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Research Article

Comparative laboratory study on the stabilization of clayey sand under strip foundations via micro cement and fly ash injection

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Abstract

This study compares micro cement and fly ash injection for improving clayey sand soil (SC) beneath a model strip foundation. A total of 54 laboratory model tests were conducted using injection pressures of 100, 200, and 300 kPa and curing periods of 7, 14, and 28 days. Performance was evaluated from load-settlement response, model test capacity, settlement at a common comparison stress of 100 kPa, unconfined compressive strength, grout consumption, cost, and a screening environmental inventory. The untreated soil had a model test capacity of 185 kPa. After 28 days, micro cement increased this capacity by 162% to 219% at pressures of 200 to 300 kPa, whereas fly ash produced gains of 146% to 189%. At the same pressures and curing age, settlement was reduced by 65% to 72% with micro cement and by 56% to 63% with fly ash. At 200 kPa and 28 days, fly ash achieved approximately 94% of the micro cement model test capacity and 90% of its unconfined compressive strength. The 28-day material-cost index was 3.41 times more favorable for fly ash ($0.044 versus $0.150 per kPa of capacity gain), while the screening inventory indicated an approximately 77% lower binder-related carbon burden. The highest measured responses occurred at 300 kPa; however, grout spread reached the chamber boundaries, so these values may include confinement effects. For the tested soil and model geometry, 200 kPa provided the most defensible balance among performance, grout consumption, cost, and experimental reliability. The results are laboratory-specific and require field trial sections and verification testing before design application.

1. Introduction

Settlement of shallow foundations on soft soils can be excessive and lead to bearing capacity and serviceability problems. Thus, ground improvement is generally the most cost-effective solution when the cost of foundation replacement or deep foundations would be excessive or the required depth is considerable [1,3]. Stabilization injection is desirable in that it allows treatment to be applied under new or existing foundations with minimal excavation. The technique injects a pumpable binder into the pore space in soil, filling voids, bonding soil particles, and modifying stiffness and strength. With strip foundations, continuity of treatment and the dimensions (width and depth) of the strengthened body of ground are particularly important, because imperfect treatment may result in unacceptable differential settlement [4-8]. Micro cement is a super-fine cementitious paste, generally composed of particles at the size of micrometers, not millimeters. Due to the small size of its particles and its high specific surface, under certain conditions micro cement particles can enhance penetrability and activity, providing it does not adversely affect water-to-cement ratio, suspension stability, filtration, and injection pressure [8-14]. Fly ash is a by-product of powdered coal combustion in thermal power stations and consists of pozzolanic materials which can react with water and a calcium-bearing activator to create cementing

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materials. Its use can lessen the need for virgin cement and the disposal of waste, but Class F fly ash usually gains strength more slowly and needs an activator and adequate curing [15-19]. Micro cement and fly ash have each been used in the literature for ground improvement, but direct comparisons on the same soil under the same injection, curing, and loading conditions are rare. There is also relatively little published work providing guidance with respect to the influence of injection pressure on the coupled competing effects of grout spread, bearing response, settlement, cost and boundary disturbance in clayey sand under strip foundations.

This study fills that gap with a controlled laboratory comparison of micro cement and activated fly ash injection for a single clayey sand and model foundation system. Specifically, the aim is to measure the pressure- and curing-dependent variations of the load-settlement curves and unconfined compressive strength, to contrast the grout usage and the price of materials, and to construct a first-approximation decision-framework on binder selection. As the analysis employs a finite laboratory chamber, the interpretation makes a clear distinction between measured model response and design capacity in the field and discusses confinement and scale effects.

1.1. Soil Stabilization Fundamentals

Soil stabilization is to enhance the resistance to bearing and stiffness, decrease the compressibility, and control the deformation. The behavior of injected soils is influenced by their gradation, fines content, plasticity, permeability, initial density, and stress state. When the fines content is greater than 12%, the plasticity of the fines determines the Unified Soil Classification System (USCS) classification and also has an effect on the grout filtration and accessibility of pores. Here the soil is a sand-dominated coarse fraction with non-plastic or low-plasticity fine fraction. So it is classified as SC soil, not as SM. The main injection problems for these soils are confined pore throats, filtration of suspending particles, preferential flow, and possible hydraulic fracturing or heave at excessive pressure. Therefore, the enhancement must be measured in terms of the mechanical behavior and the treated zone size and homogeneity.

1.2. Cement-Based Stabilization

Cement grouting densifies soil, where hydration products, mainly calcium-silicate-hydrate phases, coat particles and fill up pores. Ultra-fine micro cement allows the application of suspension grouting to soils with smaller pore sizes than those which can be treated with ordinary Portland cement. The behavior of micro cement-treated soil is controlled by cement fineness, w/c ratio, injection pressure and rate, soil permeability, filtration, and curing condition. Lower water-to-cement ratios tend to enhance strength, but decrease penetrability, higher water-to-cement ratio suspension can travel farther, but may bleed or produce weaker cemented zones [8,10,12,13]. Injection pressure should be sufficient to overcome hydraulic resistance but without promoting unwanted fissuring, soil heaving, or boundary-driven confinement. Effective control is also a matter of continuously mixing and watching for plugging, agglomeration of particles, filtration, and premature gelation. Such thinking encourages the consideration of pressure as one of a set of variables, together with grout volume and the observed treated geometry rather than simply viewing higher pressure as inherently better for soil conditions.

1.3. Fly Ash Stabilization

Class F fly ash has reactive silica and alumina, and a very low amount of self-cementing potential. The rationale is that pozzolanic reactions, when a calcium-bearing activator is also present, gradually produce cementitious compounds that strengthen and stiffen the soil over time. The stronger time dependence of fly ash treatment can be attributed to the slower rate of its reaction compared to cement hydration [15,17,19]. In many of the published reports on stabilization of soil with fly ash, fly ash is expressed as a percentage of the dry soil mass in the combined sample. That dosage cannot be converted directly for injection, as performance is dictated by concentration, water-to-solids ratio, viscosity, stability, and pumpability of the suspension. Therefore, this work investigates an injectable fly ash suspension activated with a minor Portland-cement portion rather than decoding mixing percentages as injection dosages. In terms of sustainability, the use of fly ash enables the substitution of a significant amount of virgin cementitious binder and provides a means to valorize an industrial by-product. However, environmental advantages depend on transportation distance, processing, allocation of upstream impacts, activator content, and the level of performance achieved in service. Correspondingly, this work reports a transparent screen inventory in lieu of a full life-cycle assessment [20].

1.4. Alternative Injectable Stabilization Materials

Other satisfactory mineral and cementitious powders, such as silica fume and multicomponent ultra-fine binders, have been studied to vary stability of grouts, pore filling, strength and durability. For an injection use, a different material is meaningful only if the particle size distribution, bleeding, setting behavior, and filtration enable a controlled delivery within the soil [21,22]. The review does not include comparison with dissimilar concrete, asphalt, fiber-reinforced structural members, or soil-mixing techniques. This more focused topic ensures a close literature-experimental study linkage.

1.5. Foundation Improvement and Model-Scale Considerations

Soil injection under a strip footing may enhance its bearing capacity by forming a stiffer and stronger composite soil layer that helps to spread the contact stress over a wider area and reduces the settlement. Injectable techniques may be used with minimal impact to the surface as opposed to excavation-based techniques; however, the resulting geometry is influenced by soil heterogeneity, injection spacing, pressure, and stop criteria [4,6,19]. While laboratory apparatus allows closely controlled comparisons, they can lead to overestimates of response when the treated zone or failure mechanism co-acts with rigid boundaries. Hence, model dimensions should be presented as ratios to the foundation width and findings obtained at a wall should be regarded as boundary limited rather than as unconstrained expansion of grout or bearing capacity at the field scale. The rates of hydration and pozzolanic reaction are affected by curing temperature and moisture supply. Comparative tests should be carried out under the same curing conditions, while the field application should consider ground water, seasonal temperature, drainage, and construction sequence. These concerns are baked in to the results and the limitations of the current study.

2. Materials and Methods

2.1 Soil Characterization

In all, 54 specimens were tested, 18 untreated reference specimens and 36 treated specimens for the material–injection pressure–curing period combination in duplicate tests. The soil was collected from Baghdad, Iraq. Preliminary tests were particle-size distribution from sieving and hydrometer (ASTM D6913/D6913M, ASTM D7928), Atterberg limits (ASTM D4318), water content (ASTM D2216), specific gravity (ASTM D854), compaction by Standard Proctor (ASTM D698), direct shear (ASTM D3080/D3080M), and California bearing ratio (ASTM D1883). The classification is based on ASTM D2487. The gradation fraction was 12% gravel, 45% sand, 28% silt, and 15% clay. Since 57% of the soil is coarse grained and sand is the predominant coarse fraction, the primary symbol is S. The fines content is more than 12%; with LL = 32% and PI = 14%, the measured PI lies above the A-line with a value of 8.76, means that the fines are clayey and the soil is classified as a clayey sand (SC). The other index, compaction, shear, CBR, and chemical attributes are not reiterated in the text but are presented in Table 1.

2.2 Stabilization Materials

The micro cement was a ready-to-use ultra-fine cement grout with d95 < 15 µm, a specific gravity of 3.05, and a Blaine fineness of 8500 cm^2/g. Micro cement suspensions were passed through a screen at w/c ratios of 0.6, 0.8, and 1.0; 0.8 was selected for the major pressure and curing evaluation because it represented a best compromise between pumpability and strength. The bulk physical and oxide composition are listed in Table 1. The fly ash was obtained from a coal-fired power plant and satisfied the chemical criteria for Class F fly ash in ASTM C618. The reported chemical compositions of both binders were determined by X-ray fluorescence (XRF) analysis. For injection, fly ash was activated with ordinary Portland cement equal to 3% of the fly-ash mass. Suspensions were screened at water-to-solids ratios of 0.8, 1.0, and 1.2; a ratio of 1.0 was used in the main comparison following preliminary injectability trials. The physical and chemical properties of the soil and stabilization materials are summarized in Table 1.

Table 1. Physical and chemical characteristics of the soil and stabilization materials

Property	Soil	Micro cement	Fly Ash
USCS classification (ASTM D2487)	SC	-	-
Gravel fraction (%)	12	-	-
Sand fraction (%)	45	-	-
Silt fraction (%)	28	-	-
Clay fraction (%)	15	-	-
Specific gravity (ASTM D854)	2.67	3.05	2.15
Natural water content (%)	8.5	-	-
Liquid limit (%)	32	-	-
Plastic limit (%)	18	-	-
Plasticity index (%)	14	-	-
Optimum moisture content (%)	12.5	-	-
Maximum dry unit weight (kN/m^3)	18.4	-	-
Effective cohesion (kPa)	15	-	-
Effective friction angle (°)	28	-	-
Unsoaked CBR (%)	8.5	-	-
Soaked CBR (%)	5.2	-	-
SiO_2 (%)	-	21	52
Al_2O_3 (%)	-	5	28
Fe_2O_3 (%)	-	3	8
CaO (%)	-	64	3
Blaine fineness (cm^2/g)	-	8500	3200
pH	7.8	12.5	9.2
Sulfate content (%)	0.08	-	-
Organic content (%)	<1	-	-

2.3 Experimental Setup

A physical laboratory model was developed to simulate injection-driven improvement beneath a strip foundation. The steel test chamber measured 600 mm × 300 mm × 400 mm internally, and transparent acrylic side panels were used to observe the flow of grout.

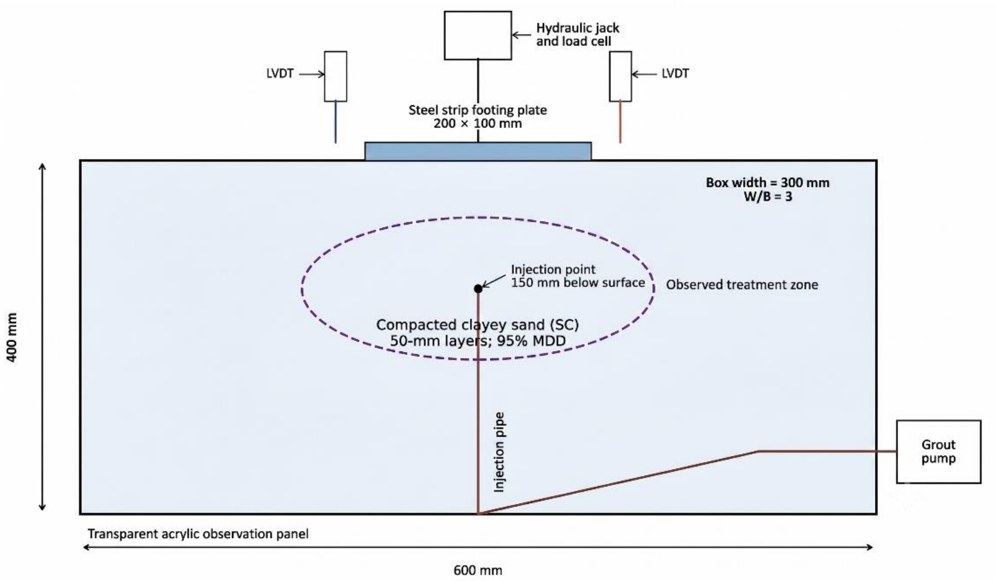

Fig. 1. Schematic of the laboratory injection and plate-load test setup (dimensions in millimetres)

Compaction was achieved by placing the soil in 50-mm thick layers and compacting each layer to 95% of maximum dry unit weight at the optimum moisture content. The model strip footing was a rigid steel plate with a length of 200 mm and a width of 100 mm and the chamber-width-to-footing-width ratio was set at W/B = 3. A single injection point was located 150 mm under the surface of the soil below the plate centerline. Grout was pumped under pressure through a pressure-regulated pump with depth measurement and a calibrated flow meter. The plate was subjected to a vertical load by the loading frame and LVDTs at the center and edges of the plate were used to measure settlement. The device, as well as the main dimensions, is schematically illustrated in Fig. 1.

2.4 Injection Procedure

Micro cement and fly ash slurries were injected at the controlled pressures of 100, 200 and 300 kPa. The basal comparison was with 0.8 water-to-cement ratio for the micro cement and 1.0 water-to-solids ratio for the activated fly ash. Pressure was raised stepwise to the target value, maintained and the injected volume, time, surface response and observed grout spread recorded. Injection was stopped when the target volume was injected, or a sudden sustained pressure increase was observed, or when substantial surface heaves or leak of grout from the surface was visually appreciated. Before injection, a 10-kPa seating stress was applied to establish the initial plate position. After injection, specimens were cured for 7, 14, or 28 days under nominal laboratory conditions of 23 ± 2°C. The surface was covered to minimize moisture loss and all specimens were handled using the same curing procedure. The reported grout volumes are actual accepted volumes and therefore vary with material and pressure.

2.5 Loading and Strength Tests

After curing, vertical contact stress was applied in 10-kPa increments. Each increment was maintained for at least 15 min and until the settlement rate had substantially stabilized before the next increment. Loading continued until pronounced nonlinear deformation was observed or the planned terminal settlement was reached. Load and settlement were recorded continuously to construct the model load-settlement curves. Because the plotted curves do not support a consistent 10%-of-footing-width failure criterion, the reported capacity is defined here as the maximum applied contact stress reached in the model test at the adopted termination condition. It is therefore termed “model test capacity” and must not be interpreted as an allowable field bearing capacity. Unconfined compressive strength (UCS) was measured on samples recovered from the central and peripheral portions of the treated zones after plate loading; the sampling location and extraction method, and the potential disturbance caused by prior loading, are considered when interpreting the UCS results.

2.6 Analysis Methods

The results were evaluated using descriptive comparisons. Model capacity improvement was calculated as 100(qt − qu)/qu, where qt and qu are the treated and untreated model test capacities. Settlement reduction at 100 kPa was calculated as 100(su − st)/su, where st and su are the treated and untreated model test settlement. Cost effectiveness was expressed as material cost divided by the increase in model test capacity. Duplicate measurements and reported coefficients of variation were used to describe repeatability; no inferential ANOVA claim is made because the available replicate structure is insufficient for a robust multifactor significance test. The charts are empirical summaries of the tested conditions and are not predictive design equations. Figure 2 compares the 28-day load-settlement response of untreated soil with micro cement- and fly-ash-treated soil at injection pressures of 100, 200, and 300 kPa. The curves show progressively lower settlement and higher terminal model stress with increasing injection pressure, while the 300-kPa results require caution because the treatment zones approached the chamber boundaries.

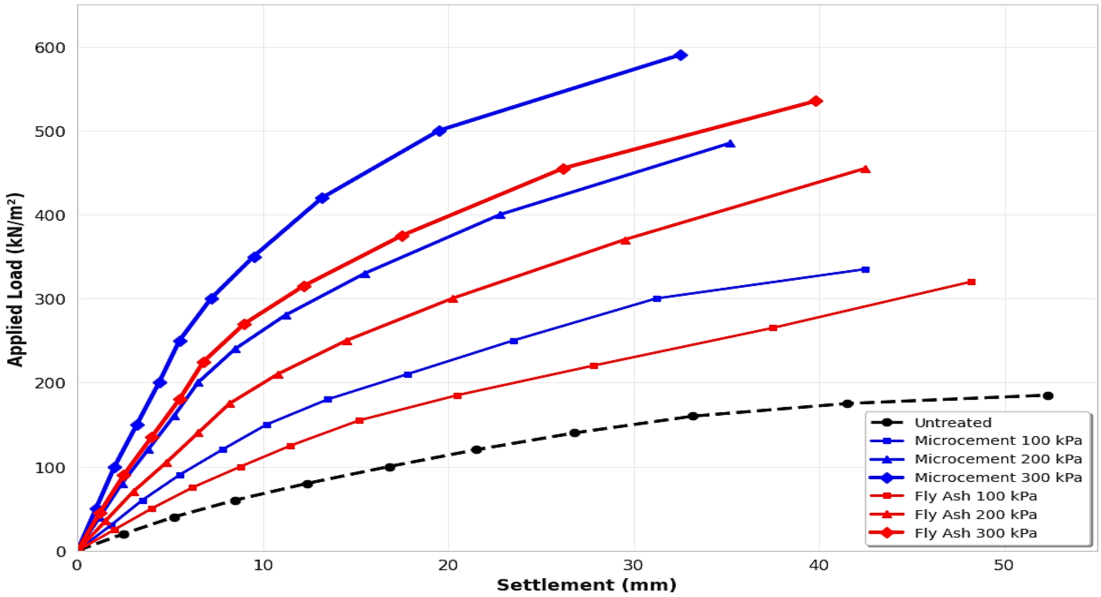

Fig. 2. Load-settlement response of untreated and treated clayey sand after 28 days of curing

3. Results and Discussion

3.1 Injection Characteristics

Micro cement and fly ash demonstrated different injection performances. Micro cement achieved the termination state at 18.5 to 24.5 min at pressures of 100 to 300 kPa, while fly ash took 32.0 to 38.0 min for the two said pressures. Through the acrylic windows visual observations showed a relatively sharper and more regular micro cement front, with the fly ash suspension yielding a more irregular interface and larger local accumulation. These results seem also in line with the finer micro cement particles and the stronger filterability of the coarser fly ash suspension, albeit microstructural imaging was not undertaken. Injection pressure had the effect of increasing both the volume of the accepted grout and the apparent size of the treatment zone (Table 2).

Table 2. Injection parameters and observed treatment-zone dimensions

Material	Injection pressure (kPa)	Injection time (min)	Accepted grout volume (L)	Horizontal extent (mm)	Vertical extent (mm)
Micro cement	100	18.5	5.5	180	120
	200	22.0	10.0	280	190
	300	24.5	14.5	≥300*	250
Fly ash	100	32.0	6.5	150	100
	200	36.5	11.5	240	160
	300	38.0	16.5	≥300*	210

** The treatment front reached the chamber wall; the unconstrained horizontal extent could not be measured.*

At the levels of 100 and 200 kPa the measured horizontal extents had not yet exceeded the 300-mm chamber width. At 300 kPa the nominal horizontal distances from visual tracing are 350 mm for micro cement and 310 mm for fly ash, which is larger than the available chamber width. Hence, these values are reported as boundary-censored (≥300 mm), indicating interaction with the side walls rather than unconstrained radial spreading. Additionally, significant surface heave and preferential pathways for the highest pressure suggests that 300 kPa was close to the upper limit of the model. The volume of accepted grout ranged between 5.5 and 14.5 L for the micro cement and between 6.5 and 16.5 L for the fly ash. The chamber volume is about 72 L, so the maximum fly ash injection is about 23% of the chamber volume. This large fraction of replacement and the wall interaction at 300 kPa, are significant scale limitations. Fly ash needed a greater volume and a longer injection time at all pressures due to its lower penetrability and even higher void filling request.

3.2 Model Test Capacity

The terminal model test strength of the clayey sand without treatment was 185 kPa. At 28 days, micro cement treatment resulted in capacities of 335, 485, and 590 kPa for injection pressures of 100, 200, and 300 kPa, respectively. These represent increases of 81%, 162%, and 219% over the baseline untreated. The result demonstrates a strong pressure-dependent improvement and is very encouraging when considering this model, but the 590-kPa should be viewed as a maximum laboratory response and not an unconstrained field capacity since the grout front reached the chamber boundary. Resistance at the end of treatment by fly ash stabilized soil increased gradually, however; it got closer to the micro cement response with curing. At 28 days, the capacities were 320, 455, and 535 kPa at 100, 200, and 300 kPa, respectively, which represent increases of 73%, 146% and 189%. At 200 kPa the strength of the fly ash was nearly 94% that of the micro cement. The change from 100 to 200 kPa was more effective than from 200 to 300 kPa for both materials. This latter increase required much more grout and was accompanied by wall effect, preferential flow, and soil heave. Therefore, the maximum observed at 300 kPa, and 200 kPa is more justifiable compromise-performance efficiency. The model capacity enhancement factor at 7, 14, and 28 d is summarized by Fig. 3. Micro cement exhibited the best early-age response, followed by the fly ash curves that increased more pronouncedly with curing age. The figure should be read as a contrast among the tested model scenarios, not as a regression equation for field design.

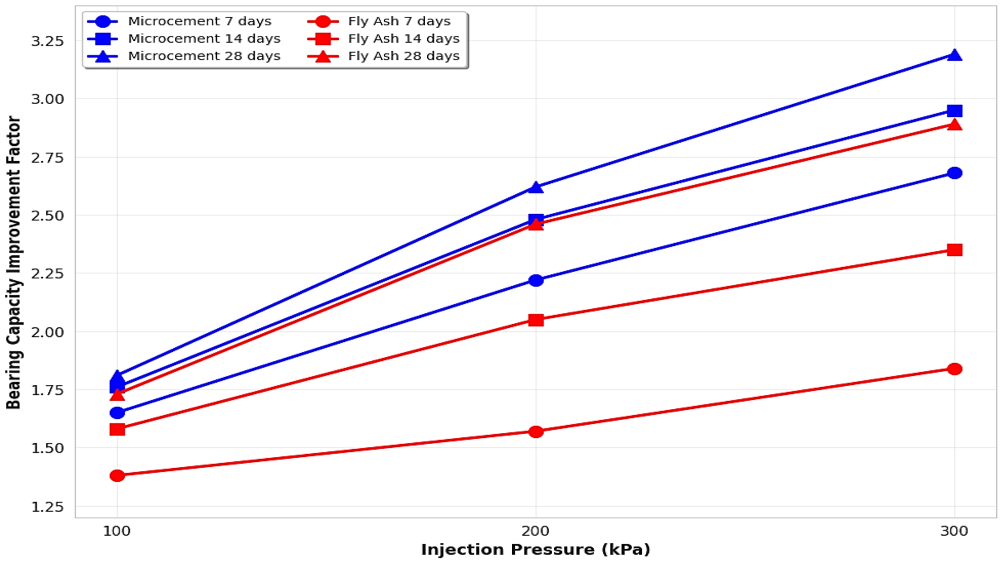

Fig. 3. Model capacity improvement factor versus injection pressure at different curing periods

3.3 Settlement Reduction

Settlement was compared at the same applied stress of 100 kPa to enable the evaluation of all specimens at the same load level. This is a test stress for laboratory comparison only and is not recommended as allowable design pressure. The untreated consolidation was 18.5 mm. At an injection pressure of 200 kPa and a curing time of 28 days, micro cement reduced the consolidation to 6.5 mm (65%), while fly ash reduced it to 8.2 mm (56%). At the injection pressure of 100 kPa, the 28-day consolidation reductions were 42% and 35% for micro cement and fly ash, respectively. When the injection pressure was raised to 300 kPa, the reductions were 72% and 63%, respectively. Yet the further improvement was relatively small compared to the extra grout consumption under conditions that the treatment front reached the chamber walls. For this reason, the 300-kPa result can be considered as an upper model response, but not as the automatically recommended field pressure. Curing had a larger effect on settlement for fly ash. At 200 kPa, the reduction obtained with micro cement was 58% (7 days) and 65% (28 days), while the rates for fly ash rose from 38% to 56% during the same interval. The distinction favors micro cement when rapid loading is needed and fly ash when longer curing is permissible. The full settlement results are tabulated in Table 3.

Table 3. Settlement at a common comparison stress of 100 kPa

Material	Injection pressure (kPa)	7-day settlement (mm)	14-day settlement (mm)	28-day settlement (mm)	28-day reduction (%)
Untreated reference	N/A	18.5	18.5	18.5	N/A
Micro cement	100	12.0	11.2	10.8	42
	200	7.8	6.9	6.5	65
	300	6.2	5.5	5.2	72
Fly ash	100	13.5	12.5	12.0	35
	200	11.5	9.2	8.2	56
	300	9.8	7.5	6.8	63

3.4 Strength Development

UCS testing offered a straightforward measure of cementation in the treated zones. The reference UCS for untreated soil was 145 kPa. For the samples retrieved from the 200-kPa micro cement treatment, the average strength values were 680, 1150, and 1420 kPa at 7, 14, and 28 days. The rapid early gain is consistent with cement hydration. Since the UCS specimens were taken after plate loading, the values may be sampling and prior-loading disturbed and should be considered post-test indices, not undisturbed in situ strengths. The fly ash equivalent strengths were 385, 825 and 1285 kPa at 7, 14, and 28 days. The lower 7 days result and higher gain from 7 to 28 days agrees with delayed pozzolanic reaction. At 28 days, fly ash achieved about 90% of the micro cement UCS, which confirms that the difference in performance reduces when sufficient curing is supplied [15,16,19]. The central samples were said to be 15% to 25% stronger than the peripheral ones. Coefficients of variation (reported) were 12% to 18% for micro cement and 18% to 28% for fly ash, suggesting higher spatial variability in the fly ash treatment. These results justify the conservative field acceptance criteria and multiple verification locations. No scanning electron microscopy or full post-test core-photograph suite exist, so any statements concerning bonding mechanisms and homogeneity in are derived from the measured macroscopic response and visual chamber observations. Figure 4 shows the UCS development at 200 kPa. Micro cement dominates at early age, whereas the fly ash curve rises more steeply between 7 and 28 days and approaches the micro cement strength at the final curing age.

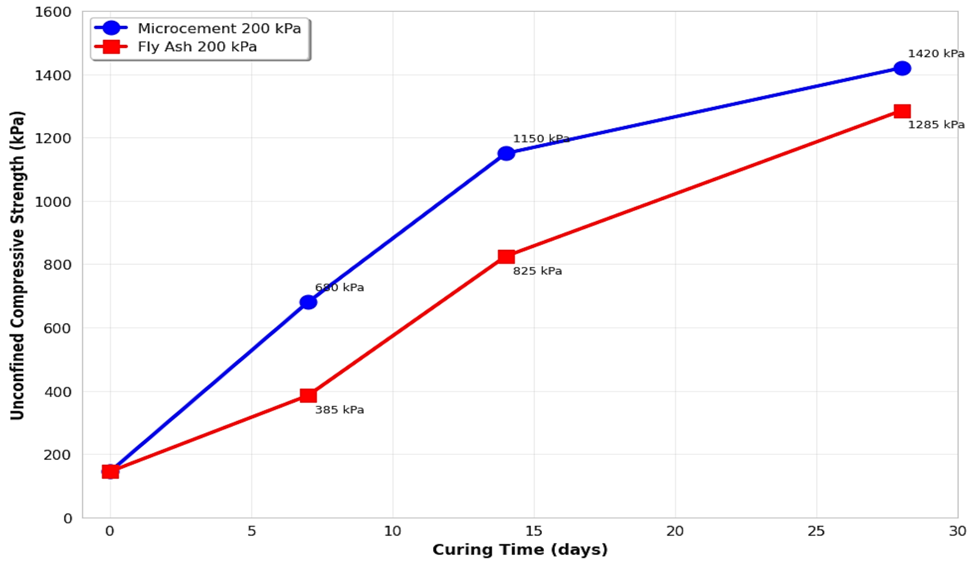

Fig. 4. Unconfined compressive strength development at an injection pressure of 200 kPa

3.5 Cost-Effectiveness Analysis

Economic analysis indicates that the selection of stabilization materials should not rely solely on technical performance parameters but must also integrate material and operational costs. The material-only economic comparison was performed for the 200-kPa condition using contemporaneous laboratory estimates for procurement in Baghdad. The estimated treatment material cost was $45 for 10.0 L of micro cement grout and $12 for 11.5 L of activated fly ash grout. Because absolute prices vary by location, supplier, currency, transport, and date, Table 4 presents normalized ratios, with fly ash assigned a material-cost index of 1.00. The two methods used broadly similar pumping equipment, although micro cement required tighter control of mixing, suspension stability, and potential early gelation. Fly ash required longer injection time and a slightly larger volume. Labor, mobilization, quality-control, and schedule costs were not included; thus, the comparison is a material-cost screening rather than a complete project estimate. At 28 days, material cost per unit increase in model test capacity was $0.150/kPa for micro cement and $0.044/kPa for fly ash. On this basis, fly ash was 3.41 times more cost effective for the 28-day response. At 7 days, the difference was smaller because micro cement developed strength more rapidly. Selection should therefore consider the value of schedule acceleration in addition to binder cost.

Table 4. Material-cost screening for the 200-kPa injection condition

Parameter	Micro cement	Fly ash	Ratio (MC/FA)
Material cost ($/treatment)	45	12	3.75
Normalized material-cost index (FA = 1.00)	3.75	1.00	3.75
Accepted grout volume (L)	10.0	11.5	0.87
7-day model test capacity (kPa)	410	290	1.41
28-day model test capacity (kPa)	485	455	1.07
Cost per kPa capacity gain, 7 days ($/kPa)	0.200	0.114	1.75
Cost per kPa capacity gain, 28 days ($/kPa)	0.150	0.044	3.41
28-day settlement reduction (%)	65	56	1.16

Notes: Costs represent laboratory-scale material estimates at the time of testing and exclude labor, equipment, transport, overhead, and quality-control costs. The normalized cost index is included to improve transferability across markets.

3.6 Sustainability Screening

A transparent binder-inventory calculation was used instead of a qualitative "overall impact score." For 10 L of micro cement grout at w/c = 0.8 and a micro cement specific gravity of 3.05, the estimated dry micro cement mass is approximately 8.9 kg. Using a representative screening factor of 0.85 kg CO_2e/kg gives about 7.5 kg CO_2e per treatment. For 11.5 L of fly ash grout at a water-to-solids ratio of 1.0, the estimated solids are approximately 7.6 kg fly ash and 0.24 kg Portland-cement activator. Using screening factors of 0.20 kg CO_2e/kg for processed fly ash and 0.85 kg CO_2e/kg for cement gives approximately 1.7 kg CO_2e, or about 77% less than the micro cement treatment. The same analysis shows about 8.9 kg to 9.4 kg of virgin cementitious binder is needed for micro cement as compared to about 0.24 kg of virgin cement activator for the fly ash mixture, and about 7.6 kg of fly ash is recovered. The results thus indicate a potential lower binder and waste-based benefit for fly ash given the specified assumptions.

This indeed is a screening comparison, not a full life-cycle assessment. It does not consider transport, plant energy, allocation of upstream burdens of fly ash, equipment, field losses, duration of construction, and effects of service life. Sulfate, acid, wet-dry and other aggressive exposures testing was not conducted and therefore no claim of superior durability is made. A project life-cycle assessment and durability program are needed before the screening result can be applied to procurement or design decisions. Figure 5 presents the underlying inventory quantities rather than a composite 0-to-100 score. The separation of carbon burden, virgin binder consumption, and waste utilization makes the assumptions and trade-offs directly auditable.

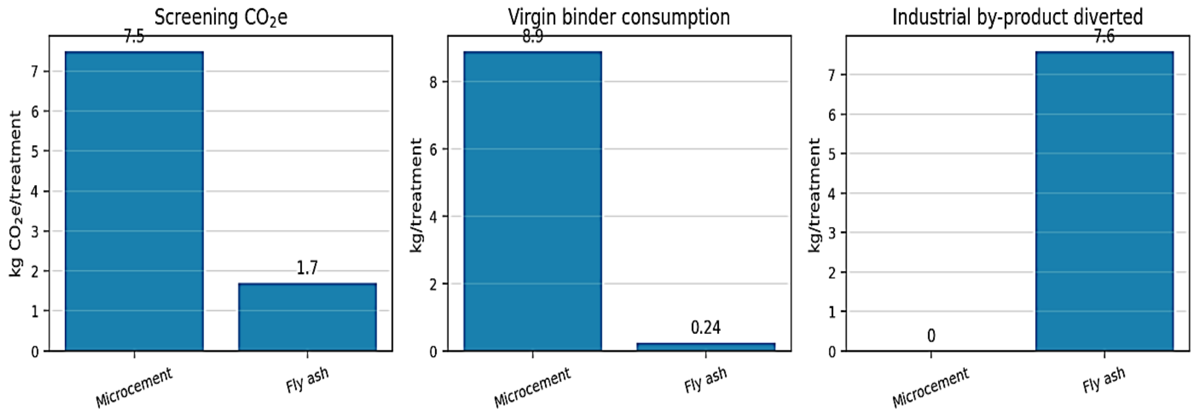

Fig. 5. Screening environmental inventory for the 200-kPa, 28-day laboratory treatments. Values depend on the stated material quantities and emission-factor assumptions

3.7 Practical Implementation Considerations

Natural soils are more variable than soil prepared in the laboratory and can include layers, fractures, water, utilities, and non-uniform stress fields. A field program, therefore, has to start from site investigation and a trial section for gathering information on grout ability, pressure limits, spacing, target volume, heave response, and the volume injected vs. the verified improvement [4,15,23]. Quality control should be a combination of direct and indirect testing. Direct methods are recovered cores or treated-soil samples, and laboratory strength tests. Indirect procedures are such as pressure-flow-volume records, measurement of surface heave, penetration tests, if applicable geophysical measurements and plate-load tests after treatment. The laboratory results showed some central-to-peripheral variability, especially for fly ash; it should be accepted on a number of locations. Micro cement is preferred in applications requiring early loading, better grout ability or more uniform treatment. Activated fly ash is preferred for at least 28 days of curing, and low material cost and embodied-carbon reduction are the benefits. In both cases, choose maximum pressure not based only on laboratory values, but determine an in-field limit to prevent hydraulic fracture, un-controlled flow, or damaging heave from developing. Figure 6 is the preliminary decision flow chart derived from the observed 28-day model capacities, grout consumption and cost screening. It is not a regression model. The 200-kPa point is recommended as the optimum value for the tested clayey sand, as it achieved significant improvement, and was the least influence by wall effect when compared to the 300-kPa condition. The chart needs to be recalibrated for other soils, foundation sizes and field conditions.

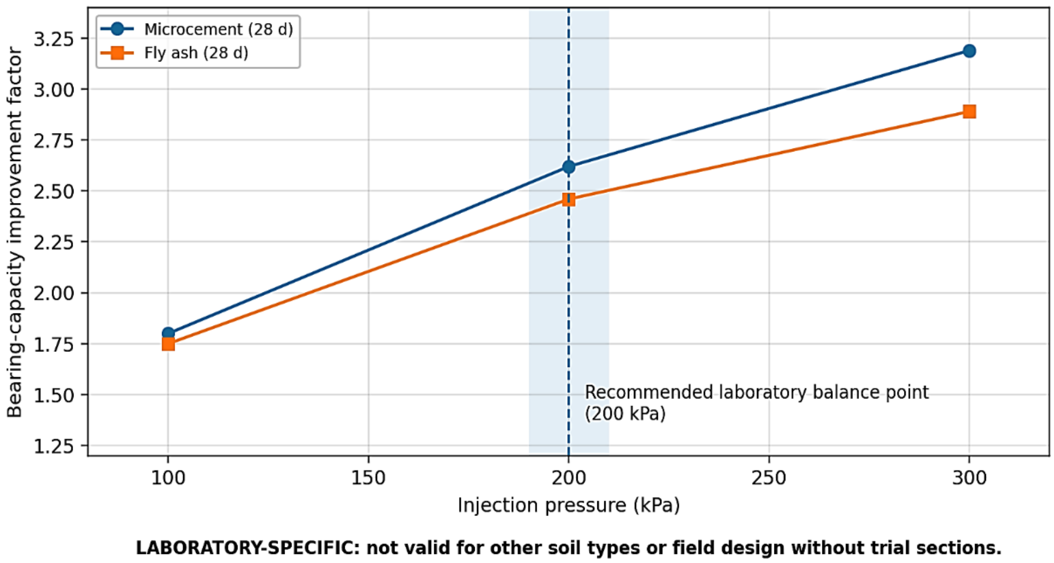

Fig. 6. Preliminary laboratory decision chart for the tested clayey sand. The chart is not a field design equation

3.8 Limitations and Future Research

The main restriction is the finite model geometry. The width of the chamber was only three footing widths (W/B = 3), and the 300 kPa grout fronts hit the lateral boundaries. The nominal horizontal spreads at that pressure are therefore censored, and the associated capacity and settlement enhancements could have been further amplified by lateral confinement. The maximum volume injected also accounted for about 23% of the chamber volume, which is significantly larger than the local treatment ratio commonly employed in field applications. Only one clayey sand, one chamber density, one injection depth and curing ages up to 28 days were investigated. The findings cannot be directly extended to clean sand, high plastic clay, collapsible soil, stratified ground or water bearing ground. Longer curing ages and durability testing under wet-dry cycling, sulfate and acid attack and under hydraulic gradients are especially necessary, in particular for activated fly ash.

The double test structure precludes robust inferential statistics and prevents meaningful multifactor ANOVA without the entire replicate-level data set. If possible, show error bars and test for the significance of raw readings in the original. Specimens of UCS were retrieved post plate loading; thus, the sampling disturbance and the pre-shear history might affect the strength presented of the sample. Dynamic and cyclic loading, repeated foundations and full-scale trial section developments were beyond the scope of this study. Figure 7 summarizes exploratory mix-ratio tests. For micro cement, lower w/c increased strength and decreased penetration, whereas for fly ash, higher water-to-solids ratio resulted in higher penetration and lower strength. These tests are indicative of the strength-grout ability trade-off and the above hold for the chosen main-test ratios of 0.8 and 1.0, respectively. Future work needs to explicitly measure viscosity, bleeding, setting time, and filtration, and employ these results to establish a soil-specific grout ability criterion.

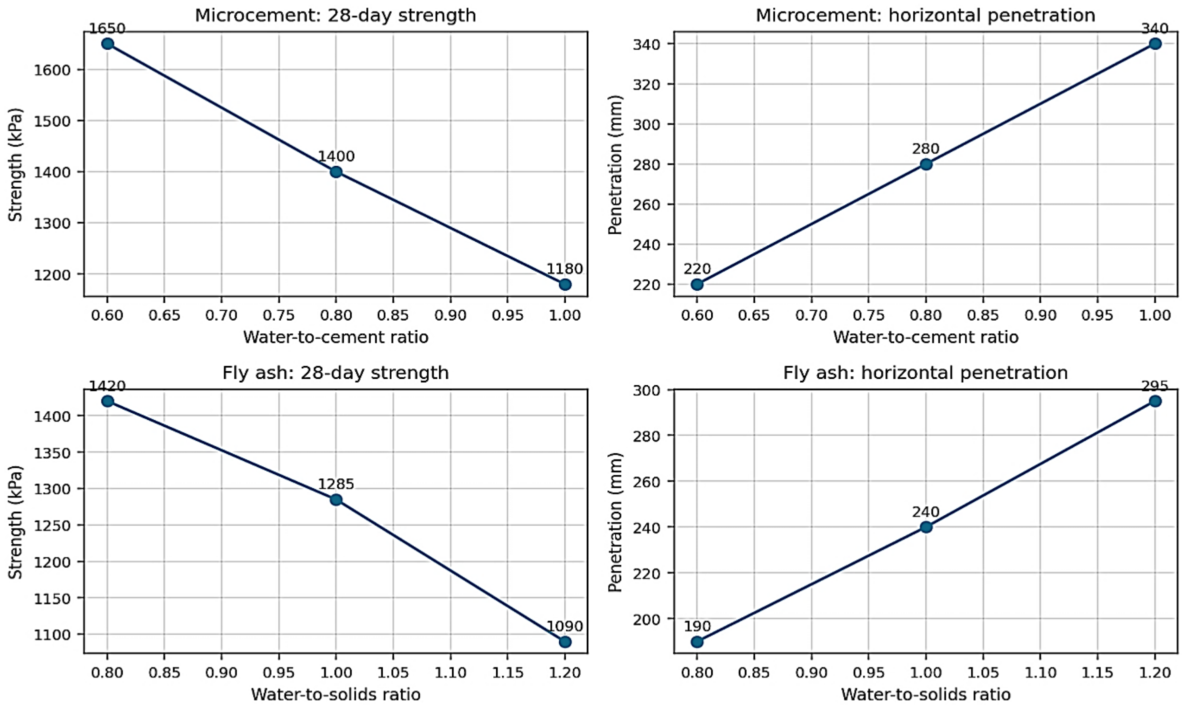

Fig. 7. Exploratory effect of suspension ratio on 28-day strength and horizontal penetration. Each panel uses a single response axis to avoid dual-axis ambiguity

This study is constrained by (W/B = 3), 300 kPa boundary-censored spread, one soil type, short-term curing, duplicated tests, UCS sampling after loading, and lack of durability and dynamic loading. Advancing the research requires larger chambers or centrifuge/full-scale models preserving entire replicate data for statistical analysis, communication of grain size distribution parameters, as well as microstructural and core evidence, and evaluation of long-term curing and excessive exposure. Within these constraints the results indicate that pressure optimization and curing time are at least as important as binder type and that activated fly ash can be competitive with micro cement performance whilst having a significantly superior 28-day cost and screening–carbon material profile. Table 5 presents decision-support summary for preliminary material selection

Table 5. Decision-support summary for preliminary material selection

Project priority	Preferred option	Reason and required control
Early loading or accelerated construction	Micro cement	Faster hydration and greater early-age strength; verify grout ability and control gelation.
Restricted pore access or treatment uniformity	Micro cement	Finer particles and more regular laboratory spread; confirm by a field trial and multiple verification points.
Lower binder cost and carbon with ≥28 days curing	Activated fly ash	Near-micro cement 28-day performance in this study; verify activator, supply consistency, and curing.
Uncertain or heterogeneous field conditions	Trial both or use staged selection	Establish pressure, grout take, heave, spread, and acceptance criteria before production treatment.

4. Conclusions

This paper is part of a series of investigations on micro cement and activated fly ash grouting in which injection into clayey sand through a strip footing is considered under strip-footing pressure application and curing conditions. Both binders showed an improved load-settlement response measured with respect to the untreated reference as drawn in the following points:

- The unmodified model achieved a terminal capacity of 185 kPa. In 28 days, micro cement yielded 335, 485 and 590 kPa for injection pressures of 100, 200 and 300 kPa that represented increments of 81%, 162% and 219%. Fly ash achieved 320, 455, and 535 kPa, representing increments of 73%, 146%, and 189%. These are model test capacities, as defined by the adopted loading termination criterion, and should not be interpreted as allowable bearing soil pressures in the field. Micro cement developed strength at a faster rate leading to shorter injection times and more regular, predictable fronts of treatment. This is advantageous for projects with early loading or greater penetrability in tight pores space.
- Fly ash-based products were more dependent on curing, however the difference between outputs decreased significantly over time. At 200 kPa and 28 days, fly ash was about 94% of micro cement model capacity and 90% of its UCS. This indicates that activated fly ash, given sufficient curing time, could be a technically competitive long-term option for when the construction schedule can be extended long enough to allow for adequate curing.
- The settlement at a common comparison stress of 100 kPa was reduced from 18.5 mm in untreated soil to 8.2 mm with fly ash and 6.5 mm with micro cement at 200 kPa after 28 days. The reductions were 65% and 56%, respectively. Although maximum capacity and settlement reduction were also measured at 300 kPa, the grout fronts reached the borders of the chamber and the injected volumes became large relative to the chamber volume. Thus, the 300-kPa results might incorporate lateral-confinement effects and should be considered as maximum laboratory responses rather than proof that the highest tested pressure is universally best.
- Under the test model with the given parameters, 200 kPa was the most reasonable compromise in terms of mechanical enhancement, grout consumption, cost and experimental reliability. For the minimum tested quality, cement cost screening at this pressure gave the values of 0.150$/kPa of capacity gain for micro cement and 0.044/kPa for fly ash at 28 days, which indicates that using fly ash was 3.41 times more profitable on this metric.
- The binder-resource screening, meanwhile, also predicted roughly 7.5 kg CO_2e for micro cement and 1.7 kg CO_2e for fly ash, a 77% reduction under the given assumptions. These

figures do not account for labor, equipment, transportation, field losses and service-life effects and thus should help, not hinder, a project-specific life-cycle cost and assessment.

The results are consistent with an opportunistic selection model. Micro cement is the choice when early strength development, high pumpability, or finer consistencies are the main needs. Activated fly ash is the choice if more than 28 days of curing are available and considerations of the lowest binder cost, the least virgin-cement demand, and the use of an industrial by-product are paramount. Neither should be based on laboratory pressure values alone. Test sections in the field must determine the pressure limitations, grout take, treatment spacing, heave tolerance, and acceptance criteria for the encountered soil.

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