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Research Article

Comparative performance-based analysis of sustainable soil stabilizers via secondary experimental data: RCA, RAC, fly ash, and nano MgO

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Abstract

In this work, the experimental data of four eco-friendly soil stabilizers—recycled concrete aggregate (RCA), recycled aggregate concrete (RAC), Class F fly ash, and nano-MgO— used for low plasticity clay (CL) are synthesized in a comparative manner. A well-organized secondary database was developed for OMC and MDD, UCS, soaked CBR, ultimate bearing capacity, and settlement. Differences between studies were controlled by limiting the data to similar test conditions and calculating changes from each source study's respective untreated control. OMC was raised by the fly ash from 17.2% to 20.2%, while MDD was decreased from 1.80 g/cm³ (3% dosage) to 1.69 g/cm³ (9% dosage). RCA and RAC yielded maximum dry density (MDD) of 1.86 and 1.89 g/cm³, respectively. At 28 days, nano-MgO exhibited the highest UCS (520 kPa) and soaked CBR (11.6%) at 1% dosage. Fly ash at 6% led to the highest ultimate bearing capacity for the non-nano cases (3,434 kPa), while the highest bearing capacity (4,120 kPa) and the lowest settlement (3.8 mm) were reached by nano-MgO. Based on UCS, CBR, bearing capacity, and settlement control, an equal-weight min-max index placed the tested conditions in this order: nano-MgO, RAC, fly ash at 9%, fly ash at 6%, and RCA. Pearson r for CBR versus UCS was 0.98 indicating very strong correlation, while r for MDD versus ultimate bearing capacity was −0.02 indicating no clear linear relation between ultimate bearing capacity and MDD. The conclusions are limited to short-term laboratory data for CL soils; cost, life-cycle impacts, durability, and field performance require separate evaluation.

1. Introduction

A number of factors that control soil bearing capacity, and the amount of settlement soil can undergo without damaging the pavement layer are key factors defining which shallow foundations are safe and serviceable. Subgrade soils beneath pavements and slabs may be weak and fail to supply enough load carrying capacity and/or deformation resistance, leading to early pavement distress and higher maintenance needs [1]. Traditional stabilization methods (e.g., with cement or lime) can achieve higher strength and stiffness but may also increase embodied carbon and material consumption, and material consumption; furthermore, excessive cement content can lead to brittle behavior [2]. These constraints have led to considering other stabilizers that could enhance bearing capacity and deformation stability, and/or decrease the reliance on virgin binders [3]. Recycled construction materials are a common consideration for geotechnical enhancement. Construction and demolition waste derived recycled concrete aggregate (RCA) can be used to enhance the performance of clayey soils because of angular-particle interlocking and further

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contributions of frictional resistance [4]. Recycled Aggregate Concrete (RAC) in which the recycled aggregate still has adhered mortar on its surface may offer enhanced bonding and stiffness, geopolymer-stabilized recycled aggregates also show promise for layer applications in pavements/road bases [5]. These products enable circular applications of construction waste, though their performance is influenced by the quality of aggregates, the dosage, and test condition. Fly ash is also an industrial by-product extensively investigated as a soil stabilizer due to the fact that its pozzolanic reactions can provide increment in strength with time [6, 7]. It also has a dosage-dependent impact on compaction: the relatively low specific gravity and high surface area of Class F fly ash tends to increase water demand and decrease dry density for larger contents. Fly ash can also decrease cement requirements and enhance subgrade performance but an appropriate curing time should be taken into account as well as the variability of the chemical composition of the fly ash [8, 9].

Nano-MgO is intriguing as the interparticle contacts and pore structure at the nanoscale can be altered with a small dosage of this material. Studies available on nano-MgO-treated clay indicate enhancement in bearing capacity and settlement response [20]. In the studies of nano-clay, nano-silica and other nanoparticles, references are available to provide mechanistic insights [10–15, 21, 22, 26], however, these studies do not address nano-MgO within the present database context. Reported nanomaterial effects are also still sensitive to dosage, curing, and moisture conditions; thus, results from contaminated or gypseous soils or soil that exhibits a very high plasticity cannot be transferred to a low-plasticity clay unambiguously. Although the individual stabilizers have been widely studied, comparative assessments of recycled aggregates, industrial by-products and nano-MgO within the same analytical context are still scarce. Therefore, the aim of this study is to collate comparable previously published laboratory results for RCA, RAC, fly ash, and nano-MgO in a low-plasticity clay and to contrast their influences on compaction, UCS, soaked CBR, ultimate bearing capacity, and settlement. The review is explicitly a synthesis of previously collected data and does not involve any new laboratory investigations. This study answers the following research questions:

- To what extent do RCA, RAC, Class F fly ash and nano-MgO enhance the strength, bearing capacity and settlement behavior of low-plasticity clay?
- What is the performance ranking when UCS, soaked CBR, ultimate bearing capacity, and settlement controls are combined in an understandable equal-weight index?
- Within the confines of the existing secondary data set, can a relationship between stabilizer application rates and any of the selected engineering parameters be established?

2. Methodology

2.1. Data Collection and Synthesis Process

Instead of performing new experiments, this work adopted a rounded, secondary-data synthesis investigation approach within the boundaries of the-peer reviewed evidence base. The present source set of literature was retrospectively registered by a focused search strategy including the terms “low-plasticity clay” or “CL soil” with “fly ash,” “recycled concrete aggregate,” “recycled aggregate concrete,” “nano-MgO,” “UCS,” “CBR,” “bearing capacity,” and “settlement.” Potential studies were screened for relevance to material, soil type, test condition, and reported engineering parameter. As exact initial counts for retrieval and exclusion were not kept during the initial database build, this work is not presented as a PRISMA systematic review; the limitation is explicitly acknowledged. Quantitative values were extracted from studies of fly ash stabilization [6, 7, 23, 25, 30, 31], RCA and RAC stabilization [5, 18, 19, 24, 27–29], and nano-MgO-treated clay [20]. References concerning nano-clay, nano-silica, or broad nanomaterial reviews [10–15, 21, 22, 26] were used only to support mechanistic discussion and were not treated as nano-MgO observations. Extracted fields included soil classification, stabilizer type and dosage, test standard or procedure, curing period, OMC, MDD, UCS, soaked CBR, ultimate bearing capacity, settlement, and the corresponding untreated-control value.

Eligibility was restricted to low-plasticity clay (CL) or closely comparable cohesive fine-grained soils. Compaction data were limited to standard Proctor energy (ASTM D698 or the comparable IS 2720 Part 7 procedure), CBR values to soaked conditions, UCS values to 7, 14, and 28-days curing periods, and load–settlement values to controlled model-footing or plate-load tests. To reduce cross-study baseline differences, each stabilized value was also expressed relative to the untreated specimen reported in the same source: change (%) = [(stabilized value − untreated value)/untreated value] × 100. Raw values at comparable conditions were retained in the summary tables. Replicate-level observations were generally unavailable; consequently, pooled standard deviations and formal inferential tests were not calculated. Missing parameters were treated as data gaps rather than imputed.

2.2. Materials and Engineering Parameters

The reference material was natural low-plasticity clay (CL). The evaluated stabilizers were Class F fly ash, RCA, RAC, and nano-MgO. The control properties used for comparison were Atterberg limits, specific gravity, OMC, MDD, UCS, soaked CBR, ultimate bearing capacity, and settlement. Table 1 summarizes the representative properties of the untreated reference soil in the synthesized database.

Table 1. Representative physical and mechanical properties of the untreated low-plasticity clay (CL) in the synthesized database

Property	Value
Liquid Limit (%)	38–42
Plasticity Index (%)	12–16
Specific Gravity	2.65–2.70
OMC (%)	17.2
MDD (g/cm^3)	1.78
UCS (kPa)	132–145
Soaked CBR (%)	2.1

Fly ash observations represented mainly low-calcium Class F ash (ASTM C618) added at 3%, 6%, and 9% of dry soil mass. These conditions provide compaction, curing-dependent UCS, soaked CBR, bearing-capacity, and settlement values over the dosage range most frequently reported in the selected sources [6, 23, 25]. RCA and RAC observations were represented at approximately 10% dry-mass replacement. RCA consisted of processed construction and demolition concrete, whereas RAC retained adhered cementitious mortar that may contribute to bonding. Nano-MgO observations were represented at 1% dry-soil mass [20]. These dosage levels were not assumed to be universally optimal; they represent the comparable and commonly reported conditions available in the selected source datasets.

Table 2. Characterization of the representative source datasets used in the secondary synthesis

Parameter	Material condition	Representative datasets (n)	Range	Principal references
OMC (%)	Fly ash (3–9%)	3	18.4–20.2	[6,23,25]
MDD (g/cm^3)	Fly ash (3–9%)	3	1.69–1.80	[6,23,25]
OMC (%)	RCA/RAC (10%)	4	18.1–18.3	[5,18,19,24]
MDD (g/cm^3)	RCA/RAC (10%)	4	1.86–1.89	[5,18,19,24]
UCS, 28 d (kPa)	All stabilized conditions	5	330–520	[6,18–20,23]
Soaked CBR (%)	All stabilized conditions	5	8.4–11.6	[6,18–20,23]
Ultimate bearing capacity (kPa)	All stabilized conditions	5	2,550–4,120	[6,18–20,23]
Settlement (mm)	All stabilized conditions	5	3.8–6.8	[6,18–20,23]

Note: n is the number of representative source datasets/conditions available for the given comparison. Replicate level data were not available and pooled standard deviations were not calculated.

Table 2 represents the characterization of the representative source datasets used in the secondary synthesis performance was evaluated using the values reported in Tables 2-4. Each stabilized condition was scored separately for four criteria: 28-days UCS, soaked CBR, ultimate bearing capacity, and settlement control. For the three benefit criteria, min–max score = $(x - x_{min})/(x_{max} - x_{min})$; for settlement, score = $(x_{max} - x)/(x_{max} - x_{min})$. The equal-weight composite index was the arithmetic mean of the four dimensionless scores. 6% and 9% Fly ash were treated as two separate treatments, and the material-level hierarchy used the maximum of its two composite scores. The index is an open descriptive ranking, not a formal AHP/TOPSIS decision model, and does not consider dosage, cost, carbon footprint, availability, or long-term durability.

3. Results

3.1. Compaction Characteristics

Compaction behavior was compared using optimum moisture content (OMC) and maximum dry density (MDD). Table 3 summarizes the untreated and stabilized conditions. The maximum dry density (MDD) and optimum moisture content (OMC) of the untreated soil were 1.78 g/cm^3 and 17.2%, respectively. Fly ash raised OMC incrementally up to 20.2% at dosage level of 9%. MDD showed a minor increase up to 1.80 g/cm^3 at 3% fly ash, followed by a decrease to 1.74 g/cm^3 at 6% and 1.69 g/cm^3 at 9% fly ash, which is in line with the reduced specific gravity and elevated water demand of the fines. RCA and RAC led to increases in MDD to 1.86 and 1.89 g/cm^3, which equates to relative improvements of 4.5% and 6.2%, respectively; this pattern concurs with granular packing and angular-particle interlocking. Up to a dosage of 1%, nano-MgO raised the MDD to 1.84 g/cm^3 (3.4%) but increased OMC only from 17.2% to 17.5%. These statements are qualitative, since the secondary dataset does not include replicate-level variances that would allow for statistical testing of significance.

Table 3. Compaction characteristics of low-plasticity clay stabilized with RCA, RAC, Class F fly ash, and nano-MgO

Stabilizer Type	Stabilizer Content (%)	OMC (%)	MDD (g/cm^3)
Untreated soil	0	17.2	1.78
RCA	10	18.1	1.86
RAC	10	18.3	1.89
Fly ash	3	18.4	1.80
Fly ash	6	19.8	1.74
Fly ash	9	20.2	1.69
Nano-MgO	1.0	17.5	1.84

3.2. Mechanical Strength and Bearing Performance

3.2.1 Unconfined Compressive Strength (UCS)

The untreated soil had UCS values of 132, 138, and 145 kPa at 7, 14, and 28 days, respectively. Table 4 summarizes the curing-dependent strength development of all conditions. All stabilizers increased UCS relative to the untreated soil. With 6% fly ash, UCS increased from 285 kPa at 7 days to 410 kPa at 28 days; at 9% fly ash, the corresponding values were 300 and 430 kPa. The time-dependent gain is consistent with progressive pozzolanic reactions reported for Class F fly ash [23].

Table 4. Unconfined compressive strength of untreated and stabilized soil at different curing periods

Stabilizer Type	Stabilizer Content (%)	UCS at 7 days (kPa)	UCS at 14 days (kPa)	UCS at 28 days (kPa)
Untreated soil	0	132	138	145
RCA	10	240	290	330
RAC	10	310	390	460
Fly ash	6	285	350	410

Fly ash	9	300	380	430
Nano-MgO	1.0	420	480	520

RCA increased from 240 to 330 kPa between 7 and 28 days, whereas RAC increased from 310 to 460 kPa. The greater RAC values may reflect residual cementitious mortar, but this mechanism is inferred from the source literature [5, 29] rather than verified by microstructural testing in the present synthesis. Nano-MgO produced the highest values, increasing from 420 kPa at 7 days to 520 kPa at 28 days. Figure 1 compares the 28-days UCS values.

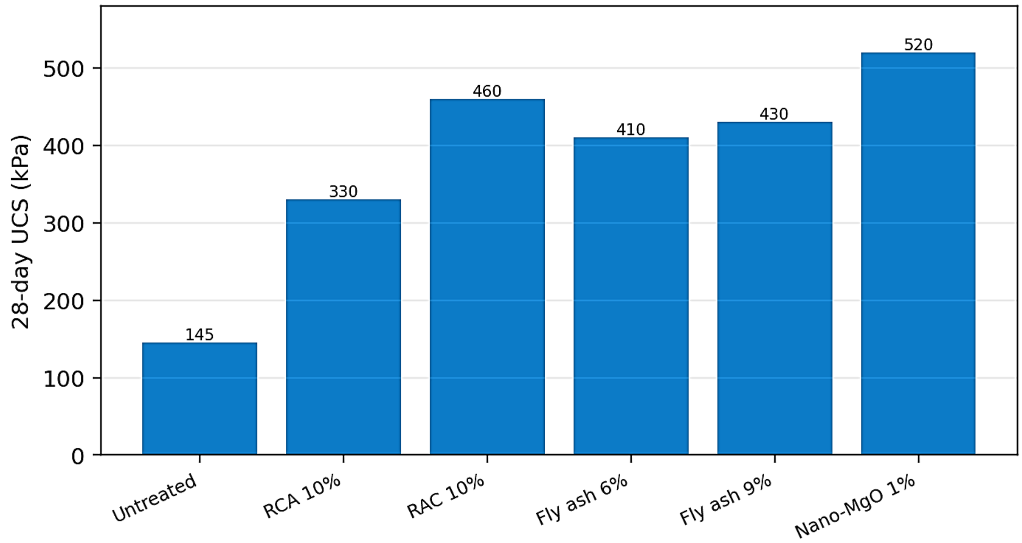

Fig. 1. Comparison of unconfined compressive strength at 28 days for untreated and stabilized soils

3.2.2 California Bearing Ratio (CBR)

The untreated soaked CBR was 2.1%. Fly ash produced values of 8.9% at 6% dosage and 10.6% at 9% dosage. RCA and RAC produced soaked CBR values of 8.4% and 10.5%, equivalent to 4.0 and 5.0 times the untreated value. Nano-MgO produced the highest soaked CBR, 11.6% at 1% dosage, or approximately 3.5 times the untreated value. Figure 2 presents all soaked CBR values. The mechanistic explanations are literature-based and should not be interpreted as direct microstructural observations from this secondary dataset.

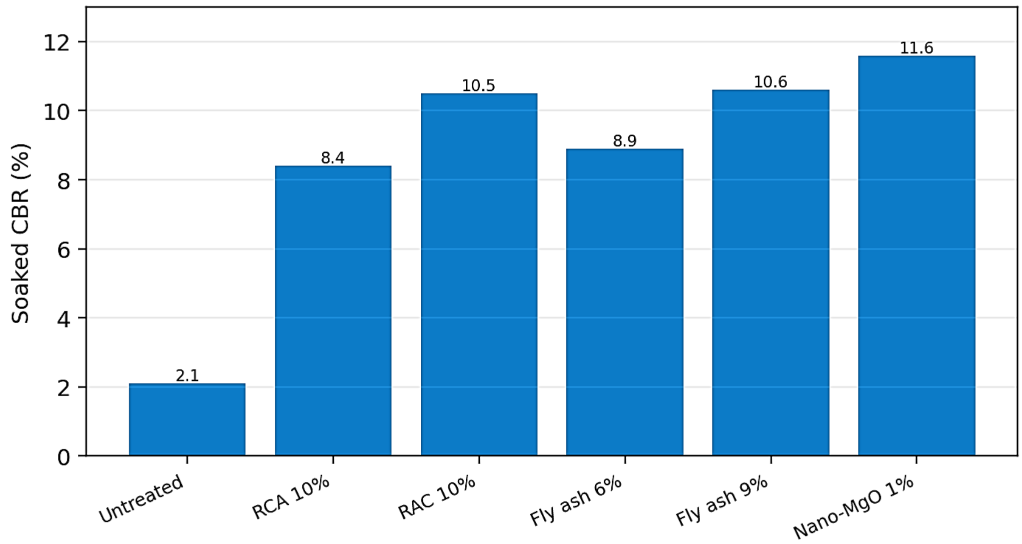

Fig. 2. Soaked California bearing ratio values for untreated and stabilized soils

3.3. Load–Settlement Behavior

Published model-footing and bearing-capacity data were used to compare the load–settlement response. Table 5 reports ultimate bearing capacity and settlement at a common applied stress of 5 kg/cm^2 (approximately 490 kPa). Standardizing settlement to this stress permits direct comparison of the reported single-point settlement values, but it does not reproduce complete load–settlement curves. The untreated soil had an ultimate bearing capacity of approximately 981 kPa and a settlement of 12.5 mm at the common applied stress. Figure 3 compares the ultimate bearing-capacity values.

Table 5. Ultimate bearing capacity and settlement of untreated and stabilized low-plasticity clay

Stabilizer Type	Stabilizer Content (%)	CBR (%)	Ultimate Bearing Capacity (kPa)	Settlement at Applied Stress of 5 kg/cm^2 (mm)
Untreated soil	0	2.1	981	12.5
RCA	10	8.4	2,550	6.8
RAC	10	10.5	2,943	5.4
Fly ash	6	8.9	3,434	6.2
Fly ash	9	10.6	3,336	6.0
Nano-MgO	1.0	11.6	4,120	3.8

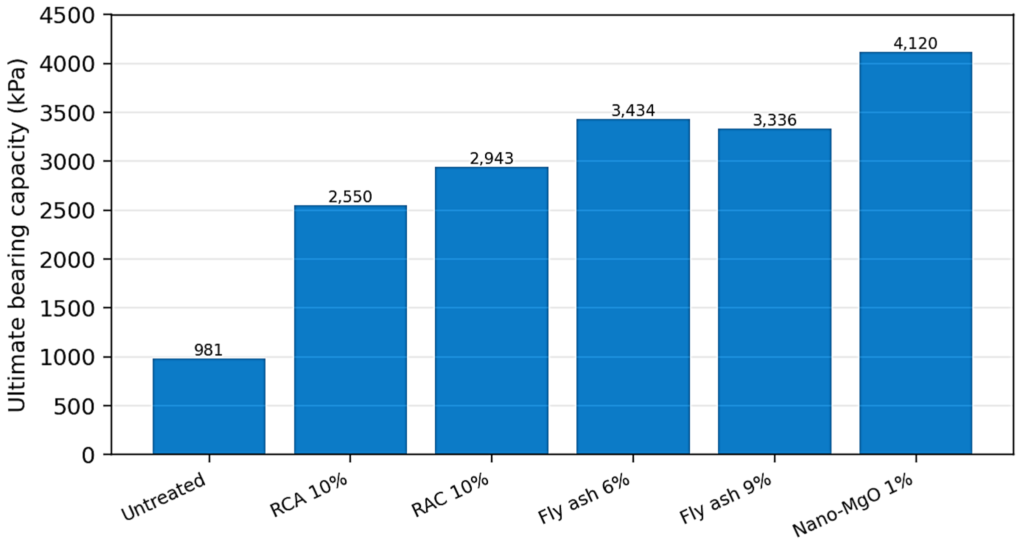

Fig. 3. Ultimate bearing capacity of untreated and stabilized soils obtained from model footing tests

Nano-MgO produced the highest ultimate bearing capacity (4,120 kPa) and the lowest settlement (3.8 mm). Fly ash at 6% produced 3,434 kPa, which exceeded the values for RAC (2,943 kPa) and RCA (2,550 kPa) in this specific parameter. RAC nevertheless provided lower settlement (5.4 mm) than fly ash at 6% (6.2 mm), fly ash at 9% (6.0 mm), and RCA (6.8 mm). Thus, the bearing-capacity result alone does not determine the overall performance hierarchy. Only one settlement value at a common stress was available for each condition. Consequently, curve stiffness, yield behavior, and ductile–brittle response was not inferred. Complete load–settlement curves should be reported in future source datasets and field validation studies.

3.4 Summary of Comparative Performance

The equal-weight min–max procedure described in Section 2.2 generated the scores listed in Table 6. Nano-MgO received the maximum score for all four criteria and therefore ranked first. RAC ranked second (composite index 0.514), narrowly ahead of fly ash at 9% (0.495). Fly ash at 6% ranked fourth (0.335), and RCA ranked fifth (0.000) within the tested set. At the material level, the resulting hierarchy was nano-MgO, RAC, fly ash, and RCA. This hierarchy reflects only the four measured short-term mechanical criteria. The normalized profiles are shown in Figure 4. Across the untreated and stabilized conditions, 28-days UCS and soaked CBR exhibited a strong positive descriptive association (Pearson r = 0.98; n = 6; Figure 5). By contrast, MDD and ultimate bearing capacity showed no clear linear association (r = −0.02; n = 6; Figure 6), indicating that density alone did not explain the bearing-capacity differences in this small dataset. These correlations are exploratory and should not be interpreted as inferential evidence because of the limited sample size and cross-study heterogeneity.

Table 6. Equal-weight normalized performance scores for the stabilized conditions

Condition	UCS score	CBR score	Bearing-capacity score	Settlement-control score	Composite index	Rank
RCA (10%)	0.000	0.000	0.000	0.000	0.000	5
RAC (10%)	0.684	0.656	0.250	0.467	0.514	2
Fly ash (6%)	0.421	0.156	0.563	0.200	0.335	4
Fly ash (9%)	0.526	0.688	0.501	0.267	0.495	3
Nano-MgO (1%)	1.000	1.000	1.000	1.000	1.000	1

Note: Benefit criteria were normalized as (x − xmin)/(xmax − xmin); settlement control was normalized as (xmax − x)/(xmax − xmin). All four criteria received equal weight.

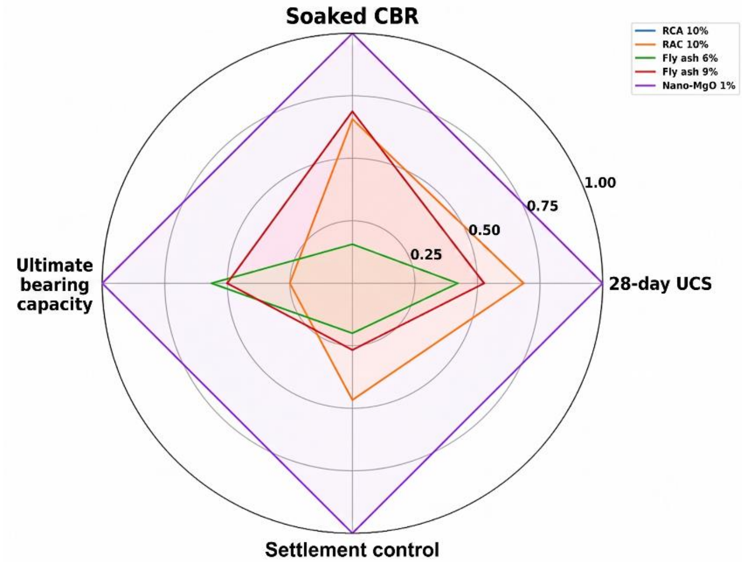

Fig. 4. Normalized performance profiles for the five stabilized conditions

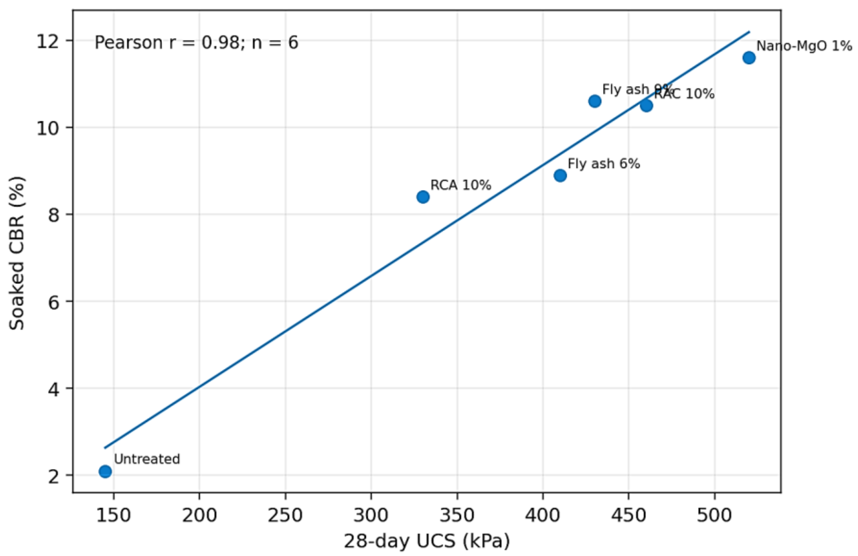

Fig. 5. Descriptive relationship between 28-days UCS and soaked CBR (Pearson r = 0.98; n = 6)

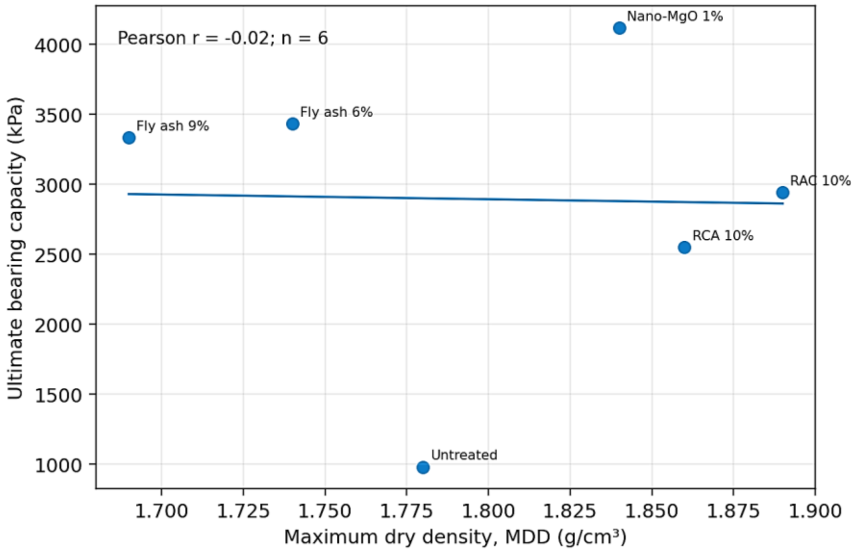

Fig. 6. Descriptive relationship between MDD and ultimate bearing capacity (Pearson r = −0.02; n = 6)

4. Discussion

The synthesized data show that the four stabilizer systems modify low-plasticity clay through different compaction and bonding pathways. Class F fly ash increased water demand and reduced MDD beyond 3% dosage, which is consistent with its low specific gravity and fine-particle dilution effect. RCA and RAC increased MDD, plausibly because angular particles improved granular packing. Nano-MgO increased MDD by 3.4% at 1% dosage with only a small OMC change, consistent with a micro-void-filling interpretation. These mechanisms are supported by cited literature but were not directly verified by chemical or microstructural tests in this secondary-data study. Strength development also differed by material. Fly ash showed gradual curing-dependent gains associated with pozzolanic reactions [23]. RCA primarily provided frictional interlocking, whereas the higher RAC values may additionally reflect bonding from adhered mortar [5, 29]. Nano-MgO produced the largest early and 28-days UCS values, which is consistent with nanoscale pore filling and interparticle bonding reported for nano-MgO-treated clay [20]. Evidence from nano-clay and other nanomaterials [10–15, 21, 22, 26] is used only as comparative context and not as direct evidence for the nano-MgO dataset.

The composite ranking explains why fly ash was not ranked based on its bearing capacity result alone. 6% FA performed better than both RA scenarios in ultimate bearing capacity, while RAC achieved significantly higher UCS, higher CBR and lower settlement. RAC was rated slightly higher than fly ash at 9% by the equal-weight index, whereas nano-MgO remained unambiguously the best. The strong UCS–CBR relationship confirms the internal consistency of the strength parameters, but the lack of a definite MDD–bearing-capacity relationship indicates that the density of compaction alone is inadequate to explain the results. Bonding, curing, particle interaction, and test configuration are likely operated as well. Using recycled aggregates and industrial by-products could be more environmentally friendly since this practice can contribute to waste management and raw material conservation [27–29, 31]. Yet, there was no assessment of the carbon footprint, of leaching, life-cycle, impacts or cost in this investigation. In the same manner, low dosage of nano-MgO alone cannot demonstrate cost-effectiveness. The environmental and economic benefits should be viewed as hypotheses that must be tested through formal life-cycle assessment and cost-benefit analysis.

5. Conclusions

A structured secondary database of published results for low-plasticity clay from laboratory tests was used in this study to evaluate RCA, RAC, Class F fly ash, and nano-MgO. The OMC, MDD, curing-dependent UCS, soaked CBR, ultimate bearing capacity, and settlement were included in the comparison. Differences across studies were mitigated through explicit inclusion criteria and normalizing to each source study's untreated control; still, the analysis is a synthesis of published data rather than a priori experimental program.

- During compaction process, OMC was increased from 17.2% to 20.2% while MDD was decreased from 1.80 g/cm^3 at 3% dosage to 1.69 g/cm^3 at 9% dosage as a result of addition of fly ash. RCA and RAC, on the other hand, resulted in an increased MDD of 1.86 g/cm^3 and 1.89 g/cm^3, respectively, and 1% nano-MgO addition increased MDD to 1.84 g/cm^3 with only a marginal rise in OMC. These findings suggest that the stabilizers may "not play the same game": fly ash alters primarily water demand and curing-dependent bonding, whereas recycled aggregates and nano-MgO have distinct packing and particle-interaction properties.
- All stabilized states, both UCS and soaked CBR, were higher than that of the untreated soil. The maximum 28-days UCS (520 kPa) and soaked CBR (11.6%) were attained by nano-MgO at 1% dosage. RAC recorded 460 kPa and 10.5%, while RCA 330 kPa and 8.4%. Fly ash attained 410 kPa and 8.9% at 6% dosage, while it was 430 kPa and 10.6% at 9% dosage. The strong descriptive UCS–CBR relationship (r = 0.98) indicates that the two strength measures are consistent for this dataset, but it does not imply causality.
- The highest ultimate bearing capacity (4,120 kPa) and lowest settlement (3.8 mm) were obtained by Nano-MgO. With 6% fly ash, the bearing capacity was 3,434 kPa, the highest among the non-nano conditions, but RAC showed better settlement control and more robust UCS/CBR results. When using the equal-weight normalized index, the order of the test conditions is nano-MgO, RAC, fly ash at 9%, fly ash at 6%, and RCA. At the predicting material level, the order was nano-MgO, RAC, fly ash, and RCA. This ranking is only for the four short-term mechanical criteria, and does not take into account the efficiency of dosage, cost, availability, durability and environmental implications.
- The findings support the technical potential of recycled aggregates, fly ash, and nano-MgO for improving CL subgrades, but they do not justify universal substitution for cement or lime. RCA may be suitable where moderate improvement and waste reuse are priorities; RAC may be preferred when higher strength and settlement control are required; fly ash is relevant where extended curing is feasible; and nano-MgO may be considered where high mechanical performance at low dosage is valuable. These statements are performance interpretations, not project-specific design recommendations.
- Variability is a source of error for source soils, laboratories, stabilizer compositions, and test configurations; replicate-level data is not completely available and formal pooled uncertainty estimates are not available; the number of comparable conditions is small; and a descriptive equal-weight index rather than a validated decision model is employed. Only short-term laboratory properties were taken into account. Durability with cyclic and wet–dry and freeze–thaw exposure, chemical deterioration, leaching, field-scale constructability, life-cycle implications, and cost were not considered. This may be applied to low-plasticity clay and is not suggested to be applied to other soil classes without confirmation.
- In future work, the entire source-level dataset and the search log should be published and the search log should be published, replicate observations should be retained, full load–settlement curves should be reported, and larger datasets should be used for regression, uncertainty, and sensitivity analysis to alternative weights. Field experiments under traffic and environmental loads are necessary to validate long-term performance. Comparative life-cycle assessment, evaluation of leachability of materials and cost benefit analysis, should be included with mechanical tests. Systems comprising RCA or RAC with nano-MgO are promising candidates for systematic research, but also in this case synergy potential has to be proven experimentally before making any claims in practical applications.

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