O$), responsible for the high mechanical strength, good adhesion properties, as well the great durability in both humid or chemically aggressive environments [54]. Those attributes render it suitable as a soil stabiliser in biological matrices since the presence of humic compounds strongly inhibits cement hydration reactions typical for Portland cement [55]. In this study, MPC was selected as a cementitious binder and combined with either sodium persulphate or sodium percarbonate during the preparation of treated peat mixtures, with the aim of evaluating the mechanical behaviour of the resulting stabilisation formulations.

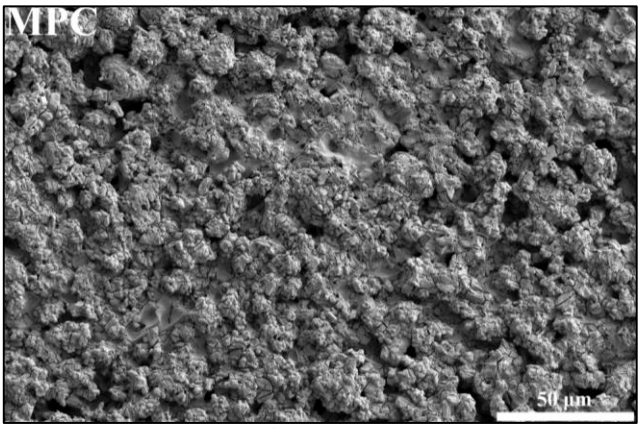

Fig. 6 Microscopic view of Magnesium Phosphate Cement [52]

Pandey et al. [56] investigated the stabilisation of a kaolinitic soil using Magnesium Phosphate Cement (MPC) dosages of 5%, 12% and 20%, obtaining unconfined compressive strengths of 2.06, 3.51 and 3.47 MPa, respectively. These findings demonstrated improvements in mechanical strength across the investigated dosages, particularly at MPC contents of 12% and 20%. Based on this experimental precedent, an intermediate MPC dosage of 15%, relative to the dry weight of the peat, was adopted in the present study and maintained constant to establish a uniform binder content and enable a comparative assessment of the effects of sodium persulphate and sodium percarbonate on the mechanical behaviour of the stabilised mixtures.

3.4.1. Magnesium Oxide

Magnesium Oxide (MgO) constitutes the active alkaline phase of Magnesium Phosphate Cement (MPC), as it reacts with soluble phosphate to form the cementitious products responsible for the hardening of the matrix [57]. It is performance relies on characteristics such as calcining,

fineness, specific surface area and purity, which control the solubility rate, reaction kinetics and initial strength (see Figure 7) [58, 59]. The incorporation of reactive MgO promotes the formation of struvite crystals ($MgKPO_4 \cdot 6H_2O$), thereby improving the internal cohesion of the cementitious matrix [24]. Here was selected based on its high reactivity (specifically with phosphate) and stable chemical anchoring contained in the treated organic matrix of the structure.

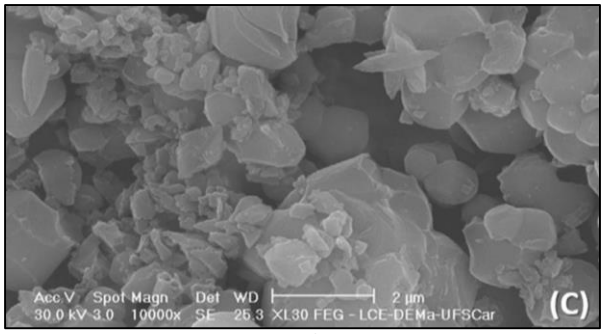

Fig. 7 Microscopic view of Magnesium Oxide [60]

3.4.2. Monopotassium Phosphate

Monopotassium Phosphate (KH_2PO_4) is an inorganic salt, which is soluble in water and acts as a center for providing a phosphate ion and potassium ions within the acid-base reaction of magnesium phosphate cement [61]. In reformulation, it is defined like a particle-agglomerate or as one of the develop and promotes potassium struvite ($MgKPO_4 \cdot 6H_2O$), which is understood to be the primary period responsible for MPC fast adjustment, cementation, and low porosity [62]. Figure 8 shows its crystalline morphology, which is represented by prismatic structures characteristic of high-purity materials. In this study, technical-grade KH_2PO_4 was used due to its reactivity within the cementitious system, supplemented with Arequipa volcanic ash to regulate setting and improve the thermal stability of the stabilised material [24].

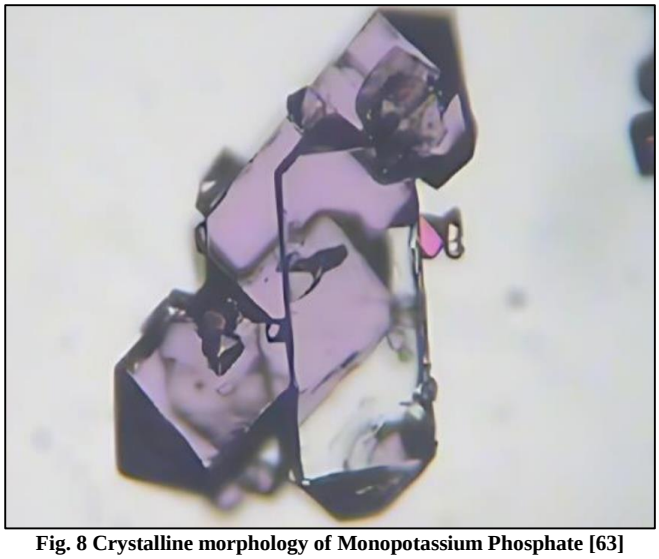

Fig. 8 Crystalline morphology of Monopotassium Phosphate [63]

3.4.3. Volcanic Ash

The incorporation of mineral and chemical additives into Magnesium Phosphate Cement (MPC) makes it possible to control its setting, workability and thermal performance [64]. In this study, ash from the Sabancaya volcano, Caylloma-Arequipa, was used as a natural mineral additive due to its high content of SiO_2, Al_2O_3 and iron oxides, compounds which confer pozzolanic potential [65, 66]. As shown in Figure 9, its microstructure consists of irregular, porous particles with a rough texture-characteristics typical of materials with an amorphous fraction and potential reactivity. Its incorporation reduced the rate of the acid-base reaction between MgO and KH_2PO_4, acting as a natural setting retarder and improving the workability of the mixture. Furthermore, the fine particles promoted pore filling, densifying the microstructure and improving the system's thermal stability and resistance to chemical attack [67]. Recent studies have indicated that a partial substitution of up to 5% does not significantly compromise mechanical strength and, on the contrary, helps to reduce shrinkage and hydration heat, thereby enhancing the durability of the cementitious material [68, 69].

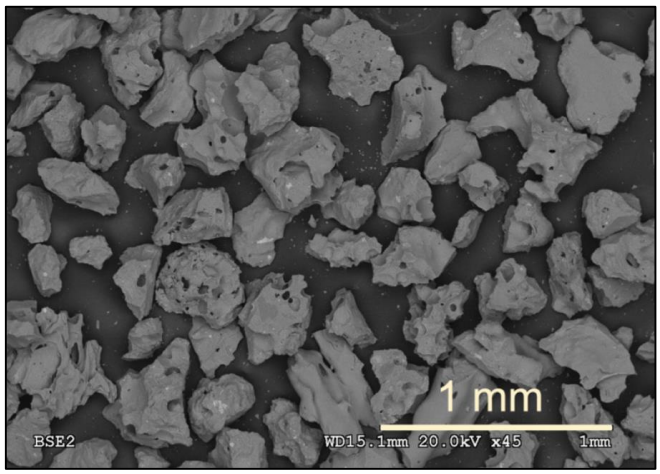

Fig. 9 SEM micrograph of volcanic ash [69]

3.4.4. Preparation of MPC Cement

Magnesium Phosphate Cement (MPC) was developed with the aim of producing a fast-setting binder with high structural stability, suitable for the stabilisation of organic soils. Its formulation was based on the controlled acid-base reaction between Magnesium Oxide (MgO) and Monopotassium Phosphate (KH_2PO_4), developed in previous research that optimised the molar ratio and curing conditions [70]. In addition, 5% volcanic ash was incorporated as a mineral additive to partially replace the MgO, whilst maintaining a constant water-to-binder ratio and curing parameters that ensured the homogeneity, reproducibility and performance of the material.

To prepare the cementitious binder, 950 g of high-purity Magnesium Oxide (MgO), previously calcined at 1600 °C, and 50 g of finely sieved volcanic ash, equivalent to a 5%

replacement by mass of the MgO, were weighed out. Both components were dry-mixed for 1 minute in a clean metal container until a homogeneous mixture was obtained. Subsequently, 1000 g of Monopotassium Phosphate (KH_2PO_4) were added, resulting in a molar Mg/P ratio of approximately 3.21:1, calculated from the quantities of MgO and KH_2PO_4 used in the formulation. As a result, a dry mixture of MPC modified with volcanic ash was obtained, which was stored in airtight bags to prevent the absorption of moisture from the ambient air. The final result of this procedure is shown in Figure 10.

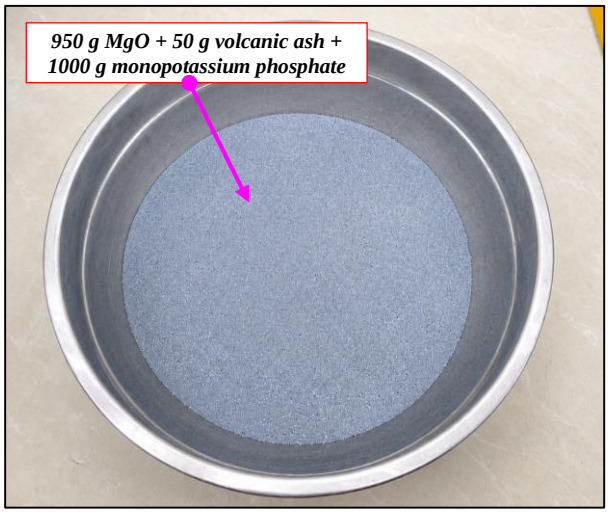

Fig. 10 Magnesium Phosphate Cement (MPC)

3.5. Soil Characterisation

3.5.1. Particle Size Distribution and Moisture Content

Particle size distribution involves the study and classification of soil particles according to their size and relative proportion, which is essential for understanding soil behaviour under loading, infiltration and consolidation [71]. In organic soils, this test is carried out using wet sieving because of the high natural moisture content and the presence of plant fibres, which make dry sieving difficult [72]. Consequently, in this study, the wet sieving method was employed, supplemented by the determination of Fibre Content (FC) in accordance with ASTM D1997-13; for this purpose, roots and coarse plant debris were manually removed during sample preparation. As shown in Figure 11, four material preparation conditions were evaluated: Material Pr, corresponding to manually disaggregated peat; Material Ps, representing the fraction passing through a 1.18 mm sieve; Comminuted using liquidiser, referring to material subjected to mechanical disintegration using a liquidiser; and Material Pb-s, corresponding to mechanically disintegrated material subsequently sieved through a 0.425 mm aperture.

The curves revealed differences in particle size distribution depending on the preparation procedure, with Material Pr exhibiting a greater proportion of coarse particles and Material Pb-s showing a predominantly finer distribution. Furthermore, particles larger than 2 mm were mainly observed in Material Pr, whereas the other preparation conditions exhibited a reduced proportion of this size fraction.

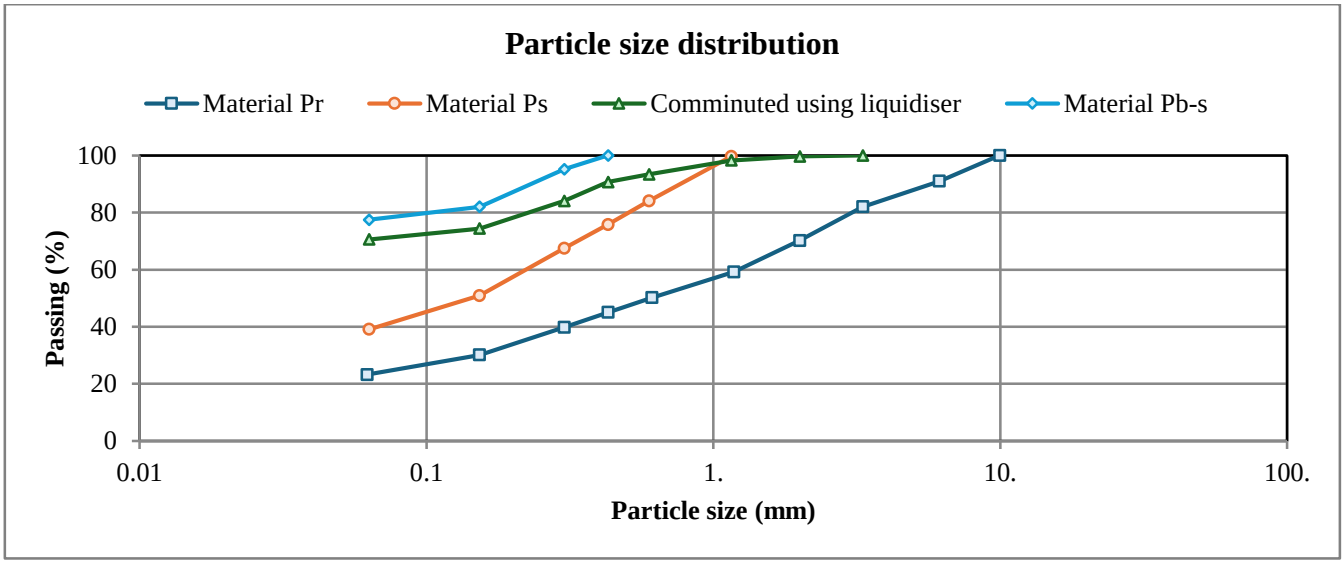

Fig. 11 Particle size distribution curve of peat soil

The moisture content test enabled the water-retention capacity of the peat-type organic soil to be quantified; this is a key parameter due to its direct influence on the material's compressibility, strength and chemical response [73, 74]. To determine this, the gravimetric oven-drying method was applied in accordance with ASTM D2974 [75].

The procedure involved weighing the empty container, recording the mass of the wet sample, drying it at 60 °C until a constant mass was reached, cooling it in a desiccator and determining its dry mass to calculate the moisture content. The value obtained was 590 per cent, a result characteristic of highly organic peats due to their high porosity and high water-

retention capacity. Taken together, this value, along with the presence of 70% plant fibres and low mineral content, confirmed that the material corresponded to a PT-type soil according to the SUCS system, with a dominant fibrous structure, high compressibility and low density [76]. The procedure developed is shown in Figure 12.



Fig. 12 Moisture content test of peat soil

3.5.2. Atterberg Limits

The Atterberg limits are of limited applicability to Peat Type soils (PT), as their organic, fibrous and highly porous structure prevents the precise definition of the consistency transitions characteristic of fine-grained mineral soils. O'Kelly [72], noted that the liquid and plastic limit values in peat are merely indicative and lack physical significance, as they depend more on the degree of fibre fragmentation than on an actual change of state.

Similarly, Khanday et al. [77] and Ahmad et al. [78] indicated that the high deformability, sponginess and heterogeneity of peat make it difficult to obtain representative and reproducible results. This limitation has also led to a focus on more appropriate parameters, such as natural moisture content, loss on ignition, degree of humification, pH, mineralogy and unconfined strength, which better describe the actual behaviour of these materials [79].

Consistent with this, during the plastic limit test, the strands formed fractured irregularly before reaching a diameter of 3 mm, without showing a defined plastic transition. This behaviour confirmed the sample's lack of cohesion and conventional plasticity, attributed to its fibrous structure and high porosity, as shown in Figure 13.



Fig. 13 Failed plastic limit test [72]

3.6. Thermogravimetric Analysis (TG-DTG)

Thermogravimetric analysis (TG-DTG) is a technique that enables the assessment of changes in a material's mass as a function of temperature under controlled heating conditions [80]. The information obtained allows the identification of dehydration, decomposition and thermal transformation processes, providing indicators of the thermal stability and composition of organic and cementitious materials [81, 82].

In this study, the analysis was conducted by the C3 Laboratory using a Shimadzu DTG-60 simultaneous thermal analyser, in accordance with ASTM E1131-20; representative 1 g samples of natural and stabilised peat were used, and the TG–DTG profiles were presented over a temperature range extending to 800 °C to compare their thermal responses and mass-loss behaviour; the procedure involved the analysis of thermal events under controlled atmospheric conditions, considering nitrogen (N_2) as an inert atmosphere and air as an oxidising atmosphere, according to the conditions applied during testing; the TG curves were expressed in terms of remaining mass (%), whilst the DTG curves were expressed as the rate of mass change (%/°C), allowing the principal mass-loss regions to be distinguished and the thermal behaviour of the eleven formulations (M0-M10) to be compared.

3.7. Direct Shear Test (τ vs σ)

Shear strength is one of the most important geotechnical properties for assessing the stability and bearing capacity of soils, as it represents the maximum shear stress that the material can withstand before failing under a given normal stress condition [83]. Direct shear test allows determination of parameters such as cohesion (c) and angle of internal friction (φ), which are commonly used in the analysis and design of foundations, slopes and retaining structures [84].

In organic soils such as peat, this test is particularly important due to their high compressibility, fibrous structure and low initial strength-characteristics that significantly influence their mechanical response to external loads [85]. In order to evaluate the effect of oxidation and cementation treatments on the soil's strength behaviour, the experimental mixtures shown in Table 1 were prepared, using 1 kg of dry peat sample as the basis for each treatment.

Table 1. Mix proportions for the direct shear test

Description	Weight (g)
Dry soil weight (g)	1000
Sodium percarbonate (1%)	10
Sodium percarbonate (2%)	20
Sodium percarbonate (3%)	30
Sodium percarbonate (4%)	40
Sodium percarbonate (5%)	50
Sodium persulfate (1%)	10
Sodium persulfate (2%)	20
Sodium persulfate (3%)	30
Sodium persulfate (4%)	40
Sodium persulfate (5%)	50
Magnesium phosphate cement (15%)	150

3.7.1. Direct Shear Test Procedure

Figure 14 illustrates the procedure followed for the direct shear test in accordance with ASTM D3080 [86]. During material preparation, the natural peat was air-dried for 72 h at approximately 25 °C until an average moisture content of 80% was reached. This moisture content was adopted as a controlled laboratory condition to facilitate homogeneous mixing and reproducible specimen preparation, rather than to reproduce the fully saturated in-situ state. It is acknowledged that drying may modify the pore structure and fibrous fabric of peat [87, 88]. The material was then crumbled by hand and sieved through a No. 4 mesh to remove coarse fibres and plant debris, resulting in a fine, homogeneous texture. In step b, the mixtures were weighed out using metal laboratory trays with a capacity of 1 kg of dry soil, using the proportions shown in Table 1. The dry mixture was homogenised for five minutes with a metal spatula until the components were evenly distributed, after which, in step c, distilled water equivalent to 25% of the total dry weight was added. The resulting wet mixture was placed into 10 × 10 cm cutting rings in three layers of equal thickness, with light static pressure applied using a flat metal piston for 30 seconds per layer to eliminate large voids and ensure uniform compaction. In step d, the moulded specimens were levelled on the surface and covered with plastic film to prevent moisture loss. Finally, in step e, the samples were tested on the direct shear machine under normal loads of 0.56, 1.11 and 1.67 kg/cm², allowing for 10 minutes of pre-consolidation until settlement stabilised, and subsequently applying horizontal displacement at a constant rate of 0.5 mm/min until failure, whilst continuously recording the shear force and displacement to determine the cohesion (c) and angle of internal friction (φ) parameters for each treatment.

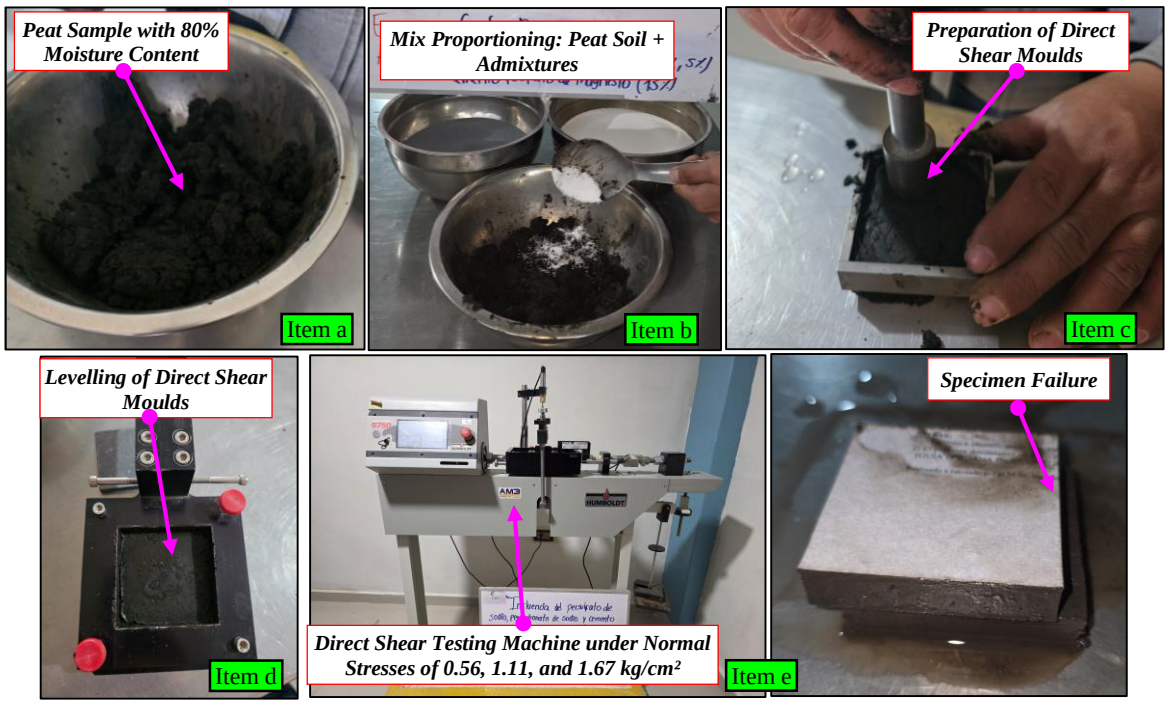

Fig. 14 Direct shear test

Following the experimental procedure illustrated in Figure 14, the cohesion (c) and internal friction angle (φ) obtained from the direct shear tests were used as the shear strength parameters for assessing the bearing capacity of the stabilised peat soil. Accordingly, the ultimate bearing capacity for a strip footing can be expressed using Terzaghi's bearing capacity equation, as follows:

$$q_{ult} = cN_c + \gamma D_f N_q + \frac{1}{2}\gamma B N_\gamma$$

Where qult represents the ultimate bearing capacity, c is the cohesion, γ is the soil unit weight, Df is the foundation embedment depth, B is the footing width, and Nc, Nq and Nγ are the bearing capacity factors determined from the internal friction angle (φ). Subsequently, the allowable bearing capacity is expressed as:

$$q_{adm} = \frac{q_{ult}}{FS}$$

Where qadm is the allowable bearing capacity, and FS is the adopted factor of safety. The calculation takes into account the foundation geometry, soil strength parameters and groundwater conditions. The detailed bearing-capacity calculations and supporting laboratory documentation are provided in Appendix 1.

3.8. Unconfined Compressive Strength (UCS)

Unconfined Compressive Strength (UCS) is defined as the maximum axial stress that a cohesive soil can withstand under compressive loading without lateral confinement, up to the point of failure [89]. This parameter is one of the most widely used properties in geotechnical engineering for assessing the consistency and bearing capacity of fine-grained soils, particularly in stability and ground improvement studies [90].

Table 2 shows the proportions used to prepare the mixtures for each treatment, determined on the basis of the dry weight of the Peat Type soil (PT) contained in each test specimen. The total weight of dry soil was determined from the volume of the test specimen (10 cm in diameter and 20 cm in height) and the dry density obtained (0.20 g/cm³), such that each sample represented a total mass of 314.149 g of dry soil.

Table 2. Mix proportions used for the UCS test

Description	Weight (g)
Dry soil weight of each specimen	314.1593
Sodium percarbonate (1%)	3.142
Sodium percarbonate (2%)	6.283
Sodium percarbonate (3%)	9.425
Sodium percarbonate (4%)	12.566
Sodium percarbonate (5%)	15.708
Sodium persulfate (1%)	3.142
Sodium persulfate (2%)	6.283
Sodium persulfate (3%)	9.425
Sodium persulfate (4%)	12.566
Sodium persulfate (5%)	15.708
Magnesium phosphate cement (15%)	47.124

3.8.1. Test Procedure (UCS)

Figure 15 shows the procedure followed for the preparation, curing and testing of the simple compression test specimens, in accordance with ASTM D2166. Step a: natural Peat Type (PT) was previously dried at 25 °C for 72 h to reach an average moisture content of around 80%, using air drying procedure, to stabilise its organic structure and facilitate handling. Then, the addition of dry components in the proportions reported in Table 2 was performed and a five-minute dry mixing until achieving a homogeneous distribution.

Distilled water equivalent to 95 per cent of the total dry weight was then added. The resulting mixture was placed into cylindrical moulds in three successive layers, which were compacted using light static pressure to reduce voids and ensure the uniformity of the material.

In item (b), measurement and curing, three opposite generatrices of diameter and height raw each specimen were recorded together with the initial weight for all specimens, which were then placed in airtight plastic bags filled with moist gauze and stored in a controlled chamber at 20 °C relative humidity during periods of 7, 14 and 28 days. Once the corresponding curing time had elapsed, the specimens were removed and allowed to stabilise for two hours at room temperature (20 °C), with a thin layer of Vaseline applied to both sides to reduce friction with the equipment's test plates.

Finally, with regards to the conduct of the test (section c), each specimen was placed centered on a spherical seat located in the lower fixed plate, and its verticality checked before loading started. Axial load was continuously applied at a constant strain rate of 2 mm/min, recording the load, axial strain and time every 10 seconds until the peak load was reached, while monitoring the failure mode and occurrence of characteristic cracks in each specimen.



Fig. 15 Unconfined Compressive Strength (UCS) test of PT soil

3.9. Initial Soil Conditions

Table 3 summarizes the basic characteristics of Peat-Type soil (PT) utilized in this study; it was observed that the material had a very high moisture content (590%), consistent with its highly porous and saturated fibrous structure; the dry density was only 0.2 g/cm³, confirming its low degree of natural compaction and the high void spaces it has; in addition, the pH of 3.1 reflected the extreme acidity due-to organic matter decomposition and humic compounds; the total loss on drying was 51.088% which confirms the presence of the volatile compounds and organic matter prone to thermal degradation; for mechanical properties, the cohesion (c) of 12.45 kPa and angle of internal friction (φ) of 14.36×10 raise to -2 indicated an extremely low shear strength which is consistent with the soft status and considerable compressibility of this material; lastly, the bearing capacity equal to 20.10 kPa confirmed that this is a of poor soil for foundations in situ what justified the use of soil improvement techniques like those used in this study.

Table 3. Initial soil properties

Parameter	Value
Moisture content (%)	590
Dry density (γd) g/cm³	0.2
pH	3.1
Total, mass loss (%)	51.088
Cohesion (c) kPa	12.45
Internal friction angle (φ)	14.36
Allowable bearing capacity kPa	20.10
Unconfined compressive strength kPa	16.57

The peat was found to have adverse geotechnical properties during early tests, which gradually increased since its moisture content was a high percentage of organic matter and mechanical strength, the others are low.

On the basis of this baseline condition, the impact of oxidation and cementation treatments was evaluated via thermogravimetry and mechanical tests summarized in the sections below.

4. Results

4.1. Thermogravimetric Analysis (TG-DTG)

Figure 16 presents the Thermogravimetric (TG) and Derivative Thermogravimetric (DTG) curves of untreated peat and the formulations stabilised with sodium percarbonate or sodium persulphate, each combined separately with Magnesium Phosphate Cement (MPC).

Figure 16(a) shows formulations M0–M4, whilst Figure 16(b) presents M5–M10. The continuous lines represent the remaining mass (%) as a function of temperature, whereas the dashed lines indicate the rate of mass change (%/°C). Table 4 presents the mass-loss percentages corresponding to the different thermal intervals, allowing the behaviour of the eleven formulations to be compared.

The untreated peat (M0) exhibited a total mass loss of 51.088 per cent, corresponding to a residual mass of 48.912 per cent at 800 °C; the greatest mass loss occurred in the range from 260 to 450 °C, reaching 45.257 per cent, which was mainly associated with the thermal decomposition of the organic components; no mass loss was recorded in the AFt and C-S-H intervals, this behaviour is reflected in the dip in the TG curve and the corresponding response of the DTG within the main decomposition region.

The sodium percarbonate formulations (M1-M5) lost progressive amounts of their original mass. Specifically, the total mass lost by M1 was 48.442%, followed by 46.766% for M2 and then 44.730% for M3. Of all of the mixtures tested, M3 had the least amount of total mass lost (residual mass = 55.270%), with a composition of 3% sodium percarbonate and 15% MPC.

Similarly, the mass lost during the OM and C-A-H intervals decreased as well. For example, M1 lost 38.457%, whereas M3 lost 31.672%. Increasing the sodium percarbonate dosage to 4% and 5% resulted in greater total mass losses than those observed in M3 (45.839% and 47.115%, respectively), showing that they retained less mass than M3.

The amount of material lost from the sample during the OM and C-A-H interval for all sodium persulfate-based formulations (M6-M10) dropped from 33.917% in M6, with 15% MPC and 3% sodium persulfate to 27.463% in M8; however, the amount of material lost from the sample during the AFt and C-S-H intervals increased from 3.276% in M6 to 8.917% in M8, with 15% MPC and 3% sodium persulfate. In addition, M9 had 10.638% of material lost, and M10 had 12.487% of material lost; in terms of the total material lost, M7, with 15% MPC and 2% sodium persulfate, lost the least amount of material in this series of formulations (45.343%) and therefore had 54.657% of material remaining. On the other hand, M8 had 45.951% of material lost, and M9 and M10 had 48.347% and 50.713% of material lost, respectively.

Overall, the TG–DTG curves and the results presented in Table 4 reveal variations in thermal behaviour according to the type and concentration of the oxidising agent.

Formulation M3 exhibited the highest mass retention among all the mixtures evaluated, whilst M7 showed the most favourable behaviour within the sodium persulphate series. Furthermore, increasing the oxidant dosages beyond these values resulted in greater total mass losses.

Table 4. Results of the Thermogravimetric analysis

Description	H_2O (%)	AFt + C–S–H (%)	MO + C–A–H (%)	$Ca(OH)_2$ (%)	$CaCO_3$ (%)	Total loss of mass (%)	Residual mass (%)
M_0: Untreated soil	3,218	0,000	45,257	0,000	2,613	51,088	48,912
M_1: Soil + PC (1%) + MPC (15%)	3,218	1,972	38,457	0,612	4,183	48,442	51,558
M_2: Soil + PC (2%) + MPC (15%)	3,218	2,946	35,128	0,598	4,876	46,766	53,234
M_3: Soil + PC (3%) + MPC (15%)	3,218	3,814	31,672	0,587	5,439	44,730	55,270
M_4: Soil + PC (4%) + MPC (15%)	3,218	3,952	32,214	0,581	5,874	45,839	54,161
M_5: Soil + PC (5%) + MPC (15%)	3,218	3,617	33,608	0,569	6,103	47,115	52,885
M_6: Soil + PS (1%) + MPC (15%)	3,218	3,276	33,917	0,604	4,982	45,997	54,003
M_7: Soil + PS (2%) + MPC (15%)	3,218	5,936	30,284	0,589	5,316	45,343	54,657
M_8: Soil + PS (3%) + MPC (15%)	3,218	8,917	27,463	0,572	5,781	45,951	54,049
M_9: Soil + PS (4%) + MPC (15%)	3,218	10,638	27,982	0,566	5,943	48,347	51,653
M_{10}: Soil + PS (5%) + MPC (15%)	3,218	12,487	28,317	0,563	6,128	50,713	49,287

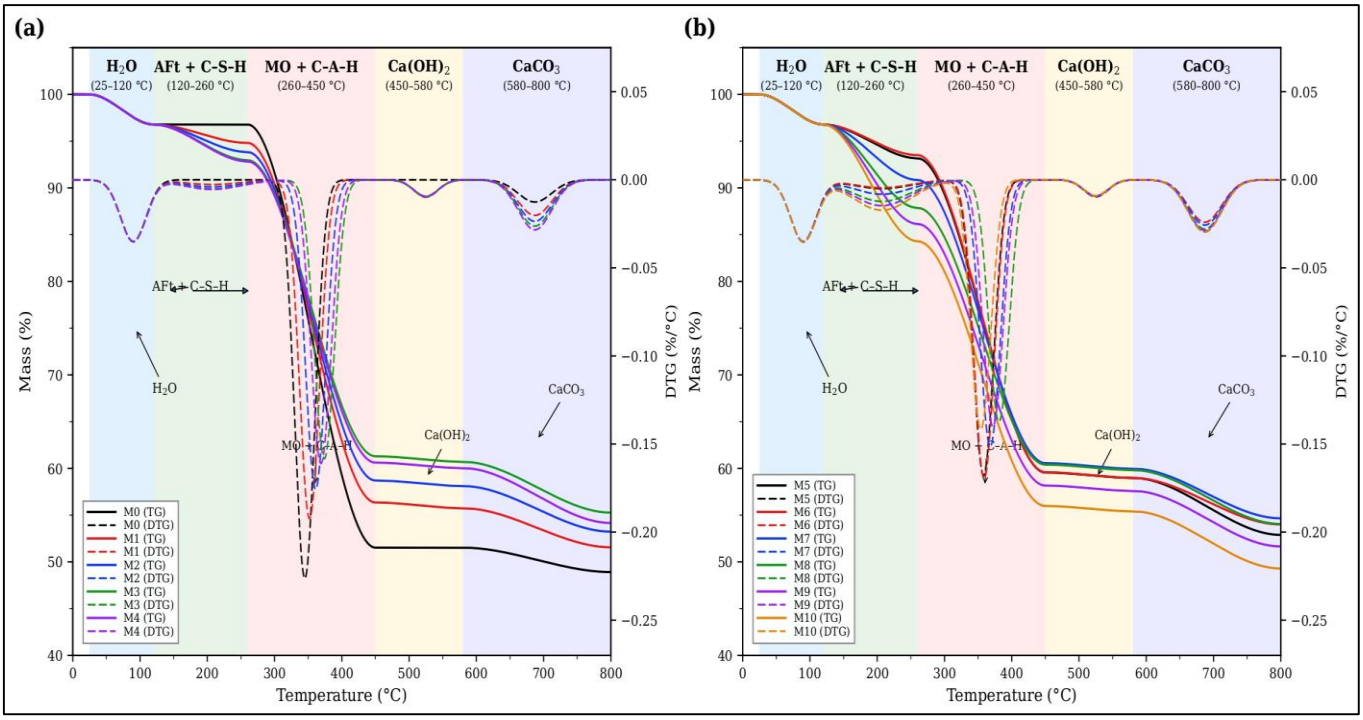

Fig. 16 Thermogravimetric (TG) and Derivative Thermogravimetric (DTG) curves of samples M0–M10 as a function of temperature

Figure 17 compares the total mass loss recorded for untreated peat and the mixtures treated with sodium percarbonate or sodium persulphate in combination with Magnesium Phosphate Cement (MPC). In comparison to the non-treated sample M0 (51.088%), all other treated samples had less overall weight loss. Within the sodium percarbonate group (M1-M5), overall weight loss was reduced with increasing amount of percarbonate, as seen by the decrease in overall weight loss from 48.442% for M1 to 44.730% for M3, which corresponds to 3% PC and 15% MPC. Overall, this reduction was approximately 12.45% less than the overall weight loss observed in M0. On the contrary, with larger amounts of percarbonate used (i.e., 4% and 5%), there was an increase in overall weight loss observed; M4 had an overall weight loss of 45.839%, while M5 had an overall weight loss of 47.115%. In the sodium persulphate series (M6-M10), total mass loss decreased from 45.997% in M6 to a minimum of 45.343% in M7, corresponding to 2% PS and 15% MPC, before increasing to 45.951% in M8, 48.347% in M9 and 50.713% in M10. These results revealed distinct variations in the thermal behaviour of the treated mixtures according to the type and concentration of the oxidising agent, with M3 exhibiting the lowest total mass loss among all treated formulations and M7 recording the lowest value within the sodium persulphate series.

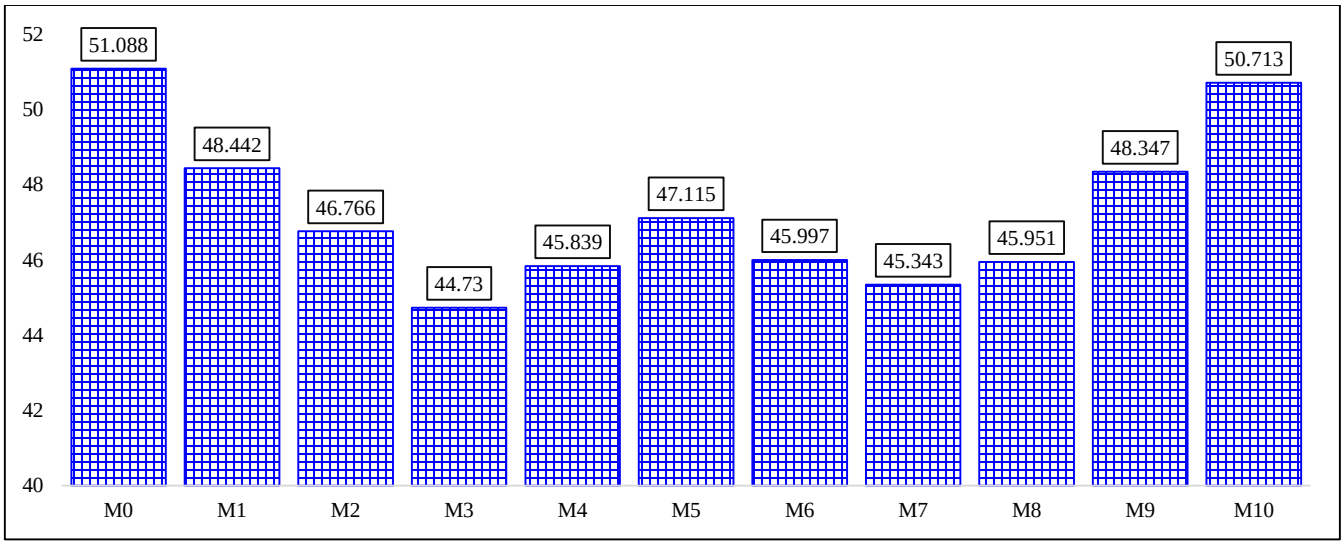

Fig. 17 Total mass loss results from the Thermogravimetric analysis (TG–DTG)

4.2. Direct Shear Test

In addition, the use of solid oxidants and magnesium phosphate cement enhanced the shear strength properties of the peat; i.e., effective cohesion, internal friction angle and allowable bearing capacity were increased. All data collected per treatment is listed in Table 5. As an illustration, the untreated control (M0) had an internal friction angle of 14.36 degrees, effective cohesion of 12.45 kPa and allowable bearing capacity of 20.10 kPa. The results show that the peat had poor shear strength because of its fibrous nature and high compressibility.

The progress in shear strength properties was evident from M_1, M_2 and M_3, as a direct result of increased percarbonate dosages, with maximums achieved at percarbonate levels of 3% in M_3; those maximums were effective cohesion (c') equal to 37.85 kPa, internal friction angle (Φ') equal to 24.71° and allowable bearing capacity (q_all) equal to 72.76 kPa. Conversely, the results for mixtures M_4 and M_5 were less than those of M_1, M_2 and M_3, as demonstrated by the fact that the effective cohesion values of M_4 and M_5 were 35.40 and 28.83 kPa, respectively; the internal friction angle values of M_4 and M_5 were 23.95° and 21.37°, respectively; and the allowable bearing capacity values of M_4 and M_5 were 69.04 and 52.07 kPa, respectively. These trends demonstrated that adding additional percarbonate beyond 3% to the investigated series did not improve shear strength properties.

In contrast to the sodium persulfate treatment, the mixtures (M_6, M_7 and M_8) demonstrated a progressive increase in shear strength parameters, as evidenced by an effective cohesion value of 44.91 kPa, an internal friction angle of 27.16° and an allowable bearing capacity of 86.89 kPa in mixture M_8. On the other hand, mixtures M_9 and M_{10} had effective cohesion values of 40.40 kPa and 32.07 kPa; internal friction angles of 25.81° and 22.94°; and allowable bearing capacities of 78.25 kPa and 60.02 kPa, respectively. There was a progressive decrease in shear strength after adding sodium persulfate to the mixtures at concentrations greater than 3%.

However, the shear strength values obtained from the laboratory tests were significantly larger than those of the untreated soil.

Table 5. Direct shear test results

Description	Friction Angle (°)	Effective Cohesion (KPa)	Allowable Bearing Capacity (kPa)
M_0: Untreated soil	14.36	12.45	20.10
M_1: Soil + PC (1%) + MPC (15%)	17.82	18.04	30.60
M_2: Soil + PC (2%) + MPC (15%)	20.46	25.79	44.91
M_3: Soil + PC (3%) + MPC (15%)	24.71	37.85	72.76
M_4: Soil + PC (4%) + MPC (15%)	23.95	35.40	69.04
M_5: Soil + PC (5%) + MPC (15%)	21.37	28.83	52.07
M_6: Soil + PS (1%) + MPC (15%)	19.64	22.46	39.03
M_7: Soil + PS (2%) + MPC (15%)	23.28	33.54	63.64
M_8: Soil + PS (3%) + MPC (15%)	27.16	44.91	86.89
M_9: Soil + PS (4%) + MPC (15%)	25.81	40.40	78.25
M_{10}: Soil + PS (5%) + MPC (15%)	22.94	32.07	60.02

Figure 18 shows the increases in shear strength parameters compared with the untreated specimen M_0. Within the percarbonate series, mixtures M_1 and M_2 showed increases in effective cohesion of 44.9 per cent and 107.1 per cent, respectively, whilst mixture M_3 achieved an increase of 204.0 per cent, accompanied by improvements of 72.1 per cent in the angle of internal friction and 262.0 per cent in the allowable bearing capacity. Mixtures M_4 and M_5 showed increases in cohesion of 184.3 per cent and 131.6 per cent, respectively, reflecting a reduction in the mechanical benefit when percarbonate dosages exceed 3 per cent.

Within the persulphate series, mixtures M_6 and M_7 increased effective cohesion by 80.4% and 169.4%, respectively. Mixture M_8 achieved the greatest improvements among all treatments, with increases of 260.7% in effective cohesion, 89.1% in internal friction angle, and 332.3% in allowable bearing capacity. At the same time, M_9 and M_{10} had cohesiveness increases of 224.5 percent and 157.6 percent. Overall, M_3 and M_8 showed the best results in terms of both of their treatment groups. M_8 also had the greatest shear strength values out of every single formulation that was tested.

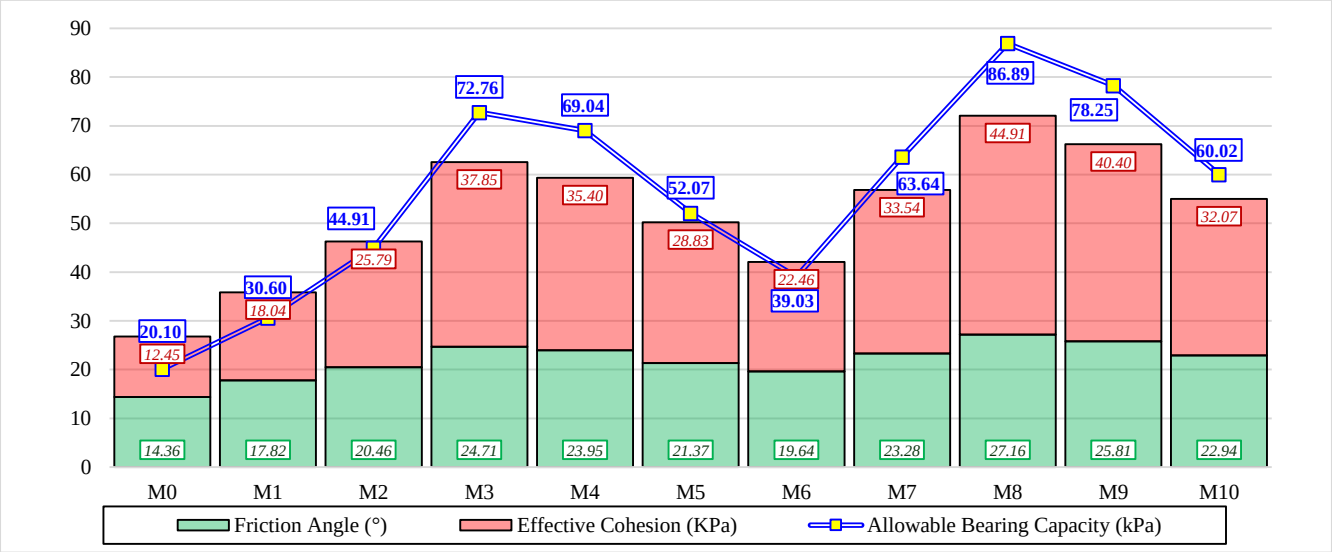

Fig. 18 Results of the direct shear test

4.3. Unconfined Compressive Strength (UCS)

The results of the unconfined compressive strength testing demonstrated that the mechanical properties of the treated peat were improved as a function of the dosage of oxidants used and the duration of curing. Table 6 provides the results of the different formulations at each of the evaluated curing times. The untreated control sample M_0 displayed very little compressive strength; the values were 15.79 kPa, 16.08 kPa, and 16.57 kPa after 7, 14, and 28 days of curing. The lack of compressive strength development displayed by the untreated peat is consistent with its fibrous nature, high water content, and compressibility.

Mixtures M_1 and M_2 showed increasing levels of compressive strength as time went on, and reached 25.79 and 41.58 kPa after 7 days, 29.32 and 47.17 kPa after 14 days, and 31.48 and 50.70 kPa after 28 days. Mixture M_3 had the highest strength of all the mixtures in the sodium percarbonate series and produced 61.00, 69.23, and 74.43 kPa at each of those curing times. This type of reaction demonstrated a positive response to increasing percarbonate dosage up to 3%, and continued to develop strength during the curing process. On the other hand, mixtures M_4 and M_5 produced lower 28-day strengths than M_3 (72.18 and 57.76 kPa). The decrease in strength at higher dosages illustrated that adding more percarbonate beyond 3% did not result in further mechanical improvements for the mixture when tested under the experimental conditions. The two persulphate-sodium mixtures, M_6 and M_7, had compressive strengths of 34.81 kPa and 56.29 kPa at seven days, which increased to 39.52 kPa and 63.94 kPa at twenty-eight days. The highest compressive strength of the various treatment options was recorded for mixture M_8, with compressive strengths of 76.59 kPa, 83.55 kPa and 86.98 kPa recorded for each of the testing periods; i.e., at seven days, fourteen days and twenty-eight days.

These results clearly demonstrated that the addition of 3% sodium persulphate to 15% MPC yielded the best compressive strength response among all of the formulation options studied. Mixtures M_9 and M_{10} had significantly lower compressive strengths at twenty-eight days (76.59 kPa and 61.49 kPa) than those recorded for mixture M_8. This finding indicates that increasing the dosage level of sodium persulphate above 3% resulted in decreased compressive strength, although the treated specimens exhibited higher compressive strengths than did the non-treated control samples.

Table 6. Unconfined Compressive Strength (UCS) test results

Description	UCS 7 days (kPa)	UCS 14 days (kPa)	UCS 28 days (kPa)
M_0: Untreated soil	15.79	16.08	16.57
M_1: Soil + PC (1%) + MPC (15%)	25.79	29.32	31.48
M_2: Soil + PC (2%) + MPC (15%)	41.58	47.17	50.70
M_3: Soil + PC (3%) + MPC (15%)	61.00	69.23	74.43
M_4: Soil + PC (4%) + MPC (15%)	59.23	67.08	72.18
M_5: Soil + PC (5%) + MPC (15%)	47.37	53.74	57.76
M_6: Soil + PS (1%) + MPC (15%)	34.81	37.95	39.52
M_7: Soil + PS (2%) + MPC (15%)	56.29	61.39	63.94
M_8: Soil + PS (3%) + MPC (15%)	76.59	83.55	86.98
M_9: Soil + PS (4%) + MPC (15%)	67.37	73.55	76.59
M_{10}: Soil + PS (5%) + MPC (15%)	53.84	58.94	61.49

Figure 19 illustrates how each of the mixtures developed unconfined compressive strength over time (after 7, 14, and 28 days of curing). Each of the treated samples showed increased strength over time; however, there were differences in the amount of strength developed depending on the type and concentration of oxidants used. After 28 days of curing, mixtures M1 and M2 demonstrated improvements in strength of 90.0% and 206.0%, respectively, above the untreated soil. Of the percarbonate mixtures, mixture M3 demonstrated the greatest improvement in strength, exhibiting a value of 74.43 kPa, which was equivalent to a 349.2% increase compared to mixture M0. Mixtures M4 and M5 demonstrated improvements in strength of 335.6% and 248.6%, respectively. The differences in strength demonstrated that the 3% percarbonate dosage had a much larger impact on improving the mechanical properties of the soils tested than did the other dosages evaluated.

The sodium persulphate series (M6 & M7) produced 28-day strength improvements of 138.5% & 285.9% over the untreated sample. The most significant improvement in strength was obtained by M8, which had a compressive strength of 86.98 kPa. This was an increase of 424.9% when compared to M0. In addition, M9 & M10 also increased by 362.2% & 271.1%, respectively. Overall, the persulphate-based treatments had higher increases in compressive strength than the similar percarbonate formulations at each level of oxidant dosage. After 28 days of curing, M8 was the top-performing treatment mechanically.

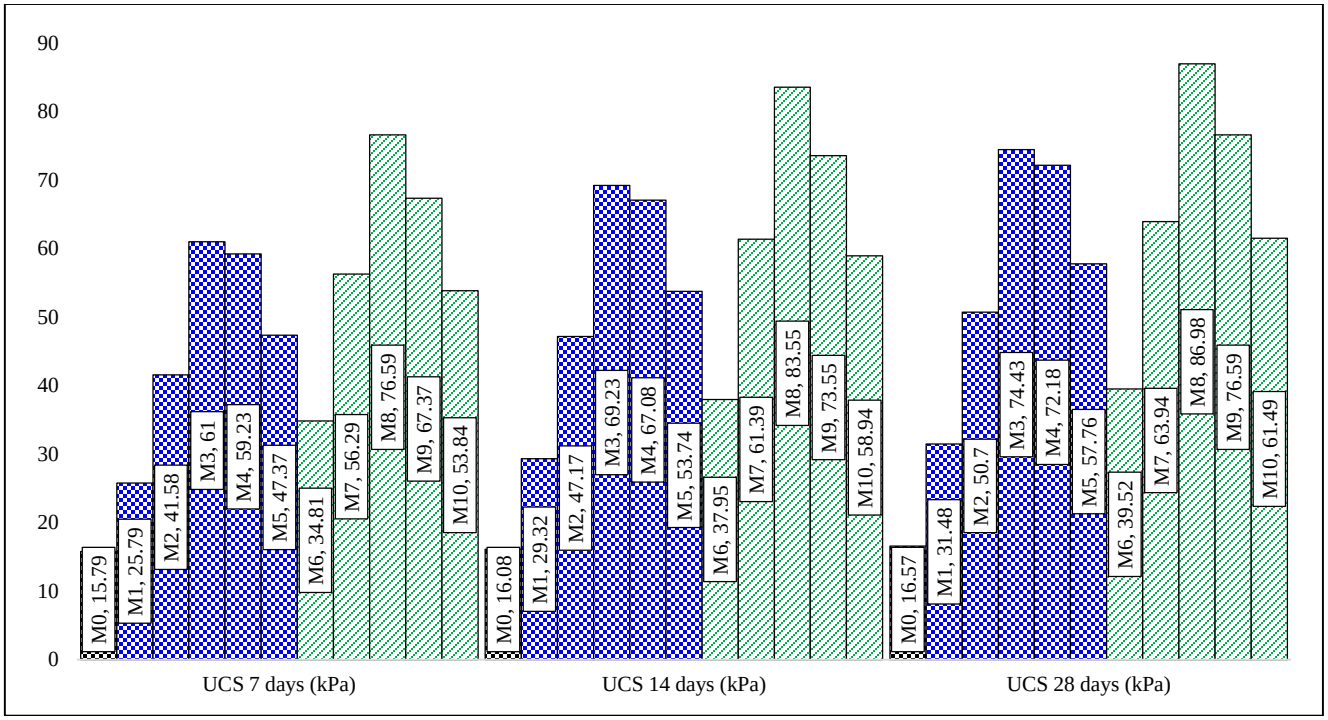

Fig. 19 Results of the Unconfined Compressive Strength (UCS) test

4.4. Optimum Oxidant Dosages with MPC

This section determines the most appropriate dose of oxidising agents for stabilising peat soils by evaluating the results of TG-DTG, UCS and direct shear tests.

The results obtained from this study show that the 3% Sodium Percarbonate (PC) in combination with the 15% Magnesium Phosphate Cement (MPC) had the best overall performance among all formulations tested as part of the percarbonate group. This formulation resulted in the lowest total mass loss (44.730%) and the greatest 28-day compressive strength (74.43 kPa).

Increasing the dosage of sodium percarbonate above 3% caused the total mass loss to increase to 45.839% at 4% and 47.115% at 5%, but also decreased the compressive strength to 72.18 kPa and 57.76 kPa. Therefore, it was found that the use of a sodium percarbonate content higher than 3% would not yield any further benefit to both thermal and mechanical response evaluations.

For the Sodium Persulphate (PS) tests, the most effective dosage in terms of compressive strength (86.98 kPa) at 28 days was achieved using 3% PS and 15% MPC. This combination had a total mass loss of 45.951%. Although the 2% PS test had the least amount of total mass loss (45.343%), the 3% PS dosage showed the best overall performance in terms of mechanical properties; i.e., it had the highest effective cohesion (44.91 kPa), internal friction angle (27.16°), and allowable bearing capacity (86.89 kPa). When higher persulphate dosages of 4% and 5% were used, there was a decrease in the compressive strength of the specimens to 76.59 and 61.49 kPa, respectively.

Therefore, the combinations of 3% PC + 15% MPC and 3% PS + 15% MPC were identified as the most favourable formulations within their respective experimental series, with the persulphate-based treatment exhibiting superior overall mechanical performance.

Based on these proportions, 1 m³ of peat soil with a dry density of 0.20 g/cm³ corresponds to a dry soil mass of 200.00 kg. Accordingly, a dosage of 3% oxidant requires 6.00 kg of either PC or PS, while a dosage of 15% MPC requires 30.00 kg, as presented in Table 7. The oxidants are considered separately for their respective treatment formulations.

Table 7. Optimum dosages for 1 m³

Description	Value
Sample volume (m³)	1.00
Dry density (g/cm³)	0.20
Weight (kg)	200.00
PC (3%) (kg)	6.00
PS (3%) (kg)	6.00
MPC (15%) (kg)	30.00

5. Recommendations

5.1. Full-Scale Application Procedure

A summary of proposed activities, equipment and control measures for full-scale peat soil stabilisation is given in Figure 20. Aspects of Design/Construction Outline: (a) Geotechnical characterisation and Site Preparation; depth, moisture content, groundwater level, degree of decomposition; bearing capacity and trafficability are determined, followed by site demarcation surface clearing without disturbing the natural structure of organic deposit.

Item b illustrates the uniform distribution of the stabilising agents, according to the optimum dosages determined experimentally, using low-pressure equipment. For treatment thicknesses exceeding 20 cm, the stabilisation shall be carried out in successive 10 cm layers [91], completing the mixing and shaping of each layer before proceeding to the next.

Item c corresponds to the in situ mixing process using lightweight equipment suitable for soft soils. As an initial condition, two overlapping passes are recommended to achieve an effective mixing depth of 15 cm, while verifying mixture homogeneity. Water shall only be added when the natural moisture content is insufficient to ensure workability and promote the MPC reaction, avoiding oversaturation. Item d presents the profiling, shaping, and light compaction of the treated surface. Four passes using low-pressure equipment are recommended to avoid pumping, exudation, lateral displacement, or excessive deformation. Finally, item e illustrates the protection of the stabilised layer for 24 h by restricting traffic and controlling moisture loss and exposure to rainfall. Before the treated area is put into service, unconfined compressive strength, bearing capacity, moisture content, density, mixing depth, treated thickness, and material homogeneity shall be verified.





Fig. 20 Construction procedure for peat soil stabilisation

6. Discussions

6.1. Thermal Behaviour and Organic Matter Reduction

According to Ahmad et al. [92], the stabilisation of fibrous peat using Ordinary Portland Cement (OPC) and Silica Fume (SF) reduced mass loss during heating and improved the thermal stability of the material. The authors associated this behaviour with the formation of hydration products, mainly C-S-H, C-A-H and ettringite, which contributed to changes in the thermal response of the organic matrix.

Similarly, in the present study, the individual incorporation of sodium percarbonate or sodium persulphate in combination with Magnesium Phosphate Cement (MPC) modified with volcanic ash resulted in lower total mass losses than those recorded for untreated peat. Total mass loss decreased from 51.09% in the control specimen to 44.73% in M3, containing 3% sodium percarbonate and 15% MPC, and to 45.95% in M8, containing 3% sodium persulphate and 15% MPC. However, within the sodium persulphate series, M7, corresponding to a 2% oxidant dosage, recorded a slightly lower total mass loss of 45.34%. This difference indicates that the formulation exhibiting the lowest total mass loss did not necessarily correspond to that with the best mechanical performance.

The findings are consistent with those of Ahmad et al. [92] in terms of reduced mass loss following treatments incorporating cementitious materials, whereas the main difference lies in the composition of the stabilisation systems. Ahmad et al. employed OPC and silica fume, while the present study evaluated formulations containing MPC modified with volcanic ash and two solid oxidants incorporated separately into different mixtures.

This difference could influence the interactions between organic compounds and cementitious constituents, as well as the distribution of mass losses during heating. In particular, the results showed that increasing the oxidant concentration did not produce a continuous reduction in total mass loss, indicating a dosage-dependent response. Therefore, the contribution of this study lies in the comparative characterisation of the thermal behaviour of natural high-altitude Andean peat treated with two distinct oxidant–MPC systems, extending the investigation of peat stabilisation beyond conventional OPC-based systems.

6.2. Unconfined Compressive Strength of Stabilised Peat

He et al. [24], investigated the incorporation of solid oxidants together with Portland cement into dredged soil containing 11.13% organic matter. With dosages of 3% sodium persulphate and 3% sodium percarbonate, they reported reductions in total mass loss from 33.20% to 19.46% and 20.34%, respectively, while unconfined compressive strength increased from 350 kPa to 1400 kPa and 1300 kPa. The researchers associated this behaviour with the oxidative action on certain organic compounds and its influence on the development of cementitious reactions within the OPC-based system.

In this study, there was an increase in the trend of strength, but under different experimental conditions and with different types of soils. The unconfined compressive strength of the peat increased from 16.57 kPa in the control specimen to 74.43 kPa in M3 and 86.98 kPa in M8 after 28 days of curing, representing increases of 349.2% and 424.9%, respectively. Although He et al. [24] achieved higher absolute strengths, the present study recorded a greater relative improvement compared with the initial condition, particularly for formulation M8. This difference should be interpreted in light of the fact that the dredged soil investigated by He et al. [24] had a considerably lower organic matter content and higher initial strength, whereas the high-altitude Andean peat evaluated in the present study was characterised by high natural moisture content, a fibrous structure and low initial strength.

The type of binder used for each study was a major difference. He et al. [24] used Portland cement as their binder; however, the current study utilized MPC modified with volcanic ash, which hardens via acid-base reactions. When binders such as these are combined with either sodium persulphate or sodium percarbonate, they may react differently with organic compounds contained within the soil. These differences in reactions will affect how quickly and well the mixtures develop strength. This is consistent with what was seen in the data collected for this research. For example, M8 developed the most strength out of all formulation options, and as the percentage of oxidant added to each mixture increased from 3%, the development of strength began to decrease. Therefore, based upon the results obtained from this research, mechanical performance cannot be solely attributed

to adding additional amounts of oxidant, but also to how much oxidant is added and the overall properties of the stabilization system.

Furthermore, Forsman et al. [93] indicated that mass stabilisation of peat is a ground improvement technique used beneath roads, urban streets, railways and embankments because of its potential to increase bearing capacity and reduce settlement. Similarly, Pallav et al. [94] reported strengths ranging from 25 to 100 kPa in stabilised peat materials and suggested that values approaching 100 kPa may be favourable for certain road applications subjected to moderate loads. In relation to these findings, the strength of 86.98 kPa achieved by M8 falls within the range reported by Pallav et al., highlighting the mechanical potential of this formulation for ground improvement applications. Nevertheless, its performance in road infrastructure should be assessed in relation to loading conditions, permissible deformations and the behaviour of the natural peat deposit.

6.3. Shear Strength and Bearing Capacity

According to Khoerani et al. [95], the fibrous peat from Palangkaraya exhibited unfavourable geotechnical characteristics associated with an organic matter content of 96.75%, a dry density of 0.13 g/cm³ and acidic conditions. The researchers have noted that the cohesion was 13.53 kPa and that the angle of internal friction was 16.26°, which means that the material has some capacity to resist shear. Similarly, the natural peat evaluated in the present study exhibited a dry density of 0.20 g/cm³, a pH of 3.1, a cohesion value of 12.45 kPa and an internal friction angle of 14.36°. The similarity between the shear strength parameters reported in both investigations indicates that fibrous peats may exhibit low initial mechanical strength despite differences in their geographical origin and composition.

The main difference compared with Khoerani et al. [95] is that the present study evaluated the behaviour of peat following the incorporation of stabilising agents. In formulation M3, containing 3% sodium percarbonate and 15% MPC, cohesion increased from 12.45 to 37.85 kPa, while the internal friction angle reached 24.71°. Meanwhile, M8, containing 3% sodium persulphate and 15% MPC, exhibited a cohesion value of 44.91 kPa and an internal friction angle of 27.16°. Similarly, the reported allowable bearing capacity increased from 20.10 kPa in the control specimen to 72.76 kPa in M3 and 86.89 kPa in M8. The results show that the treated mixes have a better shear response than the untreated mixes, and that M8 had the best shear strength parameters of all of the formulations tested.

The difference in observations can be attributed to alterations in the way that the organic components of peat interact with the cement-based binding agent. In particular, the combined incorporation of solid oxidants and MPC could promote greater resistance between the constituents of the mixture, consistent with the stabilisation mechanisms described in previous studies. Nevertheless, the response depended on dosage, as increasing the oxidant concentration beyond 3% resulted in lower cohesion and internal friction angle values. This trend complements the findings of Khoerani et al. [95] by showing that the initially low shear strength of fibrous peat can be modified through chemical and cementitious treatments. Consequently, the contribution of the present study lies in quantifying and comparing the shear response of natural high-altitude Andean peat treated with sodium percarbonate or sodium persulphate, each combined individually with MPC modified with volcanic ash.

6.4. Limitations and Considerations for Field Application

The extrapolation of experimental findings to in situ conditions is subject to limitations associated with differences between laboratory-conditioned peat and naturally saturated deposits. These differences may influence the distribution of stabilising agents, cementitious reactions and the mechanical response of the material. Furthermore, the heterogeneity of the fibrous structure, the degree of organic matter decomposition and drainage conditions are factors that should be considered when interpreting the behaviour of the treatments under natural conditions.

For full-scale application, field pilot trials are recommended to verify mixing uniformity, treatment depth and curing conditions, taking into account the geotechnical characteristics of the deposit. In addition, it would be beneficial to evaluate the development of both settlement and strength, as a result of long-term exposure to water and service load. Such investigations would help establish appropriate construction and quality control criteria for ground improvement and road infrastructure projects.

From an environmental perspective, thermal and mechanical characterisation provides information on the behaviour of stabilised materials, while their assessment under natural conditions requires consideration of potential chemical interactions with the surrounding environment. In this regard, it is recommended that the evaluation be complemented by leaching tests, monitoring of pH and electrical conductivity, and ecotoxicological assessments to characterise the behaviour of treatment constituents under prolonged saturation. These evaluations would contribute to establishing environmental safety criteria and determining the suitability of the formulations for full-scale application.

7. Conclusion

First, the combined incorporation of solid oxidants and Magnesium Phosphate Cement (MPC) modified with volcanic ash improved the thermal and mechanical behaviour of the treated peat under the experimental conditions evaluated. The TG-DTG and UCS test results demonstrated a reduction in total mass loss and an increase in the mechanical strength of the treated soil compared with untreated peat. These results

demonstrated improvements in the thermal and mechanical behaviour of the combined formulations, with lower mass losses during heating and a more favourable response under mechanical loading.

Second, MPC modified with 5% pozzolanic volcanic ash was used as the cementitious component of the stabilisation system at a constant dosage of 15% relative to the dry weight of the peat. The increased thermal properties and increased unconfined compressive strength after the 28-day curing period demonstrated by the combination of the two formulations showed that the combined formulations provided improved performance when compared to each of the evaluated curing periods.

Thirdly, Sodium Percarbonate (PC) was used as an additive to MPC to enhance both the thermal stability and mechanical properties of the peat. Out of all the oxidant concentrations tested in this study, the 3% PC concentration provided the best performance. It reduced the total mass loss to 44.73%, and it achieved an unconfined compressive strength of 74.43 kPa at 28 days. Therefore, these results indicate that the formulation exhibited excellent thermal and mechanical responses. However, as the oxidant dosage increased above 3%, the effectiveness of the treatment decreased; therefore, increasing the PC concentration above 3% did not result in further improvements in mechanical properties or thermal stability under the experimental conditions evaluated. Fourthly, when used in conjunction with MPC, Sodium Persulphate (PS) showed greater mechanical performance than the equivalent Percarbonate formulations. Over the 28-day curing period, the best possible combination was obtained by using 3% PS and 15% MPC.

This formulation produced an unconfined compressive strength of 86.98 kPa. This value was greater than any of the other formulations tested. However, treatment performance decreased at oxidant dosages of 4% and 5%. Overall, the combination of 3% PS and 15% MPC provided the most favourable mechanical strength and allowable bearing capacity within the investigated formulations.

Finally, the comparison between both oxidants demonstrated that the formulations containing sodium percarbonate and sodium persulphate exhibited different thermal and mechanical responses. The formulation containing 3% percarbonate and 15% MPC achieved the lowest total mass loss, whereas the formulation containing 3% persulphate and 15% MPC exhibited superior mechanical performance. In both cases, the combined formulations improved the mechanical strength and thermal behaviour of the treated peat compared with the untreated material. Therefore, the treatments incorporating 3% percarbonate with 15% MPC and 3% persulphate with 15% MPC represented the most favourable formulations within their respective experimental series, with potential for improving organic peat soils in geotechnical applications.

Additional Information on Trials Link

https://drive.google.com/drive/folders/1TIVjR_AKJX03A0UBxPTHKkNNdGU69nDn?usp=drive_link

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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