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EVALUATION OF THE SOIL MECHANICAL BEHAVIOR AFTER THE INCORPORATION OF CIVIL CONSTRUCTION WASTE AND SISAL FIBERS

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RESUMO

Civil construction represents one of the most important economic sectors in Brazil, generating several jobs and providing infrastructure projects that improve life in society. However, the sector has some negative aspects, especially when linked to the environment, due to the high consumption of natural resources and high waste generation. Thus, the present work aims to evaluate the soil behavior of a slope located in Recife, Pernambuco (Brazil), after adding Civil Construction Waste (CCW) and sisal fibers. Initially, the necessary materials were collected, such as soil, recycled aggregate, and sisal fibers. Then, physical and mechanical characterization tests were carried out, including compaction and simple compression, in addition to mineralogical characterization tests. Finally, a statistical analysis of the results obtained with simple compression was performed using the RSM, Response Surface Methodology. The tests were carried out for composites formed by soil; soil and residue; soil, residue and fiber; and soil and fiber in different percentages. The physical characterization showed that the soil under study corresponds to a sandy clay with low plasticity. The compaction test revealed that the percentage increase of fibers reduced the maximum dry density of the mixtures and increased the optimum moisture content. The simple compression test showed an increase in strength for the mixtures after adding fibers for the curing periods of 7, 28, and 60 days. The composite formed by soil and fiber (0.50%) showed the best results, with a percentage increase of 36.60%, 69.10%, and 58.70%, when compared to natural soil, for the curing times of 7, 28, and 60 days, respectively. Statistical analysis provided the composite contents resulting from the optimization of the materials, with values of 16.16% for the residue, 0.50% for the fiber, and 60 days for the curing time. Thus, it is concluded that the results were satisfactory from a technical and environmental point of view for the use of waste and sisal fibers as alternative elements for soil reinforcement.

Keywords: soil resistance; risk areas; construction; recycled waste.

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AVALIAÇÃO DO COMPORTAMENTO MECÂNICO DO SOLO APÓS A INCORPORAÇÃO DE RESÍDUOS DA CONSTRUÇÃO CIVIL E FIBRAS DE SISAL

RESUMO

A construção civil representa um dos setores econômicos mais importantes do país, sendo responsável por gerar diversos empregos e fornecer projetos de infraestrutura que melhoram a vida em sociedade. Entretanto, o setor apresenta alguns aspectos negativos principalmente quando estão ligados ao meio ambiente, devido ao elevado consumo de recursos naturais e a alta geração de resíduos. Dessa forma, o presente trabalho tem o objetivo de avaliar o comportamento do solo de uma encosta localizada no município de Recife/Pernambuco (Brasil), após a adição de Resíduos da Construção Civil (RCC) e fibras de sisal. Inicialmente foi realizada a coleta dos materiais necessários, como solo, agregado reciclado e fibras de sisal, em seguida foram realizados ensaios de caracterização física e caracterização mecânica, incluindo compactação e compressão simples, além dos ensaios de caracterização mineralógica. Por fim, foi realizada uma análise estatística dos resultados obtidos com a compressão simples através da metodologia RSM (*Response Surface Methodology*). Os ensaios foram realizados para os compósitos formados por solo; solo e resíduo; solo, resíduo e fibra; e solo e fibra em diferentes percentuais. A caracterização física mostrou que o solo em estudo corresponde a uma argila arenosa com baixa plasticidade e o ensaio de compactação revelou que o aumento do percentual de fibras reduziu a densidade seca máxima das misturas e aumentou a umidade ótima. O ensaio de compressão simples revelou um acréscimo de resistência nas misturas após a adição de fibras para os períodos de cura de 7, 28 e 60 dias. O compósito formado por solo e fibra (0,50%) demonstrou os melhores resultados, apresentando um aumento percentual de 36,60%, 69,10% e 59%, quando comparados ao solo natural, para os tempos de cura de 7, 28 e 60 dias, respectivamente. A análise estatística forneceu os teores do compósito resultante da otimização dos materiais, sendo encontrado os valores de 16,16% para o resíduo, 0,50% para a fibra, e 60 dias para o tempo de cura. Desta maneira, conclui-se que os resultados foram satisfatórios do ponto de vista técnico e ambiental para a utilização de resíduos e fibras de sisal como elementos alternativos para o reforço do solo.

Palavras-chave: resistência do solo; áreas de risco; construção civil; resíduo reciclado.

EVALUACIÓN DEL COMPORTAMIENTO MECÁNICO DEL SUELO TRAS LA INCORPORACIÓN DE RESIDUOS DE LA CONSTRUCCIÓN Y FIBRAS DE SISAL

RESUMEN

La construcción civil representa uno de los sectores económicos más importantes del país, siendo responsable de generar diversos empleos y brindar proyectos de infraestructura que mejoren la vida en sociedad. Sin embargo, el sector presenta algunos aspectos negativos, especialmente cuando se vincula con el medio ambiente, debido al alto consumo de recursos naturales y la alta generación de residuos. Por lo tanto, el presente trabajo tiene como objetivo evaluar el comportamiento del suelo en un talud ubicado en el municipio de Recife/Pernambuco (Brasil), después de la adición de Residuos de la Construcción (RCC) y fibras de sisal. Inicialmente se recolectaron los materiales necesarios, como tierra, áridos reciclados y fibras de sisal, seguido de ensayos de caracterización física y caracterización mecánica, incluyendo compactación y compresión simple, además de ensayos de caracterización mineralógica. Finalmente, se realizó un análisis estadístico de los resultados obtenidos con compresión simple mediante la metodología RSM (Response Surface Methodology). Los ensayos se realizaron para compuestos formados por suelo; suelo y residuos; suelo, residuos y fibra; y tierra y fibra en diferentes porcentajes. La caracterización física mostró que el suelo en estudio corresponde a un arcilloso arenoso de baja plasticidad y la prueba de compactación reveló que el aumento en el porcentaje de fibras redujo la densidad seca máxima de las mezclas y aumentó la humedad óptima. La prueba de compresión simple reveló un aumento de resistencia en las mezclas luego de la adición de fibras por periodos de curado de 7, 28 y 60 días. El compuesto formado por tierra y fibra (0,50%) demostró los mejores resultados, presentando un incremento porcentual de 36,60%, 69,10% y 59%, respecto al suelo natural, para tiempos de curado de 7,28 y 60 días, respectivamente. El análisis estadístico proporcionó los contenidos del composite resultante de la optimización de los materiales, encontrando valores de 16,16% para el residuo, 0,50% para la fibra y 60 días para el tiempo de curado. Por lo tanto, se concluye que los resultados fueron satisfactorios desde el punto de vista técnico y ambiental para el uso de residuos y fibras de sisal como elementos alternativos para el refuerzo del suelo.

Palabras clave: resistencia del suelo; zonas de riesgo; construcción civil; residuos reciclados.

INTRODUCTION

The construction materials industry acts as an engine for the economy of many countries, being one of the most important economic sectors for society (YARAS *et al*., 2021). The civil construction sector is connected to technological and innovative advances that strengthen social transformations and are related to economic development (SILVA, 2017; SANTOS, 2020).

However, the growth in the sector has been a concern for some governmental and social sectors due to the environmental damage generated by the high consumption of natural resources and the high generation of waste (SANTOS; MARCHESINI, 2018; TAVARES *et al*., 2018). One of the major problems linked to the high volume of waste produced is related to the deposition of these materials in irregular places, such as slopes, hills, streams, and riverbeds; thus, creating a serious problem for the natural environment and the quality of life of the population (OLIVEIRA *et al*., 2016; YUAN, 2017).

According to Velardo *et al*. (2021), one of the biggest difficulties related to this theme is the scarcity of areas suitable for use as a landfill for waste generated during the construction, maintenance, and/or demolition of structures. Governments, organizations, and civil society are increasingly concerned about the environmental damage suffered by the natural environment as a result of the high volume of waste produced, harming the current generation and compromising future generations.

Thus, waste management presents itself as a very present tool in political, social, environmental, and academic discussions, occupying a relevant position as an instrument of urban planning (SANTOS; MARCHESINI, 2018; CORDON; CAGNONI; FERREIRA, 2019). For Cordon, Cagnoni e Ferreira (2019), the recycling of waste at any stage of construction is essential to provide sustainable development in this sector. In addition, it reduces the use of natural resources, following the requirements of the mandates of environmental preservation According to Gottsche e Kelly (2018) and Yucenur e Senol (2021) the development of techniques that reduce waste favors cost reduction and increases process efficiency.

Nuaklong *et al*. (2021) describe that the addition of granite waste to replace natural sand provides a proper behavior to concrete, mainly in terms of strength gain; thus, it presents an environmentally adequate destination for these wastes. In this way, the reuse of these materials represents an alternative for reducing environmental problems, conserving natural resources, and reducing the load on landfills (MOHAMMED; ELKADY; ABDEL-GAWWAD, 2021).

> Irregular waste disposal is a problem that mainly affects large urban centers, which already suffer from other difficulties arising from the accelerated urbanization that leads to social issues, such as the lack of suitable areas for housing (MANTOVANI, 2016; SANTOS; FALCÃO; LIMA, 2020).

The intense migratory flow, mainly in large cities, was not accompanied by urban public planning and housing policies capable of meeting the demand for housing (SANTOS; FALCÃO; LIMA, 2020). Therefore, places naturally considered risk areas, such as hills, valley bottoms, and areas susceptible to flooding, are now occupied by the population, increasing the risk of various natural disasters (ALBUQUERQUE, 2016; OLIVEIRA; GIUDICE, 2017; MELLO, 2018).

For Mantovani (2016), accelerated urbanization brings disorganized growth and shows how unprepared urban spaces are to absorb population demand in the core aspects of infrastructure. According to Gerscovich (2016) and Mello (2018), human action in these places acts as an inducing cause for the increase in shear stresses mobilized in the soil and reducing its shear strength, increasing the risk of natural disasters.

Consequently, the relevant role that civil engineering plays in the proper disposal of waste produced by this sector, as well the reduction of natural disasters such as landslides, is notorious. In this sense, this research aims to find a feasible soil reinforcement technique, using recycled aggregate and sisal fibers, for a slope located in Recife (Brazil). The slope suffered a landslide process due to pouring rains that occurred in the winter period in 2019. It resulted in the death of one of the residents, in addition to causing several economic, social, and environmental damages to the area.

The research was carried out from laboratory tests with the joining of soil removed from the site, Civil Construction Waste (CCW), and sisal fibers, analyzing the use of these materials in different percentages. Natural fibers have the property of improving the performance of composites, especially after the peak of the compression test; however, they must be used in adequate proportions to maintain the workability of the materials and provide a gain in strength (LI *et al*, 2022).

The soil reinforcement comprises an antique technique and is performed to improve the geotechnical characteristics that the soil presents, maximizing them (MOUSAVI, KARAMVAND, 2017). Soil reinforcement with the application of fibers comprises a technique used in civil engineering and aims to add a material with high tensile strength, increasing soil strength and reducing its compressibility (MORANDINI; SCHNEIDER, 2017).

The application of fibers in the soil can provide changes in the characteristics of compaction, deformation, the appearance of cracks, and strength in soil simple compression and shear tests (SILVEIRA, 2018). The increase in soil strength, after the addition of fibers, can occur due to the appearance of an apparent cohesion intercept or due to an increase in the friction angle of the material. Fibers provide greater strength and ductility to the material depending on the adhesion that occurs between the fiber and the matrix (SILVEIRA, 2019).

METHODOLOGY

Relevance of the study and characterization of the area

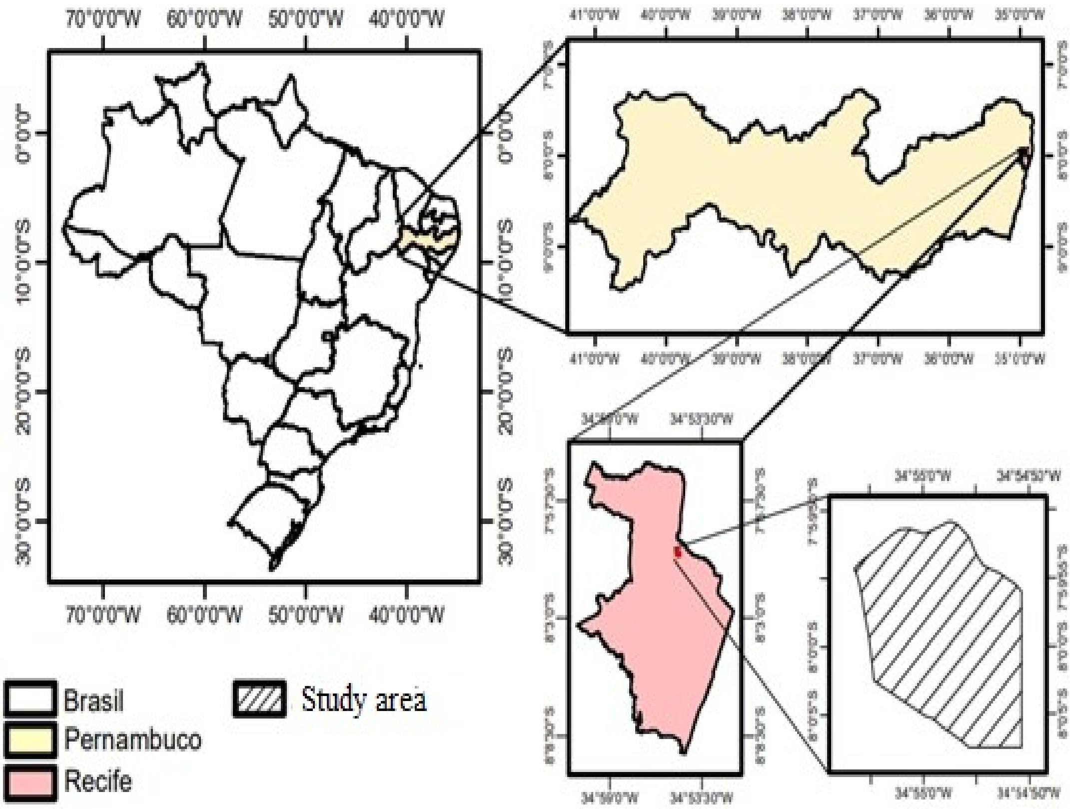
Recife is a city located in the state of Pernambuco/Brazil, which represents one of the main urban centers in the Brazilian Northeast, with an economy mainly based on the tertiary sector. The city is marked by an unbridled anthropic occupation of hills and slopes, places naturally considered risk areas, which reveal traces of the absence of urban planning, mainly by government entities.

The high rainfall usually occurs between the months of April and August, contributing to the reduction of soil resistance and increasing the risk of landslides. The landslide analyzed in this study took place in July/2019, causing the death of one of the residents and several environmental, social, and economic damages (APRÍGIO, 2019).

Given the above, the role that civil engineering plays in reducing natural disasters, such as landslides on slopes, and in the environmentally correct disposal of waste produced by this sector is evident. Thus, several types of research have been emerging to unite materials with different characteristics to reinforce the soil in a way that they complement each other, providing an improvement in the material's geotechnical properties and enabling the recycling of waste.

The area selected for study is in the city of Recife/PE (Brazil), in the Dois Unidos neighborhood, at coordinates 7º 59' 52" S and 34º 54' 57" W, on the street Córrego do Curió, and is part of Administrative Political Region II – RPA 2 A (figure 1). The Dois Unidos neighborhood has an area of approximately 3.12 km² and 32,805 inhabitants (PREFEITURA MUNICIPAL DO RECIFE, 2021).

Figure 1 - Area selected for study, Recife, Pernambuco, 2021



Authors (2021)

Materials

The soil was collected from a slope located in the municipality of Recife/PE, in the neighborhood of Dois Unidos, which recently suffered a mass landslide. About 150 kg of soil were collected and taken to the laboratory of the University of Pernambuco, where the material was chipped and homogenized following the specifications of the NBR 6457 standard (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS – ABNT, 2016).

Civil Construction Waste (CCW) was collected from a waste processing plant located in the municipality of Camaragibe/PE. About 250 kg of material were collected, including, for example, mortar, bricks, and concrete. Sisal was obtained in strips to facilitate the fiber production process. After extensive research in other studies that worked with a similar theme, the length of 30 mm for sisal fibers was adopted.

The studied samples were prepared under the NBR 6457 standard (ABNT, 2016) for the performance of granulometry, real density, Atterberg limits, compaction, and simple compression tests. The composites were formed by joining soil, recycled aggregate, and sisal fibers in different percentages (Table 1).

Table 1 – Composites, Recife, Pernambuco, 2020

Composites	**Percentages (%)**		
	Soil	**CCW**	**Sisal fiber**
Natural soil	100	-	-
SR30	70	30	-
SR50	50	50	-
SR30F0,25	69,75	30	0,25
SR50F0,25	49,75	50	0,25
SF0,25	99,75	-	0,25
SF0,50	99,50	-	0,50

Authors (2021)

Experimental methods

After the material preparation stage, physical characterization and mechanical characterization tests were carried out following the guidelines presented by the technical standards of the Brazilian Association of Technical Standards (ABNT).

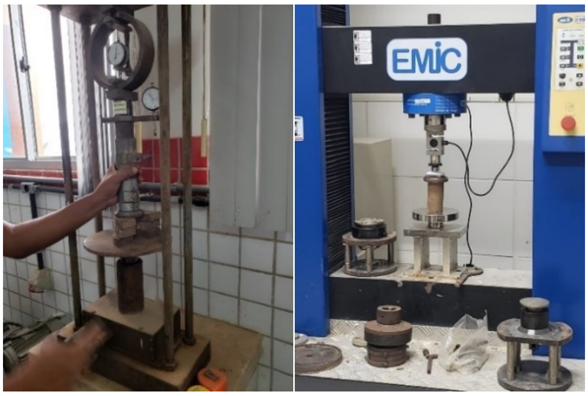
The determination of the granulometric composition of the soil, recycled aggregate, and SR30 and SR50 composites was carried out following the specifications in NBR 7181 (ABNT, 2016), allowing the identification of percentages of clay, silt, sand, and gravel. The composites under study were classified according to the Unified Soil Classification System (SUCS) and the Transportation Research Board – TRB.

The determination of the specific mass of soil, residue, and composites SR30 and SR50 followed the test execution recommendations provided by NBR 6458 (ABNT, 2016). The Atterberg limits obtained were the plasticity limits and liquidity limits, following the guidelines presented by NBR 7180 (ABNT, 2016) and NBR 6459 (ABNT, 2017), respectively.

The compaction test of materials was carried out for all composites, according to the guidelines of NBR 7182 (ABNT, 1992), aiming to obtain the maximum dry density and optimal moisture. The molding of the specimens for compaction was carried out with material reuse. The energy used in the molding was the Normal Proctor energy, using a small cylinder with 26 strokes applied to each layer, with 3 layers.

The simple compression test was performed for all studied composites and followed the NBR 12770 specifications (ABNT, 1992). The molding of the specimens was performed statically (Figure 2).

Figure 2 - Simple compression test: static molding (a) and breaking of specimens (b), Recife, Pernambuco.



(a) (b)

Authors (2021)

The mineralogical characterization was carried out using binocular magnifying glass tests, allowing an analysis of the sand fraction of the soil and the residue. The x-ray diffraction test (XRD) allowed the identification of the finest particles in the soil and the residue.

According to Garcia (2015), the clay fraction present in the material is a relevant factor to identify the potential for altering the physical attributes of the soil. The mineralogical study allows a deeper understanding of some aspects of the soil, such as plasticity, strength, and material expandability (MACEDO, 2013).

Response Surface Methodology (RSM)

Statistical analysis is essential for optimizing the content of materials incorporated into the soil. For that, the Response Surface Methodology (RSM) methodology was used. It consists of a set of statistical and mathematical techniques for project optimizations GÜNEYISI *et al*., 2014; WANG; CHENG; TAN, 2018; WANG *et al*., 2021). According to Gelis and Akyurek (2021), the RSM methodology represents a technique widely used in experimental projects aiming at obtaining system efficiency and optimizing the data provided.

The model seeks to identify the contribution of each independent variable to the result and how it can change during the process (YU; BATHURST, 2017). According to Güllü and Fedakar (2017), statistical modeling presents an adequate way to obtain the optimization content of materials, which is fundamental for reducing time and cost.

The coefficients are calculated based on the regression of a numerical test on the probabilistic distributions of the independent variables, identifying the potential influence that these variables have on the system's response (SCHOEFS; LE; LANATA, 2013).

According to Amiri *et al*. (2022), the consideration of mechanical properties is of particular importance for the optimization of material contents. In this research, the dependent variable used was the simple compressive strength, while the independent ones were the CCW content, the sisal fiber content, and the curing time. Finally, the adequacy of the model was verified through a box diagram or box plot, analyzing the variability and standard deviation of the data.

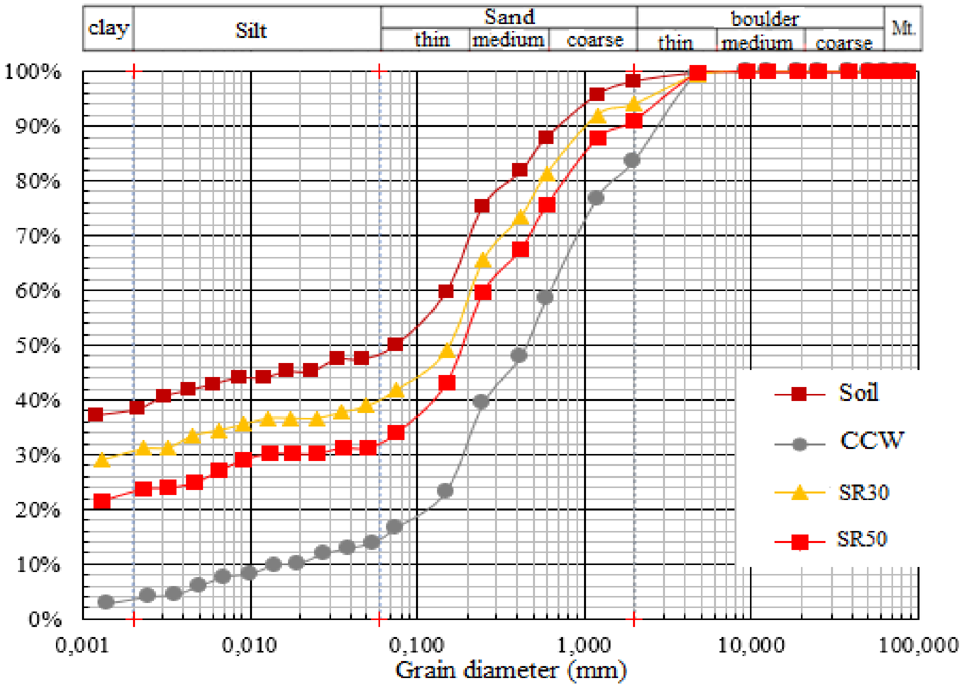
All statistical analysis was performed with the aid of Minitab Statistical Software (version 19.0), allowing the application of the RSM method. The main variables interfering in the optimization of the model are the curing time, residue content, and fiber content.

RESULTS AND DISCUSSION

Physical characterization

The particle size analysis was performed for the soil, for the RCC, and the composites formed by the junction of residue and soil (SR30 and SR50). Figure 3 shows the granulometric curves obtained for the mixtures. Table 2 shows the percentages of each granulometric fraction obtained from the tests and Table 3 presents the classification of materials according to the Unified Soil Classification System (SUCS) and according to the Transportation Research Board (TRB).

Figure 3 - Granulometric curves.



Authors (2021)

Table 2 -Granulometric fraction.

Mixtures	Clay (%)	Silt (%)	Sand (%)	Boulder (%)	Silt/clay ratio
Soil	38,30	9,70	50,26	1,74	0,25
SR30	31,12	8,88	54,02	5,98	0,28
SR50	23,50	8,50	59,09	8,91	0,36
CCW	3,50	10,60	69,51	16,39	3,03

Authors (2021)

Table 3 - Classification of materials according to SUCS and TRB.

Mixtures	Classification SUCS	Classification TRB
Soil	Sandy Clay – CL	Clay (A-6)
SR30	Clayey Sand – SC	Silt soils (A-4)
SR50	Clayey Sand – SC	Boulders and silty or clayey sands (A-2-4)
Recycled aggregate (CCW)	Well-graded Sand – SW	Stone fragments, boulders, and sand (A-1-b)

Authors (2021)

The soil was classified by SUCS as a sandy clay with low plasticity (CL), while the recycled aggregate was classified as a well-graded sand (SW). According to the TRB, the soil used belongs to group A-6, which indicates a material with poor behavior to be used as a paving subgrade. As the residue was added, its classification improved, indicating a more suitable behavior for use in paving.

The silt/clay ratio, which, according to Santos and Zaroni (2019), allows us to assess the degree of weathering suffered by the soil and its vulnerability to erosion, increased with the addition of residues, indicating a better behavior against the action of external agents.

The actual density presented the value of 2.68 g/cm³ for the soil; 2.61 g/cm³ for the SR30 blend; 2.59 g/cm³ for the SR50 mixture, and 2.48 g/cm³ for the residue. The results of the Atterberg limits are in Table 4. The values obtained were close to the results found by (SANTOS,2020; NASCIMENTO, 2019; PORTELA, 2019; MACEDO, 2013).

Table 4- Atterberg limits

Sample	LL (%)	LP(%)	IP (%)	Classification
Natural Soil	40.13	21.50	18.63	Highly plastic
SR30	31.72	21.73	9.99	Averagely plastic
SR50	28.21	19.69	8.52	Averagely plastic
Waste	-	-	-	-

Authors (2021)

Mechanical characterization

In the compaction test, it was possible to see that the addition of recycled aggregate in the mixtures increased the maximum dry density and reduced the optimum moisture content. In this way, the presence of granular materials, when compacted, provides higher specific weights and lower optimum humidity due to a better accommodation of particles, generating more compact, resistant, and durable materials (MACEDO, 2013).

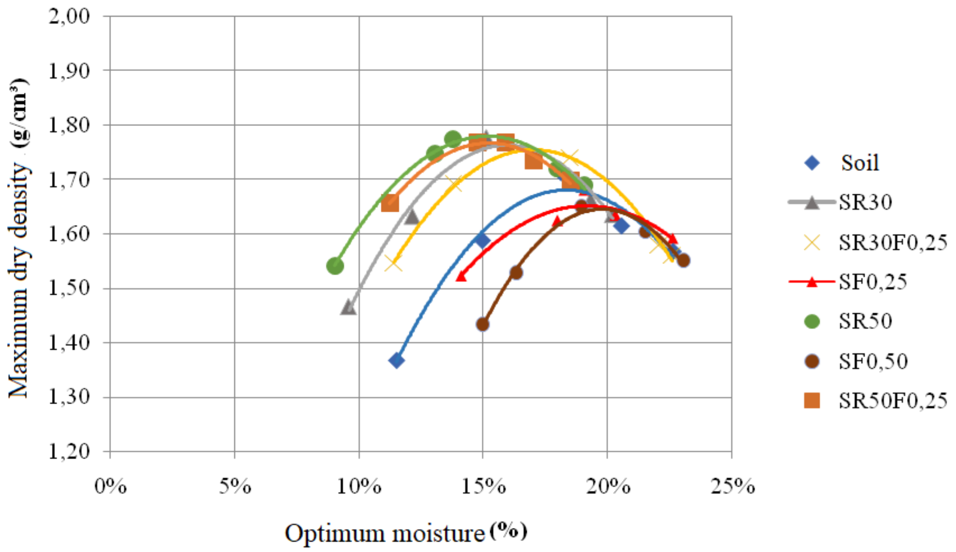
The optimum moisture content of the mixtures increased after the addition of sisal fibers. This behavior can be explained by the ability of the fibers to pile up in the soil, forming conglomerates that retain water and hinder the homogenization process (LIMA *et al.*, 2016). Table 5 presents the values found for the optimum moisture and maximum dry density with the compaction test, and Fig. 4 presents the compaction curves of the mixtures for comparative purposes.

Table 5 - Optimum moisture and maximum dry density.

Mixtures	Wot (%)	γs (g/cm³)
Soil	18,35	1,680
SR30	15,93	1,763
SR50	15,16	1,780
SR30F0,25	17,01	1,756
SR50F0,25	15,24	1,767
SF0,25	19,16	1,653
SF0,50	19,78	1,645

Authors (2021)

Figure 4 - Compaction curves.



Authors (2021)

The determination of the simple compressive strength (SCR) was performed for each composite and the curing periods of 7, 28, and 60 days. Table 6 presents the strength values obtained by the mixtures according to the curing time.

Table 6 - Simple compressive strength values.

Mixtures	7 days (kPa)	28 days (kPa)	60 days (kPa)
Soil	211,76	317,65	542,15
SR30	257,20	328,90	671,10
SR50	203,50	242,15	525,50
SR30F0,25	268,03	342,60	702,35
SR50F0,25	228,75	322,34	578,75
SF0,25	278,22	396,50	724,50
SF0,50	289,15	537,10	860,15

Authors (2021)

At 7 days of curing, the maximum strength of composites formed by residue and fiber exceeded the resistance found for the soil, and among the composites, the one that obtained the best result was the one formed by soil and fiber at a content of 0.50%, providing an increase in strength of 36.60% when compared to natural soil. Figure 5 shows the strength curves for composites with a 7-day curing period.

The composite formed by soil and 0.50% fiber also showed the best result for the 28-day curing period, providing a 69.10% gain in strength when compared to natural soil. The natural soil showed strength gain in the first 4 mm of deformation, while the soil with fiber at 0.50% showed strength gain up to the initial 7 mm before starting the decline in values. Figure 6 shows the simple compression curves formed by the materials with a 28-day curing period.

The materials also showed similar behavior at 60 days, reaching maximum strength of 860.15 kPa for the composite formed by soil and fiber at 0.50% content. This value represents a 58.70% increase in strength when compared to natural soil for the same curing period. Figure 7 shows the behavior of the composites' compression curves at 60 days.

The work carried out by Santos (2020), applying the soil reinforcement with natural babassu coconut fibers and residues, showed similar results since the mixture with the greatest increase in strength was that formed by soil and fiber at 1% content (maximum content of fibers studied by the author). According to Silveira (2019), the addition of fibers to the soil ends up forming an intercept of apparent cohesion and/or increasing the friction angle of the material.

With the results found, it is possible to see that the increase in the curing period and fiber content increased the strength of the composites in all situations, while the addition of recycled aggregate raised the strength only up to a certain point, after which the decline, since the composites formed by 50% of residue showed reduced resistance when compared to natural soil.

Figure 5 - Simple compression curves for mixtures with 7-day curing period.

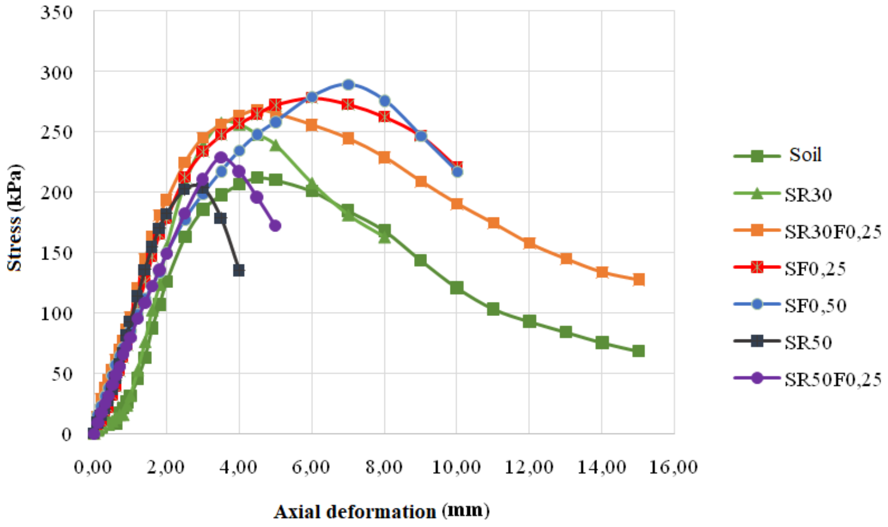


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Figure 6 - Simples compression curves for mixtures with 28-day curing period.

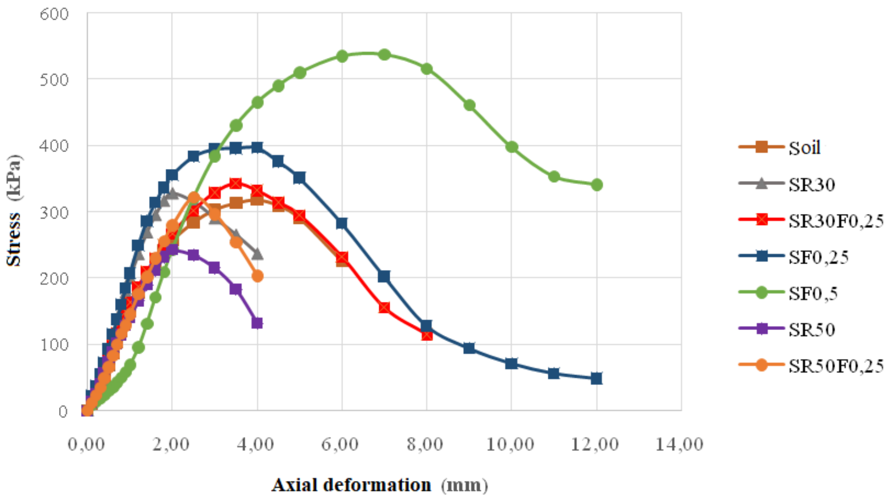

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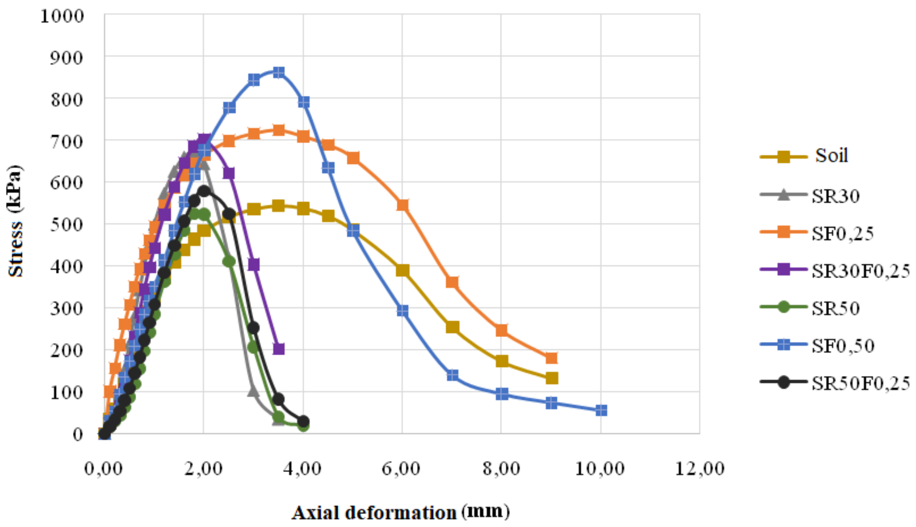
Figure 7 - Simples compression curves for mixtures with 60-day curing period.

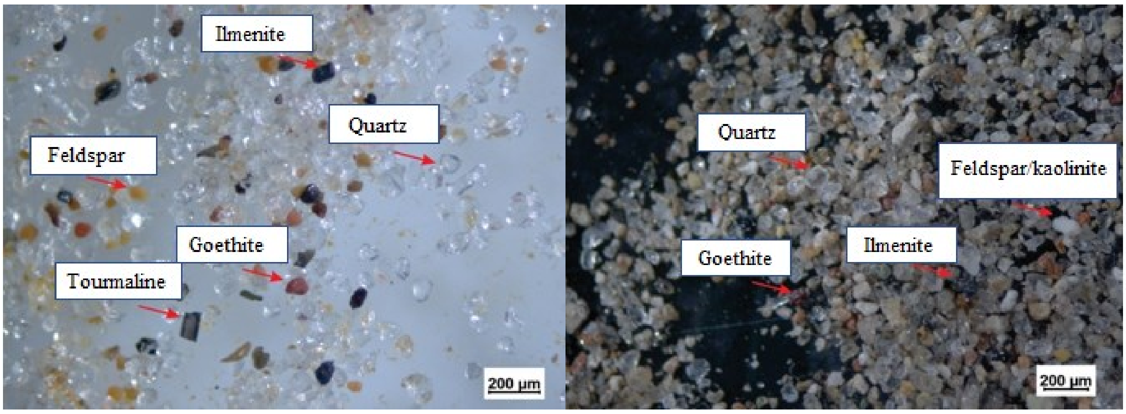


Authors (2021)

Mineralogical characterization

The binocular magnifying glass test allowed the identification of minerals such as quartz, goethite, hematite, ilmenite, and tourmaline in the soil, and minerals such as feldspar, kaolinite, goethite, hematite, ilmenite, and quartz were found in the residue (Figure 8).

Figure 8- Soil mineralogical analysis (a) and recycled aggregate mineralogical analysis (b).



(a) (b)

Authors (2021)

The knowledge of the properties of different minerals in the soil represents an important tool in the evaluation of processes related to weathering and soil evolution (SOUSA, 2015). Feldspars are classified as primary minerals that provide greater resistance to the weathering process, being a direct source of plant nutrition (MOTA *et al*., 2007; SOUSA, 2015).

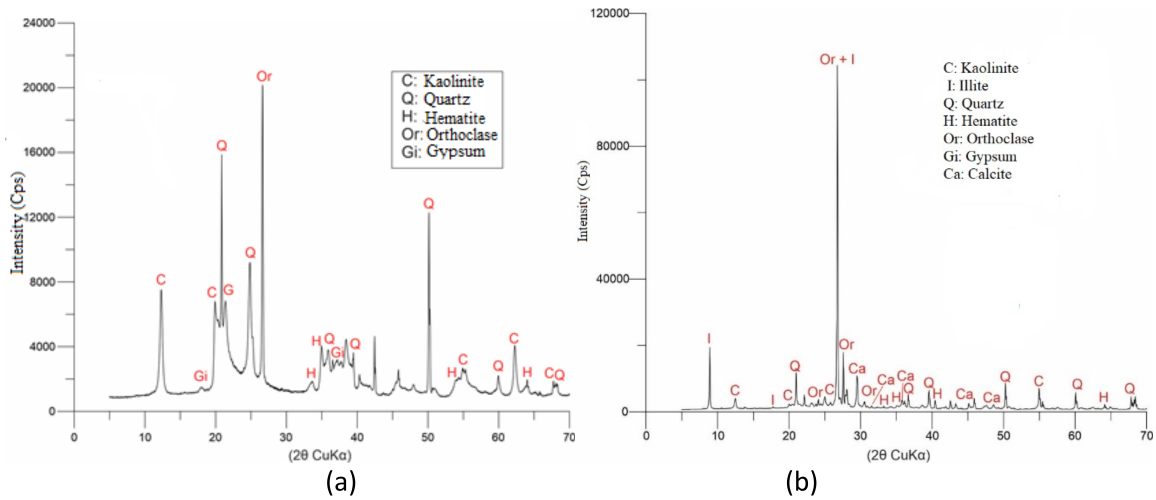
According to Earle (2019), quartz is a non-reactive material and resistant to weathering, providing greater stability to the soil. Kaolinite is a mineral present mainly in the clayey fraction of the soil, representing a fundamental source of potassium in plants. High kaolin contents may indicate areas that have suffered from the action of weathering (SOUSA, 2015).

Goethite and hematite are minerals that provide characteristic colors to the soil and have a strong relationship with the structuring and aggregation of the soil, providing greater water absorption, better infiltration, and greater erosion control (SILVA, 2016). Ilmenite is a mineral normally found in the fraction of silt and sand and is related to the release of iron ions into the soil after being dissolved by weathering (SILVA, 2016).

The X-ray diffractometry test revealed the presence in the soil of peaks of kaolinite, quartz, and orthoclase, and peaks of quartz, kaolinite, illite, orthoclase, gypsum, and calcite in the residue (Figure 9). Calcite is a mineral that represents a fertility reserve for the soil (SOUSA, 2015). According to Lee, Ng and Tanaka (2013), the increase in unconfined soil strength is proportional to the amount of calcite present.

Orthoclase is a type of feldspar with more difficult solubilization due to the strong binding of potassium ions to silicon (MELFI *et al*., 2016). Illite represents a mineral present in the clayey fraction of the soil and provides characteristics related to expandability and plasticity, generally presenting characteristics of reduced expansion, especially when compared to montmorillonites montmorilonitas (CREVELIN, 2018).

Figure 9- Soil (a) and residue (b) X-ray diffractogram.



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Statistical analysis

With the results obtained in simple compression, statistical modeling was performed to optimize the manufacturing process of the specimens, aiming to maximize the resistance value (WANG; CHENG; TAN, 2018; IPEK *et al*., 2021). According to Ipek *et al*. (2021), the Response Surface Methodology (RSM) statistical analysis is based on the optimization of independent variables aiming to provide the maximum load capacity.

Initially, the parameters that most influence strengths were defined using as a basis the work of (GÜLLÜ; FEDAKAR, 2017; SILVA, 2020). The results obtained for the parameters were the curing time, the residue content, and the fiber content, followed by the analysis interval (Table 7).

Table 7 - Range of selected variables.

Parameters	Range
Recycled aggregate (CCW)	0% a 50%
Sisal fibers	0% a 0,5%
Curing period	7 a 60 days

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According to Myres, Montgomery and Anderson-Cook (2009), the adjustment of the model depends on the reliability of the information provided, making it closer to reality. Table 8 shows the interactions between the variables entered in the Minitab 19 Statistical Software for statistical analysis.

Table 8- Interactions between the variables.

CCW (%)	**Fiber (%)**	**Curing Period (TC)**		
		7 days	**28 days**	**60 days**
0	0	211,76	317,65	542,15
30	0	257,20	328,90	671,10
50	0	203,50	242,15	525,50
30	0,25	268,03	342,60	702,35
50	0,25	228,75	322,34	578,75
0	0,25	278,22	396,50	724,50
0	0,50	289,15	537,10	860,15

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Table 9 shows the results obtained by the software, revealing good adherence to the model and making the results closer to reality. The values in Table 10 (DF, Adj SS, Adj MS, and F-Value) are fundamental for determining the P-value (significance level) that represents the range of various measurements and the influence of independent variables on the material strength so that the P-value must be below the limit of 0.05 for the variable to be representative for the model (SILVA *et al.*, 2021).

The results obtained show that the residue contents (CCW), fiber and the curing time positively interfere in the model's functioning, mainly with the interactions of the curing time, in which TC*TC and fiber*TC presented Value- P well below the 0.05 limit.

The low P-value indicates that the quadratic modeling is significant, and the variables used to exert a great influence on the material's strength (SHIRAZI, KHADEMALRASOUL E ARDEBILI, 2020). It is also possible to analyze the adequacy of the model through the results obtained for the R^2. According to Figueiredo Filho and Silva Júnior (2009), the closer to 1 the R^2, the greater the statistical dependence between the variables. Thus, the R^2 value of 97.60% obtained for the model reveals good adherence.

DeLoach and Ulbrich (2007) state that it is necessary to verify the difference between the adjusted R^2 and the predicted R^2, which must be less than 20% for a good representation of the model. The value found for this difference in the study in question was 3.30%, indicating that the modeling presented good precision.

Table 9 - Analysis of variance between independente variables.

Source variation	Degrees of freedom (DF)	Adjusted sum of squares (Adj SS)	Adjusted mean squares (Adj MS)	F-value	P-value (Significance level)
Model	7	756038	108005	76,93	0
Linear	3	659475	219825	156,58	0
CCW	1	23380	23380	16,65	0,001
FIBER	1	30020	30020	21,38	0
TC	1	569781	569781	405,86	0
Squares	2	25256	12628	9	0,004
CCW*CCW	1	11287	11287	8,04	0,014
TC*TC	1	13969	13969	9,95	0,008
Double Int.	2	20685	10343	7,37	0,007
CCW*FIBER	1	6646	6646	4,73	0,049
FIBER*TC	1	14039	14039	10	0,007
Mistake	13	18250	1404		
Total	20	774288			
R^2 (Model)	0,976	R^2 adjusted (Model)	0,964	R^2 Foreseen (Model)	0,931

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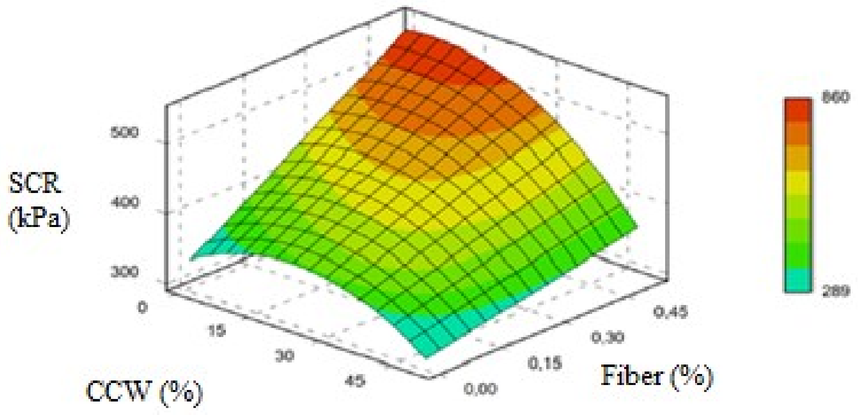
To optimize the soil improvement parameters, the mathematical model presented in Equation 1 was used.

$$SCR = 209{,}7 + 3{,}87\ CCW + 179{,}7\ FIBER + 1{,}03\ TC - 0{,}0887\ CCW*CCW + 0{,}0820\ TC*TC - 5{,}51\ CCW*FIBER + 6{,}78\ FIBER*TC \quad \textbf{Eq. (1).}$$

In this way, the behavior pattern of the Simple Compression Resistance (SCR) was traced, applying modifications in the values of the independent variables (fiber, recycled aggregate, and curing time). Thus, the response surface (Figure 10) of the model was designed and is of fundamental importance for better system optimization strategies, reducing the domain of possible solutions, and maximizing the RCS.

Figure 10 - Contour of the 3D response surface for the interrelation of fiber and TC variables.



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Several conditions were applied to the model to obtain the ideal mixture content for the study (Table 10). The fiber percentages and curing time presented values identical to the upper limit of each interval, revealing a trend of growth as these variables are high. However, the residue showed an optimal value closer to the lower limit of its range, showing a tendency for SCR to grow only up to a certain point as its content is increased.

Table 10 - SCR value optimization variables.

CCW (%)	Fibers (%)	TC (days)	SCR (kPa)
16,16	0,50	60	863,30

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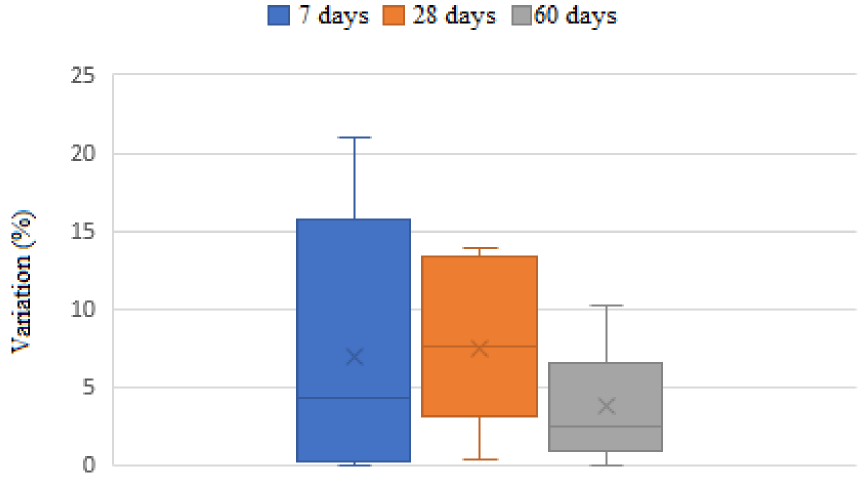
For complementation, a box plot (Figure 11) was elaborated for the variations found between the experimental tests and the results obtained with the statistical modeling, verifying its adequacy to reality. The presence of a flatter box diagram or box plot indicates less variability and a smaller standard deviation of the data (VALLADARES NETO *et al.*, 2017).

The experimental results showed behavior similar to the modeling values, with a reduced percentage of variation. The average variations were 6.90%, 7.45%, and 3.72% for the curing periods of 7, 28, and 60 days, respectively. Thus, the model showed good adherence and performance in the study of soil stabilization, allowing the optimization of materials for the composition of the mixtures.

Figure 11 - Box plot for variations between experimental and modeling results.



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CONCLUSION

Com o ensaio de granulometria, o solo foi classificado pelo SUCS como uma argila arenosa de baixa plasticidade, enquanto que o agregado reciclado foi classificado com uma areia bem graduada. Inicialmente a relação de silte/argila era de 0,25, o que indica uma maior incidência de processos erosivos. Com a adição de agregado reciclado na mistura, a relação silte/argila aumentou, indicando uma possível redução dos processos erosivos com a utilização do material.

Segundo a classificação pelo TRB, o solo foi classificado como uma argila, apresentando mau comportamento para ser utilizado em subleitos de rodovia. Já com a adição de agregado reciclado no solo, as misturas passaram a apresentar uma classificação que indica um comportamento de bom a excelente para utilização como materiais de subleito, melhorando suas características para uso em pavimentos.

Com o ensaio de compactação, foi verificado que o acréscimo de fibra nas misturas aumentou a umidade ótima e reduziu a densidade seca máxima. Esse acréscimo de umidade ótima pode ser explicado pela capacidade das fibras em se amontoarem no solo, formando aglomerados que retem a umidade. Já o acréscimo de resíduo ao solo, aumentou a densidade seca máxima da mistura e reduziu a umidade ótima dos materiais. A menor umidade ótima foi obtida para o agregado reciclado, e a maior foi obtida para a mistura de solo e fibra no teor de 0,50%.

O ensaio de compressão simples mostrou eficácia para as misturas analisadas com o acréscimo de fibras ao solo para os períodos de cura analisados. O compósito que apresentou o melhor resultado em relação ao acréscimo de resistência para os períodos de cura analisados foi a mistura de solo e fibra no teor de 0,50% aos 60 dias. O ganho de resistência foi de 58,70%, quando comparadas ao solo natural para o mesmo período de cura.

A análise mineralógica revelou a presença no solo e no resíduo de minerais como: quartzo, feldspato, goetita, ilmenita, ortoclásio e caulinita. O quartzo e o ortoclásio representam materiais que fornecem uma maior resistência ao intemperismo, conferindo uma maior estabilidade ao solo. A caulinita é um mineral encontrado principalmente em materiais cerâmicos dos Resíduos de Construção Civil (RCC) e pode ser originada do intemperismo sofrido pelo solo.

A análise estatística através da metodologia *Response Surface Methodology* (RSM) permitiu a elaboração de um modelo matemático com R^2 = 97,60%, indicando um grau elevado de aderência do modelo aos dados fornecidos. A otimização do estudo foi obtida com os valores de 16,16% para o resíduo, 0,50% para a fibra de sisal e 60 dias para o tempo de cura, fornecendo uma resistência máxima de 863,30 kPa.

De uma forma geral, a aplicação desses materiais apresentou resultados positivos no quesito de resistência, desenvolvendo assim, um método eficaz nos aspectos técnicos e ambientais. Além disso, é necessária uma maior atenção por parte das entidades governamentais e da sociedade em relação aos processos erosivos verificados no local, com ações que envolvam a medição e o monitoramento, proporcionando um planejamento urbano mais adequado para a área, visando a redução da degradação ambiental e uma melhor qualidade de vida para a população local.

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