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Optimization of the Dosage of Sustainable Materials for the Stabilization of an Erosive Soil

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Abstract

The study presents the analysis of the geomechanical behavior of composites of soil, construction and demolition waste (CDW), and wood construction waste (WCW) and investigates the optimal proportions of sustainable materials (CDW and WCW) and curing time (CT), which provide the maximum unconfined compressive strength (UCS) values for reinforcing an erosive soil. Initially, we carried out unconfined compressive tests using incorporations, in dry soil weight, from 0% to 50% of CDW and 0% to 3.0% of WCW. The optimization was performed based on the Response Surface Methodology (RSM) technique. The results showed that the incorporation of CDW in the soil increased the UCS in all the composites. The presence of WCW provided considerable increases in the RCS when incorporated individually into the soil. The composite formed by 97% of soil and 3% of WCW (S97M3) had the best results for the UCS, with soil increments of 124.2%, 268.4%, 131%, and 37,9% for 7, 28, 60, and 120 *days of curing, respectively. The statistical optimization process demonstrated that the incorporations of 6.14% of CDW and 2.92% of WCW increase the UCS value up to 1514.59 kPa (120 days). Thus, it appears that the incorporation of statistical optimization techniques can be a benefit for preliminary analyzes of soil stabilization studies.*

Keywords: Erodible Soil; Soil Stabilization; Construction Waste; Response Surface Methodology; Statistical Optimization

INTRODUCTION

Techniques to stabilize or improve a given geotechnical soil parameter have been increasingly applied in the civil construction industry, on slopes, roads, and the creation of landfills. This trend has spread, in large part due to the reduced availability of sites with soils that support the progressively more demanding load requirements of current structures as well as the accelerated advance of urbanization (Sharma, 2017; Sudhakaran; Sharma and Kolathayar, 2018; Yousefpour et al., 2021).

Soils considered to be passive for stabilization are those with lacking characteristics, from a constructive point of view, such as low load capacity, high permeability, and/or low shear strength: behaviors that can be generically associated with various groups of soils, such as soft, expansive, erosive, and collapsible soils, easily found in tropical regions. (Rahgozar, Saberian and Li, 2018).

The methodologies applied to modify the characteristics of these soils will vary according to the constructive purpose. It may differ from densification treatments (such as compaction and pre-loading) to accelerated pore-pressure reduction techniques (electro-osmosis and drying/ dehydration) for soft soils, in addition to the incorporation of materials to form composites for reinforcements (Ebrahimi et al., 2011; Horpibulsuk et al., 2012; Mengue et al., 2018).

Lime and, mainly, cement are the most used materials for geotechnical stabilization of soil parameters. In this context, many researchers have been dedicated, in recent years, to enabling the use of solid waste as stabilizers due to the technical, economic, and environmental advantages (Bouhicha, Aouissi and Kenai, 2005; Kim and Do, 2012; Güllü, 2015; Sharma and Hymavathi, 2016; Rahgozar, Saberian and Li, 2018; Portela, 2019; Santos, 2020).

Construction and Demolition Waste (CDW) is the by-product (Solid Waste) in activities performed by the civil construction industry such as repairs, demolition, maintenance of buildings, structures, roads, and excavations. When undergoing processing, they can be used for stabilization purposes (Macedo, Lima and Lafayette, 2014; Nascimento, 2019; Silva, 2020; Pedrosa, 2020; Santos, 2020; Portela, 2019).

Sharma and Hymvathi (2016), in their study on the unconfined compressive strength (UCS) of a high plasticity clay in India, observed that incorporations of CDW into the soil tend to increase by twice the value of the RCS, as they reduce the capacity of expanding. Furthermore, they found that the CDW content increased while the cohesion reduced, and the internal friction angle increased.

Ray et al. (2021) found that the addition of fiber and the replacement of natural sand increased the compressive strength of concrete from 14.15MPa to 16.05MPa in 7 days; 25.09MPa to 26.60Mpa in 28 days; and 32.12MPa for 34.14 MPa in 56 days, up to 1% and 20%, respectively.

Bouhicha, Aouissi, and Kenai (2005) investigated the influence of the incorporation of sawdust fibers from the wood residue (WCW) with the addition of Portland cement on the UCS of clayey silt from Algeria. They identified increases in the order of 7% as well as reductions in soil expandability and deformability. Therefore, they concluded that WCW sawdust fibers might act as stabilizers in conjunction with other materials. The correct definition of the inclusion levels of stabilizing materials is essential for effective intervention in the soil.

According to Güllü and Fedakar (2016), an incorrect approach at this stage might lead to major problems considering optimizing proportions. Thereby, optimization methodologies are necessary, especially when dealing with large-scale studies, such as soil stabilization works. Also, according to Güllü and Fedakar (2016), in methodologies that address ideal proportions of materials, the contribution level of each independent variable - e.g., wet chamber curing time (CT), stabilizing material contents - are changed individually, while that the other independent factors/variables are held constant. In practice, this procedure would take time and raise costs; hence statistical modeling and simulation become essential.

The methodologies/tools that model the behavior of engineering problems, such as the mechanical performance of materials, are techniques applied by engineers since the widespread use of personal computers. In this sense, several sets of techniques have become popular in product and material optimization through a design phase before their production (Myers, Montgomery and Anderson-Cook, 2009).

The Response Surface Methodology (RSM) (Myers, Montgomery and Anderson-Cook, 2009) is one of several techniques that have been widely applied to optimize the response in soil stabilization/reinforcement studies in recent years (Güllü and Fedakar, 2016; Yu and Bathurst, 2017; Han et al., 2018)

The application of the RSM in studies of mechanical soil stabilization consists of using the results of laboratory tests. In this study, we used the unconfined compressive strength (UCS) of the soil and other composite materials. Based on them, we will present the optimization of the system in the form of a mixture containing that will verify the best result of resistance to unconfined compression (Han et al. 2018). According to Olgun (2013) and Güneyisi et al. (2014), the method brings many benefits, helping in decision-making, as it promptly presents the most appropriate components.

Given the above, the study analyzes the stress and strain behavior of composites formed by soil, CDW, and WCW, and thus determines the optimum levels of incorporation of these materials, in addition to the curing time (CT) in a wet chamber, that can develop maximum UCS performance using the Response Surface Methodology (RSM). According to Güllü and Fedakar (2016), the investigation of the UCS with other tests (e.g., California Bearing Ratio) investigates the soil stabilization levels for engineering work such as embankments and pavement bases.

MATERIALS AND METHODS

Material Properties

The soil used in carrying out the tests came from a hillside region located in the city of Ilha de Itamaracá, Pernambuco state, in the northeast of Brazil. The choice of soil in this study area is associated with the alarming erosive features of the landscape, characterized by the presence of furrows and ravines. The soil was classified as high plasticity clay, according to the Unified Soil Classification System (USCS) and as an A-7-5 clayey soil by the American Association of State Road and Transportation Officers (AASHTO).

The CDW was obtained by crushing construction and demolition waste at the Environmental Cycle Beneficiation Plant, located in the city of Camaragibe, also in the state of Pernambuco. The material was physically characterized by the same procedures applied to the soil, being classified as well-graded sand (SW) and sandy soil (A-2-4) by the criteria of USCS and AASHTO, respectively. Both the soil and the CDW were previously studied by Nascimento (2019). Tables 01 and 02 present the characteristics of both.

Table 01: Soil and CDW geotechnical parameters.

Geotechnical parameters	Soil	CDW	References
Type of Soil (USCS)	CH	SW	ASTM D2487-17 (ASTM, 2017)
Type of Soil (AASHTO)	A-7-5	A-2-4	ASTM D3282-15 (ASTM, 2015b)
Actual Density	2.73	2.61	ASTM D854-10 (ASTM, 2010)
Liquidity Limit (LL)	53.28	-	ASTM 4318-10e1 (ASTM, 2010)
Plasticity Limit (LP)	21.75	-	ASTM 4318-10e1 (ASTM, 2010)
Plasticity Index (IP)	31.53	-	ASTM 4318-10e1 (ASTM, 2010)
Optimal Humidity (%)	28.19	12.69	ASTM 698-12e2 (ASTM, 2012)
Weight S. Max. (g/cm^3)	1.531	1.892	ASTM 698-12e2 (ASTM, 2012)

Source: Adapted from Nascimento (2019).

Table 02: Chemical components of soil and CDW

Oxides Components	Soil (%)	CDW (%)
SiO_2	63.18	44.01
Al2O3	20.40	22.02
Fe2O3	7.96	4.28
CaO	0.01	10.21
MgO	0.05	1.02
K2O	-	1.57
Na2O	0.06	0.31
TiO2	1.27	0.85
SO3	-	2.04
P2O5	-	0.31
Loss on Ignition	7.07	13,08

Source: Adapted from Nascimento (2019).

Used portions of wood waste (WCW) followed the recommendations of the European Union (EU) (2016), which sets parameters to enable the use of wood waste for recycling. The WCW was collected in the residential construction structures phase, which took place in the city from Olinda, Pernambuco, from January/2018 to February/2019.

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Based on the results of soil + CDW tests by Nascimento (2019), it was identified that levels of 30% and 50% of CDW inclusion in the soil demonstrated the best mechanical performance; therefore, they were selected to compose the table of composites.

Concerning WCW, all incorporation contents were elaborated based on the percentages presented by Silva (2005) and Santos (2009), which ranged from 0.5% to 6%. These values were lower than those for the addition of CDW compared to observations by Montardo, Consoli and Prieto (2001), who identified low threshold values for the increase in strength with the increase in the content of sawdust fibers. Table 03 presents the mixture contents of the studied composites.

Table 03: Identification of composite contents

Identification	Mixing Percentages	References
Soil	Soil 100%	Nascimento (2019)
S98,5M1,5	Soil 98,5% + WCW 1,5%	Autors
S97M3	Solo 97% + WCW 3%	Autors
CDW	CDW 100%	Nascimento (2019)
S70R30	Soil 70% + CDW 30%	Nascimento (2019)
S70R28,5M1,5	Soil 70% + CDW 28,5% + WCW 1,5%	Autors
S70R27M3	Soil 70% + CDW 27% + WCW 3,0%	Autors
S50R50	Soil 50% + CDW 50%	Nascimento (2019)
S50R48,5M1,5	Soil 50% + CDW 48,5% + WCW 1,5%	Autors
S50R47M3	Soil 50% + CDW 47% + WCW 3,0%	Autors

Source: authors

Experimental Procedures

To guarantee the reliability of the UCS results, the procedures established by ASTM D5102/09 (ASTM, 2009) were followed. The molding of the specimens was performed under the optimum moisture conditions of each composite, which was determined through the Normal Proctor energy of ASTM D698/12e2 (ASTM, 2012), to ensure the best degree of compactness.

The specimens (cylindrical) were statically molded in a split metal mold with dimensions of 100 mm x 50 mm (height and diameter) ASTM D1557/12 (ASTM, 2021), in three layers between them (guaranteeing better interphase adhesion), using a CBR hand press. After compaction, the samples were removed from the mold wrapped in plastic and subjected to curing with a variation of 7, 28, 60, and 120 days in a chamber with controlled temperature and humidity.

Response Surface Methodology

The development of the performance functions used a closed solution of the Response Surface Methodology (RSM), which is a mathematical and statistical technique tool used to develop, improve, and optimize questions where a response variable is influenced by multiple influence variables (Arumugam et al., 2012; Senthil Kumar and Baskar, 2014; Wang, Cheng, and Tan, 2018). Generally, central composite design in RSM is a fractional factorial design method used to find the functional relationship between response variables and independent variables (Aldahdooh et al., 2013a; Arumugam et al., 2012).

Thus, in the development of the solution, an empirical mathematical model is necessary since the RSM needs to establish the relationship between the independent variables and the response variables. Therefore, the adequacy of the problem can be measured for either first-order linear, second-order quadratic, or higher-order polynomial functions (Olgun, 2013). The model used in the research was based on the general form of the complete quadratic model presented by Güllü and Fedakar (2016), as presented in Equation 01:

$$UCS = b_0 + \sum b_i X_i + \sum b_j X_j + \sum b_k X_k + \sum b_{ii} {X_i}^2 \quad (01)$$

Where the terms X_i and b represent the i-th random variable and the coefficients of the complete quadratic model, respectively. According to Schoefs, Le, and Lanata (2013), the coefficients are calculated based on the regression of a numerical test on the probabilistic distributions of the independent variables and the potential influence they have on the system's response.

From the determination of the quadratic model, it is necessary to verify its adherence through the externalized checking of the residuals and possible outliers and calculating coefficients of determination tests (R^2), Adjusted R^2, and the expected R^2.

According to DeLouch and Ulbrich (2007), this verification works by measuring the significance levels (P-Value) of each independent variable and interaction, which should not exceed 0.05. Furthermore, the difference between the Adjusted R^2 and the Expected R^2 is analyzed, which should not exceed 20% (0.2). Once this phase is concluded, the conception of the empirical mathematical model can take shape.

The model verification formulations are presented in Equations 2 to 4, according to the model proposed by Güllü and Fedakar (2016).

$$R^2 = \frac{SSR}{SSM+SSR} \qquad (02)$$

Where the *SSR* and *SSM* coefficients are the sum of the squares of the residuals and the model, respectively. The sum of both parameters produces the SST coefficient (sum of total squares).

$$R^2 Ajustado = 1 - \frac{n-1}{n-p}(1-R^2) \qquad (03)$$

Where n and p are, respectively, the number of observations and the parameters of the model containing intercepts.

$$R^2\ Previsto = 1 - \frac{PRESS}{SST} \qquad (04)$$

Where *PRESS* is the predicted sum of squares error, this coefficient is obtained from the difference between the actual or measured and predicted values, that is, the residual sum of squares.

The general form of the independent variables used in the complete quadratic model was identified based on the analysis of the parameters obtained in the soil stabilization study, in which the unconfined compressive strength (UCS) was the response variable selected for the analysis. The independent variables were CDW incorporation contents, WCW, and curing time (CT). The use intervals ranged from 0% to 3.0% for WCW, from 0% to 100% for CDW, and from 7 to 120 days for CT.

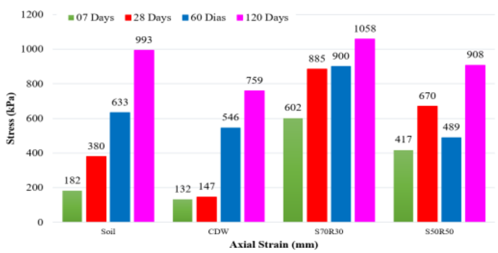
The entire analysis was performed with the aid of Minitab Statistical Software (version 19.0), which made it possible to apply the RSM method, as well as the ANOVA analysis.

RESULTS

Experimental Results Analysis

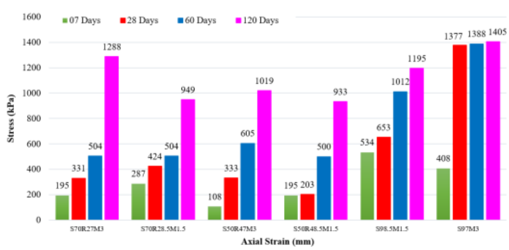
The unconfined compressive strength test (UCS) was performed to determine the average behavior of the stress (kPa) vs. axial strain (mm) curves of all materials. The procedure was performed for the breakage ages of 07, 28, 60, and 120 days. Figures 01 and 02 show the results of UCS tests for all materials and composites.

Figure 01: Comparison of compressive strength between materials and composites with CDW.



Source: Adapted from Nascimento (2019).

Figure 02: Comparison of compressive strength between composites with CDW and WCW.



We observed that the soil, highly plastic, supported greater deformation, about 15%, compared to other materials. During the execution of the UCS test, well-defined stretches of elastic and plastic behavior were observed, with no evidence of stress peaks. The UCS at 28 days increased by 108% compared to 7 days of cure.

For 60 and 120 days of curing, high rates of increase in strength were observed for almost all materials, especially for the soil that showed considerable increases in strength compared to 7 days of curing, with 633 kPa and 993 kPa, for the 60 and 120 days of curing, respectively.

According to ASTM C618 (ASTM, 2015a), such behavior was expected because soils with proportions of Silicon (SiO2), Iron (Fe2O3), and Aluminum (Al2O3) oxides, exceeding the value of 70%, are considered natural pozzolans; this feature provides resistance over time.

Similar results were found for the silty-clay sands from the studies by Mirzababei *et al*. (2012) and Sudhakaran, Sharma, and Kolathayar (2018), who observed greater deformations in the initial phase of the UCS test, until the maximum resistance stagnated in the plastic section, also without stress peaks.

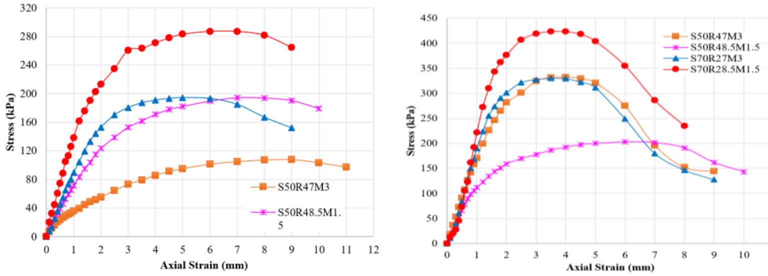
According to Nascimento (2019), CDWs present the expected behavior of a granular soil of low compressibility, with an almost imperceptible variation in the UCS. For the two curing ages (7 and 28 days), it showed well-defined rupture peaks, indicating fragile behavior and rigidity for the specimens.

Incorporating CDW in the soil, Nascimento (2019) found a significant increase in resistance, recording growth percentages of 231% and 129% concerning the soil, only for the seven days of curing, in the inclusions of 30% and 50% of CDW, respectively. As the specimens reached 60 days and 120 days of curing, growth rates nearly tripled in all composites.

Such behavior in the S70R30 and S50R50 composites was due to the incorporation of CDW. They had better conformation between the soil particles, generating better compactness in the structural matrix. It also reduced deformability and provided fragile rupture behaviour.

Figures 03a and 03b show the maximum UCS values and the stress vs. strain curves of the composites with the incorporation of CDW and WCW obtained during the tests for 7 and 28 days of curing.

Figure 03: a) Stress vs. axial strain curves of CDW and WCW composites for 7 days of curin and b) Stress vs. axial strain curves of CDW and WCW composites for 28 days of curing.

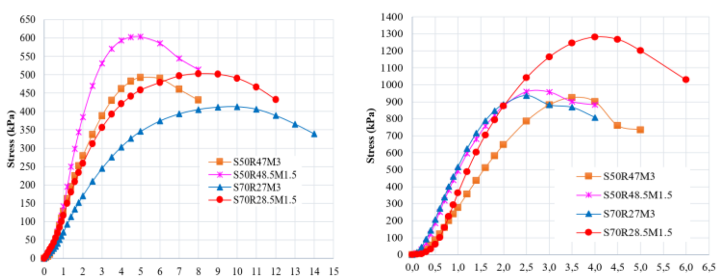


Source: authors

At 28 days of curing, the composite S70R28.5M1.5 increased the UCS value by almost 50% compared to the strength at 7 days. According to Consoli, Moraes, and Festugato (2013), this behavior is due to two factors: considerable growth of the pozzolanic reactions of the CDW with the soil (at 28 days) and continuous stiffening of the interfaces close to the WCW fibres, which lose moisture as time passes.

The maximum displacement applied to composites with WCW was 11 mm, for the age of 7 days, and 10 mm, for the 28 days, since, as the age of cure increased, the specimens presented a reduction in the capacity of deforming under the action of axial loads. Bouhicha, Aouissi, and Kenai (2005) describe that these reductions are due to organic materials, such as WCW, retain and attract moisture in the composite structural matrix. Figures 04a and 04b show the curves of composites with the incorporation of CDW and WCW obtained in the test for 60 days and 120 days of curing.

Figure 04: a) Stress vs. strain curves of CDW and WCW composites for 60 days of curing. and b) Stress vs. strain curves of CDW and WCW composites for 120 days of curing



Source: authors

At 60 days of curing, the composites formed by 70% of soil practically maintained the deformation levels presented at 28 days, while those composed by 50% of soil presented reductions of about 30% for both WCW incorporation contents. However, at 120 days of curing, considerable decreases were observed for all composites, with the specimens reaching ruptures with only 4 mm of displacement. According to Li and Yang (2020), the gradual reduction in plasticity presented by composites is due to the increased rigidity of the specimens.

At the end of the UCS test, the specimens after 7 days of curing did not present a well-defined rupture plan. However, after 28 days of curing, well-defined ruptures were evidenced in the specimens, which demonstrated the classic behavior of rigid materials (fragile type rupture). Figure 05 (a and b) shows the rupture of composites S70R27M3 and S50R47M3 at 7 days of curing. Figure 06 (a and b) shows the result of composites S70R28.5M1.5 and S50R28.5M1.5 at 28 days.

Figure 05: a) Breakage of the test specimens of composites S70R27M3 and b) S50R47M3

a)

b)

Source: authors

Figure 06: a) Breakage of the test specimens of composites S70R28,5M1,5 and b) S50R48,5M1,5

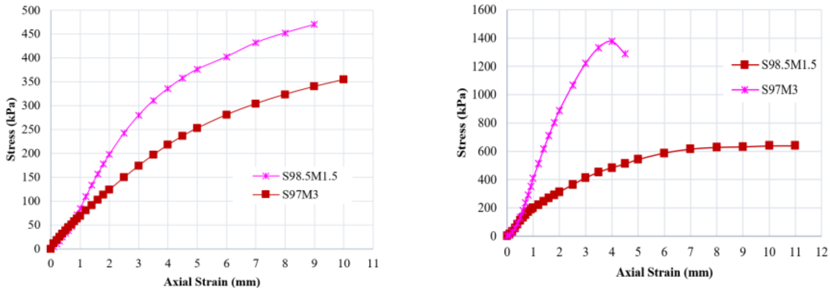

a) Source: authors b)

The rupture planes with angles of the order of 60º, observed at 28 days and in the subsequent curing times, characterize shear rupture: there is no plastic deformation in the material. Portela (2019) evidenced similar behaviours for rupture of composites prepared with soil and CDW from 7 to 120 days of curing.

For the composites formed by soil and WCW, it was possible to identify high resistance results since the initial stages of the analysis, with 534 kPa and 408 kPa for the 7 days of curing, in the incorporations of 1.5% and 3.0%, respectively. When compared with the UCS value of the soil, at the same time, both composites practically double the strength value. Figure 07a shows the curves of the composites of soil and WCW obtained in the test, for 7 days of curing.

At 7 days of curing, both soil and WCW composites did not show well-defined peak stress and/or rupture behavior, despite relatively high values when compared to other materials under the same conditions. However, at 28 days, this behavior changed to the composite S97M3, which showed peak stress with only 4% strain, reaching 1377 kPa of UCS (Figure 07b), the highest value among all composites for the same cure time.

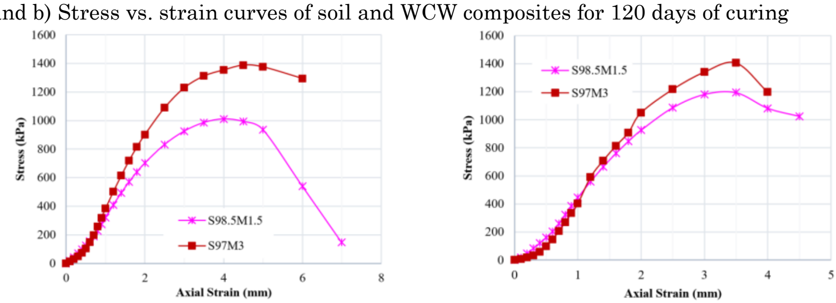
Figure 07: a) Stress vs. strain curves of soil and WCW composites for 7 days of curing and b) Stress vs. strain curves of soil and WCW composites for 28 days of curing



Source: authors

According to Maleksaeedi *et al.* (2020), this behavior may be due to continuous drying of the interfaces close to the WCW fibres, which continue to lose moisture due to absorption and possible variations in the degree of compactness of the composite. A similar result was found by Rahgozar, Saberian, and Li (2018) in marginal soil in the province of Isfahan in Iran. Figures 08a and 08b show the curves of the composite soil and WCW obtained in the UCS test, for 60 and 120 days of curing in a wet chamber.

Figure 08: a) Stress vs. strain curves of soil and WCW composites for 60 days of curing and b) Stress vs. strain curves of soil and WCW composites for 120 days of curing



Source: authors

Such as other materials, the composites practically maintained their vertical deformations after 60 days of curing and reduced by more than 60% when analysed for 120 days. However, unlike the composites formed by soil, CDW, and WCW, all specimens with soil and WCW showed peak behavior and classical ruptures during the test.

In the composite with only soil and 3.0% of WCW, the highest strength values were observed, with about 1400 kPa, a value that practically remained from 28 to 120 days of curing. However, the 1.5% content presented successive growths up to 120 days of curing, reaching 1195 kPa for the maximum performance of the UCS. A similar result was presented in the study by Rahgozar, Saberian, and Li (2018), who performed UCS tests for 7, 14, 28, and 120 days of curing, with the incorporation of garlic peel ash and cement in clayey sand.

It was found that, at 28 days of curing, for composites S50R47M3 and S50R48.5M1.5, the values of UCS decreased, concerning composites S70R27M3 and S70R28.5M1.5. Once the CDW content in the composites was reduced, the UCS increased, regardless of the moisture retention that WCW conferred on the material. However, in the incorporation of soil + WCW, the composites showed positive results concerning the natural soil.

As for the behavior of the stress x axial deformation curves, it is safe to say that CDW has a greater influence on UCS growth than WCW, in composites with soil + CDW + WCW. Thus, it appears that up to 120 days of curing, CDW contributes to the increase in the rigidity of the composite, which according to Sharma and Hymavathi (2016), is the result of the pozzolanic reactions of the material.

Given the above, the composite S70R28.5M1.5 obtained the best result for the compressive strength compared to the composites formed by soil, WCW, and CDW. The highest values of unconfined compressive strength were for the composites formed by S70R30, for the composites of (soil + CDW), and S97M3 for the composites of soil + WCW, a result that also applies to all other materials studied.

Optimization Statistical Analysis

After determining the UCS values for all materials, statistical modeling was performed to describe the behavior of the UCS. To identify the most technically suitable composite content, we defined the parameters with the greatest influence on the final strength value. According to the model presented by Güllü and Fedakar (2017), the curing time of specimens (CT) and the inclusion levels of alternative materials (CDW and WCW) are the most influential factors for soil stabilization studies (Table 04).

Table 04: Selected analysis variables

Parameter	Break
CDW Content	0% a 100%
WCW Content	0% a 3%
Cure Time (CT)	7 a 120 days

Source: authors

All interactions between the independent variables (CT, CDW, and WCW) and the response variable (UCS) are in Table 05. According to Myers, Montgomery, and Anderson-Cook (2009), the interactions between the variables provide the adjustment of the statistical model, which success depends on if the information is reliable. The reliability of the results, in the analysis, was verified by the technological control performed in the molding of the specimens.

Table 05: Interactions between independent and response variables

CDW (%)	WCW (%)	Cure Time (CT)				Reference
		07Days	28 Days	60 Days	120 Days	
0	0	182	380	633	993	Nascimento (2019)
0	1,5	534	653	1012	1195	Authors
0	3,0	408	1377	1388	1405	Authors
27	3,0	195	331	415	949	Authors
28,5	1,5	287	424	504	1288	Authors
30	0	602	885	900	1058	Nascimento (2019)
40,4	0,078	534	586	1088	1181	Authors
47	3,0	108	333	500	1195	Authors
48,5	1,5	195	203	605	1019	Authors
50	0	417	670	489	908	Nascimento (2019)
90	10	378	488	547	824	Nascimento (2019)
100	0	132	147	546	759	Nascimento (2019)

Source: authors

Table 06 presents the results by the software for all interactions approved by the acceptance criteria. Four variables/interactions (WCW*WCW, CT*CT, CDW*CT, and WCW*CT) were excluded from the model formulation. This artifice was necessary to ensure that the model was as close to reality as possible, thus achieving better results.

Table 06: Analysis of variance between independent variables.

Source of variation	Degrees of freedom (DF)	Adjusted sum of squares (Adj SS)	Adjusted mean squares (Adj MS)	F-value	P-value (Significance level)
Model	5	4836302	967260	28,40	0,000
Linear	3	4736626	1578875	46,36	0,000
CDW	1	1460441	1460441	42,88	0,000
WCW	1	620593	620593	18,22	0,000
CT	1	3221299	3221299	94,59	0,000
squares	1	229052	229052	6,73	0,013
CDW*CDW	1	229052	229052	6,73	0,013
Double Int.	1	843789	843789	24,78	0,000
CDW*WCW	1	843789	843789	24,78	0,000
Mistake	42	1430365	34056	-	-
Total	47	6266668	-	-	-

R^2 (Model)	0,772	R^2 adjusted (Model)	0,745	R^2 foreseen (Model)	0,695

Source: authors

The other factors presented in the table as DF, Adj SS, Adj MS, and F-Value are measures of the range of variation and the influence that the variables have on the UCS, the basis for determining the P-Value. It was observed that the influence of CDW and WCW contents, participating in two interactions each (CDW, WCW, and CDW*WCW), practically dictate, positively, the behavior of the model. All independent variables approved in the exclusion criterion had values well below the limit (P-value < 0.05), showing good model fitting.

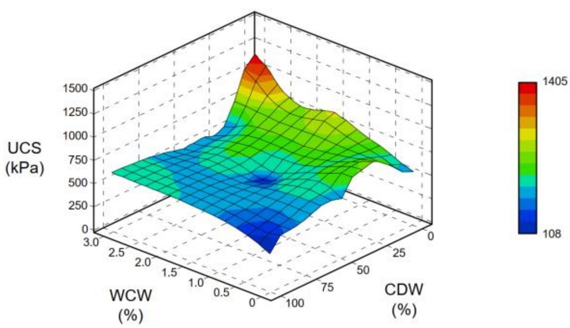
The value of 77.2% found for R^2 indicates a median degree of representation for the model in the behavior of RCS, according to DeLoach and Ulbrich (2007). The difference between the values of Adjusted R^2 (74.5%) and R^2 Expected (69.5%) was less than 20% (6.71%), qualifying the result as adequate.

For Myers, Montgomery, and Anderson-Cook (2009), when R^2 values < 95%, there is an indication of relative symmetry between the independent variables. This fact is observed in the number of points in the range of the CT variable (only 7, 28, 60, and 120 days) in relation to WCW (0%, 0.078%, 1.5% and 3.0%) and CDW (0% , 27%, 28.5%, 30%, 40.4%, 47%, 48.5%, 50%, 90% and 100%), which varies greatly between each one. The regression behavior of composites is in Equation 05.

$$UCS = 287{,}1 + 6{,}78.CDW + 145{,}4.WCW + 6{,}074.CT - 0{,}0863.CDW^2 - 6{,}01.CDW.WCW \quad (05)$$

Through Equation 05, it was possible to analyze the numerically estimated behavior of the composites and predict the results of the unconfined compressive strength from the various intervals of the incorporation contents of the materials (CDW and WCW) and the curing time (CT). Figure 09 shows the three-dimensional response surface obtained for the interrelationship of the WCW and CT variables, notably those with the greatest influence on the behavior of the UCS.

Figure 09: Contour of the 3D response surface for the interrelation of WCW and CT variables.



Source: authors

Based on the higher regions and with a high degree of slope, it was possible to predict the optimal amounts of the variables CDW, WCW and CT, to be applied in the composite, to obtain the maximum performance of resistance to unconfined compression, as shown in Table 07.

Table 07 – UCS value optimization variables

CDW (%)	WCW (%)	CT (Dias)	UCS (kPa)
0.54	3.0	120	1446,08

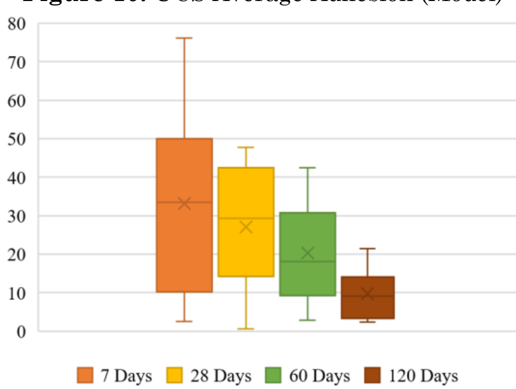
Source: authors

.

Among the independent variables, the WCW and the CT presented values practically equal to the limits of their intervals (3.0% and 120 days of curing, respectively), implying a tendency for both to vary positively as they increased. However, the CDW, despite having the largest range of variation among the variables, was close to the minimum values of their range, suggesting that the relationship between the variable CDW and the UCS is close to a function with the shape of a parabola with downwards concavity, that is, with a defined maximum point (0.54%).

Aiming to assess the limitations of the model, it was verified its ability to predict UCS results and how close to reality the forecasts are. For this purpose, tests were carried out with existing composites that were not used in the creation of the model, such as a new composite tested in the laboratory, exclusively for this function (S59.52R40.4M0.078). Figure 10 demonstrates the mean adherence for the response variable (UCS) as a function of curing time (CT).

Figure 10: UCS Average Adhesion (Model)



Source: authors

It is observed that the variations between the UCS results showed best fitting of the model as the independent variable Curing Time (CT) grows from 7 to 120 days, as shown by the reduction in the variation interval of the results in Figure 10. Average adhesions were 9.79%, 20.25%, 27.06% and 33.25% for 7, 28, 60 and 120 days, respectively.

Even with good results regarding adhesion and performance, the model presented this limitation for lower curing times. According to Güllü and Fedakar (2017), these mean variability differences are a function of the standard deviation of the UCS results, which showed a greater standardization between values with longer curing times.
Thus, the model is considered suitable for the application, in the soil stabilization study, for longer curing times (such as 60 and 120 days of cure), enabling the composite found to optimize the system (Table 07).

CONCLUSIONS

For both 7 and 28 days of cure, the CDW inclusions increased the soil UCS, with the composite S70R30 being the one with the best performance. The UCS results for composites formed by WCW revealed that moisture retention, an intrinsic characteristic of Pinus *elliottii*, provided considerable increases in the UCS, for 60 and 120 days, in all composites, which ranged from 1.5% to 3.0%.

The deformability of the composites varied with the aging of the specimens. After seven days of curing, practically all composites showed deformability above 10%, approaching the behavior of ductile materials. However, after 28 days of curing, this behavior changed significantly with high reductions in deformability, especially with WCW inclusions, directly contributing to the fragile rupture behavior.
According to the regulations, all composites formed only by soil and WCW, or soil and CDW passed the effectiveness test for use in soil stabilization at all curing times studied. Of the composites formed by the three materials used, up to 28 days of curing, only the composite S70R28.5M1.5 was considered adequate. However, after 60 days of curing, all are suitable for application in this type of work.

The statistical analysis resulted in a mathematical model with R^2 = 77.2%, with more than five terms (independent variables) approved in the analysis of variance tests. The step of adapting the model to reality showed satisfactory results for soil stabilization lasting longer than 60 and 120 days of curing, which showed an average variation of results of 20.25% and 9.79%, respectively.

The statistical optimization of the stabilization study identified that the incorporations of 0.54% of CDW and 3.0% of WCW at 120 days of curing (CT) reached 1446.08 kPa of unconfined compressive strength (UCS). The identified composite stabilized for 120 days of curing, value is within the acceptable range of the model, ensuring reliability to the result.

Thus, it is inferred that statistical optimization techniques in stabilization and/or soil reinforcement studies can optimize decision-making with empirical determination for the proportions of material incorporation and curing time.

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