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Influence of Sustainable Materials Incorporation in Soil's Unconfined Compression Strength: A Prisma Review

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Thiago Augusto da Silva*[1], Kalinny Patricia Vaz Lafayette[2], Tomi Zlatar[3], Emilia Rahnemay Kohlman Rabbani[4], Michele Joyce Pereira dos Santos[5], Luciana Cássia Lima da Silva[6]

1 Universidade Federal de Pernambuco, Brasil
2 Universidade de Pernambuco, Brasil
3 Universidade de Pernambuco, Brasil
4 Universidade de Pernambuco, Brasil
5 Universidade Federal de Pernambuco, Brasil
6 Universidade de Pernambuco, Brasil

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ABSTRACT

The modern society development model is the root of several negative environmental impacts because of the way it feeds the productive chain, which is focused on the unbridled exploitation of natural resources and the inefficient management of solid waste. An alternative to minimize those negative impacts is the incorporation of these recycled sustainable materials as feedstock for soil stabilization. The objective of this review is to investigate and discuss the interference caused by the unconfined compressive strength (UCS) with the incorporation of those sustainable materials. The review followed the guidelines set by the Preferred Review Items for Systematic Reviews and Meta-Analysis (PRISMA). The included studies were gathered and searched through the databases of "Web of Science" and "ASCE Library". The following keywords were used in combination with the Boolean operators "AND" and "OR": "soil", "stabilization", "waste", "fibers", and "construction". At first were obtained 1099 records, 899 from ASCE Library, and 210 from Web of Science. After filtering and eligibility criteria were applied, 41 studies went for a complete analysis, leading to the final 26. Of those studies, only one did not show improvement at the UCS, with the best results shown for the composites with more than one material.

INTRODUCTION

The urbanization model that global society is based on nowadays is increasingly approaching the one predicted by the sustainable model, but this adaptation process has been very late. This tardiness has been negatively affecting the environment. So, the dissemination of this theme as a subject of scientific studies is increasingly growing, especially those related to the environmental impacts and the ways of minimizing them [1].

According to [2] this development model is a common reality in developing countries, especially in large urban centers, which by itself reflects the way the environment has been changing in those locations. When these transformations occur without planning results like, degradation and pollution of the environment are expected.

As one of the key factors of that degradation, Solid Waste - SW incorrect disposal, which is merely a consequence of the uncontrolled exploitation of natural resources, has been causing direct interferences on the ecosystem such as pollution of water resources and the narrowing of rivers banks, besides generating disease proliferation conditions [3].

When the SW isn't incorrectly disposed of, usually is sent and processed to a Landfill, which in most cases means a potential waste, because if recycled the same material could perform other functions, thus returning to the production chain. Scientific studies regarding the SW are recent in developing countries like Brazil, India, and China, but growing in representativeness, which can be seen as a consequence of pressure from international entities and the creation of laws directed to the matter [4].

An excellent alternative to solve/mitigate the problem of SW disposal is the use of sustainable materials in the construction industry. These materials are mostly created from SW, which goes through a recycling process to reintroduction into the production chain.

Among the various applications within this market, one that dates back to the earliest days of geotechnical engineering is soil stabilization, a process that aims to improve soil's mechanical characteristics. This application comes as an alternative in the production of geosynthetics and or the formations of soil composites [5].

The most used SW for sustainable materials production is the fly and bottom ashes from thermoelectric plants, construction, and demolition waste - CDW, coconut fibers, etc. The great majority of those materials need addiction to other products to achieve full potential as soil stabilizers. The Portland cement - PC and the lime, for example, are the most used because of their binding nature [5-6].

In the last two decades, lots of research to investigate, and make feasible, the use of sustainable materials as soil stabilizers have been carried out [7-15]. In this context, a systematic analysis of the influence of sustainable materials added to the soil compression strength is presented in this article, through a review of the existing literature.

MATERIAL AND METHODS

The literature research was based on bibliographical searches on the internet, through two of the most reputable databases in the civil engineering field, emphasizing subjects in the soil stabilization area. The search was conducted using the Reporting Items for Systematic Reviews and Meta-Analysis - PRISMA [17] guidelines. The used databases were the American Society of Civil Engineers – ASCE Library, Web of Science, and references provided by experts in the field.

All the searches were limited to studies published in peer-reviewed journals, that used English and Portuguese languages, from 2008 to 2018 and performed unconfined compressive strength (UCS) tests for the soil and the composites. References in which the title and abstracts weren't aligned with the review subject were excluded. The studies had to demonstrate results for the main soil characterization parameters and the investigation how the sustainable material changed the soil UCS.

Were then defined 12 keywords for the search process, that were tried and combined with the Boolean operators "AND" and "OR" forming the following interactions: “Soil Behavior”, “Soils Stabilization”, “Soils Stabilization” AND “Construction Waste”, “Soil Stabilization” AND “Fibers”, “Soil Stabilization” AND “Natural Fibers”, “Soil Stabilization” AND “Waste”, “Soil Stabilization” AND (“Construction Waste” OR “Natural Fibers” OR “Waste” OR “Fibers”), “Soils Stabilization” AND (“Wood Chips” OR “Sawdust”), “Stabilized Soils”. By alternating the term "Stabilization" for "Reinforcement" another 7 keywords were then created. “Stabilization” for “Reinforcement”.

All the studies taken into consideration for this review were completely analyzed using the steps shown in Fig. 1 and a data extraction sheet, expressed in Table 1.

RESULTS AND DISCUSSION

A total of 1099 studies were initially identified, 210 from the Web of Science, 889 from the ASCE library, and 1 from the recommendations of expert researchers in the field. These results then followed the procedure described in Figure 1. Using the inclusion and exclusion criteria, in the filtering phase, 318 articles corresponded to the criteria and could be included in the investigation of titles and abstracts. After the reading of the titles, the ones that did not fit the subject were removed. At the end of the abstract reading, 41 articles were selected for eligibility analysis.

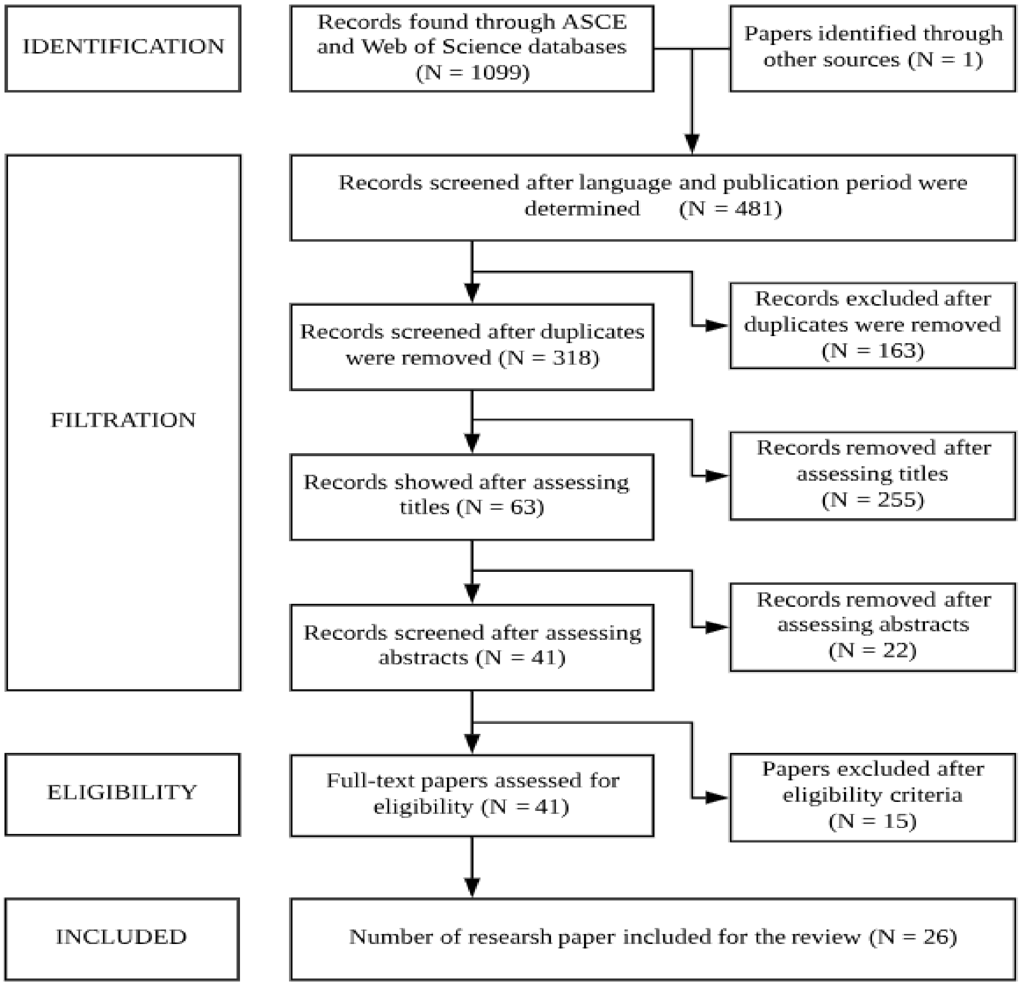

Figure No. 1: Systematic review process.

The eligibility phase happened with the full reading, excluding those who did not align with de criteria fixed in Fig 1. Of the 41 fully analyzed studies only 26 were included in the present review, Table 1 presents all the geotechnical parameters, for the soils and composites.

The soil parameters in their natural state are presented in Table 1. Only the studies of [17, 10, 12,] use predominantly sandy soils. [18-20] made use of silt soils. The study made by [13] was the only one that had a gravel predominant soil, a soil type that rarely appears in studies of this nature. All 21 other reviewed studies used predominantly clayey soils. . There was great variation in soil types when analyzed by the Unified Soil Classification System (USCS), with 16 of the studies participating in the C group of clays [21].

Table No 1. Soil and Composite Parameters.

References	0Soil Parameters						Sustainable Composite Parameters					IUCS/Curing Times (%)		
	USCS	OMC (%)	MDD (kN/m^3)	LL (%)	PL (%)	SG (g/cm^3)	Mat. Types	MP (%)	BDFR (%)	CMDD (kN/m^3)	IMD D (%)	07 Days	14 Days	28 Days
[28]	CH	18.0	16.9	61.0	22.0	2.76	CCR	0 – 10 → CCR	9 → CCR	-	-	300	-	573
							FA	0 – 10 → FA	1 → FA					
[18]	MH	37.5	12.1	63.0	37.0	2.62	RHA	0 – 12 → HL	12 → HL	-	-	284	588	831
							HL	0 – 12 → RHA	12 → RHA					
							PF	0 – 1.2 → PF	0.4 → PF					
[28]	CL	22.0	16.3	39.0	20.0	2.64	RHA	0 – 20 → RHA	0 → RHA	16.2	0.98	2697	-	4795
							CKD	0 – 20 → CKD	20 → CKD					
[23]	CH	16.4	18.3	55.0	27.0	2.72	CCR	0 – 30	7	16.6	0.91	200	-	-
[22]	CH	38.0	12.3	302.0	42.0	2.64	CCR	0 – 15	9	-	-	152	-	362
	CL	21.5	14.6	43.0	22.0	2.66	CCR	0 – 15	12	-	-	158	-	283
[24]	CL	11.0	20.1	29.0	12.0	2.68	SCS	0 – 5	0	18.0	0.90	-	-	-
							SSPF	0 – 5	5	17.9	0.89	-	-	-
	-	13.9	19.0	48.3	16.8	-	SCS	0 – 5	5	15.7	0.83	-	-	-
							SSPF	0 – 5	5	17.2	0.91	-	-	-

References	Soil Parameters						Sustainable Composite Parameters					IUCS/Curing Times (%)		
	USCS	OMC (%)	MDD (kN/m^3)	LL (%)	PL (%)	SG (g/cm^3)	Mat. Types	MP (%)	BDFR (%)	CMDD (kN/m^3)	IMD D (%)	07 Days	14 Days	28 Days
[17]	SC	17.0	19.2	31.0	13.0	2.66	RHA	0 – 8 → RHA	6 → RHA	15.1	0.79	2189	2411	2444
							PC	0 – 8 → PC	8 → PC					
[29]	-	22.0	16.5	50.0	23.5	2.62	RHA	0 – 5 → RHA	5 → RHA	15.9	0.96	-	-	-
							GSW	0 – 6 → GSW	6 → GSW					
[25]	CI	13.2	17.7	47.8	27.7	2.65	CKD	0 – 24	12	18.0	1.02	1023	1128	1238
[26]	-	16.0	17.5	51.0	23.0	2.57	CDW	0 – 24	12	17.2	0.98	184	-	194
							FA	0 – 16	16	16.9	0.97	135	-	320
							HL	0 – 5	4	16,7	0.95	196	-	212
[30]	-	19.2	16.3	56.0	29.0	-	ACF	0 – 1 → ACF	0.6 → ACF	15.5	0.96	272	-	335
							PC	3 → PC	3 → PC					
[31]	-	28.7	14.2	64.0	34.0	2.64	ACF	0 – 1.5 → ACF	1.5 → ACF	-	-	36	268	231
							BA	0 - 40 → BA	30 → BA					
							PC	3 → PC	3 → PC					

References	Soil Parameters						Sustainable Composite Parameters					IUCS/Curing Times (%)		
	USCS	OMC (%)	MDD (kN/m³)	LL (%)	PL (%)	SG (g/cm³)	Mat. Types	MP (%)	BDFR (%)	CMDD (kN/m³)	IMDD (%)	07 Days	14 Days	28 Days
[32]	-	-	-	23.0	17.0	2.60	SS	10 → SS	10 → SS	18.1	-	253*	-	1050
							HL	0 – 8 → HL	8 → HL					
							SS	10 → SS	10 → SS	18.3	-	532*	-	962*
							PC	0 – 8 → PC	8 → PC					
[33]	CH	32.0	12.9	60.2	30.1	2.60	WF	0 – 15 → WF	15 → WF	-	-	360	-	550
							POFA	20 → POFA	20 → POFA					
							NaOH	10M →NaOH	10M →NaOH					
							WF	0 – 15 → WF	15 → WF	-	-	295	-	900
							POFA	20 → POFA	20 → POFA					
							KOH	10M → KOH	10M → KOH					
[19]	MH	17.8	17.9	53.0	30.0	2.65	PC	0 – 9	9	19.1	1.07	980	-	951
[27]	CL	18.0	18.1	38.5	23.5	2.75	XGB	0 – 3	3	17.2	0.95	44	-	108
[20]	ML	16.1	17.2	32.4	23.6	2.71	OPL	0 – 15	12	18.3	1.06	313	-	753
							QL	0 – 15	15	15.2	0.88	775	-	900
[7]	CH	21.5	14.4	81.0	35.0	2.76	CCR	0 – 15 → CCR	9 → CCR	-	-	20	-	125
							BA	0 – 15 →	6 → BA					

References	Soil Parameters						Sustainable Composite Parameters					IUCS/Curing Times (%)		
	USCS	OMC (%)	MDD (kN/m³)	LL (%)	PL (%)	SG (g/cm³)	Mat. Types	MP (%)	BDFR (%)	CMDD (kN/m³)	IMDD (%)	07 Days	14 Days	28 Days
[8]	CL	13.5	19.2	37.8	19.9	2.73	CCR	0 – 6	6	-	-	21	-	98
							QL	0 – 6	6	-	-	16	-	34
[9]	CL	20.0	16.8	32.0	14.0	2.60	CF	0 – 2	2	-	-	-	-	-
[10]	SP	-	-	-	-	2.65	PVAF	0 – 1 → PVAF	1 → PVAF	-	-	-	-	-
							PC	0 – 6 → PC	2 → PC					
[11]	CL	-	-	48.1	24.5	2.66	PF	PF → 0 – 0.75	0.75 → PF	16.9	-	-	-	-
							CDW	CDW → 50	49.3 → CDW					
							PC	PC → 0 - 2	2 → PC					
[12]	SP	10.0	19.5	-	-	2.78	PF	0 – 1 → PF	0.57 → PF	-	-	-	-	-
							SSA	0 – 30 → SSA	19.95 → SSA					
[13]	GW	-	-	18.9	14.9	-	CPS	0 – 5 → CPS	1 → CPS	-	-	-	-	-
							PC	0 – 3 → PC	3 → PC					

References	Soil Parameters						Sustainable Composite Parameters					IUCS/Curing Times (%)		
	USCS	OMC (%)	MDD (kN/m³)	LL (%)	PL (%)	SG (g/cm³)	Mat. Types	MP (%)	BDFR (%)	CMDD (kN/m³)	IMD D (%)	07 Days	14 Days	28 Days
[14]	CH	28.3	13.8	80.0	52.0	2.68	QL	0 – 12	12	13.2	0.96	89	141	162
							HL	0 – 12	6	13.3	0.96	90	120	148
							PC	0 – 7.5	6	14.5	1.05	148	163	209
							FA	0 – 7.5	7.5	13.6	0.99	93	113	124
[15]	CH	16.9	17.5	62.0	26.0	2.75	QL	0 – 10 → QL	2.5 → QL	12.9	1.31	47	-	150
	OH						CKD	0 – 20 → CKD	17.5 → CKD					
							FA	0 – 75 → FA	75 → FA					

The specific gravity (SG) showed little fluctuation, ranging from 2.57 to 2.78 g/cm³. The Atterberg limits had high results fluctuation, ranging from 18.9 to 302 % and 12 to 52 %, for LL and PL respectively, with the highlight for the soil presented in [22] study, that due to its intrinsic characteristics presents excessively high values for its limits of consistency. The changes between the optimal moisture content (OMC) and maximum dry density (MDD) were 11 to 38 % and 12.1 to 20.1 kN/m³, respectively.

In the Best Proportion (BDFR) column, the percentages of soil mass substitution that best influenced the UCS had great fluctuations, with fiber inclusions reaching up to 15% of the mixture by weight of dry soil and percentages reaching up to 75% of dry soil mass, for waste materials such as ashes.

The interference in the UCS (IUCS) was calculated from the ratio between the initial soil resistance and the resistance for the BDFR, for specimens with 1, 7, 14, and 28 days of curing time. The item (IMDD) or the ratio between de soil MDD with the composite MDD (CMDD) was found for only 12 of the 26 studies in the review.

The composites structure were divided in simple composites (soil + sustainable material) and complex composites (soil + sustainable material + binder). Of the 26 studies analyzed, those of [23,22,24,25,19,26,27,20,9,14] used simple composites while the remaining 16 [28,29,18,17,30,31,32,33,34,7,8,10,11,12,13,15] used complex composites.

The research included in this review article aimed to describe soil behavior with the incorporation of materials from RS. It is possible to infer that the incorporation of sustainable materials presents an interference in the geomechanical behavior of the soil about its IUCS, increasing its value for all the studies included in the review except the composites formed by the CL soil of the study of [24]) and that of [26] which only for the 1-day curing time showed a 19% reduction, but with improvement in subsequent curing times.

The IUCS for the study of [24] presented little variation in the initial value of initial soil resistance, with increases recorded only for 1 day of cure, and only for second soil that did not have an identified USCS classification. The ideal value of the best proportion for soils that had the CL classification in the USCS was much higher than those used to perform the study 0% to 5%, indicating a possible chance of improvement if the fiber content increased.

In Table 1 when observed for the simple composites, it is possible to note that the ideal mixing percentages that maximize the resistance values turn around 7.48%, with a standard deviation of 5.39, and for the compounds is 13.14 % with a standard deviation of 7.63. These compound mixtures values of close to 10% are close to the values recommended by the [34] ranging from 3% to 10% for cement, 0% to 30% for lime, and 5% to 10% for fly ash.

About the values presented for all IUCS increments, the mean value was 224.9%, 414.4%, 616.5%, and 680.1% for 1, 7, 14, and 28 days of cure, respectively. As most of the materials used in the composites, taking away the fibers and residues, are materials with agglomerating characteristics (Lime, Ashes, and PC), this improvement is expected due to the reduction of the number of voids, through the reactions of pozzolanic and cementation which was found by [17,28,18,30].

[17] found that the IUCS showed a growth rate of 2% (1880% greater), 4% (2180% greater), and 6% (2440% greater) RHA, but when the mixture increased from 6% to 8% (2130% higher) there was a decrease, for a portland cement (PC) rate fixed at 8%, similar results were found by Anwar Hossain (2011). The very high values of increment in this study are justified in the formation of the composite structural matrix, with RHA reducing soil voids and cementation reactions by creating hydrated calcium silicate (CSH) crystals that serve as binders of the mixture particles.

The calcium carbide residue (CCR) was used in the studies of [27, 22, 23, 8, and 7] with a bulk substitution ratio varying from 0 to 30% and the mean of the best proportions equal to 8.67%. Resistance growth rates presented quite different growth rates for studies using simple composites, [22] and [23] that despite being applied in CH-type soils by USCS presented discrepant values, with the improvement of 200% for 1 day of cure in the study by [22] and 152% and 362% for 7 and 28 days respectively in [23].

Already for the compound composites that had FA for [27] and BA for [7] In addition to CCR as a sustainable material in the mixture, the values were even more discrepant when analyzed for 7 and 28 days of cure. The highest values were from the study by [27] who used a higher proportion of RCC that is 9/1 of CCR / FA) and 9/6 of (CCR / BA) in the [7] that neither for the 28 days of cure obtained values of improvement over 100%, while the former achieved 300% improvement for 7 days of cure.

For the values obtained for IUCS, the values obtained for 28 days in the majority of cases presented the highest values, even in those that were not simple composites, that is, they did not contain materials of agglomerating characteristics that when exposed to the curing time presented enormous gain of resistance. For the composite composites formed by the PC as cement/stabilizer base material, it is possible to note that all the studies presented better resistance results for the higher PC value in the mixture. For [13] this factor could be observed in a very progressive way, although it did not present quantitatively in its results.

CONCLUSION

The studies included in this review showed the interference of sustainable materials inclusion in soil's UCS. The results demonstrated slight standardization for the BPFR. The CCR was the most used stabilizing material in the CH group of soils obtaining the maximum value of 573 % for UCS improvement.

The review highlighted a large number of studies that focused on the use of soil for paving layers, that type of application needs to consider other factors besides the UCS, for example, the California Bearing Ratio – CBR. Together those and other factors can give enough information about these materials' application viability as paving layers. Many of the studies (N = 18) investigated the MDD before and after the incorporation of sustainable materials, showing a decrease in the CMDD even though the UCS showed growth.

A limitation of this review is that due to a large number of studies available in the literature strict inclusion and eligibility criteria were taken, which may have influenced the little representation (N = 1) of unsatisfactory IUCS values. However, there's no reason to believe that the results found in the present review would be less representative since all of them followed standard procedures and consolidated methods in the determination of the geotechnical parameters.

From the presented data it was possible to conclude that the determination of ideal material proportion (soil + sustainable material) it's complex and still today presents itself as a controversial query among specialists because the proportions used to develop their studies oftentimes come from literature reviews and research expertise. In this context studies like the one of [12] stand out, because it proposes mathematically substantiated methods for BDFR determinations.

As the thematic of soil stabilization covers many parameters other than UCS, like CBR, permeability, etc. In this sense, are suggested reviews regarding these soil parameters, developing investigations of possible statistical relations between them and the best material proportions, to help researchers more accurately determine the soil behavior.

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Image Author -1	**Thiago Augusto da Silva– *Corresponding Author*** Recife, PE afilliation: Universidade Federal de Pernambuco
Image Author -2	**Kalinny Patricia Vaz Lafayette** Recife, PE afilliation: Universidade de Pernambuco
Image Author -3	**Tomi Zlatar** Recife, PE afilliation: Universidade de Pernambuco
Image Author -4	**Emilia Rahnemay Kohlman Rabbani** Recife, PE afilliation: Universidade de Pernambuco
Image Author -5	**Michele Joyce Pereira dos Santos** Recife, PE afilliation: Universidade Federal de Pernambuco
Image Author -6	**Luciana Cássia Lima da Silva** Recife, PE afilliation: Universidade de Pernambuco