For DSM Binders, Cementations, Pozzolanic, and Filler Materials

[1]**AMARESH SATAPATHY,** Gandhi Institute of Excellent Technocrats, Bhubaneswar, India
[2]**SK ABDUL IMRAN,** Rayagada Institute of Technology and Management, Rayagada, Odisha, India

Abstract

Deep Soil Mix (DSM) is a demonstrated technique for ground improvement for more profound basic delicate soil layers which are in any case unreasonable to arrive at utilizing ordinary shallow soil adjustment and substitution strategies. The overwhelming fastener materials utilized are Ordinary Portland concrete (OPC) and Lime (CaO) however negative impacts to the earth from fabricate and expanding development cost have provoked examination into elective materials. This survey distinguishes pozzolans and filler materials as potential enhancements or fractional substitutes for better outcomes. The DSM technique and cover response forms during rewarded soil quality advancement are laid out and viability of various pozzolans (Fly Ash, Silica Fume, Ground Granulated Blast Furnace Slag, Rice Husk Ash, Kaolin, and Metakaolin) and filler materials (for example fine sand) talked about along with their impact factors. With numerous pozzolans, a reasonable ideal dose is seen where improved quality pinnacles. Aluminosilicate pozzolans perform better over siliceous pozzolans with Metakaolin (MK) distinguished as the best pozzolan for improving compressive quality. Forward-thinking research results on these materials are aggregated. MK mixed concretes are promptly accessible and can be promptly applied for beginning field tests. Rewarded soil quality might be managed with expansion of filler materials to additionally decrease dependence on concrete.

Keywords: Ground Improvement; Lime; Ordinary Portland Cement; Pozzolans; Deep Soil Mix.

I. INTRODUCTION

Construction in soft soil conditions require either wide footprint or deep foundations to support the overlying structure without soil shear failure or excessive settlement. Highly developed areas for infrastructure, residential, commercial and industry often encounter soft soil conditions (peat / clay / silt in river deltas, flood plains and alluvial plains etc.).

A viable alternative engineering solution is through ground improvement. The properties of the underlying soil are improved to satisfactorily support the imposed bearing pressure from the structure above. The soil properties can be enhanced by 1) full or partial replacement with stronger materials – e.g. geo-textiles, fibrous materials, etc.; 2) adding binder materials that will react with the soil to strengthen it – e.g. soil stabilization, soil reinforcement, etc.; or 3) modifying the existing consistency of the soil – e.g. pre-loading, electro-kinetic stabilization, etc.

The Deep Soil Mix (DSM) method applies soil stabilization principles, which comprises the addition and mixing of binder materials with the soil as stabilizing agents and other filler materials in the form of columns into the soil stratum. Presently, the pre-dominant binder materials utilized are cement and lime. These are classified as traditional cementitious / hydraulic binder materials.

However, industrial production of cement releases significant carbon dioxide (CO_2) (about 7% global man-made CO_2 emissions [1]) to the atmosphere which contributes to the climate change effect. Likewise, CO_2 is also a by-product when producing quicklime (CaO). Production of both materials is also energy intensive. Hence, there is incentive to research new alternative replacement materials that offer similar or better ground improvement performance but with less environmental, energy impact and financial cost. Pozzolanic and filler materials have been applied successfully to improve concrete properties and researched for soil stabilization. This paper briefly explains the reaction processes and discusses their applicability to supplement or improve performance of traditional binders in the case of DSM.

II. DEEP SOIL MIX (DSM)

In DSM, specialized equipment auger to depth, and inject binder material / filler material which reacts with the existing soil to form columns of improved soil. The primary objective of deep mixing is to produce a stabilized soil mass consisting of a group of soil-stabilized columns. In contrast, conventional soil stabilization involves applying and mixing stabilizing agents at shallow depth or excavated layer of soil. DSM has been applied in soft ground conditions such as marine clay, alluvial deposits, organic soils and peat. The deep mixing method has been developed and practiced primarily in Japan and Scandinavian countries since the 1980s as well as in the USA and central Europe since the 1990s.

Column installation in DSM may either be 1) Wet mixed (WDSM) or 2) Dry mixed (DDSM). For a wet mixing method, the binding agent is turned into wet slurry form and pressure injected into the soil through nozzles located at the end of a specialized soil auger. Column depths of 45m with 0.5 to 0.9m diameters have been achieved with column compressive strengths ranging from 1.5 to 4 MPa [2]. For the dry mixing method (considered more economical than WDSM), the dry binder is injected (using compressed air) into the soil at depth and thoroughly mixed with moist soil. The soil is pre-mixed using a specialized tool during the downward penetration of the auger until the targeted depth is reached. As the mixing tool is withdrawn, the dry binder is injected and mixed with the soil – forming a moist soil mix column. Typical column diameters range from 0.6 to 0.8m with depths of 25-30m. Design compressive strength is from 150 to 500 kPa [2].

The effectiveness and selection of which DSM installation method is dependent on moisture content of the soil layer. Generally, DDSM techniques achieve less strength for the same soil type than WDSM. WDSM is suitable for soft clays, silts, fine-grained sands with lower water content, and multiple interbedded soft and stiff /dense soil layers. DDSM is more appropriate for soft soils with high moisture content, organic soils and sludges [3].

Table 1. Some field case studies of cement treated DSM

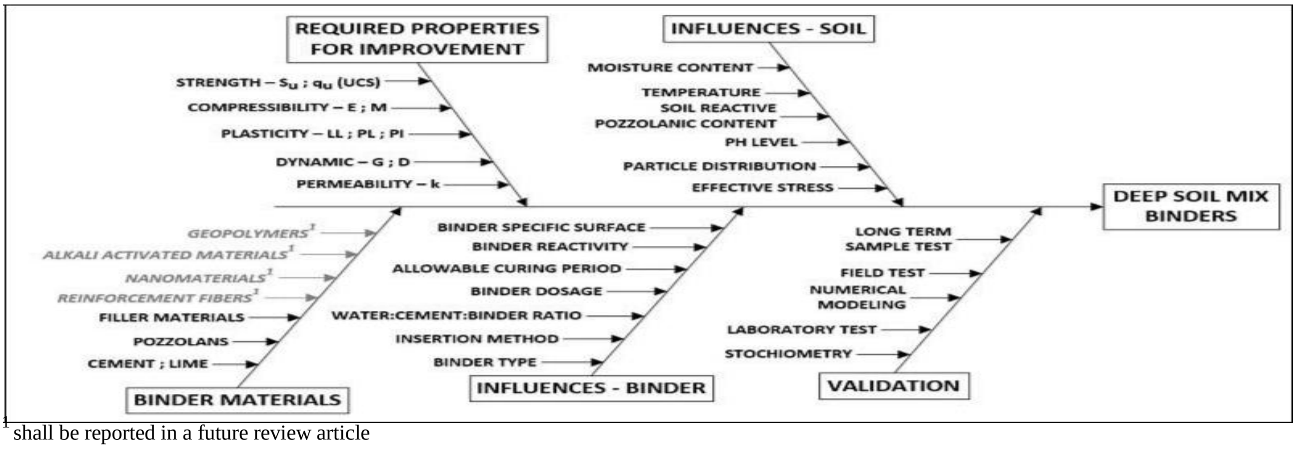
Research	Location	Method	Soil	Binder (kg/m^3)	Cement type	Actual UCS (MPa)
[4]	Japan	DDSM	Clay	130 – 290	Blast Furnace Slag Cement Type B	0.2 – 0.5 (28 d) 1.8 – 4.2 (17 yrs.)
[5]	S. Korea	WDSM	Clay (marine)	270	GGBS cement	1.1 @ 2m depth – 5.1 @ 15m depth (28 d)
[6]	USA	WDSM	Residual	Not stated	Not stated	0.69 design / 1.5 avg. (28 d)
[7]	Singapore	WDSM	Clay	280	OPC	1.7 mean
[8]	Vietnam	WDSM	Clay	200 – 240	Tower (60%) slag cement Stable soil cement	2 @ 3m depth – 3.4 @ 12m depth (28 d)

III. REQUIRED PROPERTIES FOR DSM

For DSM, the binders would seek to improve the following treated soil properties:

- Strength – cohesion (c) and internal angle of friction (φ) which determines both shear strength (s) and compressive strength (q);
- Compressibility – Youngs Modulus (E) and Constrained Modulus (M) which determines settlement behaviour;
- Plasticity – Atterberg limits which determines the critical stages of fine-grained soil state and behaviour;
- Dynamic – Shear Modulus (G) and Damping Ratio (D) which affects resistance to liquefaction and soil structure interaction (SSI) effects when dynamic loading conditions occur.

- Binder type and insertion methods – WDSM in jetted slurry form / DDSM by compressed air;
- Mixing methods – binder mix consistency with the soil;
- Binder dosage applied (higher dosage up to an optimum level lead to greater strength);
- Type and content of reactive pozzolanic material in soil – i.e. silica / aluminate material in the soil. High organic matter content in soils like peat can retard cementitious reaction process. Pozzolanic reactions will not initiate or be effective if there are insufficient reactive silica or aluminates;
- Soil temperature & pH – higher temperature increases rate of reaction. High acidity inhibits reaction rate;
- Allowable curing period – strength increases with curing time;
- Specific surface of binder particle – A higher specific surface causes faster reaction to take place (where smaller particles have a higher specific surface).



[1] shall be reported in a future review article

Figure 1. DSM Binders methodology

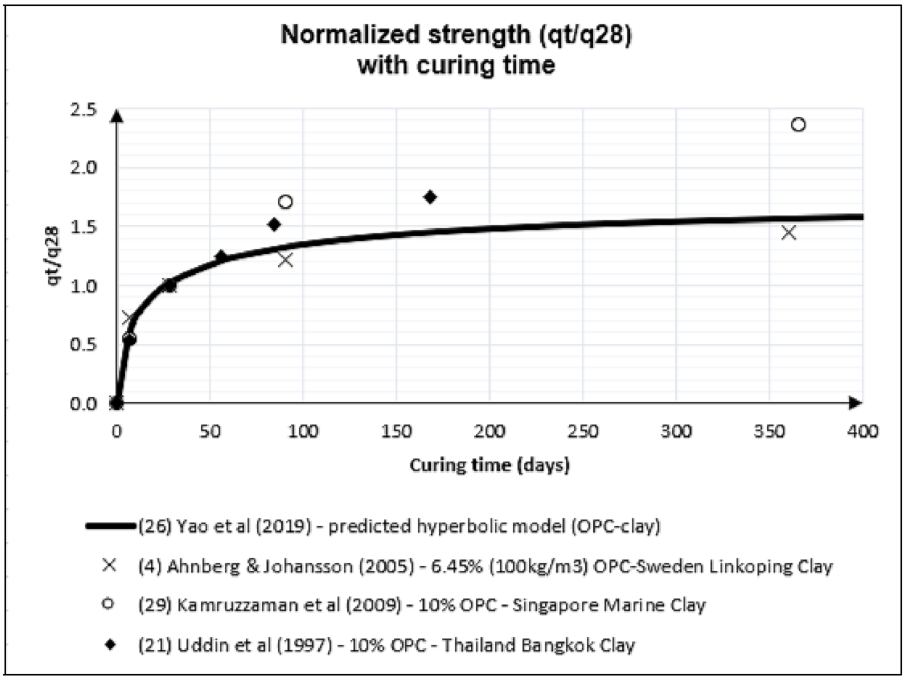


Figure 2. Normalized Strength (qt/q28) development with curing time

IV. TRADITIONAL BINDER MATERIALS

4.1. Reaction Mechanism

Traditional cementitious binder materials, OPC, lime or a combined mixture of both materials are still the most commonly used in DSM. Lime, in the form of calcium oxide (CaO), is derived from crushing and heating limestone ($CaCO_3$) at over 1000 C^{O}. When added to soil, CaO undergoes a calcareous reaction with the water content in soil to form slaked lime or hydrated lime, otherwise known as calcium hydroxide ($Ca(OH)_2$) [9]. Combining with water in soil results in hydration which reduces the water content in the soil which leads to better soil stability. Strength development is derived from secondary reactions between any pozzolanic materials mixed with lime or as particles in the soil. These secondary pozzolanic reactions form C-S-H, C-A-H and C-A-S-H which are the main contributing components to strength gain. Other benefits of lime binders come from the heat release from exothermic CaO / H_2O reaction of CaO and increase in pH due to Ca $(OH)_2$ formed which improves the pozzolanic reaction rate.

Cement (OPC) reacts hydraulically with water to form a paste which binds the soil and other binder particles together into a hardened mass. Strength development comes from formation of C-S-H and C-A-H due to reaction of C_3S, C_2S and C_3A components of cement with water.

4.2. Lime Binders

Lime as a binder in stabilization has been used in deep soil mixed columns for loose clays, silts and peat soils since the 1970s in Scandinavia. Undrained shear strengths for stabilized clay under favorable conditions of 10 to 50 times original soil strength have been recorded after one year [10, 11]. Studies were also conducted on the engineering characteristics of lime stabilized organic soils [12] and design principles for stabilization using lime columns have been established [10]. Lime neutralizes the acidity of organic matter in soils and improves soil plasticity and shear strength. However, strength development in lime columns is still susceptible to several factors:

- Soil temperature – lower temperatures slows the reaction considerably;
- Low pH in soil retards reaction and leads to long-term deterioration of the soil-lime column;
- Sulphate content – high soil sulphate content interferes with normal pozzolanic reactions between lime and any pozzolanic particles in the soil. This is similar to cementitious hydraulic reactions when low-density ettringite forms in the presence of sulphate ions leading to expansion and cracking in the brittle soil-lime soil mix [13].

Table 2. Reaction mechanism of cementitious binders in soil

Binder Type	Binder Component	Binder comp. % (wt. binder)	Reaction Equation	Reaction time	Effect
	C_3S	55	$2C_3S + 7H \rightarrow C_3S_2H_4 + 3CH$	rapid	Early strength gain
	C_2S	18	$2C_2S + 5H \rightarrow C_3S_2H_4 + CH$	slow	Long term strength gain

Cement	C_3A	10	$2C_3A + 21H \rightarrow C_4AH_{19} + C_2AH_8 \rightarrow 2C_3AH_6 + 9H$	rapid	Early set (hardening)
	$C_3A + (C\bar{S}H_2)$		$2C_3A + 3C\bar{S}H_2 + 26H \rightarrow C_6A\bar{S}_3H_{32}$	rapid	Slows down set reaction of C_3S, C_2S
	$C_4AF + (C\bar{S}H_2)$	8	[illegible] 2 AFm, t	slow	slows down set reaction of C_3S, C_2S
Lime	CaO	100	$CaO + H_2O \rightarrow Ca(OH)_2$	rapid	increases pH to ~ 12.5; reduce water content in soil
		N/A	$Ca(OH)_2$ + pozzolans in soil + H2O → C-S-H and/or C-A-S-H	slow	Long term strength gain

1 Adapted from Ahnberg and Johansson (2005)

2 CaO =Calcium Oxide ; $Ca(OH)_2$ = Calcium Hydroxide ; CH = Calcium Hydrate ; C-A-S-H = Calcium Aluminate Silicate Hydrate (ettringite) ; C-S-H = Calcium Silicate Hydrate ($C_3S_2H_4$) ; C-A-H = Calcium Aluminate Hydrate ; AFm,t = Alumino Ferrite mono and tri phases; C_3S = Tricalcium Silicate ; C_2S = Dicalcium Silicate ; C_3A = Tricalcium Aluminate ; C_4AF = Tetra calcium Alumino Ferrite ; Gypsum = $C\bar{S}H_2$

4.3. Cement Binders

Cement has been the most researched and widely utilized binder material for deep soil mixing. Deep cement columns in Japan have typically achieved over 1 MPa UCS by wet method installation and typically, 500 kPa by dry method installation methods [14]. Cement offers greater soil mechanical improvement (shear strength and compressibility) over lime [9, 15]. The design methodology for combined lime/cement and cement columns have been developed for soft clays [16, 17].

For peat soil, the application of deep soil mix columns was investigated with a series of simple scale models in the field [18–20]. Huat et al. [21] conducted a series of tests on various proportions of cement and lime binders on peat soil, showing increasing strength improvement in the order of 2 to 3 times as binder % increases. The implementation of deep mixed methods cement columns in peat soils was also studied in the lab by a series of Rowe cell tests [22]. In soft organic soils (e.g. peat), the organic matter in the soil inhibited cementitious reaction [23]. Research by Hebib and Farrell [24] supported the finding that the combination of high organic content, lack of solid and pozzolanic particles, acidic media (from humic acid) and high water: solids ratio all seek to impede efficient hydration of cement in peat soils.Investigation of the influence of cement binder dosage [25, 26] showed an increase in cement ratio leads to improved compressibility characteristics of soft clay and peat soil.

Longer curing periods also lead to greater strength development in cement-treated soil. Logarithmic models were widely used to predict strength gain over time [4, 27]. A shortcoming of a logarithmic model was that it implied indefinite strength increase with time. Logically, cement hydration should cease when reaction products are consumed. This led to an improved hyperbolic function model on strength development over time [28, 29].

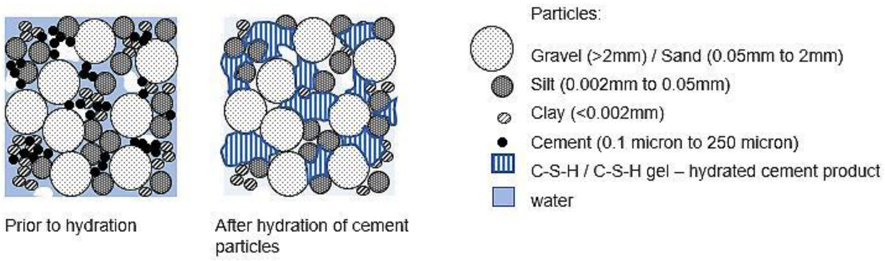


Figure 3. Structure of soil prior and after hydration/ curing of cement binder

V. POZZOLANIC BINDER MATERIALS

5.1. Reaction Mechanism

Pozzolans, are defined as "siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties" [30]. The chemical reaction between these siliceous and/or siliceous-alumina rich components, calcium hydroxide and water, is called the pozzolanic reaction. Also known as supplementary cementitious materials (SCM), pozzolans can act as a beneficial additive to cement with various performance enhancing effects for soil stabilization. Pozzolans can be categorized as:

- Natural Pozzolans – either of volcanic (unaltered pyroclastic materials e.g. vitreous pumices / ashes or altered pyroclastic materials like zeolitized tuffs etc.) or sedimentary origin (e.g. chemical sediments e.g. diatomaceous earth or detrital sediments e.g. clays, shales etc.);
- Artificial Pozzolans – e.g. Blast Furnace slag (GGBS), Fly Ash (FA), Silica Fume (SF) and burned organic matter residue with significant siliceous/aluminous materials – e.g. Rice Husk Ash (RHA).

Cementitious hydration, as mentioned earlier, not only produces Calcium Silica Hydrate (C-S-H) but also, as a by-product, Ca $(OH)_2$ (up to 25% of hydrated Portland cement). The dissolved SiO_2 (combined with water to form silicic acid ,H_4SiO_4) and Al_2O_3 in pozzolans react with dissolved Ca^{2+} and $(OH)^-$ ions from the $Ca(OH)_2$ to produce both C-S-H and Calcium Aluminate Hydrate C-A-H [31].

$$Ca^{2+} + 2(OH)^- + SiO_2(\text{in pozzolans}) \rightarrow \text{C-S-H} \quad (1)$$

$$Ca^{2+} + 2(OH)^- + Al_2O_3(\text{in pozzolans}) \rightarrow \text{C-A-H} \quad (2)$$

A similar mechanism that may reside for pozzolans in soils occurs when lime / cement is added. The derived $Ca(OH)_2$ is transported via water within the soil to combine with aluminate and/or silicate clay minerals in the soil [32]. However, enough free calcium ions and a pH level above 12 is needed (to maintain solubility of silicon and aluminium ions) to initiate and maintain the pozzolanic reaction [33]. This can be provided from Ca $(OH)_2$ that is derived from addition of either lime or cement.

Field test results from DSM samples [4, 34] and laboratory results from cement-treated soil [27] show significant long-term strength gain (up to 2.1 strength increase over 28 day strengths) well beyond the short term cement hydration phase [35]. This long term strength gain has been attributed to secondary pozzolanic reactions taking place in the soil as a result of the right conditions from cement hydration – e.g. high pH, presence of Ca^{2+} ions / $(OH)^-$ ions and pozzolanic materials in the soil [36, 37].

Pozzolanic reactions occur over longer timescales (months to years) [9, 31]. Correia et al. [38] proposed a simplified method to predict the UCS at 28 days for cement and pozzolanic stabilized clays based on soil liquidity index, specific binder type and content. The effectiveness of pozzolans (reaction and strength) is related to:

- Reactivity with lime (CaO) – The reactivity of mineral admixtures reactivity of the pozzolanic materials can be determined by the Chapelle (which determines the rate of lime (CaO) consumption) or similar tests [39];
- The proportions of the pozzolan phase state (crystalline / vitreous or amorphous) which affects strength [9, 40] – higher amorphousness leads to greater reactivity. Reactivity-based on lime consumption per mass of the amorphous phase of pozzolans using Reitveld refinement method of XRD analysis interpretation allows consideration of vitreous or amorphous phase in the pozzolanic material and more accurate determination of the effectiveness of a pozzolan [41].
- The particle size and associated specific surface of the pozzolan which affects reactivity [40] – the higher the specific surface, the greater the reactivity.

Table 3. Mineral composition of various pozzolanic materials

Binder	Mineralogy (%)					
	CaO	**Al_2O_3**	**SiO_2**	**MgO**	**Fe_2O_3**	**Others**
OPC [3]	67.7	2.8	20.4	1.4	4.6	2.9
Lime (CaO)	100.0	0.0	0.0	0.0	0.0	0.0
FA - Class C [2]	14.8	25.5	47.4	2.7	0.0	9.6
FA - Class F [2]	2.4	26.7	54.5	1.1	6.9	8.5
GGBS[2]	42.0	11.6	35.4	8.0	2.6	0.4
SF	1.0	2.0	90.0	1.5	0.0	5.5
RHA[3]	0.0	0.0	99.0	0.0	0.7	0.3
K[1]	0.3	37.8	57.6	0.6	0.9	2.8
MK[3]	0.0	38.6	53.9	1.0	1.4	5.2

Others include: SO_3, Na_2O, K_2O, TiO_2, MnO_2 etc.
Values obtained from: [1] [42]; [2] [43]; [3] [44] (Table 1).

Table 4. Typical Particle size / Specific Surface of various pozzolanic materials

Physical Property	Binder Type							
	OPC [2]	**CaO [3]**	**FA[2]**	**GGBS [2]**	**SF [2]**	**RHA [2]**	**K**	**MK [2]**
Particle size range (µm)	10–40	> 740	≤ 45	20 – 250	0.1	11.5 – 31.3	25 – 35[4]	0.5 – 20
Specific Surface (m^2/g)	1.75 BET	N/A	5 – 9 BET	0.4 – 0.6 BET	16.45 BET	30.4 – 27.4 BET	18.2[1]	12.174 BET

Values obtained from: [1] [45] Fadzil et al. 2017 - Table 2; [2] [44] Khan et al. 2014 - Table 1; [3] Quicklime for Soil stabilization ASTM C977; [4] [42] Yahaya et al. - 2017.

5.2. Fly Ash (FA)

Fly Ash (also known as "pulverized fuel ash", PFA or FA) is residue composed of pulverized coal, discharged from the combustion chamber by exhaust gases in coal-fired power plants. There are two classes of fly ash:

Table 7. Chemical content of different Fly ash classes [58]

FA Class	**Typical percentages, %**					
	CaO	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**LOI**	**sulphates**
F (anthracite | bituminous)	1–12	20–60	5–35	10–40	0–15	0 – 4
C (sub-bituminous)	5–30	40–60	20–30	4–10	0 – 3	0 – 2
C (lignite)	15–40	15–45	20–25	4–15	0 – 5	0–10

Class F FA requires an activator or cementing agent (as it contains less lime (CaO) content) mixed with water. It can form a geopolymer by combining with sodium silicate/ sodium hydroxide [59]. When utilized to stabilize soft organic soils, the addition of fly ash increases soil resilient modulus (Mr) from zero Mr without a binder to 10-100 MPa depending on % of binder used and improves unconfined compressive strength (UCS) from original untreated at 15 kPa to > 100 kPa with fly ash [60]. Similarly, for tropical peat soils, the mixing of Pond Ash (PA) binder also increases UCS. 20% PA dosage lead to doubling UCS of the original peat soil [61,62].

Significant properties enhancements were reported for fly ash binders of organic (36.9% organic content) soil from Khulna, Bangladesh, notably in the liquid (LL) and plastic limits (PL) as well as dry density leading to increased UCS [63]. Two types of Fly Ash – Class C and Class F (ASTM C 618-2017a), were tested whereby, Class C fly ash achieved noticeable higher strength gains over Class F type. Stabilized soil pH values also increased because of binder mixing.

Research	Soil Type / soil properties	Pozzolan binder	Cementitious binder	Findings	Proportion / improved Properties (% / kg/m^3 soil)	UCS[1] (kPa)
[46]	• Peat • Gyttja	• Fly Ash (F1); • GGBS; • Sand (FS); @ (50:50 / 60:40 for cement: pozzolan) % wt. binder	• OPC; • Lime; @ 100–250 kg/m^3	• Best results obtained with GGBS and bypass ash (F1) • Less clay particles in peat → no significant pozzolanic reaction • OPC more effective than lime in peat soils due to humic acids • Addition of sand filler acts as stiffener • High silica % contributes to pozzolanic reaction	• 200 kg/m^3 OPC / FA OPC: F1=50:50 • 200 kg/m^3 OPC / GGBS OPC: GGBS=50:50 • 200 kg/m^3 OPC / 100 kg/m^3 FS • 300 kg/m^3 OPC	382 (26 d) 1340 (30 d) 792 (30 d) 1250 (30 d)
[47]	• silty, sandy peat (Pt) q=15 kPa • Org. sandy lay (OL) q=57 kPa • Org. clay (ML) q=36 kPa	• Fly Ash (FA-F) (55% SiO_2 / 9% CaO); • Fly Ash FA-C (40% SiO_2 / 24% CaO); @ 10–30 % wt. soil	-	• 6 sources of Fly Ash binders with varying CaO: SiO_2 ratios tested • Clay soils (OL + ML) <30 kPa untreated to > 400 kPa (30% FA) • Peat soil (Pt) from <15 kPa untreated to > 100 kPa (30% FA). Higher SiO_2 % leads to higher UCS • Optimum water content (OWC) applies for different soils / binders • Optimum CaO / SiO2 ratio established at 0.5 - 0.8	• 30% FA / OWC=47% CaO: SiO_2=21.3:40.2 • 30% FA/ OWC=28% CaO: SiO_2=23.3:31.1 • 30% FA / OWC=21% CaO: SiO_2=21.3:40.2	148 (7 d) 411 (7 d) 490 (7 d)
[48]	• Clay (PH) PI=54% FSI=154% q=169 kPa	• GGBS; @ 0–15 % wt. soil	• OPC; @ 0–15 % wt. soil	• MDD, UCS increase as binder % increase • FSI, LL, PI decrease as binder % increase • For UCS, optimum at 10% GGBS	• 15% OPC PI=32% | FSI=100% • 10% GGBS PI=43% | FSI=105%	1861 (28 d) 779 (28 d)
[49]	• Peat q=28.5 kPa CBR=0.78%	• Silica Fume (SF) @ 5–10 % wt. OPC	• OPC; @ 5–50 % wt. soil	• UCS and CBR measured • For 5-15% cement, 10% dose SF → higher UCS • For 20-50% cement, 5% SF → higher UCS • CBR increases as binder content increases	• 5% OPC / 10% SF CBR=21.4% • 50% OPC / 5% SF CBR=21.4%	320 (90 d) 620 (90 d)
[50]	• Peat q=29.5 kPa c=0.01 kPa φ=10	• Silica Fume (SF) @ 5–10 % wt. OPC	• OPC; @ 5–50 % wt. soil	• c and ϕ increases as binder % increases • Settlement reduced by 35% with 5% cement • Presence of any type of small particle (known as particle packing or micro filling) will improve the strength in the presence of cement	• 15% OPC c=250 kPa / φ = 22 • 15% OPC / 10% SF c=280 kPa / φ = 26	N/A N/A

Table 5. Summary of some research on pozzolanic binders – Fly Ash (FA) / Ground Granulated Blast Slag (GGBS) / Silica Fume (SF)

Table 6. Summary of some research on pozzolanic binders – Rice Husk Ash (RHA) / Kaolin (K) / Metakaolin (MK)

Research	Soil Type / soil properties	Pozzolan binder	Cementitious binder	Findings	Propor tion / improved Properties (% / kg/m^3 soil)	UCS[1] (kPA)
				• UCS and CBR increase as binder	• 4% OPC / 5% RHA	

[51]	• Residual q=100 kPa CBR=3.8%	• RHA @ 0–25% wt. OPC	• OPC; @ 0–14 % wt. soil	increases • RHA addition requires less cement to achieve same UCS compared to only cement-stabilized soils. RHA cannot be used by itself to increase UCS • RHA increases resistance to reduced UCS when soaked - optimum binder content at 10% RHA	Optimum for CBR CBR=60% • 8% OPC / 28% RHA Optimum for UCS	N/A 1200 (7 d)
[52]	• Clay (CI) q=130 kPa CBR=2.6% (soaked)	• RHA @ 0–20% wt. soil	–	• PI reduces as % RHA increases • For UCS, optimum at 5% RHA • CBR (soaked) increases as binder content increases	• 5% RHA CBR=4.8% (soaked)	212 (28 d)
[53]	• Silty Clay (ML) c=35 kPa φ=35 CBR=8.9%	• RHA @ 3–7% wt. Lime	• Lime, Ca $(OH)_2$; @ 4, 6 % wt. soil	• LL / PL increases as % RHA increases • φ initially decreases as % RHA increases up to 3% • φ peaks at 5% RHA with 6% lime • c / CBR value peaks (>50%) at 5% RHA / 4% lime. • Best results achieved with 4% lime and 5% RHA	• 4% lime / 5% RHA c=168 kPa (28 d) φ = 49 | CBR=54% • 6% lime / 5% RHA c=161 kPAa (28 d) φ = 50 | CBR=51%	N/A N/A
[54]	• Silty Sand (SW-SM) q=8.2–15 kPa	• RHA @ 5–20% wt. Lime	• Lime CaO; @ 3, 5 % wt. Soil	• UCS Increases as % lime increases • UCS peaks (>50%) at 15–20% RHA with 5% lime thereafter decreases with as RHA % increases	• 5% lime / 5% RHA	250 (28 d)
[55]	• Peat	• Kaolin (K) @ 5, 10% wt. overall Binder • $CaCl_2$ @ 4% wt. Binder	• Total binder @ 300 kg/m^3 + Silica Sand @ 596 kg/m OPC @ 90% wt. total Binder	• UCS increases as binder dosage increases • Increasing silica sand as filler leads to UCS increase • Effect from hydraulic / pozzolanic and filler effects	• 90% OPC / 10% K + add. 4% $CaCl_2$ @ 300 kg/m^3 total binder	485 (7 d)
[56]	• Clay	• Metakaolin (MK) @ 3–10% wt. soil	• OPC @ 27–50% wt. soil	• UCS increases as MK / OPC dosage increases and is high enough to be considered as (soilcrete) structural material • Youngs modulus (E) improves also	• 27% OPC / 3% MK • 40% OPC / 10% MK	17 MPa (28 d) 57 MPa (28 d)
[57]	• Clay (CH)^2 c=94.76 kPa q=190 kPa	• Metakaolin (MK) @ 3–10% wt. soil	–	• MDD increase | OMC decreases as % MK increases • UCS peaks at 10% MK with 5% lime thereafter decreases with as MK % increases	• 10% MK c=315 kPa	630 (1 d) @ 2.8% strain

[1] extracted from Figures in articles; [2] prepared from Bentonite and sand mixture.

5.3. Ground Granulated Blast Slag (GGBS) or Slag

Slag, alternately known as Ground Granulated Blast Furnace Slag (GGBS or GGBFS) is formed as a by-product from iron production by quenching molten iron slag from a blast furnace to produce a glassy, granular material that is dried and ground into a fine powder. Chemical composition varies with the composition of raw materials in iron production and is mainly composed of – CaO [typically 30-50%]; SiO_2 [from 28-38%]; Al_2O_3 [8-24%] and MgO [between 1-18%]. Properties of GGBS when blended with cement and in soil stabilization [64] that are useful in DSM are:

- Lower early temperature rise – which reduces the risk of thermal cracking for mass pours;
- Reduced soil plasticity (lower PI) and quc increase in clays;
- Reduced risk of alkali-silica reaction (ASR) – a swelling reaction over time in concrete between highly alkaline cement paste and reactive non-crystalline (amorphous) silica in aggregates;
- Greater resistance to sulphate attacks and to chloride infiltration in cement-GGBS mix;

GGBS is considered a latent hydraulic material and requires activation (by hydraulic binder material like cement or lime or alternatively by using alkalis and sulphates) before it can react with water in the soil [9]. The reactivity of the GGBS also depends on its phase state which results from the rate of cooling after leaving the furnace. Rapid cooling leads to an amorphous, highly reactive slag while slow cooling would lead to crystalline inert slag, which is unsuitable as an additive for stabilization in deep soil mixing [9].

Typically, GGBS would be utilized as a partial substitute to a primary cementitious binder (e.g. OPC) with substitution ratios that have been researched from 75% OPC:25% GGBS to 50% OPC:50% GGBS for total dosages between 75 to 300 kg/m^3 [65, 66].

Studies on clay & silt in Sweden showed slower strength development with combinations of slag-cement-slag ratio binder mixes compared to cement alone [11]. This is due to the slower reaction of GGBS, which has a lower CaO/SiO_2 ratio to cement. Although better reaction product quantities from GGBS-lime mix vs GGBS-cement mix were reported, they were still inferior to lime-cement mix or lime binder in clay [11]. Comparison between cement and GGBS as binders to expansive clays showed that 10% GGBS (optimum) (779 kPa) achieved an equivalent 28 day UCS to 5% cement content (764 kPa) [48].

For peat soil, research results showed lower compressive strength at 7 days curing for 75% OPC:25% GGBS binder mix compared to 100% OPC binder mix with 25% silica sand [67]. Axelsson et al. [68] concluded that cement: GGBS binder mix provided better results for compressive strength than for cement binder alone in peat.

5.4. Silica Fume (SF)

Silica Fume (SF) is a pozzolanic by-product material derived from the production of silicon metal/ferro silicon alloys in smelters using electric arc furnaces – e.g. aluminium and steel production, computer chip fabrication plants, silicone production etc. SF typically consists of spherical particles with an average particle diameter of 150 nm and is typically 85-97 % SiO2 with less than 1% CaO.

Because of its chemical composition and fineness, SF only enhances the properties of concrete and is not meant as a replacement material for Portland cement such as Fly Ash or GGBS. The major improvement effect on fresh concrete is a more cohesive slurry mix leading to:

- Improved bond strength; little or no bleeding in the concrete;
- Reduced permeability which improves durability and resistance to chloride and sulphate attack;
- Enhanced UCS and E for the treated soil.

The small particle size of SF also leads to greater surface area and therefore allows the SiO_2 to react more readily with $Ca(OH)_2$ in the pozzolanic reaction to produce C-S-H, leading to improved strength properties.

Because it is not utilized as a replacement for cement, SF can only be considered as a minor additive to cement in soil stabilization. Typical SF content may range between 10 to 75 kg/m^3 or 4 - 15% of cement content by weight.

Research performed on cement with SF (5,10% by weight cement) on peat soil showed that the addition of SF has contributed to settlement reduction and increased bearing capacity [69, 70]. Optimum dosage up to 5% cement content in soil was achieved with 10% SF, thereafter, 5% SF by cement weight was more effective.

5.5. Rice Husk Ash (RHA)

Rice Husk Ash (RHA) is formed by burning, at a specific temperature range, rice hulls / husk which are separated from rice grains as a by-product in rice milling. About 10^8 tons of rice husk are generated annually in the world [71]. The ash residue from the combustion is a potential source of non-crystalline / amorphous reactive silica (of up to 95%)

[72]. Typical composition of RHA (depending on specific combustion conditions) can be 88 [39] – 99 % SiO_2 [73]. RHA has the highest specific surface area amongst the pozzolanic materials covered in this review [39].

Again, a small particle size leads to greater surface area and therefore allows improved reaction by SiO_2 with $Ca(OH)_2$ to produce strength enhancing C-S-H.

The type of RHA used is important – the amorphous form of SiO_2 has higher pozzolanic reactivity compared to the crystalline form of SiO_2 [74]. The composition of SiO_2 is dependent on the combustion process which leads to the structural transformation of the SiO_2 in the ash residue. High-temperature combustion produces more crystalline forms of SiO_2 as opposed to the low temperature combustion process. This can be differentiated through colour – high temperature ash (>900 ^{o}C) produces fully crystalline silica and is white / pink in colour whereas lower temperature ash (500-700 ^{o}C) is darker (grey to black) with more amorphous silica that is more reactive [75]. This is counteracted by less SiO_2 derived from lower furnace temperature furnaces vs higher furnace temperature. RHA with lower carbon content produces higher pozzolanic activity [76].

Basha et al. [77] tested the addition of RHA with cement binder on residual granite soil. Like SF, RHA cannot be utilized as a full replacement for cement but as a supplement to the cement to achieve multiplier effects on enhancing soil properties. This can be seen when RHA only treated soil encountered decreased CBR values with increasing % RHA vs increasing CBR with an increase in % cement.

RHA does not appear to improve all types of soils. Alhassan [71] utilized RHA as binder material sans cement for tests on ferruginous tropical soils and recorded insignificant bearing capacity improvement over original soil.

Research on clayey silt showed a 63% increase in compressive strength after 7 days curing over original soil with an optimum 15% by soil weight [78]. Choobbasti et al. [79] investigated the influence of RHA as an additive binder to slaked lime for silty clay soils and proposed an optimum mix of 4% lime and 5% RHA to maximize c & φ properties in the soil. Roy [80] recommended optimizing at 6% cement and 10% RHA for clay soils. Research by Rahman et al. [81] on the addition of RHA binder to silty sand, showed shear strength improving as RHA % increases.

5.6. Kaolin (K)

Kaolin (K), also known as china clay is a naturally occurring soft white clay of which the mineral kaolinite is obtained from. The chemical formula for Kaolinite is 2 2 5( ). Kaolinite is one of the most common minerals; it is mined in various countries throughout the world [82].

Chemical composition of Kaolin powder consists of 57.6% SiO2 | 37.8% Al2O3 | 0.9% Fe2O3 | 0.6% MgO being the main constituents [42]. Being both a siliceous and aluminous material, Kaolin is a partial pozzolanic additive for cement reacting to form C-S-H and C-A-H products [83].

Wong et al. [84] proposed kaolin mixed with lime / cement for use as partial replacement and pozzolanic additive in stabilized peat columns. Additionally, kaolin and silica sand (as a filler) on peat soils demonstrated combined action of hydrolysis of the cement, the pozzolanic reaction of kaolin, and the filler effect of well-graded silica sand in the soil.

5.7. Metakaolin (MK)

Metakaolin (MK), is produced by heating kaolin clay to high temperatures (calcination in the range starting from 700-850 ^{o}C) [85]. The chemical formula for Metakaolinite mineral (MK) is $_{2}$ $_{3}$. 2 $_{2}$[56]. Metakaolin (MK) powder chemical composition is similar to Kaolin at 53.2% $_{2}$| 43.9% $_{2}$ $_{3}$ | 0.38% $_{2}$ $_{3}$ | 0.02% CaO being the main constituents [86] depending on the supplier. Metakaolin has a specific surface of 12680 cm^2/g [86] which is almost 4 times greater than cement, and hence has greater reactivity.

Considered to have twice the reactivity of most other pozzolans, metakaolin is a valuable admixture for concrete/cement applications. When replacing Portland cement with 8–20% (by weight) metakaolin produces a concrete mix which exhibits favorable engineering properties that includes: the filler effect, the acceleration of OPC hydration, and the pozzolanic reaction. The filler effect is immediate, while the effect of pozzolanic reaction occurs between 3 and 14 days. Kolovos et al. [56] investigated soil-crete mixtures modified with metakaolin. MK addition to binder mix improved UCS significantly over just cement binder in clay through a reduction in porosity and microcracking and formation of dense cement gel.

VI. Filler Materials

6.1. Fine Sand

Fine sand acts as an inert filler and does not contribute to cement hydration or pozzolanic reactions. However, it provides a structure for the binder particles to attach to and form a load bearing stabilized soil and also contributes to densification by filling the void spaces in the soil during stabilization [55]. Tests with increasing sand content in highly compressible soil – e.g. peat, has shown improved settlement characteristics [87]. Wong et al. [88] researched the effect of Kaolin (as Supplementary Cementitious Material) and Silica sand (as a filler) on peat soils, Klang, Selangor whereby:

- An increase in silica sand (0 – 596 kg/m^3) led to increased UCS (from 175 kPa to 460 kPa);

- Threshold silica sand dosage of 460 kg/m^3 is suggested to achieve minimum UCS = 345 kPa;
- Increases density and reduces the porosity of stabilized soil;

However, the fine sand does not contribute to secondary pozzolanic reaction (with nano materials and cement) or geo-polymerization (with the right chemical additive), being non-crystalline (amorphous) silica.

VII. Discussion

Adding pozzolan materials to lime / cement binder mix can be effective when treating soils with little or no pozzolanic particles since follow on strength development (which may account for another 50-100% of 28-day strength) beyond short term hydration is due to pozzolanic reactions [37]. However, pozzolans are ineffective by themselves and require Ca $(OH)_2$ presence in aqueous solution to supply enough quantities of Ca^{2+} and OH^- for the pozzolanic reaction to take place. The Ca $(OH)_2$ is usually provided by a cementitious binder.
Pozzolans may be divided into two categories:

- Siliceous materials (> 90% SiO2) – e.g. RHA, SF, FA etc.;
- Aluminosilicate materials (with both SiO2 and Al2O3) – e.g. GGBS, K, MK.

From the compilation of research results for different pozzolan binders in Tables 5 and 6, there is a clear trend showing alumino silicate pozzolans producing greater compressive strength in combination with cementitious binders. The lower proportion of amorphous form of siliceous materials, which determines pozzolanic reactivity, also contributes to the disadvantage to alumino silicates.

Alumino silicate pozzolans exhibit higher initial rates of reaction over siliceous pozzolans due to Al_2O_3, which form C-A-S-H and C-A-H [86]. The greater specific surface area and smaller particle size of MK would lead to greater reaction rate over GGBS.

With pozzolans, there is an optimum dosage limit that applies, whereupon performance peaks. For example, the 10% optimum dosage by weight with MK has been observed in several researches [56, 57, 86] . This suggests a required concentration of Ca $(OH)_2$ greater than what is provided from the cement hydration, that must be maintained in relation to the pozzolan in order to retain rate of pozzolanic reaction. The effect from more Ca $(OH)_2$ in order to increase effectiveness of a higher pozzolan dosage limit by adding lime should be investigated further.

In terms of compressive strength improvement, the optimum dosage for some siliceous binder types (15 to 28% for RHA [54,77]) differ from aluminosilicate binders (5 to 10% replacement dosage for GGBS [48] and MK [56,57,86]). A comprehensive comparison of optimum dosage between the two groups of pozzolans when combined with cementitious binder for different soil types e.g. clay, silts, sands, organic soils etc. would be useful.

Frias and Cabrera [35] noted also that a higher water/binder (w/b) ratio may accelerate the completion of pozzolanic reaction for MK. Thus, the long term slow pozzolanic reaction beyond typical 28-day cement binder hydration may be accelerated with a combination of w/b ratio and use of MK blended-cement upon further investigation. It is noted that w/b ratios can only be controlled with the WDSM method.

The actual beneficial effect of filler materials has been sparsely researched. A good starting point would be applying research performed on effect of aggregate in concrete as a starting point to how filler materials can provide solid particles for binder paste to adhere to. Filler materials mixed with binders would be feasible if injected as a slurry in WDSM method for organic and very soft soils. They can act as economic inert substitutes when lower strengths are only required.

Finally, the influence of binders on dynamic properties of treated soil in context of DSM is not well covered in literature. As compressive strength, modulus of elasticity and shear modulus of soil are co-related, comprehensive investigation should be carried out to determine the extent of beneficial influence by binder treated soil when laid in DSM columns.

VIII. CONCLUSIONS

This review paper explains the reaction mechanism and compiles research results to date of cementitious and pozzolanic binders as well as filler materials. The following conclusions are made:

Cement is well established as the binder of choice in DSM ground improvement. Lime binders require further secondary reaction with any existing pozzolanic materials in the soil, hence it is not as effective in soils deficient in pozzolans. Strength development progresses, not to the same degree as for cement and take a longer time measured in weeks / months. With cement binders, increasing dosage leads to proportionate increase in treated soil strength gain.

With pozzolans, effectiveness depends on % and form of Si material (more reactive amorphous form vs. crystalline), binder particle surface area / fineness, pH level in the soil, presence of calcium (Ca) (since pozzolanic reactions are also calcium based like cement hydration), and enough quantity and distribution of the Si/Al/Ca components. Aluminosilicate pozzolans are more effective than siliceous pozzolans. MK is identified as the most effect pozzolan when combined with cement. For pozzolans, an optimum dosage limit applies where improvement effects peak (~10 % replacement of cementitious binder being reported).

Although not contributing to further hydration or pozzolanic reaction, filler materials such well-graded silica sand provide solid particles for the reacted binder particle to adhere to. This is applicable to soils with very high water and organic matter content such as peat [67, 84, 89].

Possible research opportunities to pursue have been identified. They include:

- A stoichiometric approach expanding on earlier studies to determine proportions of different pozzolans when combined with cement / lime binders in different soil conditions. Optimum dosage for various pozzolans can then be established for different soils and validated with laboratory testing;
- The effect of different filler materials and proportions to treated soil strength improvement;
- Study into the effect on dynamic properties of binder treated soils;
- The hydration and pozzolanic strength development of different clay mineral types can be tested. By determining the clay content and clay mineralogy of the soil, and therefore understand the pozzolanic content and reactivity, effectiveness with different clay types can be established;
- Determine efficiency of the both hydration and pozzolanic reactions which can be derived by determining Ca $(OH)_2$ content in treated soil at different curing periods. They can also be co-related with other parameters, notably, water/binder ratio (w/b), plasticity index (PI) and void ratio (e);
- Testing and comparison between field and laboratory samples to measure the difference between in reaction effectiveness and efficiency due to mixing and installation;
- Non pozzolanic materials – e.g. reinforcement fibers, nanomaterials, and alkali activated materials and geopolymers.

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X. CONFLICTS OF INTEREST

The authors declare no conflict of interest.

XI. REFERENCES

[1] Harvey, C. Cement Producers Are Developing a Plan to Reduce CO2 Emissions. Scientific American, E & E News, Jul 09, 2018.

[2] Geo-Solutions. Deep Soil Mixing Method Comparison. Available online: https://www.geo-solutions.com/wp-content/uploads/2017/05/17_Deep_Soil_Mixing_Method_Comparison.pdf. (accessed on 27 Dec., 2018).

[3] Keller. Deep Soil Mixing (DSM): Improvement of Weak Soils by the DSM Method.

[4] Hayashi, Hirochika, Jun'ichi Nishikawa, Kanta Ohishi, and Masaaki Terashi. "Field Observation of Long-Term Strength of Cement Treated Soil." Grouting and Ground Treatment (January 29, 2003). doi:10.1061/40663(2003)32.

[6] Lee, W., Im, J.-C., and Seo, M. "A Study on the Unconfined Compressive Strength of Improved Soil by DCM Method through Field Test." Electronic Journal of Geotechnical Engineering, Vol. 23, No. 04, 2018, pp. 667–673.

[7] Ruffing, D. G., M. J. Sheleheda, and R. M. Schindler. "A Case Study: Unreinforced Soil Mixing for Excavation Support and Bearing Capacity Improvement." Grouting and Deep Mixing 2012 (August 17, 2012). doi:10.1061/9780784412350.0026.

[8] Liu, Y., Jiang, Y. J., and Lee, F. H. "Determination of Representative Strength of Deep Cement-Mixed Clay from Core Strength Data." Géotechnique, Vol. 67, No. 4, 2017, pp. 350–364. doi:10.1680/jgeot.16.P.105.

[9] Vu, P. T. A. "Ground Improvement Using Soil-Cement Method: A Case Study with Laboratory Testing and In-Situ Verification for A Highway Project in Southern Vietnam." Geotechnical Engineering Journal of the SEAGS & AGSSEA, Vol. 47, No. 1, 2016, pp. 45–49.

[10]Janz, M., and Johansson, S.-E. "The Function of Different Binding Agents in Deep Stabilization." Swedish deep stabilization research centre, report, Vol. 9, 2002, pp. 1–35.

[11] Broms, Bengt B. "Stabilization of Soil with Lime Columns." Foundation Engineering Handbook (1991): 833–855. doi:10.1007/978-1-4615-3928-5_24.

[12] Ahnberg, H., and Johansson, S. "Increase in Strength with Time in Soils Stabilised with Different Types of Binder in Relation to the Type and Amount of Reaction Products." Proceedings of Deep Mixing '05, Stockholm, 2005, pp. 195–202.

[13] Arman, A., and Munfakh, G. A. "Lime Stabilization of Organic Soils." Highway Research Record, Vol. 381, 1972, pp. 37–45.

[14] Abdi, M. R., and Wild, S. "Sulphate Expansion of Lime-Stabilized Kaolinite: I. Physical Characteristics." Clay Minerals, Vol. 28, No. 04, 1993, pp. 555–567. doi:10.1180/claymin.1993.028.4.06.

[15] Kitazume, M., and Terashi, M. The Deep Mixing Method. CRC Press, 2013.

[16] Bhattacharja, S., and Bhatty, J. "Comparative Performance of Portland Cement and Lime Stabilization of Moderate to High Plasticity Clay Soils." Portl. Cem. Assoc, 2003.

[17] Broms, BengtB. "Keynote Lecture: Design of Lime, Lime/cement and Cement Columns." Dry Mix Methods for Deep Soil Stabilization (November 13, 2017): 125–154. doi:10.1201/9781315141466-17.

[18] Kivelö, M., and B.B. Broms. "Mechanical Behaviour and Shear Resistance of Lime/cement Columns." Dry Mix Methods for Deep Soil Stabilization (November 13, 2017): 193–200. doi:10.1201/9781315141466-23.

[19] Hashim, R., and Islam, M. S. "Properties of Stabilized Peat by Soil-Cement Column Method." Electronic Journal of Geotechnical Engineering, Vol. 13, 2008, pp. 1–9.

[20] Islam, M. S., and Hashim, R. "Stabilization of Peat Soil by Soil-Column Technique and Settlement of the Group Columns." International Journal of Physical Sciences, Vol. 5, No. 9, 2010, pp. 1411–1418.

[21] Islam, S., and Hashim, R. "Bearing Capacity of Stabilised Tropical Peat by Deep Mixing Method." 2009, p. 7.

[22] Huat, B. B. K., Maail, S., and Mohamed, T. A. “Effect of Chemical Admixtures on the Engineering Properties of Tropical Peat Soils.” American Journal of Applied Sciences, Vol. 2, No. 7, 2005, pp. 1113–1120. doi:10.3844/ajassp.2005.1113.1120.

[23] Huat, B. B., Kazemian, S., Prasad, A., and Barghchi, M. “A Study of the Compressibility Behavior of Peat Stabilized by DMM: Lab Model and FE Analysis.” Scientific Research and Essays, Vol. 6, No. 1, 2011, pp. 196–204.

[24] Hampton, M. B., and Edil, T. B. Strength Gain of Organic Ground with Cement-Type Binders. Presented at the Soil improvement for big digs, 1998.

[25] Hebib, S., and Farrell, E. R. “Some Experiences on the Stabilization of Irish Peats.” Canadian Geotechnical Journal, Vol. 40, No. 1, 2003, pp. 107–120. doi:10.1139/t02-091.

[26] Uddin, K., Balasubramaniam, A. S., and Bergado, D. T. “Engineering Behavior of Cement-Treated Bangkok Soft Clay.” Geotechnical Engineering, Vol. 28, No. 1, 1997, pp. 89–119.

[27] Kazemian, Sina, Afshin Asadi, Bujang B. K. Huat, Arun Prasad, and Irman B. A. Rahim. “Settlement Problems in Peat Due to Their High Compressibility and Possible Solution Using Cement Columns.” Forensic Engineering 2009 (November 2, 2009). doi:10.1061/41082(362)26.

[28] Kitazume, Masaki, Takeshi Nakamura, Masaaki Terashi, and Kanta Ohishi. “Laboratory Tests on Long-Term Strength of Cement Treated Soil.” Grouting and Ground Treatment (January 29, 2003). doi:10.1061/40663(2003)31.

[29] Xiao, H. W., Lee, F. H., and Kheng, G. H. “Yielding of Cement-Treated Marine Clay.” Soils and Foundations, Vol. 54, No. 3, 2014, pp. 488–501. doi:10.1016/j.sandf.2014.04.021.

[30] Yao, K., Li, N., Chen, D. H., and Wang, W. “Generalized Hyperbolic Formula Capturing Curing Period Effect on Strength and Stiffness of Cemented Clay.” Construction and Building Materials, Vol. 199, 2019, pp. 63–71. doi:10.1016/j.conbuildmat.2018.11.288.

[30] Malhotra, V. Mohan, and Povindar Kumar Mehta. Pozzolanic and cementitious materials. CRC Press, 2004.

[31] Sargent, P. “The Development of Alkali-Activated Mixtures for Soil Stabilisation.” Handbook of Alkali-Activated Cements, Mortars and Concretes (2015): 555–604. doi:10.1533/9781782422884.4.555.

[32] Duxson, P., Fernández-Jiménez, A., Provis, J. L., Lukey, G. C., Palomo, A., and van Deventer, J. S. J. “Geopolymer Technology: The Current State of the Art.” Journal of Materials Science, Vol. 42, No. 9, 2007, pp. 2917–2933. doi:10.1007/s10853-006-0637-z.

[33] Cherian, C., and Arnepalli, D. N. “A Critical Appraisal of the Role of Clay Mineralogy in Lime Stabilization.” International Journal of Geosynthetics and Ground Engineering, Vol. 1, No. 1, 2015. doi:10.1007/s40891-015-0009-3.

[34] Ikegami, M., Ichiba, T., Ohishi, K., and Terashi, M. Long-Term Properties of Cement Treated Soil 20 Years after Construction. Presented at the 16th International Conference on Soil Mechanics and Geotechnical Engineering, Osaka, 2005.

[35] Frias, M., and Cabrera, J. “Pore Size Distribution and Degree of Hydration of Metakaolin–Cement Pastes.” Cement and Concrete Research, Vol. 30, No. 4, 2000, pp. 561–569. doi:10.1016/S0008-8846(00)00203-9.

[36] Kamruzzaman, A. H., Chew, S. H., and Lee, F. H. “Structuration and Destructuration Behavior of Cement-Treated Singapore Marine Clay.” Journal of Geotechnical and Geoenvironmental Engineering, Vol. 135, No. 4, 2009, pp. 573–589. doi:10.1061/(ASCE)1090-0241(2009)135:4(573).

[37] Sasanian, S., and Newson, T. A. “Basic Parameters Governing the Behaviour of Cement-Treated Clays.” Soils and Foundations, Vol. 54, No. 2, 2014, pp. 209–224. doi:10.1016/j.sandf.2014.02.011.

[38] Correia, A., Venda Oliveira, P., and Lemos, L. Prediction of the Unconfined Compressive Strength in Soft Soil Chemically Stabilized. Presented at the Proc., 18th Int. Conf. on Soil Mechanics and Geotechnical Engineering, 2013.

[39] Khan, S. U., Nuruddin, M. F., Ayub, T., and Shafiq, N. “Effects of Different Mineral Admixtures on the Properties of Fresh Concrete.” The Scientific World Journal, Vol. 2014, 2014, pp. 1–11. doi:10.1155/2014/986567.

[40] Walker, R., and Pavía, S. “Physical Properties and Reactivity of Pozzolans, and Their Influence on the Properties of Lime– Pozzolan Pastes.” Materials and Structures, Vol. 44, No. 6, 2011, pp. 1139–1150. doi:10.1617/s11527-010-9689-2.

[41] Quarcioni, V. A., Chotoli, F. F., Coelho, A. C. V., and Cincotto, M. A. “Indirect and Direct Chapelle’s Methods for the Determination of Lime Consumption in Pozzolanic Materials.” Revista IBRACON de Estruturas e Materiais, Vol. 8, No. 1, 2015, pp. 1–7. doi:10.1590/S1983-41952015000100002.

[42] Yahaya, S., Jikan, S. S., Badarulzaman, N. A., and Adamu, A. D. “Chemical Composition and Particle Size Analysis of Kaolin.” Traektoriâ Nauki= Path of Science, Vol. 3, No. 10, 2017, pp. 1001–1004. doi:10.22178/pos.27-1.

[43] Seco, A., F. Ramirez, L. Miqueleiz, P. Urmeneta, B. Garca, E. Prieto, and V. Oroz. “Types of Waste for the Production of Pozzolanic Materials – A Review.” Industrial Waste (March 7, 2012). doi:10.5772/36285.

[44] Khan, S. U., Nuruddin, M. F., Ayub, T., and Shafiq, N. “Effects of Different Mineral Admixtures on the Properties of Fresh Concrete.” The Scientific World Journal, Vol. 2014, No. ID 986567, 2014, p. 11. doi:10.1155/2014/986567.

[45] Fadzil, M. A., Muhd Nurhasri, M. S., Norliyati, M. A., Hamidah, M. S., Wan Ibrahim, M. H., and Assrul, R. Z. “Characterization of Kaolin as Nano Material for High Quality Construction.” MATEC WEb of Conferences (EDP Sciences), Vol. 103, 2017, p. 09019. doi:10.1051/matecconf/201710309019.

[46] Axelsson, K. G., Johansson, S.-E., and Andersson, R. Stabilization of Organic Soils by Cement and Puzzolanic Reactions – Feasibility Study. Publication 3. Swedish Deep Stabilization Research Centre, 2002, pp. 1–51.

[47] Tastan, E. O., Edil, T. B., Benson, C. H., and Aydilek, A. H. “Stabilization of Organic Soils with Fly Ash.” Journal of Geotechnical and Geoenvironmental Engineering, Vol. 137, No. 9, 2011, pp. 819–833. doi:10.1061/(ASCE)GT.1943-5606.0000502.

[48] Phanikumar, B. R., and Nagaraju, T. V. “Engineering Behaviour of Expansive Clays Blended with Cement and GGBS.” Proceedings of the Institution of Civil Engineers - Ground Improvement, Vol. 171, No. 3, 2018, pp. 167–173. doi:10.1680/jgrim.17.00054.

[49] Kalantari, B., Prasad, A., and Huat, B. B. K. “Stabilising Peat Soil with Cement and Silica Fume.” Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, Vol. 164, No. 1, 2011, pp. 33–39. doi:10.1680/geng.900044.

[50] Kalantari, B., Prasad, A., and Huat, B. B. K. “Cement and Silica Fume Treated Columns to Improve Peat Ground.” Arabian Journal for Science and Engineering, Vol. 38, No. 4, 2013, pp. 805–816. doi:10.1007/s13369-012-0369-0.

[51] Basha, E. A., Hashim, R., Mahmud, H. B., and Muntohar, A. S. “Stabilization of Residual Soil with Rice Husk Ash and Cement.” Construction and Building Materials, Vol. 19, No. 6, 2005, pp. 448–453. doi:10.1016/j.conbuildmat.2004.08.001.

[52] Adhikary, S., and Jana, K. “Potentials of Rice-Husk Ash as a Soil Stabilizer.” International Journal of Latest Research in Engineering and Technology, Vol. 2, No. 2, 2016, pp. 40–42.

[53] Choobbasti, A. J., Ghodrat, H., Vahdatirad, M. J., Firouzian, S., Barari, A., Torabi, M., and Bagherian, A. “Influence of Using Rice Husk Ash in Soil Stabilization Method with Lime.” Frontiers of Earth Science in China, Vol. 4, No. 4, 2010, pp. 471–480. doi:10.1007/s11707-010-0138-x.

[54] Behak, Leonardo. “Soil Stabilization with Rice Husk Ash.” Rice - Technology and Production (March 22, 2017). doi:10.5772/66311.

[55] Wong (2013b), L. S., Hashim, R., and Ali, F. “Improved Strength and Reduced Permeability of Stabilized Peat: Focus on Application of Kaolin as a Pozzolanic Additive.” Construction and Building Materials, Vol. 40, 2013, pp. 783–792. doi:10.1016/j.conbuildmat.2012.11.065.

[56] Kolovos, K. G., Asteris, P. G., Cotsovos, D. M., Badogiannis, E., and Tsivilis, S. "Mechanical Properties of Soilcrete Mixtures Modified with Metakaolin." Construction and Building Materials, Vol. 47, 2013, pp. 1026–1036. doi:10.1016/j.conbuildmat.2013.06.008.

[57] Ahmed, M. D., and Hamza, N. A. "Effect of Metakaolin on the Geotechnical Properties of Expansive Soil." Journal of Engineering, Vol. 21, No. 12, 2015, pp. 29–45.

[58] Wikipedia contributors. Fly Ash. Wikipedia, The Free Encyclopedia. Available online: https://en.wikipedia.org/wiki/Fly_ash (accessed on 27 Dec., 2019).

[59] Moayedi, H., Huat, B. B. K., Kazemian, S., and Daneshmand, S. "Stabilization of Organic Soil Using Sodium Silicate System Grout." International Journal of Physical Sciences, Vol. 7, No. 8, 2012, pp. 1395–1402. doi:10.5897/IJPS11.1509.

[60] Tastan, E. O., Edil, T. B., Benson, C. H., and Aydilek, A. H. "Stabilization of Organic Soils with Fly Ash." Journal of Geotechnical and Geoenvironmental Engineering, Vol. 137, No. 9, 2011, pp. 819–833. doi:10.1061/(ASCE)GT.1943-5606.0000502.

[61] Kolay, P., Sii, H., and Taib, S. "Tropical Peat Soil Stabilization Using Class F Pond Ash from Coal Fired Power Plant." International Journal of Civil and Environmental Engineering, Vol. 3, No. 2, 2011, pp. 79–83.

[62] Kolay, P., and Suraya, N. Stabilization of Organic Soil by Different Types of Stabilizer. In International Conference on Civil Engineering in the New Millennium: Opportunities and Challenges, Bengal Engineering and Science University, Shibpur, India, No. 3, 2007, pp. 1394–1400.

[63] Nath, B. D., Molla, Md. K. A., and Sarkar, G. "Study on Strength Behavior of Organic Soil Stabilized with Fly Ash." International Scholarly Research Notices, Vol. 2017, 2017, pp. 1–6. doi:10.1155/2017/5786541.

[64] Pathak, A. K., Pandey, V., Murari, K., and Singh, J. P. "Soil Stabilisation Using Ground Granulated Blast Furnace Slag." Int. Journal of Engineering Research and Applications, Vol. 4, No. 5, 2014, pp. 164–171.

[65] Åhnberg, H. Strength of Stabilised Soils: A Laboratory Study on Clays and Organic Soils Stabilised with Different Types of Binder. Thesis. Lund University, Lund, 2006.

[66] Wong, L. S., Roslan, H., and Faisal, A. "Unconfined Compressive Strength Characteristics of Stabilized Peat." Scientific Research and Essays, Vol. 6, No. 9, 2011, pp. 1915–1921. doi:10.5897/SRE10.060.

[67] Wong (2011a), L. S., Roslan, H., and Faisal, A. "Unconfined Compressive Strength Characteristics of Stabilized Peat." Scientific Research and Essays, Vol. 6, No. 9, 2011, pp. 1915–1921. doi:10.5897/SRE10.060.

[68] Axelsson, K., Johansson, S.-E., and Andersson, R. "Stabilization of Organic Soils by Cement and Puzzolanic Reactions– Feasibility Study." Swedish Deep Stabilization Research Centre, Report, Vol. 3, 2002, pp. 1–51.

[69] Kalantari, B., Prasad, A., and Huat, B. B. K. "Stabilising Peat Soil with Cement and Silica Fume." Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, Vol. 164, No. 1, 2011, pp. 33–39. doi:10.1680/geng.900044.

[70] Kalantari, B., and Prasad, A. "Strength Evaluations for Treated Peat with Cement and Polypropylene Fibres Using CBR Tests." 2013, p. 6.

[71] Alhassan, M. "Potentials of Rice Husk Ash for Soil Stabilization." Technical Report, 2008, p. 5.

[72] Della, V. P., Kühn, I., and Hotza, D. "Rice Husk Ash as an Alternate Source for Active Silica Production." Materials Letters, Vol. 57, No. 4, 2002, pp. 818–821. doi:10.1016/S0167-577X(02)00879-0.

[73] Seco, A., F. Ramirez, L. Miqueleiz, P. Urmeneta, B. Garca, E. Prieto, and V. Oroz. "Types of Waste for the Production of Pozzolanic Materials – A Review." Industrial Waste (March 7, 2012). doi:10.5772/36285.

[74] Bui, L. A., Chen, C., Hwang, C., and Wu, W. "Effect of Silica Forms in Rice Husk Ash on the Properties of Concrete." International Journal of Minerals, Metallurgy, and Materials, Vol. 19, No. 3, 2012, pp. 252–258. doi:10.1007/s12613-012-0547-9.

[75] Behak, L. Soil Stabilization with Rice Husk Ash. In Rice - Technology and Production (Amanullah and S. Fahad, eds.), InTech.

[76] Zain, M. F. M., Islam, M. N., Mahmud, F., and Jamil, M. "Production of Rice Husk Ash for Use in Concrete as a Supplementary Cementitious Material." Construction and Building Materials, Vol. 25, No. 2, 2011, pp. 798–805. doi:10.1016/j.conbuildmat.2010.07.003.

[77] Basha, E. A., Hashim, R., Mahmud, H. B., and Muntohar, A. S. "Stabilization of Residual Soil with Rice Husk Ash and Cement." Construction and Building Materials, Vol. 19, No. 6, 2005, pp. 448–453. doi:10.1016/j.conbuildmat.2004.08.001.

[78] Moayedi, Hossein, Babak Aghel, Mu'azu Mohammed Abdullahi, Hoang Nguyen, and Ahmad Safuan A Rashid. "Applications of Rice Husk Ash as Green and Sustainable Biomass." Journal of Cleaner Production 237 (November 2019): 117851. doi:10.1016/j.jclepro.2019.117851.

[79] Choobbasti, A. J., Ghodrat, H., Vahdatirad, M. J., Firouzian, S., Barari, A., Torabi, M., and Bagherian, A. "Influence of Using Rice Husk Ash in Soil Stabilization Method with Lime." Frontiers of Earth Science in China, Vol. 4, No. 4, 2010, pp. 471–480. doi:10.1007/s11707-010-0138-x.

[80] Roy, A. "Soil Stabilization Using Rice Husk Ash and Cement." International Journal of Civil Engineering Research, Vol. 5, No. 1, 2014, pp. 49–54.

[81] Rahman, Z. A., Ashari, H. H., Sahibin, A., R., Tukimat, L., and Razi, I. W. M. "Effect of Rice Husk Ash Addition on Geotechnical Characteristics of Treated Residual Soil." American-Eurasian J. Agric. & Environ. Sci., Vol. 14, No. 12, 2014, pp. 1368–1377.

[82] Wikipedia contributors. Kaolinite. Wikipedia, the Free Encyclopedia. Available online: https://en.wikipedia.org/w/index.php?title=Kaolinite&oldid=877920516 (accessed on 27 Dec., 2018).

[83] Rana, J., and Rughooputh, R. "Partial Replacement of Cement by Ground Granulated Blast Furnace Slag in Concrete." Journal of Emerging Trends in Engineering and Applied Sciences, Vol. 5, No. 5, 2014, pp. 340–343.

[84] Wong (2013a), L. S., Hashim, R., and Ali, F. "Utilization of Sodium Bentonite to Maximize the Filler and Pozzolanic Effects of Stabilized Peat." Engineering Geology, Vol. 152, No. 1, 2013, pp. 56–66. doi:10.1016/j.enggeo.2012.10.019.

[85] Rashad (2013a), A. M. "Metakaolin as Cementitious Material: History, Scours, Production and Composition – A Comprehensive Overview." Construction and Building Materials, Vol. 41, 2013, pp. 303–318. doi: 10.1016/j.conbuildmat.2012.12.001.

[86] Poon, C. S., Lam, L., Kou, S. C., Wong, Y. L., and Wong, R. "Rate of Pozzolanic Reaction of Metakaolin in High-Performance Cement Pastes." Cement and Concrete Research, Vol. 31, No. 9, 2001, pp. 1301–1306. doi:10.1016/S0008-8846(01)00581-6.

[87] Hassan, Z. A., Daud, M. N. M., Yahya, Mu. A., and Shaharuddin, M. S. "Effect of Granular Material on the Rate of Consolidation of Peat Soil." Electronic Journal of Geotechnical Engineering, Vol. 18, No. Bund. Z, 2013, pp. 6113–6123.

[88] Wong, L. S., Hashim, R., and Ali, F. H. "A Review on Experimental Investigations of Peat Stabilization." Australian Journal of Basic and Applied Sciences, Vol. 3, No. 4, 2009, pp. 3537–3552.

[89] Wong (2011b), L. S., Hashim, R., and Ali, F. "Effect of Binder and Silica Sand on Unconfined Compressive Strength of Cemented Peat." International Journal of the Physical Sciences, Vol. 6, No. 13, 2011, pp. 3047–3053.