Research on Engineering Structures & Materials
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Research Article

Improving the consolidation behavior of soft clay through chemical stabilization: Selection of the optimum mixture, physical model assessment, and SEM analysis

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Article Info

Article History:

Received 31 Aug 2026
Accepted 03 Oct 2026

Keywords:

Soft clay;
Chemical stabilization;
Consolidation settlement;
Cement;
Silica fume;
Physical model;
SEM

Abstract

Soft clay is characterized by high compressibility and may experience considerable consolidation settlement under sustained loading. This study evaluates the effectiveness of chemical stabilization using ordinary Portland cement (OPC), silica fume (SF), and SikaControl®-3705 in reducing the consolidation settlement of soft clay collected from Al-Bawia, Diyala Governorate, Iraq. Thirteen mixture conditions, comprising untreated soil, individual stabilizers, binary blends, and ternary combinations, were prepared and cured for 28-days. One-dimensional consolidation tests were performed on replicate specimens (n = 3) to evaluate settlement, compression index (Cc), initial void ratio (e_0), coefficient of volume compressibility (mv), and coefficient of consolidation (Cv). Using a two-stage quantitative criterion based on a minimum 50% settlement reduction followed by the Improvement-to-Dosage Ratio (IDR), the practical optimum was identified as 10% OPC + 5% SF + 1% SikaControl®-3705, which achieved a 55.9% settlement reduction and an IDR of 3.49. The mixture with the highest technical performance, containing 13% OPC + 7% SF + 1.5% SikaControl®-3705, reduced settlement to 2.60 mm (61.8%). The selected mixture was subsequently assessed in a physical model under incremental loading up to 100 kg over a 28-day observation period. The final settlement decreased from 11.20 mm for untreated soil to 2.82 mm for the selected mixture, representing a 74.8% reduction. Scanning electron microscopy (SEM) revealed a transition from a relatively open structure in the untreated soil to a denser and better-bonded structure in the stabilized specimen. Under the conditions investigated, the combined use of OPC and SF with SikaControl®-3705 effectively reduced the consolidation settlement of the tested soft clay.

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1. Introduction

Soft clay soils are highly compressible and have low shear strength, which can result in significant settlement and foundation problems [1–5]. Chemical stabilization has been widely used to improve the engineering and consolidation behavior of soft and problematic soils, particularly through cement, lime, and silica fume treatment [6–11]. Recent studies have also investigated silica fume and other additives for improving the mechanical and swelling characteristics of expansive soils [12–17]. Several studies have examined cement dust, nano-silica fume, and other stabilization techniques for problematic soils [18–21]. Other recent approaches include biological, magnetized-water, and green stabilization methods [22–25], as well as alternative treatment techniques such as emulsified asphalt stabilization [26]. Accordingly, this study investigates the use of cement, silica

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DOI: http://dx.doi.org/10.17515/resm2026-2278ic0831rs

fume, and SikaControl®-3705 to reduce the consolidation settlement of soft clay and identify an effective stabilizer mixture.

2. Materials and Methods

2.1 Study Area and Soil

The soft clay was collected from the Al-Bawia area, Diyala Governorate, Iraq. The soil properties are summarized in Table 1. Standard ASTM procedures were followed for water content (D2216), specific gravity (D854), Atterberg limits (D4318), particle-size distribution (D6913/D6913M and D7928), soil classification (D2487), compaction (D698), and one-dimensional consolidation (D2435/D2435M) [27–34]. The soil had a specific gravity of 2.68, natural water content of 24%, liquid limit of 38%, and plasticity index of 18%. Its particle-size distribution comprised 55% clay, 40% silt, and 5% sand, classifying the soil as CL according to USCS.

Table 1. Physical and mechanical properties of the untreated clay and stabilizing materials

Property	Symbol	Value	Unit
Specific gravity	Gs	2.68	–
Natural water content	wn	24	%
Liquid limit	LL	38	%
Plastic limit	PL	20	%
Plasticity index	PI	18	%
Shrinkage limit	SL	12	%
Clay content	–	55	%
Silt content	–	40	%
Sand content	–	5	%
Maximum dry density	γd(max)	1.68	g/cm^3
Optimum moisture content	wopt	15	%
USCS classification	–	CL	–
Unconfined compressive strength	UCS	50	kN/m^2
Undrained cohesion	Cu	25	kN/m^2
Angle of internal friction	φ	18	°
pH	pH	8.0	–
Total dissolved solids	TDS	2.2	%
Organic matter	OM	3.0	%
Calcium oxide	CaO	14.0	%
Silicon dioxide	SiO_2	15.0	%
Aluminum oxide	Al_2O_3	4.0	%
Iron oxide	Fe_2O_3	5.5	%
OPC Type I specific gravity	–	3.15	–
OPC initial setting time	–	45	min
OPC final setting time	–	375	min
OPC compressive strength	–	42.5	MPa
Silica fume SiO_2 content	–	91.5	%
Silica fume specific surface area	–	20,000	m^2/kg
Silica fume specific gravity	–	2.2	–
SikaControl®-3705 density	–	1.1	g/cm^3
SikaControl®-3705 dosage	–	0.5–1.5	% by dry soil

2.2 Stabilizing Materials

Ordinary Portland cement (OPC), silica fume (SF), and SikaControl®-3705 were used in the stabilization program. OPC was used as the primary cementitious material, SF as a supplementary pozzolanic material, and SikaControl®-3705 as a shrinkage-reducing admixture [35]. In the present study, SikaControl®-3705 was considered a shrinkage-reducing admixture rather than a primary binder. Its possible contribution to settlement reduction was considered indirect, through reducing shrinkage-related microcracking and maintaining the integrity of the stabilized soil structure. However, this mechanism was not independently quantified by dedicated shrinkage or cracking tests.

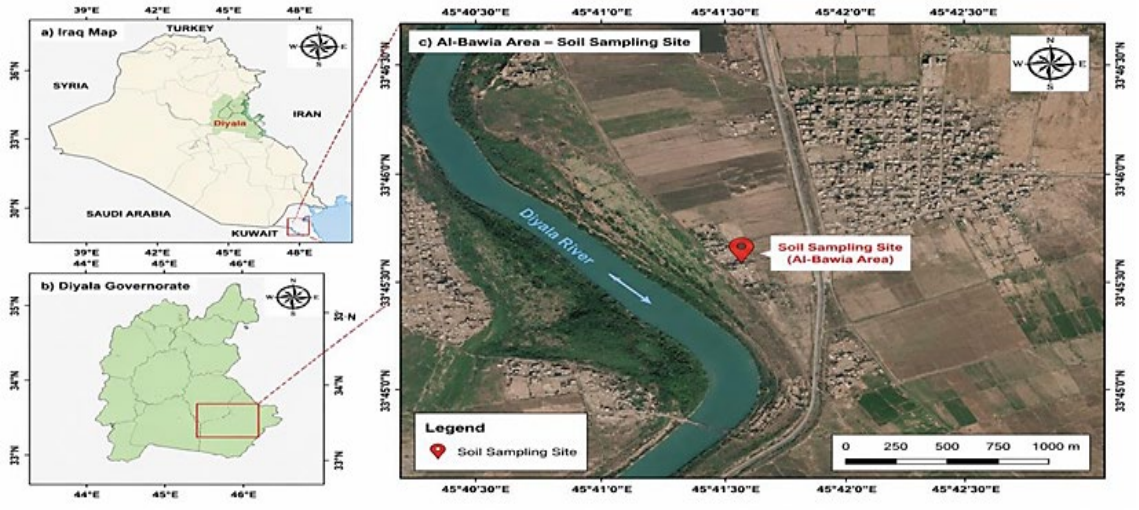


Fig. 1. Location of the soil sampling site in Al-Bawia, Diyala Governorate, Iraq

All stabilizer dosages were based on the dry mass of soil. The soil was air-dried, pulverized, and passed through a 2-mm sieve. OPC and SF were first dry-mixed for 5 min and then added to the prepared soil and mixed for 10 min. SikaControl®-3705 was diluted with the mixing water and uniformly sprayed during mixing. Mixing was continued for 15–20 min until a visually uniform mixture was obtained. The same mixing sequence and durations were maintained for all specimens to promote consistent distribution of the dry stabilizers and mixing water. The initial water content was maintained at 24%.

2.3 Stabilization Mixtures and Curing

Several combinations of OPC, SF, and SikaControl®-3705 were prepared to evaluate their effects on the consolidation behavior of the soft clay. OPC was used at 7%, 10%, and 13%, silica fume at 3%, 5%, and 7%, and SikaControl®-3705 at 0.5%, 1.0%, and 1.5%. All treated mixtures were cured for 28-days before testing. The mixture proportions and curing conditions are presented in Table 2. The 28-day curing age was selected as a common reference condition for comparing the different mixtures and to allow sufficient development of cementitious and pozzolanic reactions under the laboratory conditions. The conclusions are therefore limited to the investigated 28-day curing period, and longer-term strength and durability development were not evaluated.

Table 2. Stabilizer mixtures, proportions, and curing conditions

Mix ID	OPC (%)	SF (%)	Sika (%)	Total (%)	Curing	Description
Untreated	0	0	0	0.0	0 day	Natural soft clay
C7	7	0	0	7.0	28-days	Cement only
C10	10	0	0	10.0	28-days	Cement only
C13	13	0	0	13.0	28-days	Cement only
SF3	0	3	0	3.0	28-days	Silica fume only
SF5	0	5	0	5.0	28-days	Silica fume only
SF7	0	7	0	7.0	28-days	Silica fume only
C7SF3	7	3	0	10.0	28-days	Binary blend
C7SF3S0.5	7	3	0.5	10.5	28-days	Combined stabilizers
C10SF5	10	5	0	15.0	28-days	Binary blend
C10SF5S1	10	5	1.0	16.0	28-days	Practical optimum
C13SF7	13	7	0	20.0	28-days	High-performance binary blend
C13SF7S1.5	13	7	1.5	21.5	28-days	Highest technical performance

2.4 One-Dimensional Consolidation Test

Three specimens were tested for each mixture (n = 3). The settlement results are presented as mean ± standard deviation (SD). The coefficient of variation (CV) was calculated as SD/mean × 100

to indicate the variability among the replicate measurements. The coefficient of consolidation (Cv) was determined from the recorded consolidation-time response.

Table 3. One-dimensional consolidation parameters and settlement results (n = 3)

Mix	Settlement (mm)	Improvement (%)	Cc	e_0	mv (m^2/kN)	Cv (m^2/s)	IDR
Untreated	6.80 ± 0.12	0.0	0.27	0.98	0.00125	5.3×10^{-9}	0.00
C7	5.40 ± 0.10	20.6	0.22	0.92	0.00102	6.8×10^{-9}	2.94
C10	4.20 ± 0.08	38.2	0.17	0.86	0.00082	8.7×10^{-9}	3.82
C13	3.80 ± 0.07	44.1	0.15	0.82	0.00071	9.6×10^{-9}	3.39
SF3	6.10 ± 0.11	10.3	0.25	0.95	0.00115	5.9×10^{-9}	3.43
SF5	5.20 ± 0.09	23.5	0.22	0.91	0.00101	6.7×10^{-9}	4.70
SF7	4.80 ± 0.09	29.4	0.20	0.89	0.00095	7.3×10^{-9}	4.20
C7SF3	4.30 ± 0.08	36.8	0.18	0.85	0.00080	8.6×10^{-9}	3.68
C10SF5	3.40 ± 0.06	50.0	0.14	0.79	0.00066	9.9×10^{-9}	3.33
C13SF7	3.00 ± 0.05	55.9	0.12	0.75	0.00058	1.07×10^{-8}	2.80
C7SF3S0.5	4.30 ± 0.08	36.8	0.18	0.84	0.00079	8.8×10^{-9}	3.50
C10SF5S1 (Optimum)	3.00 ± 0.05	55.9	0.12	0.76	0.00060	1.10×10^{-8}	3.49
C13SF7S1.5 (Highest technical performance)	2.60 ± 0.05	61.8	0.11	0.72	0.00052	1.14×10^{-8}	2.87

IDR = improvement (%) / total stabilizer content (% by dry soil mass).

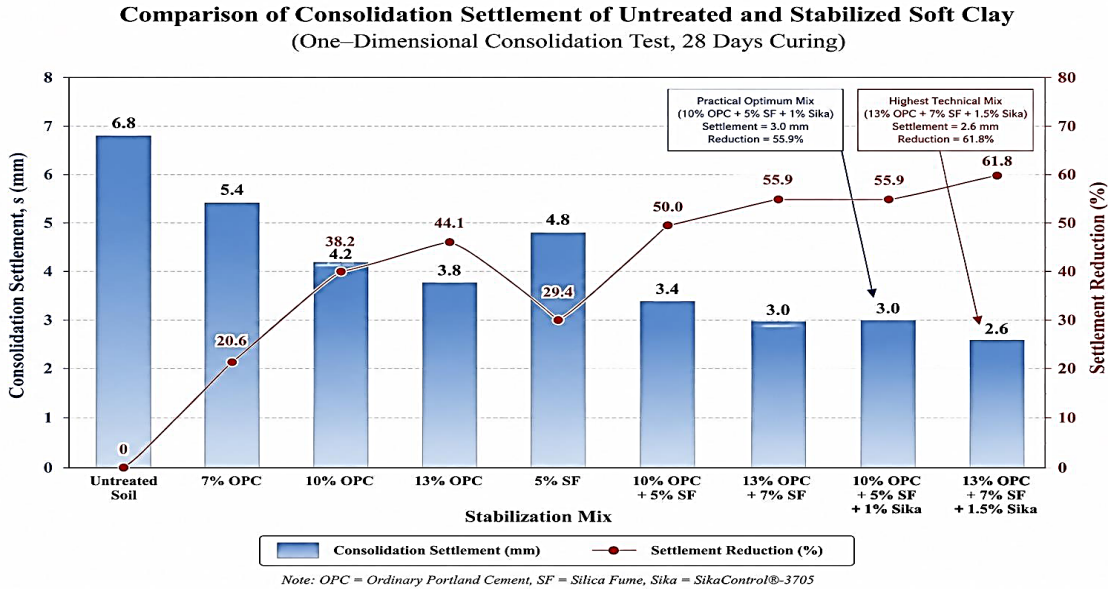


Fig. 2. Comparison of consolidation settlement for selected untreated and stabilized soft clay mixtures

The initial void ratio (e_0) was determined from the initial condition of the specimen. The compression index (Cc) was obtained from the slope of the virgin compression segment of the e–log σ′ relationship, while the coefficient of volume compressibility (mv) was determined from the change in vertical strain corresponding to the change in effective stress. The coefficient of consolidation (Cv) was calculated from the recorded consolidation-time response using the time-dependent procedure adopted for the oedometer test. Accordingly, Cc, mv, and Cv were obtained from the compression, stress–strain, and consolidation-time responses, respectively, and were used to assess changes in soil compressibility and consolidation behavior. The calculated Cv values were used to characterize the consolidation rate under the applied test conditions and were not interpreted as direct measurements of permeability. The determination procedures were applied to the recorded consolidation data, and no additional e–log σ′ or settlement–time curves were reconstructed.

2.5 Physical Model Assessment

A physical model was employed to compare the settlement behavior of untreated and chemically stabilized soft clay under incremental loading. Nine conditions (M0–M8) were investigated, including untreated soil and selected mixtures containing OPC, SF, and their combinations. The model consisted of a container measuring 60 × 40 × 60 cm, filled with soil to a depth of 50 cm, and an 8 × 8 cm loading plate positioned at the center. Loads were applied incrementally from 10 to 100 kg, and settlement measurements were recorded at predetermined time intervals.

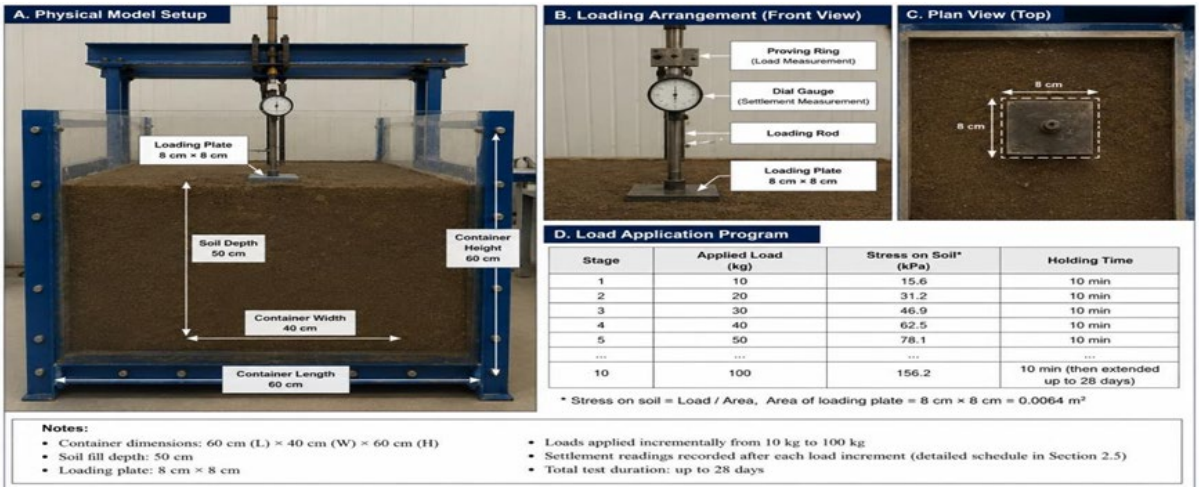


Fig. 3. Physical model setup (A), loading arrangement (front view) (B), plan view (C), and load application program (D)

The applied pressure was calculated using p=mg/A, resulting in a maximum pressure of 153.2 kPa for the 100-kg load. Settlement readings were continued under the final load at 7, 14, 21, and 28-days to assess the longer-term response of the stabilized soil. The clear distances from the loading plate to the container boundaries were 26 and 16 cm, corresponding to 3.25B and 2.0B, respectively, while the soil depth was 6.25B. These dimensions reduce, but do not eliminate, potential boundary effects. Accordingly, the physical model results are interpreted as comparative laboratory evidence rather than direct predictions of field performance. Since each condition was tested once (n=1), the results are presented descriptively, and no statistical inference was applied. For mixture M7, the settlement increased from 0.020 mm at 10 min to 0.08 mm at 20 min, indicating a gradual increase in settlement during the initial loading period. These readings were considered part of the recorded settlement-time response and were used in interpreting the subsequent settlement behavior of the stabilized soil.

Table 4. Settlement readings of the physical-model conditions (M0–M8) under incremental loading

Time	Applied pressure (kPa)	M0 Untreated	M1 10% OPC	M2 13% OPC	M3 5% SF	M4 7% SF	M5 10% OPC+5% SF	M6 10% OPC+5% SF+0.5% Sika	M7 10% OPC+5% SF+1% Sika	M8 10% OPC+5% SF+1.5% Sika
10 min	15.3	0.05	0.03	0.02	0.04	0.038	0.03	0.025	0.020	0.018
20 min	30.6	0.15	0.1	0.08	0.13	0.12	0.09	0.07	0.08	0.07
30 min	46.0	0.35	0.24	0.2	0.3	0.27	0.22	0.145	0.18	0.155
1 hr	61.3	0.5	0.48	0.4	0.62	0.48	0.38	0.25	0.32	0.28
2 hr	76.6	1.2	0.95	0.8	1.25	1.0	0.75	0.45	0.65	0.55
4 hr	91.9	2.2	1.82	1.5	2.45	1.65	1.25	0.75	1.05	0.85
8 hr	107.3	4.8	3.05	2.65	4.1	3.4	2.2	1.25	1.55	1.15
24 hr	122.6	7.8	4.95	4.0	6.05	4.95	3.35	1.8	1.95	1.45
3 days	137.9	9.2	6.05	5.05	7.35	5.7	3.9	2.05	2.2	1.65
7 days	153.2	10.2	6.65	5.75	8.05	6.2	4.2	2.25	2.45	1.9
14 days	153.2	10.8	6.85	5.95	8.4	6.6	4.55	2.4	2.6	2.05
21 days	153.2	11.0	6.95	6.1	8.55	7.15	4.8	2.55	2.72	2.2
28 days	153.2	11.2	7.0	6.2	8.6	7.95	5.90	3.05	2.82	2.55

2.6 SEM Analysis

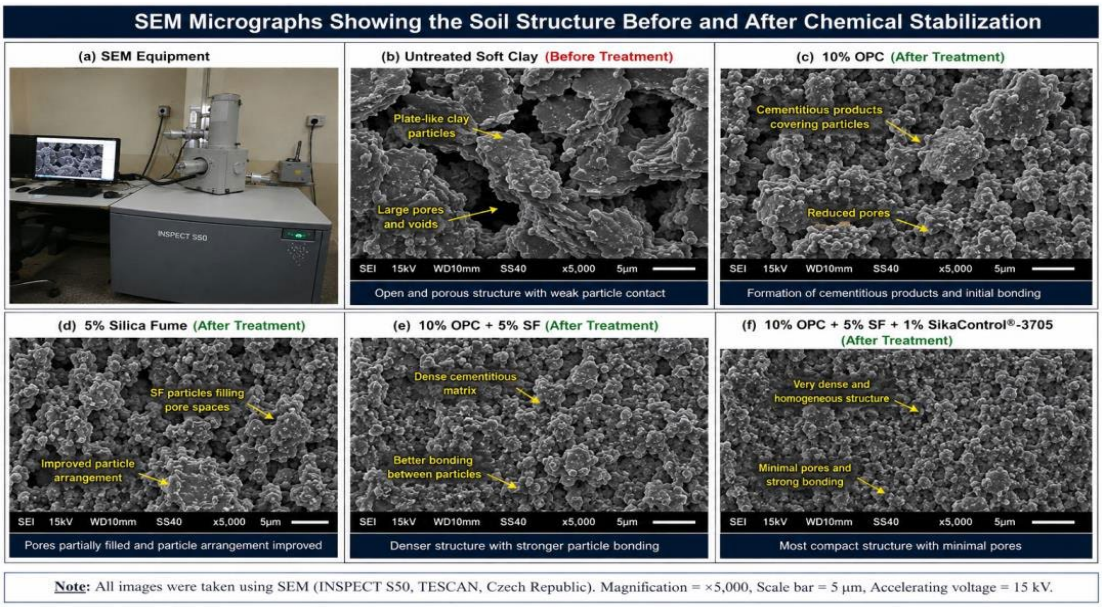


Fig. 4. SEM equipment and representative micrographs of untreated and stabilized soil specimens

2.7 Data Analysis and Optimization Criterion

The practical optimum was selected using two criteria: mixtures achieving at least 50% settlement reduction were first identified, then ranked using the Improvement-to-Dosage Ratio (IDR), defined as settlement improvement (%) divided by total stabilizer dosage (%). IDR was used only as a comparative screening indicator, not as a formal economic index. Because the mixture matrix was not a factorial design, one-way ANOVA was used to compare mixture means without estimating individual or interaction effects of the stabilizers. For the selected optimum (10% OPC + 5% SF + 1% SikaControl®-3705), settlement was 3.00 ± 0.05 mm (n = 3; CV = 1.67%), compared with 2.60 ± 0.05 mm (CV = 1.92%) for the highest-performance mixture (13% OPC + 7% SF + 1.5% SikaControl®-3705). The low CV values indicate good repeatability.

3. Results and Discussion

3.1 One-Dimensional Consolidation Results

Stabilization substantially reduced the consolidation settlement of the treated specimens. The untreated soil exhibited a settlement of 6.80 mm, whereas increasing the OPC content from 7% to 13% reduced the settlement to 5.40, 4.20, and 3.80 mm, respectively. Silica fume also contributed to settlement reduction, while the combined OPC–SF mixtures produced greater reductions, reaching 3.40 mm for C10SF5 and 3.00 mm for C13SF7. These trends are generally consistent with previous studies reporting improved compressibility and consolidation behavior following chemical stabilization of clay soils [3–6,11]. The stabilization treatment also resulted in lower values of e_0, Cc, and mv, indicating a reduction in the compressibility of the treated soil. In contrast, Cv increased from 5.3×10^{-9} to 1.14×10^{-8} m^2/s, indicating a faster consolidation response under the conditions of the present tests. This increase may be associated with changes in soil structure following stabilization; however, permeability and elastic stiffness were not directly measured in this study. Therefore, the observed increase in Cv should not be interpreted as a direct increase in permeability or stiffness. The SEM observations provided qualitative evidence of a denser and more aggregated soil fabric after stabilization, which is consistent with the reduction in compressibility observed in the consolidation tests. However, the SEM analysis was qualitative and did not include quantitative measurements of pore size, porosity, contact area, or elemental composition.

Table 5. One-way ANOVA of final oedometer settlement across the 13 mixtures

Source	SS	df	MS	F	p
Between mixtures	57.0692	12	4.7558	703.36	<0.001
Within mixtures	0.1758	26	0.006762	—	—
Total	57.2450	38	—	—	—

Table 6. Tukey HSD post-hoc comparisons of the practical optimum C10SF5S1 with the other mixtures

Comparison	Other mean (mm)	Mean difference	q	Adjusted p	Decision
Untreated	6.80	-3.80	80.04	<0.001	Significant
C7	5.40	-2.40	50.55	<0.001	Significant
C10	4.20	-1.20	25.28	<0.001	Significant
C13	3.80	-0.80	16.85	<0.001	Significant
SF3	6.10	-3.10	65.30	<0.001	Significant
SF5	5.20	-2.20	46.34	<0.001	Significant
SF7	4.80	-1.80	37.91	<0.001	Significant
C7SF3	4.30	-1.30	27.38	<0.001	Significant
C10SF5	3.40	-0.40	8.43	<0.001	Significant
C13SF7	3.00	+0.00	0.00	1.000	Not significant
C7SF3S0.5	4.30	-1.30	27.38	<0.001	Significant
C13SF7S1.5	2.60	+0.40	8.43	<0.001	Significant

3.2 Physical Model Assessment

The selected mixture was evaluated under incremental loading in the physical model. At 153.2 kPa (100 kg on the 8 × 8 cm plate) after 28-days, settlement decreased from 11.20 mm for untreated soil to 2.82 mm for the selected C10SF5S1 mixture, corresponding to a 74.8% reduction. The final settlements for M1–M8 were 7.00, 6.20, 8.60, 7.95, 5.90, 3.05, 2.82, and 2.55 mm, respectively, corresponding to settlement reductions of 37.5%, 44.6%, 23.2%, 29.0%, 47.3%, 72.8%, 74.8%, and 77.2% relative to untreated soil.

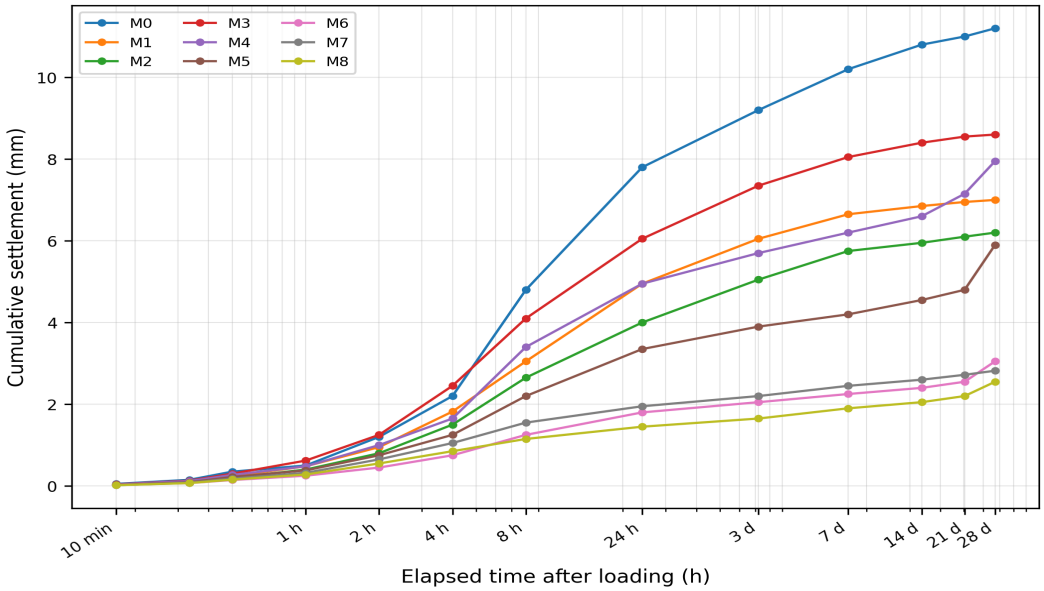


Fig. 5. Settlement–time curves of the physical-model conditions (M0–M8) under the applied loading program

3.3 SEM Analysis

SEM was used to qualitatively examine microstructural changes in untreated and stabilized soil, focusing on particle arrangement, visible pore spaces, and particle bonding. The representative micrographs are shown in Fig. 4. The SEM observations were used only to support the consolidation and physical-model results. No quantitative measurements of pore size, porosity, contact area, or elemental composition were performed; therefore, the microstructural interpretation is limited to visible morphological changes.

3.4 Overall Discussion

The consolidation tests, physical-model assessment, and SEM observations provide complementary evidence of the stabilization effect. The oedometer tests were used to compare the 13 mixtures and select the practical optimum, while the physical model assessed nine selected mixtures under incremental plate loading. At 100 kg (153.2 kPa), M0 reached 11.20 mm settlement, compared with 2.82 mm for M7 and 2.55 mm for M8, corresponding to reductions of 74.8% and 77.2%, respectively. These values are not directly equivalent to the 55.9% oedometer improvement because the two tests differ in geometry, drainage, stress distribution, loading history, and boundary conditions. SEM observations qualitatively supported changes in particle aggregation, pore structure, and bonding, without quantitative measurements.

3.5 Comparison with Previous Studies

The obtained improvement is broadly consistent with previous chemical-stabilization studies, although direct numerical comparison is limited by differences in soil type, stabilizer dosage, curing period, and testing procedures. Previous studies reported reductions in compressibility and increased resistance to consolidation following cement, lime, and silica-fume treatment [1,3,5,11]. In the present study, C10SF5S1 reduced oedometer settlement by 55.9% and physical-model settlement by 74.8%. These results fall within the range reported for chemically stabilized clays, but should not be considered universal performance values.

3.6 Limitations and Future Work

- Several limitations should be considered when interpreting the results. First, each physical-model condition was tested once (n = 1); therefore, the physical-model results are presented as comparative laboratory evidence without statistical inference. The container boundaries may also affect the measured settlement response, limiting direct extrapolation to field conditions.
- Second, the consolidation tests were performed using three specimens for each mixture, and the reported statistical analyses were based on these replicate results. Individual replicate-level data were not retained beyond the analyses reported; therefore, no additional statistical reconstruction was performed.
- Third, dedicated shrinkage, cracking, pore-water pressure, and quantitative mixing-homogeneity tests were not performed. The contribution of SikaControl®-3705 was therefore considered as part of the overall stabilization response rather than independently quantified. Brittleness was assessed only descriptively.
- Finally, the study used soil from a single location and evaluated the treated soil at 28-days of curing. Future work should include replicated physical-model tests, different soil types, longer curing periods, pore-pressure and shrinkage measurements, quantitative SEM/EDS analysis, durability testing, and detailed cost assessment.

4. Conclusions

Chemical stabilization substantially improved the consolidation behavior of the investigated soft clay under the laboratory conditions considered in this study. The combined use of ordinary Portland cement (OPC), silica fume (SF), and SikaControl®-3705 produced measurable reductions in settlement and compressibility compared with untreated soil.

- Increasing OPC and SF contents generally reduced consolidation settlement and compressibility. The combined OPC–SF mixtures provided greater improvement than the individual stabilizers, indicating the beneficial effect of combining cementitious and pozzolanic stabilization.
- The selected practical mixture, consisting of 10% OPC + 5% SF + 1% SikaControl®-3705, reduced the oedometer settlement from 6.80 mm for untreated soil to 3.00 mm, corresponding to a 55.9% reduction. The mixture also showed reduced compressibility parameters compared with untreated soil.
- The 13% OPC + 7% SF + 1.5% SikaControl®-3705 mixture produced the lowest oedometer settlement of 2.60 mm and the highest settlement reduction of 61.8%. However, it required a substantially higher total stabilizer dosage.
- A quantitative two-stage criterion was therefore used for practical mixture selection. Mixtures were first required to achieve at least 50% settlement reduction and were then ranked using the Improvement-to-Dosage Ratio (IDR). The selected 10% OPC + 5% SF + 1% SikaControl®-3705 mixture achieved the highest IDR of 3.49 and was consequently identified as the practical optimum. This selection reflects measured performance and stabilizer dosage rather than a formal cost–benefit analysis.
- The physical-model assessment confirmed substantial settlement reduction under concentrated incremental plate loading. At 100 kg, equivalent to approximately 153.2 kPa, untreated soil reached 11.20 mm final settlement, whereas the selected mixture reached 2.82 mm, corresponding to a 74.8% reduction. The mixture containing 13% OPC + 7% SF + 1.5% SikaControl®-3705 reached 2.55 mm and a 77.2% reduction. The difference between these two mixtures was only 0.27 mm despite the higher stabilizer dosage of the latter.
- The physical-model results should be interpreted as comparative laboratory evidence rather than direct field-scale predictions because each condition was tested once (n = 1) and the container imposed lateral boundary restraint. Replicated physical models and field-scale investigations are required before generalization.
- SEM observations qualitatively indicated a more aggregated and relatively denser structure after stabilization, consistent with the observed reduction in compressibility and settlement. However, quantitative pore-size, porosity, contact-area, and elemental analyses were not available.
- The conclusions are limited to the investigated soil, mixture proportions, loading conditions, and 28-day curing period. Future work should include replicated model testing, pore-water pressure monitoring, quantitative microstructural analysis, longer curing periods, durability testing, and detailed cost and life-cycle assessment. The specific contribution of SikaControl®-3705 should also be quantified through dedicated shrinkage testing.

Acknowledgement

The authors acknowledge the support provided by the Department of Civil Engineering, University of Diyala, Iraq.

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