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Exploring the Impact of Incorporating Fine-Grained Materials on the Resistance Characteristics of Cement-Reinforced Clay

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Abstract: This study, conducted with meticulous attention to detail, examined the influence of fine-grained materials on the resistance components of clay, with and without cement reinforcement. Micro-silica, perlite, crystal barite, gypsum, silica and talc were added to investigate this matter and samples were created and modeled under standard laboratory conditions. The current study aimed to examine the effectiveness of organic granules with varying weight categories and their impact on the fracture angle of the samples, as well as the soil resistance. The research also examined the effect of cement consolidator on all samples and presented the outcomes. It should be noted that the research comprehensively demonstrates the impact of the presence or absence of cement stabilizer in conjunction with the addition of fine aggregate. Various weight conditions for fine grain and cement were explored during the laboratory modeling phase. The prototypes were divided into 13 different categories and strength testing was performed using Unconfined Compressive Strength (UCS) on 234 samples, with three different categories for the weight mixing of fine grain and cement. All 234 samples were tested under identical and curing conditions within seven days. According to the findings, the samples that contained gypsum and crystal barite exhibited a larger impact on increasing the soil's resistance when cement was considered. However, it is worth mentioning that other fine-grained materials also enhanced the soil's resistance, albeit with a slightly lower effect than gypsum and crystal barite. The manner and angle of fracture in the samples suggest that incorporating fine grains and cement into the soil had a notable impact on the fracture angle and its deviation from the normal state.

Keywords: Fine-Grained, Unconfined Compressive Strength, Cement-Reinforced Clay, Refraction Angle

Introduction

One of the fundamental principles in civil works is to have resistant land. From an engineering standpoint, soil is crucial as a support structure that must withstand the forces and stresses of constructing roads and buildings. Clay soils typically have low resistance and bearing capacity and can experience swelling problems. Soil stabilization involves techniques aimed at improving the engineering characteristics of soil, bringing it closer to the desired properties. These measures can increase resistance, reduce swelling and improve efficiency, among other highly beneficial effects. Fine-grained materials can significantly impact soil properties, which can affect the mechanical characteristics and behavior of the soil. For a long time, researchers have been studying the impact of Fine-grained materials on clay (Clare and Cruchley, 1957). At the start of the 20th century in the United States, cement was initially employed as a stabilizing agent to create road materials by mixing with soils. Later on, a variety of other materials, such as lime, fly ash and organic polymers and their combinations have been utilized as stabilizing agents (Bell, 1996; Dermatas and Meng, 2003; Lahalih and Ahmed, 1998). Research on soil effects suggests that incorporating plastic waste into soil improvement efforts could yield comparable results (Azadpour *et al.*, 2023). In the study by Zhu and Liu (2008) stabilizing agents were added to the soil and the properties of the soil were analyzed. The results show that incorporating stabilizing agents notably enhances both stability and strength (Zhu and Liu, 2008). Latifi *et al*., (2016) through studying the properties of polymers in soil and examining their resistance to pollen, researchers have concluded that the direct application of polymers can enhance the soil. Over the past year, due to the rapid progress of industries and the subsequent surge in waste production, we have witnessed a significant dispersion of waste materials and a consequent rise in environmental issues. Particularly concerning plastics, which tend to possess high mechanical and tensile strength, are resistant to acids, bases and other chemical substances and do not biodegrade easily, these materials can remain in nature for years (Latifi *et al*., 2016). Given this, extensive research has been conducted to identify solutions for waste removal and reuse. To address this problem, various methods have been proposed, including recycling these materials for industrial use. Within the reinforced soil method, which aims to provide sufficient tensile strength to the soil for withstanding incoming loads, a range of tensile elements such as metal strips, geosynthetics and plastic waste are used (Babu and Chouksey, 2011; Munfakh, 1997). Notably, employing plastic waste for soil improvement has the advantage of being cost-effective, making this type of reinforcement economically significant (Fauzi *et al*., 2016; Consoli *et al*., 2002). A significant proportion of waste materials cannot be utilized in their original industry or for producing the same materials, consequently leading to their application in other industries. Using waste materials, including their ash, for soil stabilization is a viable solution that helps mitigate environmental issues and pollution. It can also enhance the properties of stabilized soils if appropriate materials are selected (Choudhary *et al*., 2010; Tingle and Santoni, 2003). Liquefaction of soil is a phenomenon commonly studied in earthquake engineering. During liquefaction, the soil transitions from a solid phase to a temporary liquid state and flows. When structures are present on the liquefying soil, the static equilibrium of the structures is disrupted and in the best-case scenario, they settle uniformly. This phenomenon can have a detrimental impact on the soil's stability and strength. Taslimian *et al.* (2015) they discussed different methods and soil sampling techniques for soil Liquefaction in porous environments, including non-darcy flows, permeability coefficients and large deformations on soil samples. Their studies comprehensively investigated the effects and factors affecting liquefaction (Taslimian, 2024; Taslimian and Noorzad, 2024; Taslimian *et al*., 2015; 2023a-b).

Another advantage of this method is its ability to reduce the depletion of natural resources commonly used for road stabilization. It is also highly effective in increasing soil resistance, strength and permeability while limiting water absorption, erosion and settlement. Moreover, it is a cost-effective solution. In recent years, environmental and economic concerns have prompted the exploration of alternative uses for waste materials such as worn tires, bottles and glasses. These materials can be used to modify and enhance soil properties. Soil stabilization and strengthening methods generally involve geosynthetics, cementing agents (lime, cement, etc.,) synthetic and non-synthetic fibers, or rubber scraps. These materials can increase resistance, reduce deformation and settlement, control swelling and shrinking, minimize corrosion, improve durability and reduce soil permeability. Reinforced or stabilized soils typically comprise composite materials formed by combining and optimizing the properties of individual ingredients. One of the latest approaches for improving soil properties is the use of plastic materials obtained from bottles (Chebet, 2013; Kalkan *et al*., 2019). In a study by Naeemifar and Yasrobi (2022), The unstable behavior of clayey sands was investigated concerning plasticity. The findings revealed that increased clay led to decreased strength, considering the state of plasticity and fine grains (Naeemifar and Yasrobi, 2022).

Previous studies utilized inorganic granules and recycled materials to create the samples. However, the current study aimed to investigate the effectiveness of organic granules with varying weight categories and their impact on the fracture angle of the samples, as well as the soil resistance. The research also examined the effect of cement consolidator on all samples and presented the outcomes. It should be noted that the research comprehensively demonstrates the impact of the presence or absence of cement stabilizer in conjunction with the addition of fine aggregate. The current study aimed to assess the effect of microbeads, such as talc, silica, gypsum, crystal barite, perlite and micro-silica, on cement-reinforced soil. To this end, laboratory samples were created and subjected to an axial pressure test. To cover a broad range of weights for fine grain and cement materials, 13 categories of fine grain samples were selected, consisting of 3 tests and five weight ranges of cement and fine grains, resulting in 234 produced and tested samples. All samples were treated under identical conditions for seven days. To ensure optimal response and suitable adaptation, the samples were polished at the beginning and end, followed by the fracture process. In the laboratory modeling process, 200 g of clay and 300 g of water were used, which were then combined with varying quantities of fine grain materials in 5 categories (10, 20, 40, 80 and 160 g) and cement in 6 categories (10, 20, 25, 40, 80 and 100 g). Additionally, five samples were constructed and tested without the addition of cement. According to the findings, the samples that contained gypsum and crystal barite exhibited a larger impact on increasing the soil's resistance when cement was considered. However, it is worth mentioning that other fine-grained materials also enhanced the soil's resistance, albeit with a slightly lower effect than gypsum and micro-silica. The manner and angle of fracture in the samples suggest that incorporating fine grains and cement into the soil had a notable impact on the fracture angle and its deviation from the normal state.

Materials and Methods

Soil and Fine-Grain

The clay required for this study is from a depth of 1-1.5 m in the southern part of Shahrekord, which is situated in Iran. The physical properties of the clay are listed in Table 1, while the size distribution of clay is illustrated in Fig. 1. Based on the ASTM D 2487 (ASTM, 2017) Standard, the soil is classified as Lean Clay (CL). This research involves the use of various fine-grained materials to explore their individual effects on clay's resistance components. The study assesses how each material influences soil resistance when mixed with clay, with or without cement reinforcement, by incorporating micro-silica, perlite, crystal barite, gypsum, silica and talc. By including a diverse selection of fine-grained materials, the study can comprehensively analyze how different additives impact the soil's properties, including strength, durability and fracture behavior. The choice of fine-grained materials such as micro-silica, perlite, crystal barite, gypsum, silica and talc is based on their inherent characteristics like porosity, density and grain shape. It's important to cover a diverse range and spread the sizes of different grains across the spectrum. Each material possesses unique characteristics that may either enhance or modify the resistance components of the clay samples.

Table 1: Physical properties of soil

Soil properties	Values
Specific gravity	2.70
Liquid limit	36.00
Plasticity index	18.00
Unified soil classification	CL
Compaction study	
Maximum dry density	17.90 (kN/m^3)
Optimum moisture content	16.0%
Grain size analysis	
Gravel	0.00
Sand	12.00
Clay and silt	88.00

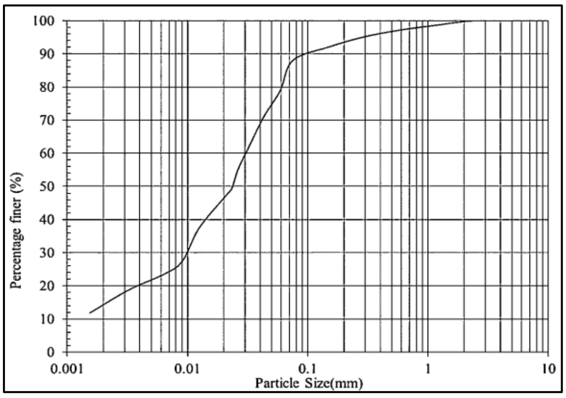

Fig. 1: Particle size distribution of the soil

Furthermore, examining various fine-grained materials allows for comparisons between different additives, facilitating the identification of the most effective materials for improving soil resistance. This information holds significant value for engineers, geologists and researchers interested in optimizing soil stabilization techniques and enhancing the performance of clay-based materials in construction and geotechnical applications.

The particle size distribution of the soil particles is illustrated in Fig. 1.

The specifications, including specific gravity, particle size and bulk density of fine grains used in laboratory simulations, are given in Table 2.

The physical characteristics of fine grains used in all the categories and weight percentages mentioned in table 1 are presented in Table 2. Laboratory samples were created and subjected to an Unconfined Compressive Strength (UCS) test. To cover a broad range of weights for fine grain and cement materials, 13 categories of fine grain samples were selected, consisting of 3 tests and five weight ranges of cement and fine grains, resulting in 234 produced and tested samples. All samples were treated under identical conditions for seven days. To ensure optimal response and suitable adaptation, the samples were polished at the beginning and end, followed by the fracture process. In the laboratory modeling process, 2000 of clay and 300 g of water were used, which were then combined with varying quantities of fine grain materials in 5 categories (10, 20, 40, 80 and 160 g) and cement in 6 categories (10, 20, 25, 40, 80 and 100 g). Additionally, five samples were constructed and tested without the addition of cement. The soil type utilized in this experiment is clay soil obtained from the southern region of Shahrekord. To facilitate recognition and present the results more coherently, all fine-grained materials have been abbreviated in the tables and presented consistently. Specifically, Micro-Silica (MS), Perlite (P), crystal Barite (B), Gypsum (ZH), Silica (S) and Talc (T) are used. The specifics of the sample modeling process, as well as the weight of fine grain and cement, can be found in Table 3.

The specifics of the laboratory sampling process are outlined in Table 3. It is important to note that all samples were created using 300 of water and 2000 g of soil and for each code listed in the table, three samples were produced and tested (e.g., three samples were created for B101). Given that there are five categories of fine grains, there are 13 codes for each sample category, with three samples in each code. For example, in category B, codes 101-113 encompass 13 different weight categories, with three samples produced and tested for each weight category, resulting in 39 samples created and fractured for category B.

Table 2: Specifications of fine grains used in laboratory simulations

	Fine grains					
Parameters	(MS)	(P)	(ZH)	(B)	(S)	(T)
Specific gravity	2.43	2.3	2.50	4.03	2.25	2.07
Particle size (μm)	0.01	1000.0	40.00	0.02	26.00	2.00
Bulk density (Mg/m^3)	1.13	1.1	1.28	2.91	2.24	1.43

Table 3: Modeling details of laboratory samples

Typical	Code	Fine-grained (*g*)	Cement (*g*)	Number of samples
MS	101	10	-	
P	102	20	-	
B	103	40	-	
ZH	104	80	-	
S	105	160	-	
T	106	10	40	
	107	20	80	3
	108	40	100	
	109	40	10	
	110	80	20	
	111	100	40	
	112	50	50	
	113	25	25	

Unconfined Compressive Strength

During the study's testing process, the Uniaxial Compressive Strength (UCS) was evaluated following the (ASTM, 2016) Standard. All samples, regardless of weight categories and codes, were tested using cement and other fine particles.

Results

This section presents the laboratory results of the sample failure and UCS test, along with the investigation into the impact of fine grains on the fracture angle of samples. The study considers both cement and non-cement conditions.

Laboratory Results

The following section presents the outcomes of UCS tests conducted on all the samples. The details of the UCS test for the clay without any addition of fine grains, along with the ultimate failure response, are given in Table 4. This table compares the results of samples with fine grains and clay consolidated with cement.

Table 5 displays the results of the UCS test carried out on clay with micro-silica and cement. The sample codes for each weighting can be found in Table 3. The table shows the ultimate failure and the loading amounts for each step of the UCS test. Table 5 shows that samples with clay soil and micro-silica in the first 3 conditions (101-103) have exhibited suitable conditions with an almost appropriate final failure response. In the next step (cases 106-110), the samples that contain clay with micro-silica and cement show a reduced response compared to those without cement (cases 101-103). The samples with cement, in some cases, exhibit a lower response than those without cement. Finally, in case 111, where clay, micro-silica, 100 g of micro-silica and 40 g of cement are present, the response of the final failure of the samples is at its worst state. Table 6 displays the results of the UCS test carried out on clay with perlite and cement. Based on the laboratory findings, it was observed that in case 111, the inclusion of cement in MS samples led to a decrease in strength, mainly when the weight percentage of cement to fine grains was 2.5. It is evident that under these conditions, the addition of cement reduced the resistance of the resulting structure and composition in the samples. Generally, it can be inferred that MS samples exhibit good resistance in the absence of cement and only under specific conditions does the weight percentage of cement to fine grains diminish the sample's strength. Additionally, it can be noted that the strength of the MS samples is susceptible to the weight percentage of cement and fine grains. The sample codes for each weighting can be found in Table 3. The table shows the ultimate failure and the loading amounts for each step of the UCS test.

Table 6 indicates that the samples with clay soil and perlite in the first three conditions (101-103) have shown almost suitable final failure responses. In the next step (cases 104-106), the samples containing clay with perlite and cement exhibit a reduced response compared to those without cement (cases 101-103). Moreover, in cases 107 and 108, where clay, perlite and cement with different amounts are present (state 107: 20 and 80 g and state 108: 40 and 100 g), the final failure response of the samples will be in the best situation. The results of Table 6 suggest that the final failure response of the samples and the impact conditions of the cement will be better when its amount is higher than the fine grain. This finding contradicts the results of Table 5, which suggests that the presence of fine grains more than cement provides a more suitable answer. Based on the lab results and the inherent characteristics of the perlite samples, their porosity and fine grain can be utilized to increase sample resistance. By adding cement and placing cement particles in different pores, the penetration of cement in the pores and the creation of integrity will directly enhance the sample's resistance. This improvement is directly linked to the cement-to-fine-grain ratio, influencing the sample's strength. According to the lab data, the optimal weight percentages of cement to perlite are 107 and 108 for achieving the desired results. Table 7 displays the results of the UCS test carried out on clay with crystal barite and cement. The sample codes for each weighting can be found in Table 3. The table shows the ultimate failure and the loading amounts for each step of the UCS test.

Table 4: USC test details of clay without added fines

Typical	Code	0.5	1	1.5	2	2.5	Final failure (kg/cm^2)
Clay	1	31	290	411	-	-	501
		16	130	350	-	-	550
		17	72	170	390	500	533
	2	18	82	224	340	-	340
		27	66	220	380	-	532
		85	300	-	-	-	500
	3	80	315	400	-	-	517
		16	235	469	-	-	500
		31	172	470	-	-	542

Table 5: USC test details of clay with mico silica

Typical	Code	0.5	1	1.5	2	2.5	Final failure (kg/cm^2)
MS	101	170	514	-	-	-	530
		93	290	375	-	-	390
		150	480	-	-	-	588
	102	96	295	-	-	-	315
		314	545	-	-	-	602
		112	470	-	-	-	530
	103	15	168	560	-	-	585
		52	370	475	-	-	500
		13	100	300	-	-	430
	104	36	249	-	-	-	472
		23	260	-	-	-	279
		17	160	374	-	-	436
	105	127	347	-	-	-	367
		99	230	330	-	-	358
		150	366	-	-	-	390
	106	50	207	360	480	-	538
		77	203	340	430	-	469
		60	158	245	320	393	440
	107	96	265	397	500	-	644
		122	400	700	970	-	1057
		107	250	390	470	540	660
	108	109	230	357	398	-	432
		167	472	860	1200	-	1331
		150	560	940	-	-	1054
	109	4	100	170	232	-	283
		123	256	340	-	-	358
		27	115	257	311	-	320
	110	27	89	103	141	177	180
		101	255	343	-	-	370
		49	167	283	-	-	328
	111	41	200	336	521	680	722
		92	203	331	426	-	430
		46	140	270	378	-	405
	112	15	131	260	390	494	537
		85	270	501	700	-	720
		54	126	180	250	332	470
	113	98	201	290	390	429	451
		94	201	296	357	-	373
		27	81	119	162	203	220

Table 6: USC test details of clay with perlite

Typical	Code	0.5	1	1.5	2	2.5	3	3.5	Final failure (kg/cm^2)
P	101	252	543	-	-	-	-	-	576
		61	208	450	-	-	-	-	477
		48	357	-	-	-	-	-	382
	102	92	400	-	-	-	-	-	545
		157	319	-	-	-	-	-	322
		58	315	-	-	-	-	-	350
	103	87	440	-	-	-	-	-	604
		27	285	-	-	-	-	-	497
		37	367	650	-	-	-	-	732
	104	89	253	324	-	-	-	-	369
		47	236	380	485	-	-	-	517
		69	270	384	-	-	-	-	406
	105	86	409	-	-	-	-	-	432
		174	342	407	-	-	-	-	517
		37	268	376	-	-	-	-	390
	106	43	140	235	-	-	-	-	302
		57	115	153	190	215	252	290	334
		72	166	249	-	-	-	-	258
	107	150	322	512	700	-	-	-	850
		110	209	350	540	734	-	-	777
		62	287	680	-	-	-	-	1152
	108	103	252	423	630	800	887	-	905
		30	167	313	450	555	666	750	795
		31	201	380	490	622	752	-	786
	109	32	224	350	-	-	-	-	367
		109	185	235	276	-	-	-	291
		122	252	327	-	-	-	-	337
	110	208	300	390	490	547	-	-	567
		95	195	289	334	-	-	-	361
		133	249	305	349	404	-	-	432
	111	84	201	301	411	482	-	-	515
		214	700	1050	-	-	-	-	1100
		63	232	359	480	575	650	-	735
	112	200	412	605	-	-	-	-	681
		132	232	306	388	500	586	-	632
		135	222	293	336	405	485	-	553
	113	105	258	351	389	-	-	-	395
		75	150	-	-	-	-	-	150
		88	191	246	-	-	-	-	306

Based on Table 7, it is evident that the final failure response of the clay soil samples, along with crystal barite, in the first six cases (101-106), is almost suitable and they have displayed ideal conditions. In the subsequent step, samples were taken in such a manner that in cases 109-113, clay is present with crystal barite. In the presence of cement in the samples, the response is reduced from samples without cement and from cases (101-106) where cement is present in the sample, the response is not lower. In the next step, it can be concluded that there are states 107 and 108, where clay is present along with crystal barite and cement with the amount (state 107: 20 g and 80 g and state 108: 40 and 100 g) and the final failure response of the samples will be at its highest position. From the results of Tables 6-7, it can be inferred that we will have the final failure response of the sample and the impact conditions of the cement in situations where its amount is higher than the fine grain. This point contradicts the findings of Table 5 the presence of fine grains more than cement provides a more suitable response. Table 8 displays the results of the UCS test carried out on clay with gypsum and cement. The sample codes for each weighting can be found in Table 3. The table shows the ultimate failure and the loading amounts for each step of the UCS test. Table 8 shows that the final failure response of the clay samples with gypsum, in the first two cases (101 and 102), had the highest ultimate failure response. In the subsequent step, samples were taken in such a way that in cases 103-106, where clay is present along with gypsum and the presence of cement in some samples, the response is reduced from samples without cement and cases (101 and 102) where cement is present in the sample, the response is not lower. In the next step, it can be concluded that there are states 107 and 108, where clay is present along with gypsum and cement with the amount (state 107: 20 and 80 g and state 108: 40 and 100 g), the final failure response of the samples will be in good condition and there will only be a slight difference from samples 101 and 102. From the results of Table 7, it can be inferred that samples without cement exhibit a better final failure response and only in situations where the cement is more than the fine grains in the sample does its response with a small difference equal to the condition without cement. This point contradicts the findings of Table 5 that show the presence of fine grains more than cement and in Tables 6-7, the results of samples with less fine grains than cement are presented. Table 9 displays the results of the UCS test carried out on clay with silica and cement. The sample codes for each weighting can be found in Table 3. The table shows the ultimate failure and the loading amounts for each step of the UCS test. Table 9 shows that the final failure response of the samples with clay and silica, in the first three cases (101-103), demonstrated suitable conditions in the final failure responses. In the subsequent step, samples were taken in such a way that in cases 104-110, which contain clay with silica and the presence of cement in some samples, the response is reduced from the samples without cement and from cases (101-103) where cement is present in the sample, the response is not lower. In the next step, it can be concluded that mode 111, clay with silica and cement with 100 and 40 g, elicited the highest response. From the results of Table 8, it can be inferred that samples without the presence of cement exhibit a better final failure response and only in situations where the cement is more than the fine grains in the sample its response with a small difference is equal to the condition without cement and it will be in samples. It is worth mentioning that the results of this sample are almost in line with the findings of Tables 6-7, which have fewer fine grains than cement.

Table 10 displays the results of the UCS test carried out on clay with talc and cement. The sample codes for each weighting can be found in Table 3. The table shows the ultimate failure and the loading amounts for each step of the UCS test. Based on the data presented in Table 10, the final failure responses of clay samples containing talc in the first three cases (101-103) have demonstrated suitable conditions. Moving forward, the samples were taken such that cases 104-106, where clay is present alongside talc and cement in some samples, resulted in a reduced response compared to the samples without cement. This response was also lower than in cases (101-103) with cement in the sample. Further analysis revealed that mode 107, comprising clay with silica and cement with 20 and 80 g, respectively, had the highest response. Based on the results presented in Table 8, it can be concluded that samples without cement did not exhibit proper final failure response conditions. The response was deemed appropriate only when the cement content exceeded the fine grain content in the sample. Moreover, increasing the cement content and reducing the fine grain content resulted in poor final failure response conditions. Figure 2 displays the final failure response of samples in various weight conditions, along with the corresponding codes mentioned in Table 3. Based on the results presented in Tables 5-10 and described in Fig. 2, it can be concluded that the samples with higher cement content than fine grain content tend to have a more suitable final response. On the other hand, the samples without cement can also yield good final results, with the fine grain failing even in the absence of cement. Moreover, the laboratory sample with crystal barite fine grain shows the most appropriate and highest response rate when the cement content is four times the amount of fine grain in the sample. This condition yields better results than the without cement samples.

Table 7: USC test details of clay with crystal barite

Typical	Code	0.5	1	1.5	2	2.5	3	Final failure (kg/cm^2)
B	101	25	162	-	-	-	-	610
		3	29	390	790	-	-	838
		180	600	-	-	-	-	750
	102	90	234	454	-	-	-	539
		32	193	-	-	-	-	450
		13	190	420	-	-	-	565
	103	78	460	-	-	-	-	539
		77	440	532	-	-	-	620
		56	290	700	855	-	-	940
	104	5	50	300	540	-	-	605
		28	278	-	-	-	-	382
		140	399	-	-	-	-	451
	105	135	510	-	-	-	-	564
		110	334	-	-	-	-	432
		95	530	-	-	-	-	640
	106	30	181	252	315	391	482	590
		81	167	249	356	487	-	500
		36	153	340	547	-	-	585

Table 7: Continue

107	62	375	690	889	-	-	954
	7	53	165	270	460	667	680
	38	177	350	570	728	-	744
108	134	380	680	950	-	-	1000
	41	151	310	520	770	-	1160
	68	323	670	832	-	-	849
109	101	209	276	-	-	-	298
	34	240	340	-	-	-	354
	105	237	-	-	-	-	238
110	129	209	283	-	-	-	334
	118	290	420	-	-	-	430
	135	304	-	-	-	-	390
111	12	128	215	316	450	-	588
	145	294	502	-	-	-	596
	50	128	275	380	-	-	481
112	127	444	634	-	-	-	673
	106	224	427	656	869	-	890
	140	320	512	695	-	-	733
113	70	122	225	311	383	-	395
	67	214	383	-	-	-	421
	39	226	400	-	-	-	500

Table 8: USC test details of clay with gypsum

Typical	Code	0.5	1	1.5	2	2.5	3	3.5	4	Final failure (kg/cm^2)
ZH	101	27	38	170	720	-	-	-	-	940
		270	600	-	-	-	-	-	-	650
		150	700	-	-	-	-	-	-	785
	102	200	790	-	-	-	-	-	-	950
		40	22	700	-	-	-	-	-	733
		45	270	760	-	-	-	-	-	780
	103	15	57	140	-	-	-	-	-	404
		500	650	-	-	-	-	-	-	780
		3	31	250	680	-	-	-	-	690
	104	100	49	-	-	-	-	-	-	690
		16	46	100	340	-	-	-	-	560
		500	-	-	-	-	-	-	-	785
	105	25	66	180	-	-	-	-	-	580
		15	460	-	-	-	-	-	-	790
		310	-	-	-	-	-	-	-	540
	106	33	170	265	-	-	-	-	-	305
		17	177	350	450	490	-	-	-	510
		26	100	160	235	334	420	530	-	600
	107	60	212	400	612	-	-	-	-	700
		13	80	199	325	430	-	-	-	475
		50	100	177	270	330	-	-	-	351
	108	24	71	138	216	330	470	620	-	800
		90	190	277	365	430	500	-	-	532
		65	133	243	329	412	490	570	670	721
	109	40	193	420	-	-	-	-	-	479
		41	100	300	-	-	-	-	-	382
		170	360	-	-	-	-	-	-	360
	110	88	160	245	-	-	-	-	-	270
		81	170	222	-	-	-	-	-	306
		27	91	199	274	-	-	-	-	350
	111	3	101	180	304	415	-	-	-	430
		16	94	290	500	-	-	-	-	520
		22	52	101	168	240	-	-	-	300
	112	108	265	458	-	-	-	-	-	543
		42	97	136	174	-	-	-	-	270
		51	143	211	260	311	-	-	-	356
	113	30	130	200	314	-	-	-	-	369
		70	128	200	255	-	-	-	-	290
		6	114	268	-	-	-	-	-	301

Table 9: USC test details of clay with silica

Typical	Code	0.5	1	1.5	2	2.5	3	Final failure (kg/cm^2)
S	101	18	145	32	-	-	-	334
		24	290	450	63	-	-	640
		10	45	290	-	-	-	450
	102	70	270	-	-	-	-	316
		107	500	-	-	-	-	995
		75	400	590	-	-	-	600
	103	80	318	600	-	-	-	706
		30	154	450	-	-	-	524
		45	245	520	-	-	-	563
	104	70	345	700	-	-	-	750
		17	50	175	-	-	-	670
		60	200	440	-	-	-	470
	105	20	80	240	540	-	-	710
		55	280	580	-	-	-	699
		120	400	550	-	-	-	570
	106	45	190	400	-	-	-	484
		10	66	172	260	320	-	435
		16	80	150	212	290	-	310
	107	15	94	235	370	500	600	657
		100	222	350	490	-	-	564
		55	139	250	390	530	-	597
	108	70	240	420	-	-	-	485
		28	260	370	-	-	-	380
		24	135	350	570	-	-	590
	109	50	220	280	-	-	-	280
		45	100	148	200	255	-	313
		22	34	113	200	260	-	315
	110	140	244	-	-	-	-	250
		50	130	215	300	-	-	318
		39	94	175	224	-	-	254
	111	40	130	211	-	-	-	277
		13	77	135	206	-	-	250
		25	99	144	177	-	-	200
	112	36	160	272	-	-	-	293
		48	190	320	-	-	-	333
		27	90	180	285	-	-	351
	113	34	50	86	106	120	-	141
		41	95	148	-	-	-	193
		32	120	150	-	-	-	213

Table 10: USC test details of clay with talc

Typical	Code	0.5	1	1.5	2	2.5	Final failure (kg/cm^2)
T	101	5	31	178	400	-	434
		6	40	132	420	-	510
		22	80	175	313	368	420
	102	75	400	-	-	-	488
		35	109	240	300	-	389
		130	33	400	-	-	450
	103	190	306	360	-	-	380
		130	360	-	-	-	483
		11	150	464	-	-	464
	104	8	49	150	300	450	601
		16	100	170	300	390	424
		9	33	185	390	-	489
	105	55	250	290	-	-	370
		26	84	220	295	-	323
		9	38	300	560	-	663
	106	100	332	-	-	-	533
		85	230	400	-	-	590

Table 10: Continue

	40	145	288	-	-	310
107	120	380	620	-	-	650
	45	100	179	-	-	226
	16	50	145	390	-	400
108	7	48	215	-	-	490
	180	450	-	-	-	569
	80	300	650	-	-	860
109	55	224	400	-	-	431
	60	230	320	-	-	374
	37	110	270	-	-	320
110	40	240	318	-	-	327
	90	360	550	-	-	570
	100	266	-	-	-	280
111	70	166	-	-	-	200
	21	99	-	-	-	175
	46	144	-	-	-	170
112	5	96	160	224	288	320
	30	130	214	299	-	333
	67	140	218	300	400	450
113	60	86	-	-	-	131
	26	139	260	-	-	300
	30	130	176	-	-	239

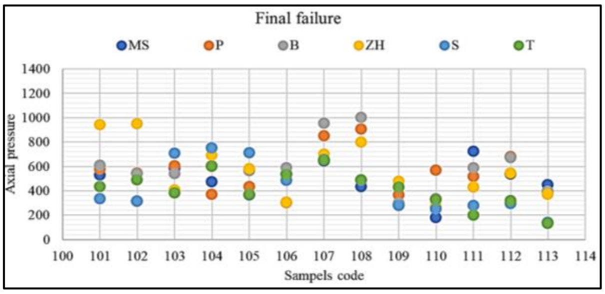

Fig. 2: Details of the final failure response of samples under the UCS test

Examining the Fracture Angle of the Samples

This section covers the impact of incorporating fine grains into the samples on forming cracks and their crushing. We will examine the effect of fine grains on the samples in the following sections. After conducting lab tests, it has been inferred that the samples made with MS have experienced groove damage, cracks in the middle of the sample, both horizontally and vertically, as well as peeling. Interestingly, some samples remained intact even after loading. Figure 3 provides some examples to further illustrate this.

It has been deduced from the sample and laboratory analysis that the samples containing P have experienced damage, such as collapsed, horizontally layered, vertical cracks and destruction in the upper, middle and lower parts of the sample after loading. Some examples of these damages can be seen in Fig. 4. Fractures and cracks in samples made with P.

Based on the sample and laboratory tests, it can be inferred that samples produced using B exhibit a vertical crack and fracture in the lower third of the sample. Additionally, these samples show a fracture at the center of the sample and partial damage at the top and bottom of the sample. Some examples of these samples are shown in Fig. 5. Fractures and cracks in samples made with B.

Drawing upon observations of the sample and the examination of laboratory and tested samples, it can be inferred that the use of ZH in the samples resulted in various outcomes such as collapse, layering on the top surface, partial destruction on the top, vertical cracks, damage in the upper and lower thirds and relatively good condition of some samples. Figure 6 visually illustrates these outcomes.

Based on observations from the sample and analysis of laboratory and tested samples, it can be inferred that samples made with S and T exhibit vertical cracks, halving with a vertical axis, destruction in the middle and upper thirds, collapses and groove destruction. Figure 7 provides visual examples.

Figure 7 fractures and cracks in samples made with S and T drawing upon observations of the sample, as well as analysis of laboratory and tested samples, it can be deduced that the samples made with clay exhibit vertical and transverse cracks, as well as destruction in the upper and lower thirds. Figure 8 provides visual examples.

According to the laboratory findings, the samples of ZH and MS with fine grains experienced less damage and breakage than the other samples during the USC test. This outcome is ideal for an additive used in soil reinforced with cement and fine grains, as these materials can enhance soil resistance and make cracks, fractures and damage more manageable. Based on the observations, it can be inferred that the use of ZH and MS altered the crack angle and fracture modes and, in some instances, the samples remained intact without any damage, even after loading.

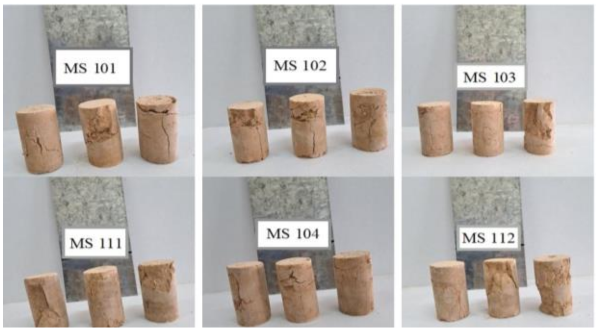

Fig. 3: Fractures and cracks in samples made with MS

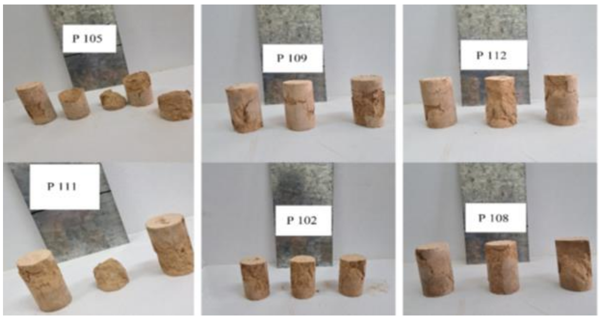

Fig. 4: Fractures and cracks in samples made with P

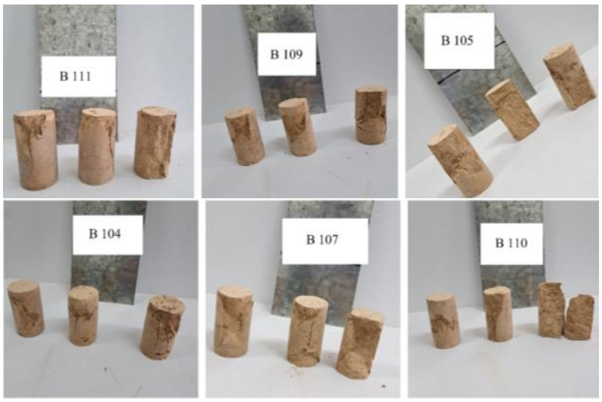

Fig. 5: Fractures and cracks in samples made with B

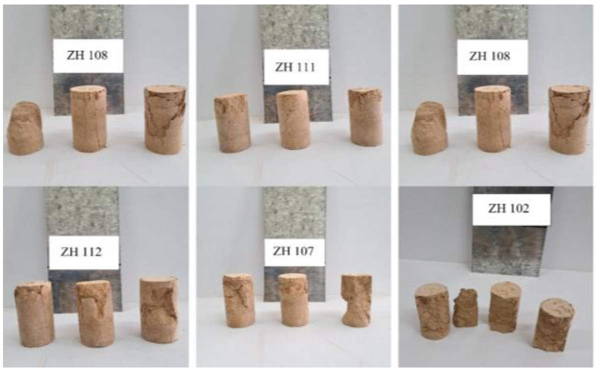

Fig. 6: Fractures and cracks in samples made with ZH

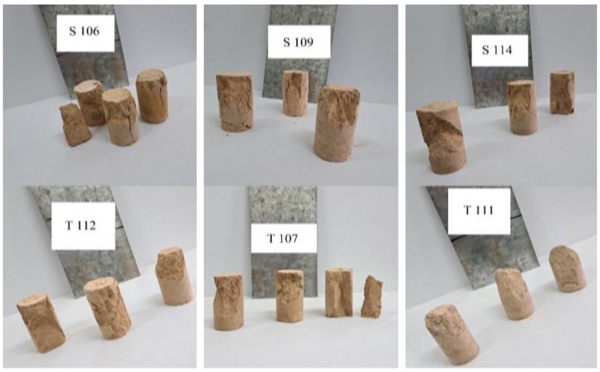

Fig. 7: Fractures and cracks in samples made with S and T

Fig. 8: Fractures and cracks in samples made with clay

Discussion

The study comprehensively analyzes the final failure response of different clay samples under varied weight conditions and in the presence of other materials. The findings, outlined in Tables 5-10, offer valuable insights into the final failure response of clay samples under specific conditions. For instance, Tables 10 suggests that clay samples containing Talc (T) exhibited favorable final failure responses in the first three cases. In contrast, the presence of cement in some samples resulted in diminished responses compared to samples without cement. Moreover, increased cement content and decreased fine grain content led to poor final failure responses. Similarly, Tables 5-9 provide detailed insights into the final failure responses of clay samples containing Silica (S), Gypsum (ZH), crystal Barite (B), Perlite (P) and Micro-Silica (MS) under various conditions and in the presence of cement. The presence of cement in some samples generally resulted in reduced responses, except in specific situations. Also, from Figs. 3-7, it can be seen that the samples using fine-grained materials and weight percentages and the presence or absence of cement significantly affect the way of failure, the way of cracking and the way of disintegration of the samples. For example, samples made with MS have experienced groove damage, cracks in the middle of the sample, both horizontally and vertically and peeling. Interestingly, some samples remained intact even after loading, but in the same conditions as samples made with S and T exhibit vertical cracks, halving with a vertical axis, destruction in the middle and upper thirds, collapses and groove destruction. Based on the laboratory data, the failure mode and failure angles of samples made with different materials will directly impact the mixing of cement and fine-grained materials with clay. The weight percentage and mixing process will influence the fracture angle and damage of the samples. The size and distribution of grains in the samples will also affect the failure process. Another significant factor is the orientation of fine grains in the samples, which influences the failure process. The varying responses of samples made with different materials during the failure process and changes in the failure angles are attributed to these factors.

Conclusion

The research offers detailed insights into how various clay samples respond to different weight conditions and the presence or absence of fine-grain materials. The findings indicate that the reaction of samples containing talc, silica, gypsum, crystal barite, perlite and micro-silica to the presence of cement varies. The most effective final failure responses occur when the cement content surpasses the fine grain content in the sample. Additionally, the type of material alongside the clay also influences the response. The study presents valuable information for further research in this area and provides distinct results for each sample with different levels of fine grains. For instance, samples composed of MS display an adequate response in the absence of cement, but fine grain and cement reduce the final failure response. Optimal outcomes are achieved when the Micro-silica to cement ratio is nearly 2:1. Samples with MS exhibit groove damage, horizontal and vertical cracks and peeling. Some samples remained intact even after being subjected to loading. Samples produced with P demonstrate a positive response in the absence of cement, with the highest final failure response when the cement-to-fine-grain ratio is almost 3:1. These samples experienced collapse, horizontal layering, vertical cracks and destruction in various parts after loading. Among other fine grains, samples made with B show the highest response. They display a suitable response in the absence of cement. Still, the final failure response is highest when the cement-to-fine-grain ratio is almost 3:1. Samples produced using B experienced vertical cracking fractures and damage in different parts after loading. Samples made with ZH exhibit the highest response in the absence of cement. However, the final failure response is slightly lower in the presence of fine grain and cement, with a difference of almost 3:1 in favor of cement. The use of ZH resulted in collapse, layering, partial destruction, vertical cracks and damage in various parts, with some samples in relatively good condition. Samples containing S show a favorable response in the absence of cement. Still, the final failure response is highest when the cement-to-fine-grain ratio is approximately 1:3. They experienced vertical cracks, halving, destruction, collapses and groove destruction. Similarly, samples made with T display a positive response in the absence of cement, with the final failure response highest when the cement-to-fine-grain ratio is approximately 3:1. The response decreases significantly with an increase in fine grains-samples produced using T experienced vertical cracks, halving, destruction, collapse and groove destruction. Based on the numerical and laboratory data, it can be inferred that variations in sample strength in S and MS states are directly linked to the presence or absence of cement with varying granulation percentages in the samples. The presence of cement (particularly the percentage of fine grains and cement) impacts the composite structure and strength of the samples. Samples containing P, B, ZH and T show improved resistance when cement is present. A specific weight percentage (in the optimal range) significantly enhances sample strength in these samples. These samples are less affected by cement and reach peak strength under optimal cement and fine grain weight conditions.

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Author’s Contributions

Sayed Amirhossein Hosseini Chaleshtori: Investigation, methodology, supervision of tests, visualization, written review and editing.

Mohammad Alibabaei Shahraki: Methodology, visualization, written-original drafted, reviewed and edited.

Ethics

The authors would like to disclose that Mr. Mohammad Alibabaei Shahraki (corresponding author) is a member of the American Journal of Engineering and Applied Sciences Review Board.

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