**Appendix A. Supplementary data**

**Table A1**. Summary of the performance of different additives on soil stabilization.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Additive | Suitable soil type | Mechanism involved | Optimum dosage | Effect | Influencing factor | Key benefit | Limitation | Source |
| Lime | Clay with high to low plasticity | Cation exchange, flocculation and agglomeration, pozzolanic reaction | Up to 10% based on soil plasticity and clay content | OMC↑, *γ*dmax↓, pH↑, UCS↑, shear strength↑, CBR↑, secant modulus↑, *M*r↑, permanent deformation↓, *G*↑, *δ*↓, *LL*↓, *PL*↑, *PI*↓, *SL*↑, *k*↑, volumetric shrinkage↓, FSI↓, swelling potential↓, swelling pressure↓, durability against F-T cycles↑, durability against W-D cycles↑ | Soil mineralogy, soil type, type of lime, lime content, curing period, curing temperature, delay in compaction, soil pH, molding water content, F-T cycle, organic content, sulfate content | More suitable for improving soil workability | The deleterious effect of sulfate and organic content is higher | Bell, 1993; Boardman et al., 2001; Al-Rawas et al., 2005; Dash and Hussain, 2012; Cherian and Arnepalli, 2015; Eisazadeh and Eisazadeh, 2015; Jha and Sivapullaiah, 2016; Zhao et al., 2020 |
| Cement | Granular materials with enough fines and clay with low to medium plasticity | Cementitious hydration, cation exchange, flocculation and agglomeration, pozzolanic reaction | Up to 16% based on soil plasticity and fines content (high plastic clay requires more cement) | OMC↑, *γ*dmax↓, pH↑, UCS↑, shear strength↑, CBR↑, secant modulus↑, *M*r↑, permanent deformation↓, shear wave velocity↑, *G*↑, *δ*↓, *LL*↓, *PI*↓, *SL*↑, *k*↑, swelling pressure↓, swelling potential↓, durability against F-T cycles↑, durability against W-D cycles↑ | Soil mineralogy, soil type, type of cement, cement content, water-cement ratio, curing period, curing temperature, compaction delay, F-T cycles, W-D cycles, nano-silica content, organic content, sulfate content | Strength improvement is rapid, more suitable for improving soil strength and stability. It can reduce effects of F-T and W-D | Cement becomes hard to blend with highly plastic clay due to the formation of lumps. Less effective in improving soil workability | Bell, 1995; Prusinski and Bhattacharja, 1999; Puppala et al., 2004; Horpibulsuk et al., 2005; Wang et al., 2018; Chen et al., 2019; Gao et al., 2020; Kulanthaivel et al., 2020 |
| FA | Clay with high plasticity | Cation exchange, flocculation and agglomeration, pozzolanic reaction | 10%-20% based on soil plasticity | OMC↓, *γ*dmax↑, *LL*↓, *PI*↓, UCS↑, secant modulus↑, shear strength↑, CBR↑, volumetric shrinkage↓, swelling pressure↓, swelling potential↓, *k*↓, FSI↓, *M*r↑, permanent deformation↓ | Soil type, type of fly ash, fly ash content, molding water content, curing period, curing temperature, compaction delay, organic content, sulfate content | Economical and environmentally sustainable substitute. It can reducedeleterious effect of sulfate | FA alone cannot improve soils significantly | Young, 1972; Ferguson, 1993;Sivapullaiah et al., 1998b;Tishmack et al., 1999; Senol et al., 2006; Binal, 2016; Dutta and Saride, 2016; Cheshomi et al., 2017 |
| CKD | Clay, silt with low plasticity | Cation exchange, flocculation and agglomeration, pozzolanic reaction | 16%-20% | OMC↑, *γ*dmax↓, pH↑, *LL*↓, *PI*↓, UCS↑, CBR↑, volumetric shrinkage↓, free swell↓, *k*↓, durability against W-D cycles↑, durability against F-T cycles↑ | Soil type, CKD content, curing period | CKD is economical, environmentally sustainable, and can provide similar benefit as lime and cement | CKD contains sulfate and is highly alkaline, hence not effective for sulfate-rich soils | Baghdadi, 1990; Miller and Zaman, 2000; Miller and Azad, 2000; Peethamparan et al., 2009; Amadi and Eberemu, 2013; Ismail and Belal, 2016; Ogila, 2021 |
| LKD | Clay, silt with low plasticity | Cation exchange, flocculation and agglomeration, pozzolanic reaction | 5%-8% | OMC↑, *γ*dmax↓, *LL*↓, *PI*↓, pH↑, swelling potential↓, UCS↑, CBR↑, *M*r↑, permanent deformation↓, electrical conductivity↓, durability against F-T cycles↑, durability against W-D cycles↑ | Soil type, LKD content, curing period | LKD is environmentally sustainable, and can be used as a replacement of hydrated lime | LKD alone cannot improve soil strength significantly, to be used in, combination with FA | Chesner et al., 2002; Chen et al., 2009; Cetin et al., 2010; Kakrasul et al., 2017, 2018 |
| GGBS | Clay with low to high plasticity | Cation exchange, flocculation and agglomeration, pozzolanic reaction | 6%-10% | OMC↑ or ↓, *γ*dmax↓ or ↑, *G*s↑, *PI*↓, UCS↑, swelling potential↓, swelling pressure↓, shrinkage strain↓ | Soil type, GGBS content, curing period | GBBS is environmentally sustainable, works similar to lime, and provides better improvement for sulfate bearing soils | GGBS provides better stabilization effect in presence of activators such as MgO and lime | Cokca et al., 2009; Obuzor et al., 2011; Yadu and Tripathi, 2013; Sharma and Sivapullaiah, 2016; Yi et al., 2016; Al-Dakheeli et al., 2022 |
| CCR | Clay with low to high plasticity | Cation exchange, flocculation and agglomeration, pozzolanic reaction | Up to 15% | OMC↑ or ↓, *γ*dmax↓ or ↑, *PI*↓, shear stress↑, UCS↑, CBR↑, *M*r↑, swelling potential↓, swelling pressure↓ | Soil type, CCR content, curing period, curing temperature | CCR exhibits identical chemical composition ashydrated lime, and can replace lime and cement | CCR-mixed admixtures exhibit higher initial, as well as final setting times than that of cement | Cardoso et al., 2009; Horpibulsuk et al., 2013; Phetchuay et al., 2014; Hatmoko and Hanjitsuwan et al., 2017; Hatmoko and Suryadharma, 2017 |
| Salt (NaCl, KCl, MgCl2, CaCl2, AlCl3) | Clay with low to high plasticity | Cation exchange, flocculation and agglomeration, pozzolanic reaction | Up to 7% or 1 mol/L (if salt solution is used) | OMC↑, *γ*dmax↓, *LL*↓, *PL*↑, *PI*↓, *SL*↑, swelling pressure↓, swelling potential↓, UCS↑ | Soil type, salt type, salt concentration, curing period | Salt can minimize the deleterious effect of organic content on strength of the stabilized clays | Salts being water soluble are susceptible to leaching, and amenable to loss; hence wet environment can affect its performance | Gleason et al., 1997; Tingle et al., 2007; Shon et al., 2010;Turkoz et al., 2014; Barman and Mishra, 2019 |
| SO | Clay with high plasticity | Cation exchange, flocculation, physical bonding | 0.02%-1.25% | OMC↓, *γ*dmax↑, *LL*↓, *PL*↓, *PI*↓, swelling potential↓, swelling pressure↓, shrinkage↓, UCS↑ | Soil type, SO content | Addition of a small proportion of SO can provide a significant improvement in soil strength | SO has no benefit when used on sands, gravel or any low plastic soil | Scholen, 1995; Onyejekwe and Ghataora, 2015; Soltani et al., 2019, 2020 |
| Geopolymer | Clay with low to high plasticity | Physical bonding | Up to 20% | UCS↑, *E*↑, *G*↑, shrinkage↓ | Soil type, geopolymer type, geopolymer content | Geopolymer provides better stabilization to sulfate bearing soils |  | Rovnaník, 2010; Zhang et al., 2015; Khadka et al., 2018; Abdullah et al., 2021 |
| Enzyme | Clay with high affinity for water | Physical bonding, cementation | 0.002% and 0.1% | UCS↑, CBR↑, *k*↓, tensile strength↑, desiccation cracks↓, permanent deformation↓, swelling potential↓, durability against W-D cycles↑ | Soil type, enzyme type, curing period, curing temperature | Enzymes are not consumed by the reactions, used in low concentration | Silt and granular soil do not have enough affinity of water, not suitable for enzyme treatment | Tingle et al., 2007; Naagesh and Gangadhara, 2010; O’Donnel, 2015; Pooni et al., 2019, 2020; Khan et al., 2020; Xie et al., 2020; Thomas and Rangaswamy, 2021 |

Note: ↑: increase; ↓: decrease; *γ*dmax: maximum dry density; *LL*: liquid limit; *PL*: plastic limit; *SL*: shrinkage limit; FSI: free swell index; *δ*: damping ratio; *G*s: specific gravity; *E*: Young modulus.

**Table A2.** Comparison between the performance of lime, cement and FA on soil behavior.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Source | Soil type | Investigated property | Curing period (d) | Additives used | CaO content (%) | Optimum additive content (%) | Effect | Remarks |
| Jones (1958) | CH, *LL* = 71.9%, *PI* = 47.5% | *PI* | 30 | HL |  | 8 | *PI* = 4% | Lime more effective in reducing soil plasticity than cement |
| C |  | 6\* | *PI* = 27% |
| Estabragh et al. (2013) | CH, *LL* = 88%, *PI* = 57%, *S* = 440 kPa | *S* | 0 | HL |  | 10 | *S* = 50 kPa | Lime more effective in reducing swellof soil than cement |
| C (Type I) | 61.3 | 10\* | *S* = 280 kPa |
| Cokca (2001) | CH, *LL*=74%,  *PI* = 52%, *SP* = 33% | *SP* | 0 | HL | 67.08 | 8 | *SP* = 11.2% | CaO content of lime and cement was almost same, effect on SP was almost similar |
| C\*\* | 61.9 | 8 | *SP* =12.8% |
| CFA | 18.98 | 20 | *SP* = 11.3% |
| FFA | 2.18 | 25 | *SP* = 10.15% |
| Wang et al. (2013) | MH, *LL* = 76.1%, *PI* = 40.8%, *UCS* = 530 kPa | *UCS* | 28 | L | ≥90 | 3 | *UCS* = 760 kPa | Rapid cement hydration forms more cementitious gels, therefore strength of cement treated soil was much higher |
| C\*\* | 63.3 | 9 | *UCS* = 2250 kPa |
| Sharma and Hymavathi (2016) | CH, *LL* = 51%, *PI* = 28%, *CBR*s = 1.61% | *CBR*s | 4 | L | 84.1 | 4 | *CBR*s= 12.7% | Lime was more effective than FFA in improving *CBR*s of soil due to its higher CaO content |
| FFA | 2.3 | 16 | *CBR*s= 3.22% |
| Phanikumar (2009) | CH, *LL* = 100%, *PI* = 73%, *SP* = 26.7% | *SP* | 0 | L |  | 4 | *SP* = 3% | Lime was more effective than FFA in reducing *CBR*s of soil |
| FFA | 1.02-3.39 | 20 | *SP* = 8.9% |
| Mahedi et al. (2020) | CH, *LL* = 74%, *PI* = 49%, *UCS* = 221.2 kPa | *UCS* | 7, 28 | L | 74 | 7 | *UCS*7 d= 1003.5 kPa, *UCS*28 d = 1615 kPa | C3S content of cement being high (66%), *UCS* at early curing was high. C2S content of cement being low (6%), effect of curing on *UCS* was less |
| C (Type-I/II) | 64.4 | 16 | *UCS*7 d = 1302.8 kPa |
| 6 | *UCS*28 d = 1157.5 kPa |
| CFA | 26.2 | 20 | *UCS*7 d = 770.25 kPa  *UCS*28 d = 880.3 kPa |
| Al-Rawas et al. (2005) | CH, *LL* = 50%, *PI* = 20%, *S* = 249 kPa | *S* |  | L |  | 6 | *S* = 0 kPa | Lime was more effective in reducing swelling pressure than cement |
| C(Type-I) |  | 9\* | *S* = 92 kPa |
| Solanki et al. (2010) | CH, *LL* = 58%, PI = 29%, *M*r = 162 MPa | *M*r | 28 | HL | 68.6 | 6 | *M*r=678 MPa | Lime showed greater improvement in *M*r than FFA |
| CFA | 24.4 | 15\* | *M*r=388 MPa |
| Cheshomi et al. 2017) | CH, *LL* = 120%, *PI* = 84.1%, sulfate = 2.45%, *S* = 9.9 kPa | *S* |  | HL | 66.7 | 7\* | *S* = 15.4 kPa | FFA-treated soil shows less swelling pressure of sulfate-bearing clay compared to hydrated lime |
| FFA | 1.13 | 7\* | *S* = 6 kPa |
| Solanki et al. (2009b) | CL, *LL* = 37%, *PI* = 11%, sulfate = 15,400 ppm | *LL* | 28 | HL | 68.6 | 6 | *LL* = 51% | FFA contains less CaO, ettringite formation was less, therefore the rise in *LL* was more |
| CFA | 24.4 | 15 | *LL* = 39% |
| Hoyos et al. (2006) | CH, *LL* = 74%, *PI* = 45%, sulfate = 33,048 ppm | Retained *UCS* after 32 W-D cycles | 7 | C (Type-V) | 62.6 | 10\* | *UCS* = 2143 kPa | Performance of sulfate resisting cement (Type-V) was better than FFA for sulphate-rich soil exposed to W-D cycles |
| FFA | 1.1 | 20\* | *UCS* = 213.2 kPa |
| Saride et al. (2013) | CH, *LL* = 59%, *PI* = 38%, organic content = 6.1% | *LL*, *PI* |  | L |  | 8 | *LL* = 58%, *PI* = 30% | Increase in *LL* of cement-treated organic clay was more |
| C (Type-I) |  | 6.5 | *LL* = 64%, *PI* = 34% |
| Pedarla et al. (2011) | CH, *LL* = 56%, *PI* = 37%, *UCS* = 289.5 kPa | Retained *UCS* after 21 W-D cycles | 3 | L |  | 8 | *UCS* = 137.9 kPa | Cement-stabilized soil was more durable against W-D cycles |
| C (Type-I/II) |  | 6 | *UCS* = 172.4 kPa |
| Zhang et al. (2016) | CL, *LL* = 33%, *PI* = 15%, *CBR* = 2.8% | Retained *CBR* after 2 F-T cycles | 7 | CFA | 25.3 | 20\* | *CBR* = 17.9% | Cement-stabilized soil showed negligible frost susceptibility, but CFA-treated soil exhibited low frost susceptibility |
| C (Type II) |  | 10\* | *CBR* ˃ 200% |
| Wang et al. (2018) | MH, *LL* = 76.1%, *PI* = 40.8%, *UCS* = 530 kPa | Retained *UCS* after 20 F-T cycles | 28 | L | ≥90 | 6 | *UCS* = 615.5 kPa | Cement-stabilized soil was more durable against F-T cycles |
| C (Type-I/II) | 63.3 | 9\* | *UCS* = 1656.4 kPa |

Note: CH: high plasticity clay; CL: low plasticity clay; MH: high plasticity silt; L: quicklime; HL: hydrated lime; C: cement; *S*: swelling pressure; *SP*: swelling potential; *CBR*s: soaked CBR; \* maximum dosage used; \*\* type of cement was not mentioned in the corresponding literature.

**Table A3.** Influence of additives (individual and combined) on performance of clays.

|  |  |  |  |
| --- | --- | --- | --- |
| Source | Untreated soil | Additive | Effect |
| Sirivitmaitrie et al. (2011) | *UCS* = 87 kPa | 4% L | *UCS*7 = 1395 kPa |
| 4% L + 4% C | *UCS*7*=* 1730 kPa |
| Zha et al. (2008) | *S* = 240 kPa | 3% L | *SP* = 240 kPa |
| 3% L + 15% FA | *SP* = 85 kPa |
| Indraratna et al. (1995) | *σ*′p = 80 kPa | 5% C | *σ*′p = 150 kPa |
| 5% C +25% FA | *σ*′p = 300 kPa |
| Wang et al. (2013) | *UCS* = 500 kPa | 3% L | *UCS*28*=* 750 kPa |
| 3% L + 3% FA | *UCS*28*=* 950 kPa |
| Kolias et al. (2005) | *UCS* = 200 kPa | 10% FA | *UCS*90= 1800 kPa |
| 3.66% L | *UCS*90= 650 kPa |
| 10 FA + 4% L | *UCS*90= 2500 kPa |
| Sharma et al. (2012) | *UCS* = 24.73 kPa | 20% FA | *UCS* = 63.38 kPa |
| 20% FA + 8.5 % L | *UCS* = 105.2 kPa |
| Shafiqu and Abass (2018) | *S* = 199.85 kPa | 9% L | *SP =* 174.52 kPa |
| 16% CKD | *SP =* 147.42 kPa |
| 9% L + 16 % CKD | *SP =* 74.93 kPa |
| James et al. (2008) |  | 5% L | *UCS*28=33 kPa |
| 5% L + 25% GGBS | *UCS*28=1917 kPa |
| Celik and Nalbantoglu (2013) | *SP* = 3% | 5% L | *SP*′= 0.5% |
| 5% L + 10,000 ppm Na2SO4 | *SP*′= 8% |
| 5% L + 10,000 ppm Na2SO4 + 6% GGBS | *SP*′*=* 1% |
| McCarthy et al. (2014) | *UCS* = 400 kPa | 3% L | *UCS*90 = 1100 kPa |
| 3% L + 24% FA | *UCS90*= 2200 kPa |
| 3% L + 9% GGBS | *UCS*90 = 1800 kPa |
| Horpibulsuk et al. (2013) | *UCS* = 1100 kPa | 10% CCR | *UCS*90 = 9000 kPa |
| 10% CCR+ 21% FA | *UCS*90 = 20,000 kPa |
| Koslanant et al. (2006) |  | 10% L | *UCS*28=100 kPa |
| 10% L+ 10% NaCl | *UCS*28=1295 kPa |
| Eujine et al. (2017) | *CBR* = 3.6% | 0·059 mL/kg E | *CBR*28 *=*13.2% |
| 3% L | *CBR*28 *=* 16% |
| 0·059 mL/kg E + 3% L | *CBR*28 *=* 19.6% |
| Thomas and Rangaswamy (2021) | *UCS* = 28 kPa | 0.06 mL/kg E | *UCS*28=104 kPa |
| 0.06 mL/kg E + 1% C | *UCS*28=354.07 kPa |
| Thomas and Rangaswamy (2020) | *UCS* = 28 kPa | 0.06 mL/kg E + 1% C | *UCS*28=127.1 kPa |
| 0.75% NS +1% C | *UCS*28=161.1 kPa |
| 0.06 mL/kg E + 1% C + 0.75% NS | *UCS*28=206.1 kPa |

Note: E: enzyme; NS: nano-silica; *σ*′p*:* pre-consolidation pressure; *S*: swelling pressure; *SP*: swelling potential; *CBR*28: CBR after 28 d of curing; *UCSx*: UCS after *x* days of curing.

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