anpet
brazilian association for transportation research and education
TRANSPORTES
ISSN: 2237-1346
transportes.anpet.org.br

Ornamental stone industry waste in soil mixtures for geotechnical applications: a literature review

Resíduos da indústria de rochas ornamentais em misturas de solos para aplicações geotécnicas: uma revisão de literatura

João Renato Remede Prandina[1] **and Marcio Muniz de Farias**[2]

[1]Universidade de Brasília, Brasília, Distrito Federal, Brasil, renatoprandina@gmail.com, 0009-0002-3551-8339
[2]Universidade de Brasília, Brasília, Distrito Federal, Brasil, muniz@unb.br, 0000-0002-5257-911X

Received: 24 July, 2025
Revised: 8 December, 2025
Accepted: 18 December, 2025
Published: 10 March, 2026

Associate Editor:
Jorge Barbosa Soares
Universidade Federal do Ceará, Ceará, Brazil

Keywords:
Ornamental Stone Residue (OSR);
Geotechnical applications;
Soil stabilization;
Waste management.

Palavras-chave:
Resíduo de Rocha Ornamental (RRO);
Aplicações geotécnicas;
Estabilização de solos;
Gestão de resíduos.

DOI: 10.58922/transportes.v34.e3155

ABSTRACT
The Ornamental Stone Industry (OSI), an important economic sector in Brazil and other countries, faces significant environmental disposal challenges, generating vast quantities of Ornamental Stone Residue (OSR), still treated as waste. This study investigates the geotechnical application of OSR as a sustainable construction material, aligning with circular economy principles. OSR is a fine-grained, predominantly silty material, whose mineralogical and chemical properties are dictated by the parent rock, such as granite or marble. Generally classified as a non-hazardous residue (Class II-B) under the Brazilian code system, the OSR offers potential for soil stabilization. The incorporation of OSR into soils can yield significant changes in their geotechnical properties, consistently reducing Atterberg limits and the Plasticity Index (PI), which improves workability, and increasing maximum dry density (MDD). While the effect on compaction parameters is complex and depends on mixture proportions, mechanical strength shows consistent improvements. Well-established parameters such as the Resilient Modulus (MR), Unconfined Compressive Strength (UCS), and the California Bearing Ratio (CBR) often increase, allowing the mixtures to meet the criteria for earthworks and pavement layers, such as base, sub-base, and subgrade.

RESUMO
A Indústria de Rochas Ornamentais (IRO), um importante setor econômico no Brasil e em outros países, enfrenta desafios significativos para realizar o descarte ambiental dos seus resíduos. A IRO gera anualmente grandes quantidades de Resíduo de Rocha Ornamental (RRO), ainda tratado como inservível. Este estudo investiga a aplicação geotécnica do RRO como um material de construção sustentável, alinhado aos princípios da economia circular. O RRO é um material de granulometria fina, predominantemente siltoso, cujas propriedades mineralógicas e químicas são ditadas pela rocha matriz, como granito ou mármore. Geralmente classificado como um resíduo não perigoso (Classe II-B) pelo sistema de normas brasileiro, o RRO oferece potencial para a estabilização de solos. A incorporação de RRO em solos pode resultar em mudanças significativas em suas propriedades geotécnicas, reduzindo consistentemente os limites de Atterberg e o Índice de Plasticidade (IP), o que melhora de plano sua trabalhabilidade, e aumentando a densidade máxima aparente seca. Embora o efeito nos parâmetros de compactação seja complexo e dependa das proporções da mistura, a resistência mecânica apresenta melhorias regulares para boa parte dos casos. Parâmetros consagrados como Módulo de Resiliência (MR), a Resistência à Compressão Simples (RCS) e o Índice de Suporte Califórnia (ISC) frequentemente aumentam, permitindo que as misturas atendam aos critérios para obras de aterros e camadas de pavimento, sejam base, sub-base e subleito.

1. Introduction

Ornamental stone residue (OSR), mostly treated and disposed as waste, are generated in large quantities, particularly from marble and granite processing, causing environmental problems (Pequeno, 2020; Bacarji *et al.*, 2013). Figure 1 shows that the state of Espírito Santo, with 78% of Brazilian exportations (Abirochas, 2024) and, coincidentally, 78% of the sawing machines in Brazil, leads the number of processing industrial plants and the number of these equipment to cut block rocks (Abirochas, 2021), with Bahia in second place with 5.6%. Nonetheless, OSR has been studied scarcely in geotechnical applications, with rare or even unfound practical implementations.

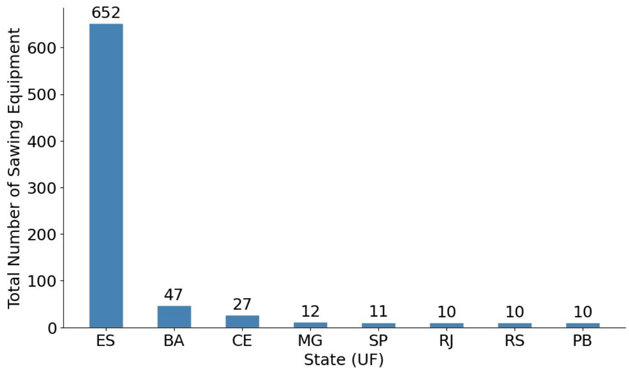

Figure 1 • Top 8 of 19 Brazilian states with registered industrial sawing block cutters. Source: Abirochas (2021).

Generally, in Espírito Santo and Brazil, industrial plants process simultaneously granite and marble blocks, with no restriction to geology type of the rock. In other countries, some industrial plants process only OSR-M (OSR from marble parent rock), OSR-G (OSR from granite parent rock) generating geologically mixed dust, slurry or sludge due to different reasons, such as commercial and local availability, therefore many international papers can differ the OSR parent rock.

OSR's physical and chemical properties, influenced by processing and mineralogy, are the fundamental engineering properties of these fine-grained residues, which are rich in calcium and siliceous compounds, can react with certain soils through pozzolanic and cementation processes, enhancing mechanical strength and controlling expansion, making them promising stabilizing agents (Nascimento, 2019; Mello, 2019).

Nevertheless, studies, though limited, have explored OSR possible applications in pavement engineering, landfill lining, and earthworks (Pequeno, 2020; Lunz, 2021). These investigations suggest that proper OSR mixing can improve maximum dry density (MDD), California Bearing Ratio (CBR), resilient modulus (MR), unconfined compressive strength (UCS), and hydraulic conductivity of natural soils. For example, modest OSR additions have shown the potential to significantly increase support capacity and stiffness, even outperforming mixes with higher additive content under specific compaction (Araújo, 2018; Lunz, 2021). Optimizing mixing ratios and compaction energy is thus a possible parameter for pavement design using residues (Araújo, 2018; Nascimento, 2019). The low cost and environmental benefits of substituting natural soils or binders further support the potential for OSR use (Lunz, 2021; Cardoso, 2019).

The reuse of OSR in geotechnical engineering aligns with sustainable infrastructure development. Studies have shown its potential in applications such as pavement layers and landfill barriers, where its incorporation can improve key soil properties like strength, stiffness, and plasticity, thereby enhancing durability and performance. By converting this industrial residue into a valuable engineering component, its application addresses waste management challenges while promoting material recycling, an issue of particular importance in regions with a major ornamental stone industry.

The focus of this study on Brazil is justified by the country's position as a world-leading producer and exporter of ornamental stones, which generates a volume of waste that demands sustainable solutions. Furthermore, the Brazilian residue has a distinct profile, typically consisting of a mix of granite and marble from simultaneous processing. This unique characteristic, combined with local logistical factors, makes the Brazilian scenario a relevant and specific case study.

While this review concentrates on geotechnical applications, other significant uses exist, primarily in manufacturing. These include its role as a raw material in the ceramics industry (Bacarji *et al.*, 2013) and as a fine aggregate replacement in specialized cementitious products (Zichella *et al.*, 2020). Acknowledging these industrial pathways helps to frame the distinct context of OSR's use as a bulk soil modifier of soils, especially in earthworks and pavement layers.

This study aims to consolidate and analyse the Brazilian literature on the geotechnical application of OSR, identifying key advances, knowledge gaps, and its technical feasibility for infrastructure projects.

By systematically reviewing the existing body of work, this study establishes a foundation for continued research and provides a strong justification for pursuing more in-depth studies in this field.

2. Methodology of the review

This study adopted a narrative review approach. This decision was justified by the scarcity of peer-reviewed national literature on the geotechnical applications of OSR. Consequently, the research focused on works that could represent the local and national state-of-the-art, without the need for a strict or exhaustive search protocol. Nevertheless, the strategy of using local scientific studies not yet published in peer-reviewed journals has proven its quality once these studies have their literature relying on the scarce international literature on geotechnical applications of OSR, as exemplified in Table 1.

2.1. Search strategy

The search for references was conducted across key databases and academic repositories, including Capes Periódicos, Scielo, Google Scholar, Scopus, Web of Science, and Brazilian university repositories (for theses and dissertations).

The search keywords used were based on both Portuguese and English terminology related to the subject. The primary boolean terms included: “resíduo de rocha ornamental” (ornamental rock waste), “estabilização de solos com resíduos de rochas” (soil stabilization with rock waste, stone waste), and “utilização de resíduos de indústria de rochas ornamentais (IRO) em pavimentação” (use of ornamental rock industry (IRO) waste in pavement). Alternative and synonymous terms were also employed, such as “marble and granite,” “dimension stone industry”, and other variations such as “marble dust”, “granite dust” (or slurry, or sludge), all combined, to ensure comprehensive coverage. The specific search strings applied to each database to retrieve the relevant literature are detailed in Table 2.

After applying the search strings across the databases, a total of 142 references were identified. This initial dataset comprised a comprehensive mix of peer-reviewed sources (journals and conference proceedings) and grey literature (doctoral theses, master’s dissertations, and B.Sc. capstone projects), reflecting the state-of-the-practice of the OSR research programs. From this total, a screening process was applied based on the exclusion criteria (Section 2.2), removing duplicates and studies focused on non-geotechnical applications (e.g., ceramics, structural concrete, or mortars). The Brazilian references,

Table 1 • Connection between Brazilian research and international peer-reviewed literature

Brazilian Reference cited	Referenced journal paper	Country	Publisher
Dias (2024) and Lunz (2021)	Eltwati *et al.* (2020). Potential of granite dust to improve the engineering properties of soft soils for road construction.	Libya	Science Proceedings Series.
Dias (2024) and Mello (2019)	Galetakis & Soultana (2016). A review on the utilisation of quarry and ornamental stone industry fine by-products in the construction sector.	Greece	Construction and Building Materials.
Dias (2024)	Lohar & Shrivastava (2025). Feasibility of granite processing waste as a fill material in geotechnical applications.	India	Materials Today: Proceedings.
Dias (2024)	Moraes, Oliveira & Pires (2018). Characterization of Stone Slurry Waste for Reutilization Purposes as Building Construction Material.	Brazil	Journal of Geological Resource and Engineering.
Dias (2024) and Prandina & Farias (2025)	Sivrikaya, Kıyıldı & Karaca (2014). Recycling waste from natural stone processing plants to stabilise clayey soil.	Turkey	Environmental Earth Sciences.
Prandina, Fall & Sedano (2017)	Lohar & Shrivastava (2025). Beneficial use of dimensional stone industry wastes in geotechnical fills: Geotechnical, environmental and economic perspectives.	India	Resources Policy

Table 2 • Search strings and boolean operators applied across databases

Database / Repository	Search Strings / Keywords Applied
Google Scholar	(“resíduo de rocha ornamental” OR “resíduo de mármore e granito” OR “lama de beneficiamento”) AND (“estabilização” OR “pavimentação” OR “solo”)(“ornamental stone residue” OR “dimension stone waste” OR “marble dust” OR “granite dust”) AND (“soil stabilization” OR “pavement” OR “geotechnical”)
Scopus & Web of Science	(“ornamental stone” OR “dimension stone” OR “marble” OR “granite”) AND (“residue” OR “waste” OR “dust” OR “sludge”) AND (“soil” OR “pavement” OR “road” OR “geotechnical”)
Scielo & Capes Periódicos	(“resíduo de rocha” OR “resíduo de granito” OR “resíduo de mármore”) AND (“solo” OR “pavimento” OR “estabilização”) “ornamental stone waste” AND “soil”
Brazilian University Repositories	Keywords: “resíduo de rocha ornamental”; “estabilização de solos”; “uso de resíduos em pavimentação”; “lama abrasiva”; “resíduo de tear”; “dimension stone waste”.

which constituted the majority of the initial dataset, originated from 14 different states, primarily affiliated with federal universities, as shown in Figure 2.

After an extensive search, 140 references were found. Of these, 101 (∼72%) were from Brazilian sources, authors affiliated with Brazilian institutions, including conference papers, bachelor’s theses, and master’s dissertations. Fifty-two (∼52%) of the Brazilian references were journal papers authored by Brazilians. Additionally, most of these references focused on OSR in non-geotechnical applications. The Brazilian references originated from 14 different Brazilian states, primarily affiliated with the federal universities in each state, as shown in Figure 2.

The screening process involved a preliminary visual inspection of the full texts to verify the existence of primary experimental data. Studies were only pre-selected if they contained datasets regarding physical characterization, compaction parameters, and mechanical testing.

To ensure data reliability, a hierarchy of evidence was applied during the final eligibility phase. Priority was given to peer-reviewed journal articles, followed by conference papers involving established research groups (faculty and students). Regarding grey literature, a strict academic hierarchy was adopted: Doctoral theses were prioritized over Master’s dissertations, which took precedence over undergraduate theses and technical reports. This strategy ensured that the review relied primarily on validated experimental data supervised by senior academic researchers.

The protocol for this narrative review was designed to consolidate recent advances in geotechnical literature focused on the Brazilian context, specifically regarding ornamental stone residue (OSR). The

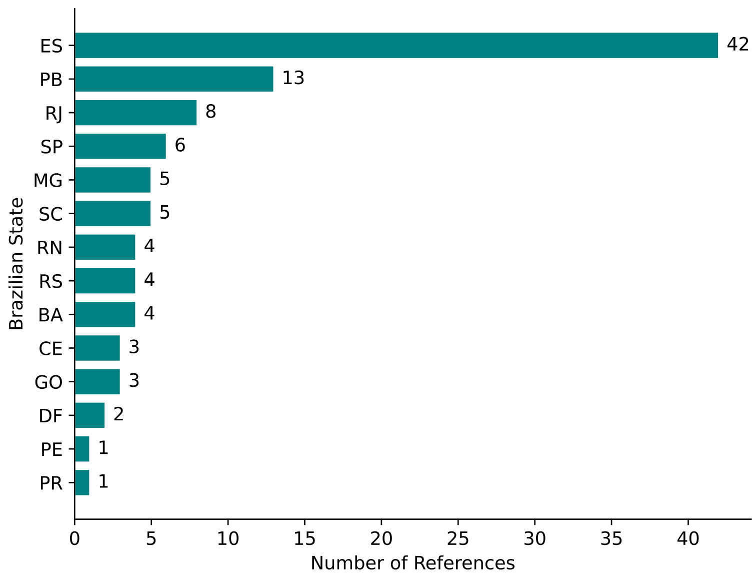

Figure 2 • Distribution of Brazilian references found on ornamental stone residue (OSR) by state.

search was restricted to publications in the English and Portuguese languages. To focus on the most recent research advances, and as a follow-up to prior conceptual work (e.g., Prandina & Farias (2025)), a primary time frame was established for publications from 2015 onward. This date marks a period of intensified directed studies on the subject in Brazil. The systematic search was completed in September 2025. The definition of this post-2015 time frame is methodologically significant. It coincides with the maturation and cultural transition within Brazilian pavement engineering, which began to more widely adopt mechanistic methods (based on Resilient Modulus, MR) over purely empirical methods (such as the CBR).

Prior to this period, mechanistic research was incipient using residues and focused on natural materials, even as residues like steel slag (SS) were already being applied in the field out of practical necessity, validated by empirical methods. Therefore, focusing the review on this period makes it possible to capture the state-of-the-art in geotechnical research on residues (such as OSR) that is aligned with modern mechanistic practice.

2.2. Inclusion, exclusion criteria, and organization of findings

The inclusion criteria were scientific papers, theses, and dissertations focused exclusively on the geotechnical applications of OSR within Brazil, generated from the industrial process of the transformation of raw blocks into finished products, which involves a sequence of cutting, shaping, and polishing operations, each generating significant quantities of solid and slurry waste most of the time destinated to landfills (Prandina & Farias, 2025).

Conversely, the exclusion criterion was any research addressing other uses, such as applications in the ceramics industry. Additionally, studies including only residues from quarries were not considered. For example, the Brazilian scientific production is cited in the international journal papers, however it only happens to be found for non-geotechnical applications, even in a geotechnical application study such as Vikas & Ramana (2023), as exemplified in Table 3.

To ensure methodological transparency and reproducibility, the systematic selection process is illustrated in Figure 3. This PRISMA flow diagram details the attrition of records from the initial identification of 142 references to the final inclusion of 45 studies, specifying the screening and eligibility phases where non-geotechnical literature was excluded.

The findings (Figure 4), most of them journal papers, in support of the main subject of this study, which is the possibility of geotechnical applications of OSR in soil mixtures, not counted the examples of Table 3, were organized to explore typical geotechnical properties relevant to soil applications in geotechnical infrastructures, such as in embankments and pavement. The results are presented systematically, first by type of property (physical, chemical, and mechanical), and then by application (embankments, base, subbase, and subgrade).

3. Physical, mineralogical, chemical, and stabilizing potential of OSR

The viability of OSR in geotechnical applications is dictated by its fundamental, interdependent properties. The mineralogical composition of the residue, determined by the parent rock, directly governs its chemical makeup, its physicochemical behavior (such as pH), and, consequently, its potential for soil stabilization.

Table 3 • Brazilian studies on OSR applied in non-geotechnical applications cited in international papers

International journal publication, country	Brazilian reference cited	Area of Application in the Citing Article
Song *et al.* (2021), Crystals, China	Carvalho *et al.* (2014)	Soil-Cement Blocks
Salehi *et al.* (2021), KSCE Journal of Civil Engineering, Iran	Amaral *et al.* (2020)	Cement-Stabilized Soil
Vikas & Ramana (2023), Materials Today: Proceedings, India	Menezes *et al.* (2002)	Raw Materials for Ceramics

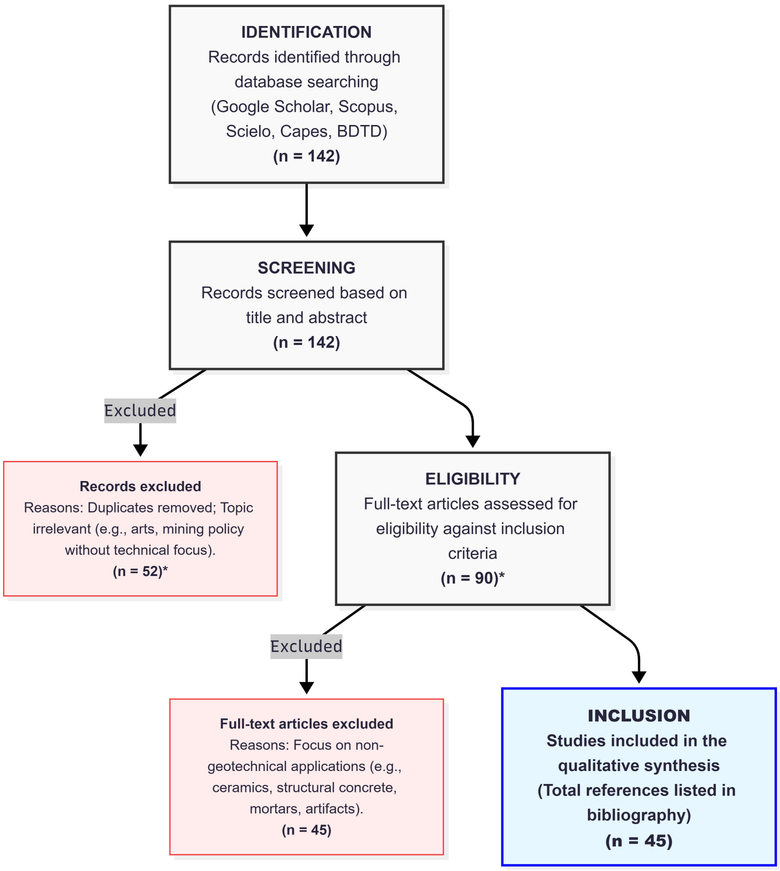

Figure 3 • PRISMA flow diagram detailing the literature search, screening, and selection process.

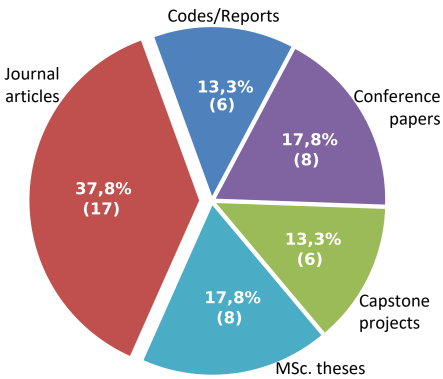

Figure 4 • Distribution of references selected and cited by publication types on OSR in geotechnical applications.

3.1. Grain size distribution (GSD)

The OSR physical and morphological properties are basic and fundamental for its application in geotechnical engineering, particularly for landfills, embankments, subgrades, and pavement layers. OSR is solid particulate, defined as a byproduct of industrially processed rock blocks during cutting, sawing, grinding, and polishing ornamental stone, like granite and marble, constitutes up to 40% of quarried stone, with approximately 26% being fine particles mixed with cutting slurries (Mello, 2019; Dias, 2024).

Moreira *et al.* (2021) studied 70 samples collected in 4 different landfills of Espírito Santo, which GSD maximum (Max) and minimum (Min) limits are seen in Figure 5: the OSR primarily exhibit a very fine particle size distribution, ranging from medium sand with grains of approximately 0.250 mm to very fine clay with grains reaching the 0.00024 mm range, with approximately 80% of the waste materials are smaller than 0.053 mm.

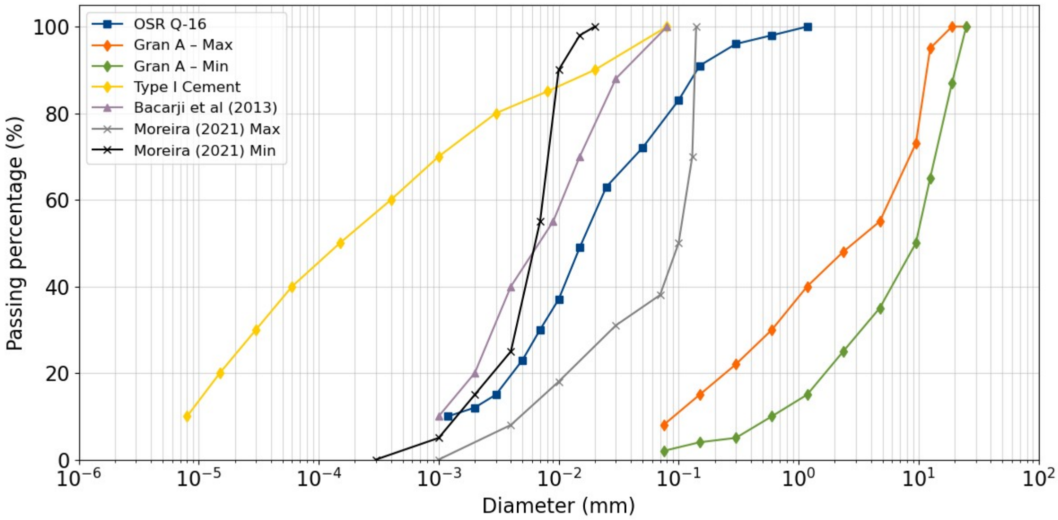

Figure 5 • Grain size distribution of different ornamental stone residue samples, compared to coarse aggregate and Portland cement limits. Adapted from Prandina, Fall & Sedano (2017).

Therefore, OSR typically exhibits a fine, well-graded granulometry, primarily silt and fine sand (Bacarji *et al.*, 2013; Lunz, 2021). Figure 5 also shows curves of Type I cement and limits of Granular A (Gran A) of Canadian codes (Prandina, Fall & Sedano, 2017). In Brazil, NBR 7181 (ABNT, 2016) was used as the standard method for obtaining the GSD of OSR samples in the studies reviewed. Although no specific Brazilian technical code has been instituted for OSR, other ABNT (Brazilian Association of Technical Codes) and DNIT (National Department of Transportation Infrastructure) codes already allow for the use of residues in pavement engineering and earthworks.

OSR's specific gravity and grain density are comparable to natural aggregates. Variability in OSR properties necessitates systematic screening and potential separation by lithological source to maximize performance, as shown by comparative studies (Chicon, 2019).

3.2. Mineralogical composition as a primary factor

The mineralogical diversity of OSR is governed by its geological origin, encompassing primarily silicate and carbonate minerals. The residue's composition is, therefore, directly dependent on the type of rock processed, such as granite or marble. Granite-derived OSR (OSR-G) is predominantly composed of quartz (SiO2), feldspars, micas, and accessory minerals. Marble-derived OSR (OSR-M) is rich in calcite. X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) are used to identify these minerals. Investigations by Lunz (2021) using XRD on OSR mixtures showed the presence of minerals such as quartz, kaolinite, and calcite (Figure 6).

Furthermore, SEM analysis reveals angular or sub-angular particles with irregular edges, a morphology that promotes mechanical stabilization and enhances load-bearing capacity through particle interlocking.

Lohar, Shrivastava & Sharma (2023) used X-ray Diffraction (XRD) either to identify the primary minerals in OSR, finding it composed mainly of quartz, feldspar, calcite, mica, microcline, orthoclase, and kaolinite, aligned with Lunz (2021) results. The authors highlighted that the presence of these stable minerals, and the noted absence of those prone to swelling, is the primary reason for the material's non-swelling nature.

3.3. Elemental chemical composition

The chemical composition of OSR is a direct reflection of its mineralogy, forming a silt-sandy mixture that is typically low in plasticity. The residue is essentially a silicate-rich matrix derived from quartz and

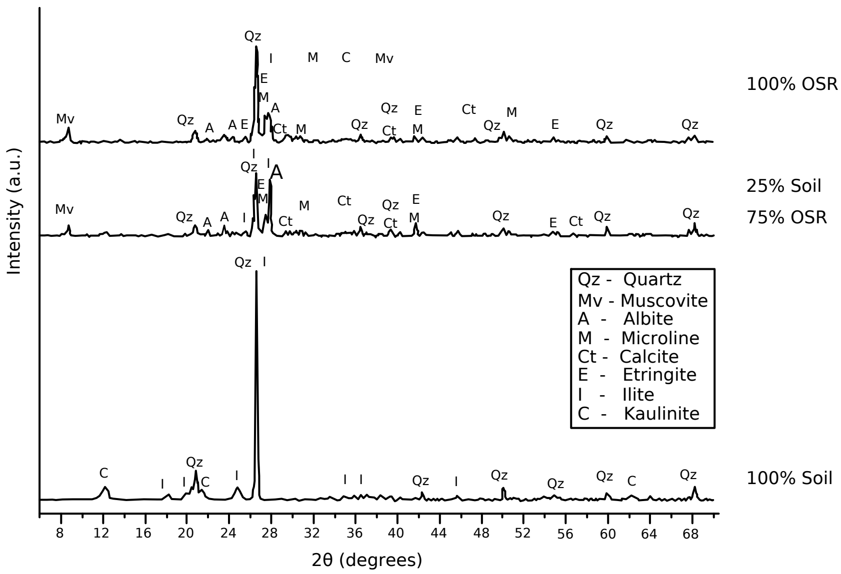

Figure 6 • XRD of samples: 100% Soil; 100% ornamental stone residue (OSR); 25% Soil + 75% OSR mixture (Lunz, 2021).

feldspathic minerals. The major oxides of OSR are silica (SiO_2), typically the most abundant component, often exceeding 60-70% by mass, which can contribute to the rigidity of resulting mixtures. This effect is especially pronounced in clayey soils due to particle interaction and replacement, as will be demonstrated by the studies presented in this work (Table 4).

Other oxides present in smaller quantities include alumina (Al_2O_3), alkali and alkaline-earth oxides (K_2O, Na_2O, CaO, MgO), iron oxides (Fe_2O_3), and titanium oxides (TiO_2). The elemental diversity varies with the parent rock's geology and industrial practices. The variability of OSR is illustrated in Table 4, which shows the chemical composition from four different research studies, their average, and a comparison to the median results of a larger study of 70 samples by Moreira *et al.* (2021). The comparison shows that the differences between the averages are small, suggesting a consistent chemical profile for OSR in the region studied.

Galetakis & Soultana (2016), for instance, conducted an extensive review and summarized the typical chemical compositions of OSR. They noted that OSR-M is predominantly calcareous, with high concentrations of CaO, around 55%, while OSR-G is mainly siliceous, with high levels of SiO_2 reaching even 70%.

Despite variations, the accessory oxides and trace metals generally do not compromise the inert

Table 4 • Chemical composition of the ornamental stone residue (OSR) in percentages

	a	b	c	d	e	f	g	h
Chemical element	Neves et al. (2018)	Oliveira et al. (2016)	Lunz (2021)	Dias (2024)	Average (a, b, c, d)	Std. Dev. (a, b, c, d)	Moreira et al. (2021)	Variation |e−g|
SiO_2	63.80	62.40	48.70	46.10	55.25	9.00	53.56	1.69
Al_2O_3	16.50	15.30	15.90	10.30	14.50	2.83	12.03	2.47
Fe_2O_3	5.30	7.60	6.40	6.80	6.53	0.99	6.41	0.12
CaO	1.30	1.60	9.80	16.50	7.30	7.14	10.61	3.31
MgO	0.80	1.10	2.40	1.10	1.35	0.69	4.50	3.15
K_2O	4.80	3.80	1.30	1.30	2.80	1.74	3.45	0.65
Na_2O	3.50	3.40	0.40	0.10	1.85	1.78	2.64	0.79
TiO_2	0.80	1.00	0.80	0.80	0.85	0.10	0.76	0.09
P_2O_5	0.20	0.20	0.20	0.20	0.20	0.00	0.32	0.12
MnO	0.10	0.10	0.20	0.10	0.13	0.05	0.08	0.05
SO_3	0.10	0.20	—	0.30	0.20	0.10	0.34	0.14
LOI	2.80	2.80	13.90	16.40	8.98	7.20	4.36	4.62

nature of OSR, which is environmentally compatible for use in geotechnical fills, subgrade improvement, and pavement layers (Freitas, Raymundo & Jesus, 2012; Oliveira, 2015; Pequeno, 2020; Dias, 2024), results also obtained by Lohar & Shrivastava (2025), which environmental analysis indicated a low leaching risk, with heavy metal concentrations remaining within permissible limits for application in geotechnical fills, following the methodology of the U.S. Environmental Protection Agency (USEPA).

3.4. pH and chemical reactivity

The mineralogical profile also defines the chemical behavior of OSR, particularly its pH. Freshly collected industrial OSR samples exhibit high alkalinity and strongly basic conditions. This high pH stems primarily from alkaline earth metals, notably calcium compounds found in the residue's mineral structure.

Upon exposure to atmospheric CO_2, a carbonation process occurs that reduces the material's basicity. During this "mineralogical evolution," calcium hydroxide ($Ca(OH)_2$) reacts with CO_2 to form calcium carbonate ($CaCO_3$), a less soluble and more stable mineralogical phase. This formation of secondary minerals is a key factor in the OSR's long-term chemical stability and ecological safety in engineering applications.

3.5. Implications for geotechnical stabilization

The combination of its mineralogical, chemical, and physical properties (fine particle size and angular morphology) gives OSR significant potential for use in soil stabilization techniques for road infrastructure. Recent geotechnical investigations of Lohar & Shrivastava (2025) confirmed that OSR are non-plastic and non-swelling, with hydraulic conductivity similar to that of silty sands. The study demonstrated the high stability of the materials, which exhibited high internal friction angles ranging from 36.5° for OSR-M to 44.8° for OSR-G. The improvement mechanisms can be categorized as follows:

1. Chemical stabilization: traditionally achieved with cement or lime, this technique now increasingly focuses on industrial byproducts like OSR due to environmental motivations. The calcium and siliceous compounds in OSR might induce pozzolanic and cementitious reactions and/or contribute to the processes with certain soils, enhancing mechanical strength.
2. Mechanical and granulometric stabilization: mechanical stabilization enhances soil properties by blending with materials like OSR, which is particularly viable where suitable natural soils are scarce. Incorporating fine-grained OSR into coarser or finer soils optimizes the overall gradation (granulometric stabilization), influencing compaction parameters and often improving stability. This process might improve the granular skeleton, reduce void ratio, and can increase load-carrying capacity, helping and or not affecting OSR-soil mixtures meet critical thresholds for parameters like the MR in pavement layers. The large-scale availability of OSR in Brazil strengthens the feasibility of this approach.

4. Effect of OSR addition on soil properties

4.1. Physical and compaction properties

4.1.1. OSR classification in international systems

OSR is typically characterized as a fine-grained, silty material, classified as ML on UCS (Unified Classification System). Lunz (2021) explicitly classifies a 100% OSR sample as A-4 under the Transportation Research Board (TRB) system adopted by the American Association of State Highway and Transportation Officials (AASHTO), noting that its addition to a higher-quality A-2-4 soil was sufficient to change the mixture's classification to A-4 as well.

Figure 7 provides a direct visual comparison of the particle morphology and scale, which supports the classification of OSR as a fine-grained material. In Figure 7 (a), the pure soil sample exhibits a distinctly aggregated structure. The soil particles are clustered into larger agglomerates, many of which appear equal to or larger than the 50 μm scale bar. This illustrates a coarser texture where individual fine particles are bound together. In contrast, Figure 7 (b) shows the OSRs sample, which is composed of much finer, more discrete particles.

The majority of these individual particles are visibly smaller than the 50 μm scale bar, confirming its fine-grained and silty nature as described by Oliveira (2015). Highlighting these evidences, it has been demonstrated the OSR strong silt-like properties (Figure 5). Brazil adopts UCS and TRB in its different codes, such as the ones published by DNIT and ABNT.

Table 5 summarizes the geotechnical characterization of OSR from key national and international studies, highlighting both consistent trends and notable variations. A consistent finding across all research is the predominance of the silt fraction, which ranges from 61% to 75%. This high silt content is the primary reason for its classification as a fine-grained material, typically as ML (low-plasticity silt) under the USCS or as A-4 and A-6 in the TRB system ASTM (2024). The data from Brazilian studies, such as Oliveira (2015) and Mello (2019), align well with the international findings from Barrientos *et al.* (2010) in Spain, reinforcing this general geotechnical profile.

Overall composition and resulting gradation of soil-OSR mixtures can be tailored to the target application, accounting for constituent grain size characteristics. Findings on the material's inertness, while based on specific cases (Oliveira, 2015; Dias, 2024), indicate environmental feasibility for the use of OSR in soil mixtures.

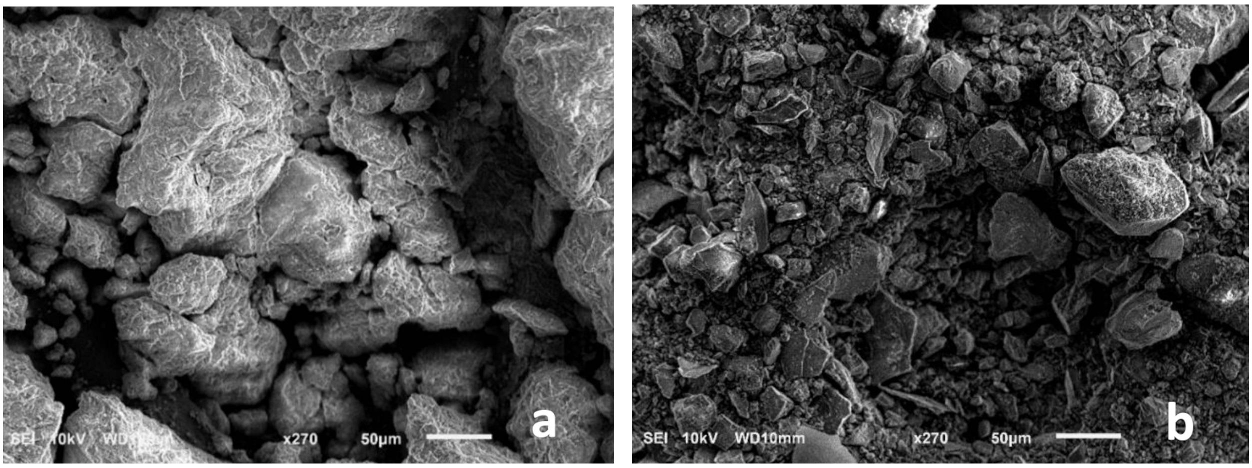

Figure 7 • Scanning Electron Microscopy (SEM) of the pure soil (a) and OSR samples (b). Source: Lunz (2021).

Table 5 • Comparative summary of OSR composition and classification from key studies

Study	Material and Origin	Particle Size (%)			Classification/Key Findings
		Silt	Clay	Sand/Gravel	
Barrientos et al. (2010)	OSR-G granite sawdust from Spain	70–75	10–15	10–20	Classified as a sandy clayey silt, corresponding to a low-plasticity silt (ML) under the USCS.
Oliveira (2015)	OSR from a processing plant in São Paulo (syenite, granite, and gneiss mixture)	62	18	20	ML (low-plasticity silt), with 80% fines and PI of 5%. Environment: Class II B (Inert).
Mello (2019)	Typical OSR from Espírito Santo, Brazil	63	27	10	Characterized by a high percentage of fines.
Dias (2024)	OSR from ADAMAG landfill (ES), from diamond wire sawing process	61	35	4	A-6 (TRB) and ML (SUCS) with an IG of 16. The material is non-plastic. A 50/50 mixture with soil was classified as Class II B (Inert).

4.1.2. Maximum dry density (MDD) and optimum moisture content (OMC)

Maximum dry density (MDD) and optimum moisture content (OMC) are key parameters for evaluating soil-OSR mixture compaction behavior in many geotechnical applications. OSR inclusion alters soil particle interaction, affecting compaction density and required moisture. The specific gravity (Gs) of OSR ranges from 2.587 to 2.770 in different studies (Santos & Leandro, 2017; Teixeira, Bezerra & Borges, 2017a; Marques, Costa Farias & Moraes Garcia, 2019; Mello, 2019; Braz, 2024).

Characterization studies also differentiate OSR based on the industrial processing technology used. Moraes, Oliveira & Pires (2018), for example, specifically compared waste generated by conventional metallic blade looms with that from diamond wire looms. The Gs of the conventional loom OSR (2.84) was notably higher than that of the diamond wire OSR (2.56), a difference attributed to the presence of steel grit. This was further confirmed by chemical analysis, which showed a high and variable iron content (up to 24.1%) in the conventional waste, a direct result of abrasive wear from the metallic blades and grit, which was absent in the waste from the diamond wire process.

Proctor compaction testing easily determines these parameters for soils and OSR blends (Mello, 2019). OSR incorporation modifies compaction curves, in the different energies: standard (S), intermediate (I), and modified (M). The incorporation of OSR on soils shifts peak of MDD and OMC for both sides depending on the proportions of soils and OSR. The MDD of compacted OSR alone with standard and intermediate energies ranges from 15.71 kN/m³ up to 19.50 kN/m³, while its OMC ranges from 9.2 to 24.5% (Oliveira, 2015; Oliveira, Ribeiro & Moreiras, 2016; Meneguete, Batista & Cesconetto Júnior, 2018; Chicon, 2019; Marques, Costa Farias & Moraes Garcia, 2019; Dias, 2024)

In silt-rich soils (over 50% silt), predominant grain size can lead to uniform packing and more voids, potentially lowering MDD. Since OSR often has a high percentage of silt-sized particles, its incorporation may shift soil towards a more uniformly graded material. GSDs of natural soils and OSR are characterized via sieve analysis and hydrometer tests, yielding cumulative curves to determining gradation (well-graded vs. poorly graded). Higher OSR fine particle content can transition well-graded soil to a gap-graded or silty profile, reducing intergranular contact and potentially increasing void ratio (Silva & Isewaki, 2018; Mello, 2019). Even moderate OSR admixtures significantly alter silt and clay-sized particle fractions (Nascimento, 2019).

Variation in MDD and OMC relates directly to OSR proportion and inherent properties of both soil and residue. When OSR is capable of offer complementation on particle gradation, MDD increases and OMC decreases. However, typically high percentages of OSR usually decreases MDD, often due to particle size and density differences between soil and OSR. Table 6 shows the impact of OSR on MDD and OMC from different studies.

Engineering parameters findings confirm effective OSR use in soil improvement depends on careful OSR-to-soil ratio adjustment, granular association, moisture control, and compaction energy selection, with 8 references showing MDD positive gains, which represents 57% of the cases. OMC, ensuring sufficient lubrication without excess pore water, must be tailored for each blend. This approach harnesses OSR benefits (economic, environmental) without compromising mechanical performance (Teixeira, Bezerra & Borges, 2017b; Mello, 2019; Scherer, Knierim & Klamt, 2023).

In summary, OSR's impact on MDD and OMC shows a complex but manageable relationship, engineered through material characterization and compaction analysis. Integrating OSR into soil for geotechnical use requires a comprehensive view of compaction dynamics, knowledge of each residue geotechnical properties, and OSR-soil interaction (Teixeira, Bezerra & Borges, 2017b; Araújo, 2018; Mello, 2019; Lunz, 2021; Scherer, Knierim & Klamt, 2023). In addition, the study of Sivrikaya, Kıyıldı & Karaca (2014) also found that the inclusion of OSR increased the MDD while decreasing the OMC.

The variation of OSR content and the grain size distribution curve alterations can optimize the mix designs, maximizing engineering performance while ensuring standard compliance (Silva & Isewaki, 2018; Aguiar, 2019; Mello, 2019; Nascimento, 2019; Dias, 2024).

Table 6 • Comparative summary of geotechnical properties and compaction behavior of soils and OSR-Soil Mixtures

	Compaction Test Curve Parameters					MDD	
Reference	Energy	MDD (kN/m³)	OMC (%)	Soil Type	OSR (%)	Mixture (kN/m³)	Gain (%)
Aguiar (2019)	S	15,50	22,00	High-plasticity Clay (CH/A-7-5)	30, 40, 50	N/A	—
Araújo (2018)	S, I, M	17,60	15,60	Clayey Sand (SC/A-2-6)	2, 5	19.5 (at 2% OSR, M. Energy)	11,0
Braz (2024)	S	15,40	22,00	High-plasticity Clay (CH/A-7-6)	11.10, 25, 42.86	16.2 (at 42.86% OSR)	5,0
Dias (2024)	I	20,50	8,70	Silty Sand (SM/A-2-4)	10, 20, 30, 50	20.35 (at 10% OSR)	−1, 0
Jaffar et al. (2022)	S	17,10	14,50	Low-plasticity Clay (CL/A-6)	3, 5, 7, 9, 11, 13	18.8 (at 9% OSR)	10,0
Lunz (2021)	S	17,30	19,00	High-plasticity Silt (MH)	25, 50, 75	16.7 (at 25% OSR)	−3, 0
Lunz (2021)	S	20,50	10,00	Clayey Sand (SC)	25, 50, 75	18.9 (at 25% OSR)	−7, 0
Marques et al. (2019)	S	19,10	12,00	Sandy Soil (A-2-4)	5, 10	N/A	—
Mello (2019)	S	18,50	14,50	Silty Sand (SM/A-2-4)	5, 10, 15, 20, 25	18.2 (at 5% OSR)	−2, 0
Nascimento (2019)	S	17,20	17,50	Silty Sand (SM/A-2-4)	5, 10, 15, 20, 25	18.1 (at 20% OSR)	5,0
Oliveira (2015)	S	16,50	19,00	Clayey Sand (SC/A-2-6)	10, 20, 30, 50	17.5 (at 50% OSR)	6,0
Cardoso (2019)	S	14,40	28,10	High-plasticity Clay (CH/A-7-5)	3, 5, 7, 9	15.2 (at 7% OSR)	6,0
Farias et al. (2018)	I	19,40	10,70	Sandy Soil (A-2-4)	20, 30, 40, 50	20.96 (at 50% OSR)	8,0
Pequeno (2020)	S	14,80	24,60	Bentonite Clay (CH/A-7-5)	10, 20, 30	15.5 (at 30% OSR)	5,0

4.1.3. Atterberg limits and OSR-soil classification

Plastic (PL) and liquid (LL) limits define soil consistency and influence geotechnical behavior. The plasticity index (PI = LL − PL) quantifies plastic range. OSR integration into soils can significantly modify these Atterberg limits, altering consistency and construction performance. Studies show OSR addition causes distinct shifts in LL and PL of soil-residue blends.

Standard acceptance parameters for subgrade and subbase often specify maximum LL and PI to reduce water-induced softening. Testing protocols verify compliance (Dias, 2024). OSR-induced limit alterations can enhance or constrain usability. Granulometric and mineralogical factors intertwine with limit behavior. OSR admixture can disrupt clay aggregation, sometimes reducing soil's water retention and lowering both LL and PL Cardoso (2019). However, OSR may contribute reactive minerals or induce pozzolanic activity, subtly changing limits over time depending on interaction products. Figure 8 shows the behavior of LL, PL, PI of different studies.

Incorporating OSR into fine-grained soils significantly modifies their plasticity index and classification. Laboratory studies consistently show OSR reduces liquid limit (LL) and plasticity index (PI) of expansive soils. For example, 30% OSR can drop LL from 65% to 31%; 40% OSR to 25%. Plastic limit (PL) shifts from 25% to 15% with higher OSR content Braz (2024).

Such reductions directly lower PI. OSR introduction often decreases blows needed in the Casagrande test, reflecting stiffer, less plastic character (Mello, 2019; Braz, 2024). This signifies a fundamental change in soil consistency, transitioning soils from highly plastic (compressible, moisture-sensitive) to moderately or low-plasticity states.

Further supporting these findings, a comparative study by Sivrikaya, Kıyıldı & Karaca (2014) evaluated the effectiveness of different types of stone waste (OSR-M, OSR-G) on the stabilization of clayey soils.

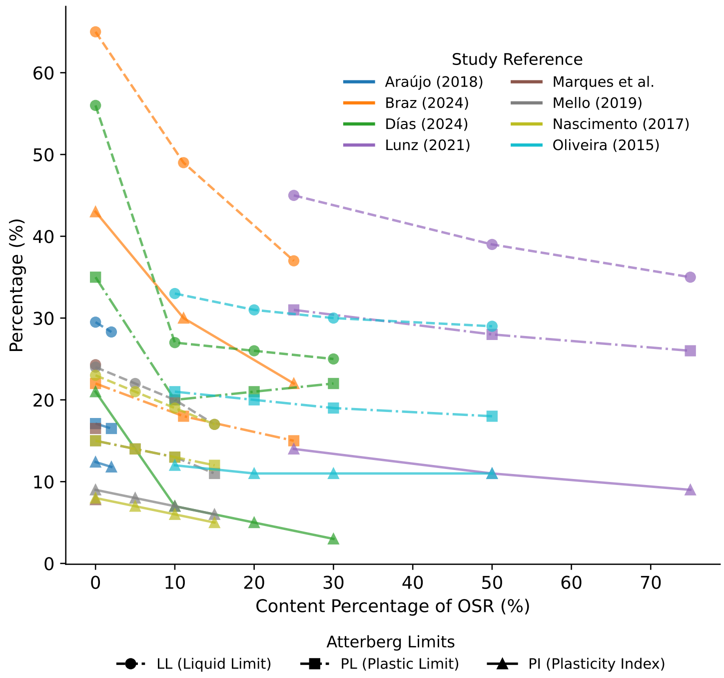

Figure 8 • Effect of OSR content on Atterberg Limits.

Their results consistently demonstrated that as the percentage of any of the waste powders increased, the liquid limit and plasticity index of the soil decreased significantly, effectively changing the soil's classification from high-plasticity clay (CH) towards low-plasticity silt (ML).

This transformation is instrumental for engineering applications where high plasticity is undesirable, like subgrades or pavement layers. Combined data illustrates that careful proportioning of OSR converts problematic soils into materials with lower PI, changed classifications, and can result in better engineering properties for modern construction Freitas (2008); Mello (2019); Nascimento (2019); Braz (2024).

4.2. Mechanical and strength properties

4.2.1. Unconfined compressive strength (UCS)

UCS of OSR-treated soils is a strength parameter which can indirectly identify its geotechnical and pavement engineering suitability, showing mechanical improvement from residue additions, allowing comparison in strength improvements with fast and low-cost lab test. OSR's chemical and mineralogical composition (quartz and calcite), alongside its non-plastic nature, influences composite material mechanical behavior, compactability, and strength (Lunz, 2021), especially when clayey soil kaolinite and illite as being dominant are mixed with the OSR. UCS relates directly to shear strength, which depends on particle interaction, arrangement, and stabilizing agents. OSR alters particle size, density, and porosity, directly impacting shear resistance (Cardoso, 2019).

Cardoso (2019) and Scherer, Knierim & Klamt (2023) investigated OSR contents from 5% up to 35% with the 20% mixture yielding the best UCS performance and the 15% OSR mixture increasing the UCS of approximately 29%, respectively.

Experimental UCS results vary with OSR proportion, type, compaction, and curing. Aguiar (2019) fixed cement content (6%) and dry specific weight (15 kN/m3) to evaluate how adding different percentages of OSR affected the UCS of the soil-cement mixture. Aguiar (2019) fixed the binder content, found that adding OSR to soil-cement mixtures progressively increased the UCS, with the 30% OSR dosage yielding a strength of approximately 380 kPa.

Proportions require optimization to balance compaction/density gains with possible reductions in bonding/coherence due to granulometric changes. Results indicate OSR's positive UCS contribution is generally inferior to traditional binders. Mixed solutions or combined stabilization strategies might be necessary for high UCS demands (Nascimento, 2019; Cardoso, 2019; Dias, 2024).

The existence of an optimal content is also observed for UCS. A study by Vikas and Ramana (2023) on the stabilization of expansive soil with OSR-G provides a clear example of this behavior. For uncured samples, they found that the UCS increased with the addition of OSR-G, reaching a peak value of 339 kPa at an optimal content of 30%. However, when the OSR content was further increased to 40%, the UCS decreased to 308 kPa, demonstrating a clear ORC for immediate strength. Interestingly, the study also revealed that for samples cured over time (7, 14, and 28 days), the UCS continued to increase up to the highest tested content of 40%. This suggests that while there may be an optimal content for short-term, compaction-related strength, long-term pozzolanic reactions could allow for the effective use of higher residue contents.

4.2.2. California bearing ratio (CBR)

The California Bearing Ratio (CBR) test is traditionally used in geotechnical engineering to evaluate the suitability of soils for application in subgrades and pavement layers. Although the current state-of-the-art recognizes more representative performance parameters, such as the MR, the CBR remains an important classificatory parameter in national and international standards. In Brazil, for instance, the DNIT 108/2009-ES (DNIT, 2009) standard specifies minimum CBR values for the final layer of embankments, which constitute the highway subgrade.

CBR is still applied in road engineering in Brazil and worldwide as at least a secondary tool for the preliminary assessment of soils and geomaterials. Its persistence is due to its low cost, simplicity of execution, and widespread familiarity among professionals, which ensures its continued presence in engineering projects and even academic research.

While direct measurement through Cyclic Load Triaxial Test (CLTT) is the standard for determining the MR, the CBR test can also serve as a valuable preliminary tool for estimating this parameter, a practice highlighted by Barrientos *et al.* (2010). In this study on pure granite residue (OSR-G), Barrientos *et al.* (2010) demonstrated a clear correlation between compaction energy, MDD and CBR.

OSR integration in subgrades alters their CBR values, with impact depending on residue content and base soil characteristics. Investigations show clayey soils (e.g., HRB/USCS A-7-6) with moderate natural CBR can exhibit enhanced bearing capacity with OSR under optimized designs (Nascimento, 2019).

Optimizing the mixture is critical, as different proportions can lead to varying outcomes. Lunz (2021) observed that a mixture with 50% OSR achieved a higher CBR than the pure soil, whereas other ratios showed no strength gain. Therefore, determining an Optimum Residue Content (ORC) through systematic laboratory testing is essential to harness the full potential of OSR for enhancing soil performance in subgrades and pavements.

4.2.3. Resilient modulus and deformability

MR evaluates soil mechanical behavior and deformation under repeated loading, as in pavement and subgrade applications. OSR integration markedly influences MR values and overall deformability. In assessing deformability, OSR introduction commonly reduces plasticity index, indicating a shift towards more granular behavior and reduced cohesive traits. This transition may suppress excessive deformation, as the modified soil matrix probably reduces plastic flow. Atterberg limits testing confirms native soil plasticity attenuates with OSR admixture, granting improved resistance to permanent deformation under repeated stress (Mello, 2019; Nascimento, 2019).

High plasticity soils are typically a problem in earthworks and pavement engineering. There are basically two mechanisms of MR improvement in high-plasticity soils. The enhancement of the MR, especially in high-plasticity soils, such as the A-7-5 and A-7-6 clays studied by Lunz (2021) and Braz (2024), is driven by two primary mechanisms: physical modification and, in some cases, chemical stabilization. Table 7 expands the discussion, compartmenting the mechanism, its description and the resulting geotechnical effect.

The next section will concentrate on the importance of MR and discuss research results of OSR applications driven to investigate its impact on the MR. In practice, MR enhancements and permanent strain reductions translate to longer service life and improved structural integrity for geotechnical loaded layers adopting OSR–soil mixtures, driven the calibration OSR proportioning investigation. ORC focusing on MR (Prandina & Farias, 2025), adopting a sequence of CLTT trials, should balance strength gain with adequate ductility for resilient yet durable performance (Cardoso, 2019) of pavement structure.

5. Cases of OSR application in pavement layers

5.1. OSR mixture as base and subbase materials

Before examining OSR in complex soil mixtures, it is instructive to understand the mechanical properties of the pure residue itself. A key study by Barrientos *et al.* (2010) provides an illustration of how compaction energy directly influences the material's density (MDD) and strength (CBR), although the long term mechanical performance of the OSR stiffness through CLTT to study its MR. It was shown that for unsaturated conditions, applying a higher compaction energy, equivalent to 60 blows with a modified Proctor hammer, resulted in a CBR of approximately 73%. Conversely, a lower energy (15 blows) yielded a CBR of 19%, which indicates clearly the energy influences compacted OSR for MDD and CBR. This illustrates the significant influence of the compaction state on the shear strength of the pure OSR, a useful observation to consider when designing mixtures for pavement layers where achieving adequate density is paramount for performance.

Dias (2024) evaluated the use of OSR in pavement layers, testing mixtures of soil (A-2-4) with 10%, 20%, and 30% OSR content. The mixture with 30% OSR was recommended for subbase application based on CBR and swelling criteria. Regarding the material characteristics, it is important to distinguish the residue type used in this specific study. While researches such as Jaffar *et al.* (2022) focused on marble waste (OSR-M), the chemical composition analysis presented by Dias (2024) —highlighting the specific balance of siliceous elements—characterizes the material adopted in these mixtures as a granite-derived residue (OSR-G). Dias (2024) interpreted the MR tests on the 70% soil and 30% OSR mixture comparing the last pair of stresses, leading to a 21% reduction compared to the reference soil (Figure 9). Despite this, this proportion showed a CBR value suitable for subbase layers considering CBR thresholds of current Brazilian codes of DNIT. For non-plastic materials, high percentages of OSR-G generally seems to reduce MR for the greater stresses, therefore limited percentages between 3 to 10% might increase MR due particle packing.

The compiled experimental findings here consistently demonstrate the technical viability of incorporating OSR into pavement base layers combined with soils and/or soil and other residue mixtures, particularly when combined with Reclaimed Asphalt Pavement (RAP), Recycled Concrete Aggregates

Table 7 • Mechanisms and geotechnical effects of OSR addition to cohesive soils

Mechanism / Concept	Description	Resulting Geotechnical Effect
Physical Modification & Granulometric Improvement	Fine, non-plastic OSR particles act as a filler, occupying voids within the aggregated structure of a cohesive soil: • Reduction of the plastic clay fraction overall influence; • Creates a denser particle skeleton with a probably better grain-to-grain contact.	• Reduced plasticity index (PI). • Reduced potential for swelling and deformation. • Increased stiffness and a higher MR.
Optimal Residue Content (ORC)	The improvement in stiffness is non-linear and depends on the OSR percentage: • Below ORC: OSR particles effectively fill voids and reinforce the soil's structure. • Above ORC: Excess fine OSR particles begin to dominate and push the soil's structural skeleton apart, reducing intergranular friction.	• Below ORC: Steady increase in MR. • At ORC: Peak (maximum) MR is achieved. • Above ORC: Decrease in MR.

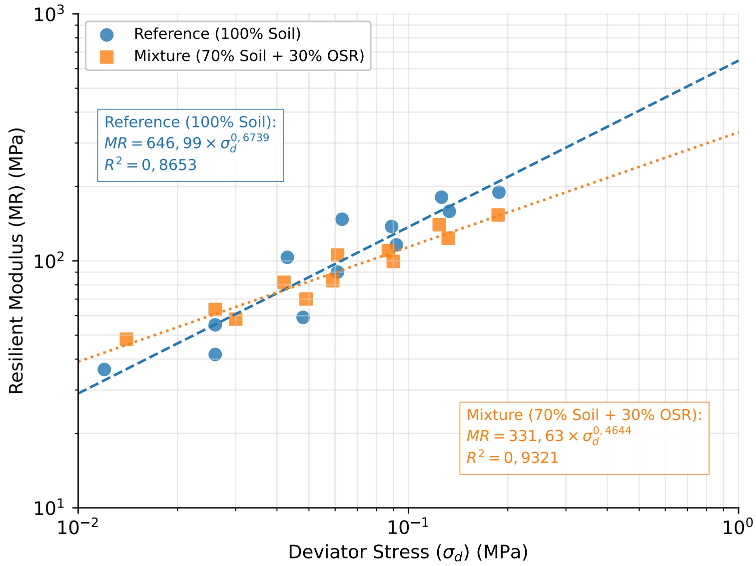

Figure 9 • MR of an A-2-4 soil mixed with ornamental stone residue from granite parent rock. Adapted from Dias (2024).

(RCA), lime or Portland cement, or in specific soil mixtures, can yield MR and CBR values that meet or exceed strength requirements for traditional base materials, making OSR a promising and sustainable alternative for road construction.

Farias, Fernandes & Espíndola (2018) evaluated OSR mixed with soil from the AL-22, a state highway. The mixtures with 20% to 50% OSR were proposed. All tested soil-OSR mixtures (20%, 30%, 40%, 50% OSR) met DNIT requirements for subbase layers (CBR $\geq$ 20% and expansion $\leq$ 1%). The 50% soil-OSR mixture showed the highest CBR, reaching 42.5%.

These studies point to the significant potential of OSR as a sustainable and effective material for granulometrically stabilized subbases in pavement construction in Brazil. These findings demonstrate that OSR-inclusive mixtures, meet or exceed the DNIT specifications for CBR and swelling.

Santos & Leandro (2017), who investigated mixtures of lateritic gravel, RAP, and OSR-G for use in bases and subbases, noted that typical MR values for traditional base materials range from 300 to 500 MPa, suggesting these mixtures are viable, once the first mix (5% OSR-G, 40% RAP, 55% gravel) studied presented a MR of 332 MPa at the base depth. By changing the amount of RAP, the second mix (5% OSR-G, 60% RAP, 35% gravel) showed an MR of 316 MPa (Figure 10).

Teixeira, Bezerra & Borges (2017b) studied similar mixtures with the CLTT, using the same OSR-G, reaching the MR of their first mixture (5% OSR-G, 50% RAP, 45% gravel) the high level of 466 MPa. The second mixture (5% OSR-G, 30% RAP, 65% gravel) reached the MR of 411 MPa. Teixeira, Bezerra & Borges (2017a) concluded these mixtures were technically viable for base or subbase layers due to the MR values found, where the addition of OSR-G up to 5% of the total mass did not compromise the MR results. All tested mixtures achieved MR values that are technically viable for use in pavement base layers. This performance suggests a clear potential for a trade-off, where OSR-G can replace a percentage of traditional aggregates without sacrificing structural integrity. Such an application is particularly valuable for infrastructure projects in urban areas, offering a sustainable pathway to reuse an industrial byproduct while reducing the demand for virgin materials.

In Brazil, DNIT Standard 139/2010-ES (DNIT, 2010) is the in-place code for granulometrically stabilized subbases, governing the criteria for design and construction of this layer. The constituent materials are soils, soil mixtures with other materials, such as residues, or mixtures of soils and crushed rock materials. The strength parameter CBR of the subbase material must surpass 20% and the swelling must be lower than 1%. In the case of lateritic soils, the materials subjected to the above tests may present a Group Index different from zero and expansion greater than 1.0%, provided that in the expansibility test they show a value inferior than 10%. This is relevant, because the granulometric criteria already have exceptions for different materials than typical natural soils.

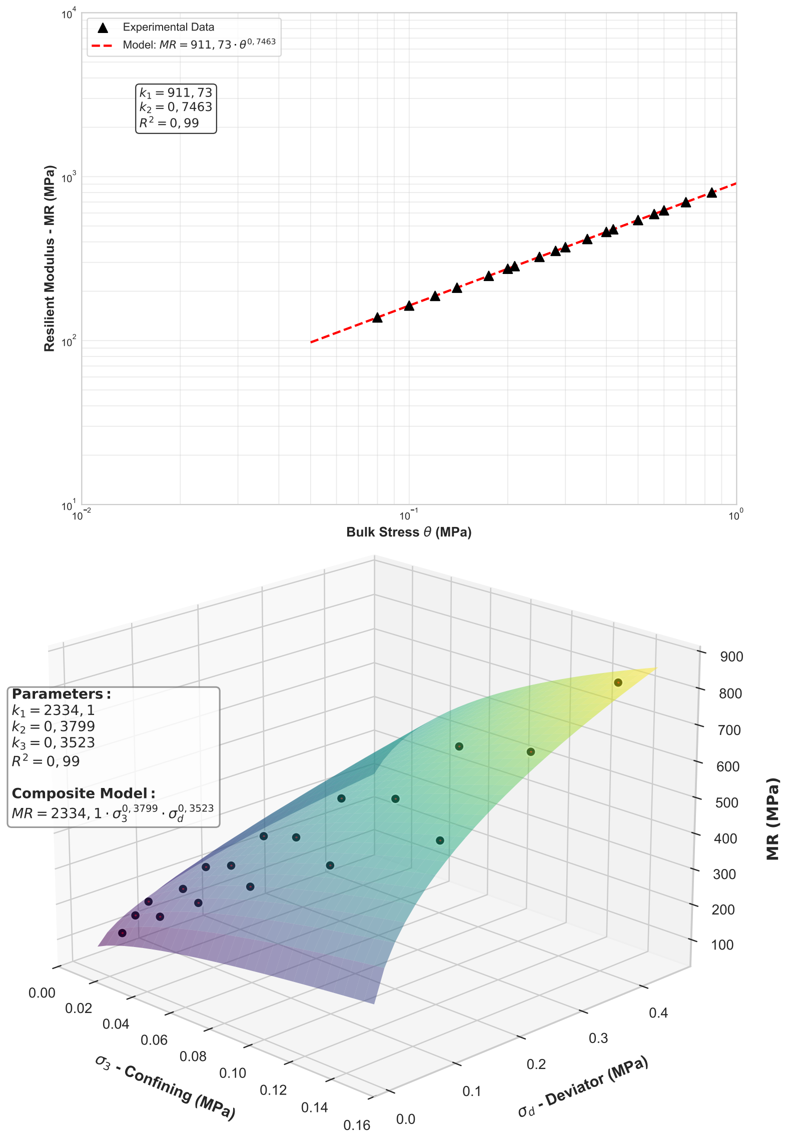

Figure 10 • MR graphs obtained from the models for first mix (5% ornamental stone residue from granite, 40% reclaimed asphalt pavement, 55% gravel): Simplified Model θ (Bulk); (ii) Composite Model. Santos & Leandro (2017).

Marques, Costa Farias & Moraes Garcia (2019) investigated the use of OSR in soil-cement blends for pavement bases, with Portland cement (PC) as a binding agent. The study's evaluation, however, was limited solely to the CBR test. Although the authors reported that adding OSR significantly increased CBR values—over 200% for some mixtures, meeting DNIT strength parameters for semi-rigid pavements—a critical limitation exists. The CBR test is not the appropriate laboratory method for chemically stabilized mixtures; such an evaluation should have been carried out using UCS tests, which is the standard for materials with cementitious behavior.

5.2. OSR mixtures as subgrade materials

Subgrades serve as the foundation for pavement layers, and in Brazilian practice, the method for their assessment has evolved to align with modern engineering principles. While empirical parameters like the CBR are still applied for certain contexts, particularly guided by standards like DNIT 108/2009-ES (DNIT, 2009), they are no longer the sole parameter for subgrade evaluation, especially for more critical infrastructure. The current official standard for federal projects is the mechanistic-empirical approach, fully implemented in the National Pavement Design Method (MeDiNa – abbreviation in Portuguese for Método de Dimensionamento Nacional). Developed by the National Department of Transport Infrastructure (DNIT) in partnership with Brazilian universities, MeDiNa represented a paradigm shift from traditional, index-based design to a performance-based system. Design of pavements in Brazil had been relying on empirical indices, the current method MeDiNa models pavement behavior using the fundamental mechanical properties of the materials. For unbound layers like the subgrade, this means the MR replaces the CBR as the primary input for characterizing the material's structural response to traffic loading. This shift towards a performance-based parameter like MR is central to the analysis of any new or alternative material, including the OSR-soil mixtures discussed in this review. Jaffar *et al.* (2022) investigated A-6 clay soil mixed with varying percentages of OSR-M by dry weight, comparing to other mixtures with lime and sand soil. The percentages tested were 3%, 5%, 7%, 9%, 11%, and 13%. These specimens were then subjected to CLTT testing to directly measure their MR. Figure 11 shows a regular MR chart for 3 different confining pressure of a A-6 soil mixed with 9% OSR-M and another mixture of soils, with 12% sand on the same A-6 soil.

The MR of the stabilized soil increased progressively from 270 MPa at a 3% addition rate to a pronounced peak value of 546 MPa at a 9% addition rate. Beyond this point, further addition of OSR-M led to a decrease in stiffness, with the MR falling to 384 MPa at 13% content (Figure 11). These results demonstrate that while OSR-M can provide a substantial improvement in subgrade stiffness—in this case, more than doubling the modulus relative to the lower addition rates—there is a clear optimal residue content (ORC).

This stiffening effect, as explained by Jaffar *et al.* (2022), is primarily a chemical process. The OSR-M, rich in calcium compounds, induces flocculation and aggregation of the clay particles, which modifies the soil structure to be more granular. Concurrently, these compounds promote the gradual formation of new cementitious bonds that bind the particles together, significantly increasing the overall stiffness.

The study also noted the significant influence of moisture content, observing that the MR values tended to decrease as the water content increased beyond the optimum for a given mix, a finding consistent with the general behavior of subgrade soils.

The results of Jaffar *et al.* (2022) also allow the concept of ORC, presented in the , revealing a distinct and non-linear relationship between the OSR-M content and the resulting A-6 subgrade stiffness.

Additional theoretical discussion on the Figure 12 as a tool for designs with any specific residue and engineering parameter is extended and represented in the Figure 13 shows the concept inherent to the use of residue on soil mixtures for earthworks and pavement layers.

In case of systematic applications of different levels of proportion on soil mixtures using residues,

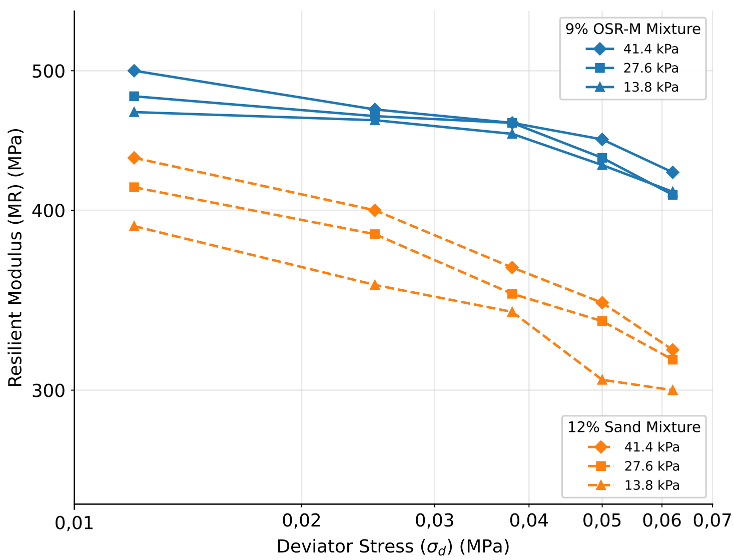

Figure 11 • MR results of: i) Optimum residue content (ORC) of ornamental stone residue from marble parent rock (OSR-M) added to A6 soil; ii) Optimum proportion of sand added to the same A6 soil. Source: Adapted from Jaffar *et al.* (2022).

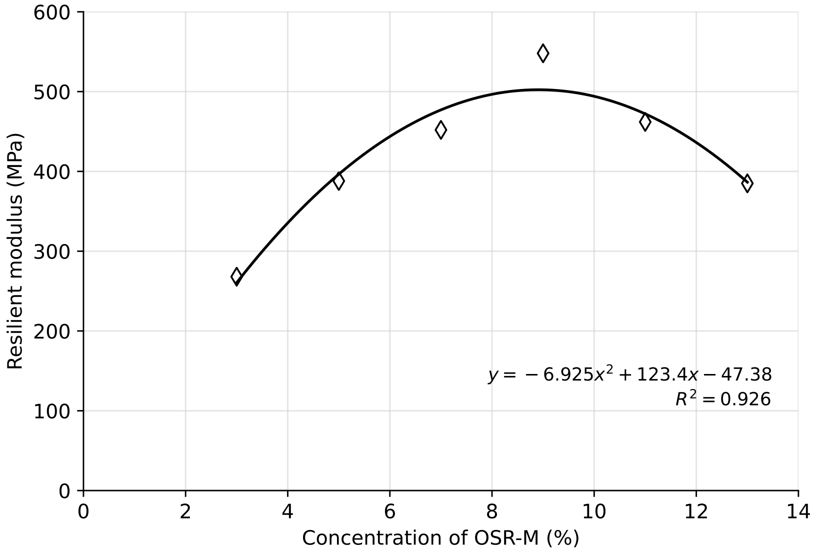

Figure 12 • Effect of ornamental stone residue from marble parent rock (OSR-M) content on the MR of an A-6 soil. Source: Adapted from Jaffar *et al.* (2022).

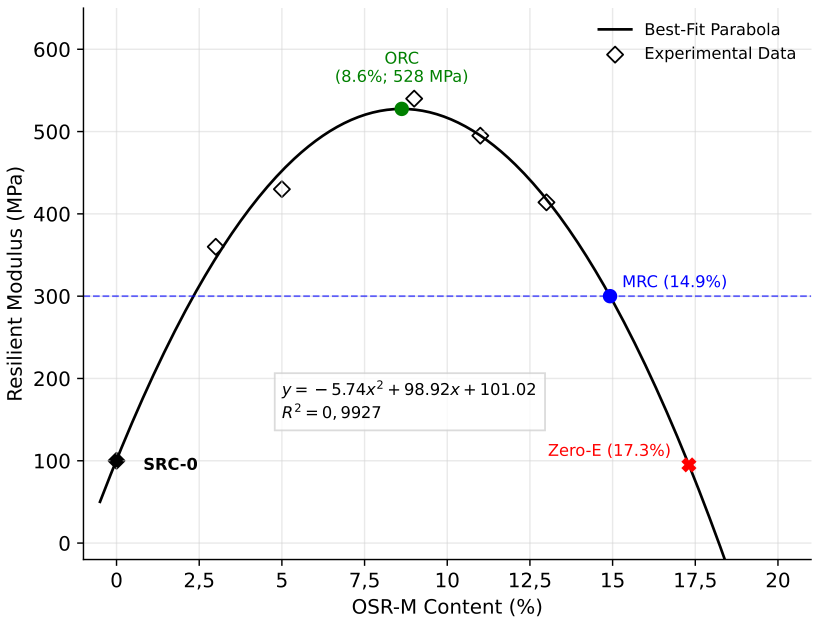

Figure 13 • Hypothetical curve of ornamental stone residue (OSR) content effect on the MR to present the design concepts of soil-residue content (SRC): optimum residue content (ORC), maximum residue content (MRC), zero equivalent residue content (Zero-E), and soil-residue content zero (SRC-0).

the soil-residue content (SRC) will range from zero, in other words, the natural soil with no residue, which can be defined as SRC-0; than it might have a minimum residue content (MiRC), which does not change the engineering parameter for less than 5% from the natural condition (SRC-0). The optimal residue content (ORC), the maximum residue content (MRC), and the zero-equivalent residue content (Zero-E) were already stated by Prandina & Farias (2025), and can also be seen in Figure 13, respectively at 8.23%, 14.9% and 17.36% for the MR.

The concept of an ORC is not unique to the mixtures studied by Jaffar *et al.* (2022). Similar behavior was observed by Eltwati *et al.* (2020), who investigated the stabilization of a high-plasticity clay soil (A-6) with granite dust. Their results showed a clear peak in mechanical performance, identifying an ORC of approximately 8% OSR, where both the CBR and MDD reached their maximum values. Beyond this optimal percentage, the CBR values began to decline, illustrating the phenomenon that necessitates the definition of a MRC for a given performance threshold. This reinforces the principle that while OSR can significantly improve soil properties, there is a distinct optimal range, beyond which the excess fine particles may begin to compromise the granular structure of the mixture.

Mello (2019) focused on the stabilization of subgrade soils using OSR; all the percentages increased the CBR, and the 25% OSR mixture reached 3.7%, an improvement over the natural soil's one of 2.3%, with all the samples increasing the CBR more than 60%.

Aguiar (2019) evaluated the strength of an expansive soil from Paulista-PE, Brazil, stabilized with Portland cement and OSR. The study focused on UCS after 7 days of curing, with residue additions of 30%, 40%, and 50% (cement content fixed at 6%). Results indicated that the OSR from marble polishing increased the soil's UCS as its content increased, compared to soil stabilized only with cement. An addition of 30% residue to the soil-cement mixture increased qu by 130 kPa compared to the soil-cement without residue, an addition of 65% in UCS.

Cardoso (2019) studied the mechanical behavior of a Guabirotuba Formation soil (often problematic for subgrades) with the addition of OSR at 3%, 5%, 7%, and 9% over cure times of 30, 60, and 90 days. Parameters included CBR, qu, qt, shear strength, and one-dimensional consolidation. The 3% OSR content generally showed the best improvement in soil properties, followed by 5% OSR. The UCS qu and qt generally increased with OSR addition (Table 8).

Scherer, Knierim & Klamt (2023) verified the stabilization of a clayey soil with OSR for pavement layers. Proportions of 15%, 25%, and 35% OSR were tested for UCS and CBR. The 15% OSR mixture showed an increase in UCS of approximately 29% compared to the pure soil. For CBR, the 35% OSR mixture showed a 23% increase compared to the pure soil. The 15% OSR mixture was deemed best for reinforcing subgrade layers due to its RCS performance.

Braz (2024) assessed the reduction of expansiveness in soil stabilized with OSR, using oedometric tests. The study investigated mixtures of expansive soil from Mossoró-RN, Brazil, with 11.10%, 25.00%, and 42.86% OSR. Results indicated that OSR has potential to mitigate soil expansivity by altering soil properties, such as reducing the clay fraction and adding non-plastic materials.

After the review of the studies, the Table 6 lump sum for case where the OSR mixed to the soil improved the geotechnical application reached 9 out of 15 cases, an overall percentage of 60% of positive results in the literature.

5.3. Synthesis of mechanical performance in Brazilian studies

The mechanical performance of OSR-soil mixtures, as detailed in the reviewed Brazilian studies, is highly dependent on the geotechnical characteristics of the parent soil. The data reveals two distinct trends based on whether the soil is granular and competent or cohesive with high plasticity and problematic.

For competent granular soils with low plasticity (e.g., A-2-4), which already possess a good structure, the addition of fine-grained OSR have complex influence on strength and deformation parameters, such as UCS and MR. When surpassing the ORC, there are clearly a negative impact because the fine residue particles replace stronger, interlocking sand and gravel particles. However, even with this reduction, the mixtures often meet the necessary criteria for subbase layers (CBR ≥ 20%), as demonstrated by Dias (2024), once not all granular soils will serve to base layers. In these cases, the engineering goal might be to determine the Maximum Residue Content (MRC) that maintains satisfactory performance, an advantageous trade-off for the environment.

Table 8 • Unconfined compressive strength (UCS) gains of different percentages of soil and ornamental stone residue (ORC) content

Study Reference	Soil Type	Compaction Energy	OSR Fraction Tested (%)	Pure Soil UCS (kPa)	Max Gain in UCS (%)	OSR % at Max Gain
Cardoso (2019)	High-plasticity Clay (CH / A-7-5)	S	3,5,7,8	172.9 (at 30 days)	32%	5%
Scherer, Knierim & Klamt (2023)	High-plasticity Clay (CH / A-7-6)	S	15,25,35	155.78	29%	15%

Conversely, for problematic cohesive soils with high plasticity (e.g., A-7-5 or A-7-6), the addition of OSR generally improves mechanical properties. The non-plastic OSR acts as a stabilizer, reducing the soil's plasticity and creating a more robust granular skeleton. This leads to an increase in UCS, as clearly shown in the studies by Cardoso (2019) and Scherer, Knierim & Klamt (2023), often with an optimal content around 5-15%. The influence on the MR is more complex; while adding too much OSR to a high-quality granular soil may decrease its stiffness, its addition to a weaker soil can provide significant gains, as observed in one of the soils tested by Lunz (2021).

6. Optimization of OSR-soil mixtures for geotechnical solutions

6.1. Determination of optimal and maximum residue content

For a targeted improvement, it is essential to determine the ideal proportion of OSR. This involves identifying key thresholds, as proposed by Prandina & Farias (2025): the ORC, which maximizes a specific geotechnical parameter (e.g., strength or stiffness); the MRC, the highest proportion of OSR that meets minimum performance criteria; and Zero-E, the maximum OSR content that equalizes a parameter to that of the pure soil. The selection among these thresholds depends on a strategic balance between maximizing residue use and achieving project-specific engineering properties.

The scientific determination of ORC and MRC is a multidimensional task. It requires strategically combining laboratory evaluation of key performance metrics (Atterberg limits, MDD, CBR, UCS, MR), granulometric modeling, and chemical compatibility assessments, while also considering the local availability of materials. The final choice may be guided by different strategies, such as maximizing mechanical performance or minimizing life cycle costs and environmental impact.

6.2. Influence of curing time

The influence of curing time on the mechanical properties of OSR-soil mixtures is not uniform and is fundamentally linked to the residue's parent rock mineralogy. Granite-derived OSR (OSR-G), being rich in crystalline quartz and other silicates, is largely chemically inert. Any potential for time-dependent strength gain would likely stem from slow pozzolanic reactions, which require an alkaline environment and the presence of reactive soil minerals.

In contrast, marble-derived OSR (OSR-M) is rich in calcium carbonate. This composition provides a source of calcium that can participate in more rapid cementitious reactions with aluminosilicates from clayey soils, potentially forming bonds that increase the mixture's strength and stiffness over time, as observed in studies with extended curing periods like Cardoso (2019). Therefore, a significant curing effect is more probable in mixtures containing OSR-M or residues from processes involving lime, whereas mixtures with OSR-G may exhibit more stable, immediate strength with limited long-term gains unless a chemical stabilizer is also introduced.

This time-dependent strength gain was clearly demonstrated by Cardoso (2019), who observed significant increases in both UCS and CBR in OSR-soil mixtures over a 90-day curing period. Similarly, Scherer, Knierim & Klamt (2023) noted that CBR values tended to increase with curing time. This evidence confirms that the strategic management of curing time can maximize the mechanical advantages of OSR inclusion, ensuring the long-term efficacy of the stabilized material in civil infrastructure applications.

7. Conclusions

The analysis of incorporating OSR into soil mixtures for geotechnical applications, as detailed in this paper, confirms its potential as a valuable and sustainable resource for pavement engineering. Importantly, its environmental classification as a Class II-B (non-hazardous and inert) residue reinforces its safe profile for engineering reuse.

The physical and chemical characterization of OSR revealed it to be a fine-grained, predominantly silty material, typically classified as ML (USCS) or A-4/A-6 (AASHTO), whose mineralogical properties are directly dependent on the parent rock, such as granite or marble, and which exhibits a distinct chemical behavior, including a high initial alkalinity that stabilizes through carbonation.

This study demonstrated that the addition of OSR to soils significantly modifies their geotechnical properties. A consistent reduction in Atterberg limits (LL, PL, PI) can be typically observed, which improves the workability and decreases the moisture sensitivity of problematic soils. Regarding compaction parameters, the behavior of the soil-OSR mixture is complex, although the majority of the literature shows MDD increasing and OMC diminishing, varying according to the soil-residue content (SRC) and characteristics of the constituent materials.

In terms of mechanical performance, the incorporation of OSR resulted in improvements in key indicators such as MR, UCS, and CBR. The practical application of these results revealed the viability of using soil-OSR mixtures in earthworks and pavement layers, frequently meeting the standard criteria for subgrade and subbase.

The OSR use in base layers also proved promising, especially when it is combined with other materials and residues, such as Portland cement, lime, RAP, etc.

ORC and MRC of these mixtures arise as strategies to a successful application, making the determination of an ORC that maximizes the desired mechanical performance a fundamental design strategy. Additionally, curing time can positively influence the strength properties of the mixtures, especially in the presence of cementitious reactions.

While this review confirms the technical viability and benefits of using OSR in geotechnical applications, several avenues for future research are recommended to advance its practical implementation. Future studies should focus on the long-term performance and durability of soil-OSR mixtures under realistic environmental and loading conditions to ensure their service life in pavement structures. Furthermore, the development of optimized mix design models, incorporating artificial intelligence and machine learning techniques, could streamline the determination of ORC and MRC for varying soil types and residue characteristics.

Finally, comprehensive Life Cycle Assessments (LCAs) are essential to quantitatively compare the environmental and economic impacts of geotechnical solutions using OSR against traditional methods, thereby providing robust data to support its adoption as a sustainable construction material.

In summary, this study consolidates the evidence that OSR, when properly characterized and proportioned, is transformed from an environmental liability into an effective engineering material. Its utilization contributes to the construction of more resilient and sustainable geotechnical infrastructure, aligned with the principles of the circular economy.

CRediT authorship contribution statement

João Renato Remede Prandina: Methodology, Resources, Investigation, Data curation, Writing – original draft; *Márcio Muniz de Farias*: Supervision, Resources, Writing – review & editing.

Use of artificial intelligence-assisted technology

Use of artificial intelligence tools in the research process: generation and editing of figures using Gemini to generate Python codes; grammatical correction; and verification of in-text citations and reference lists.

Competing interests statement

No competing interests have been declared with regard to this paper or its contents.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon request.

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