



Fibers, Geopolymers, Nano and Alkali-Activated Materials for Deep Soil Mix Binders

John Kok Hee Wong^{a*}, Sien Ti Kok^b, Soon Yee Wong^b

^a Ph.D. Student, Faculty of Science and Engineering, University of Nottingham Malaysia, Malaysia.

^b Assistant Professor, Faculty of Science and Engineering, University of Nottingham Malaysia, Malaysia.

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Abstract

Ordinary Portland Cement (OPC) and Lime (CaO) have traditionally been used as binder materials for Deep Soil Mix (DSM) ground improvement. Research has been conducted into possible alternatives such as pozzolans to reduce reliance on either cement or lime. However, pozzolans still undergo similar calcium-based reactions in the strengthening process. In this review, further alternative binder materials for soil strength development are explored. These recent developments include fiber reinforcement materials, alkali activation methods, nanomaterials and geopolymers, which can potentially achieve equal or improved performance. Research to date has shown that alkali-activated materials and geopolymers can be equivalent or superior alternatives to pozzolanic supplemented cement binders. The case is made for GP cements which potentially produces 80% less CO₂ than conventional portland cement during manufacture. One-part AAM and GP cements are a promising substitute for portland cement in DSM. A combined approach which incorporates both Ca and alkali activated/geopolymer types of materials and hence reactions is proposed.

Keywords: Reinforcement Fibers; Nanomaterials; Alkali-Activated Materials; Geopolymers; Deep Soil Mix.

1. Introduction

The Deep Soil Mix (DSM) method applies soil stabilization principles, which comprises inserting binder materials with other fillers and mixing together with the soil to form strengthened columns of treated soil below ground. The manufacture of the predominant binder materials, cement and lime, impose significant CO₂ emission and high energy demands. Although studied as a potential supplement and/or partial replacement to reduce the usage of OPC and lime, pozzolanic materials still rely primarily on similar calcium (Ca) reaction processes to produce the same calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gel products for treated soil compressive strength improvement. In addition, pozzolanic binders react incompletely and require a longer time to realize improvements in the treated soil.

This paper reviews several alternatives to Ca type reactions to improve soil properties for DSM, which offer different pathways for strength / soil properties improvement. The primary soil properties of interest for improvement are 1) shear strength (S_u); 2) Compressive strength (q_u); 3) Stiffness (Young's Modulus, E); 4) Dynamic properties (G, D) and 5) Permeability (k).

* Corresponding author: evxjw1@nottingham.edu.my

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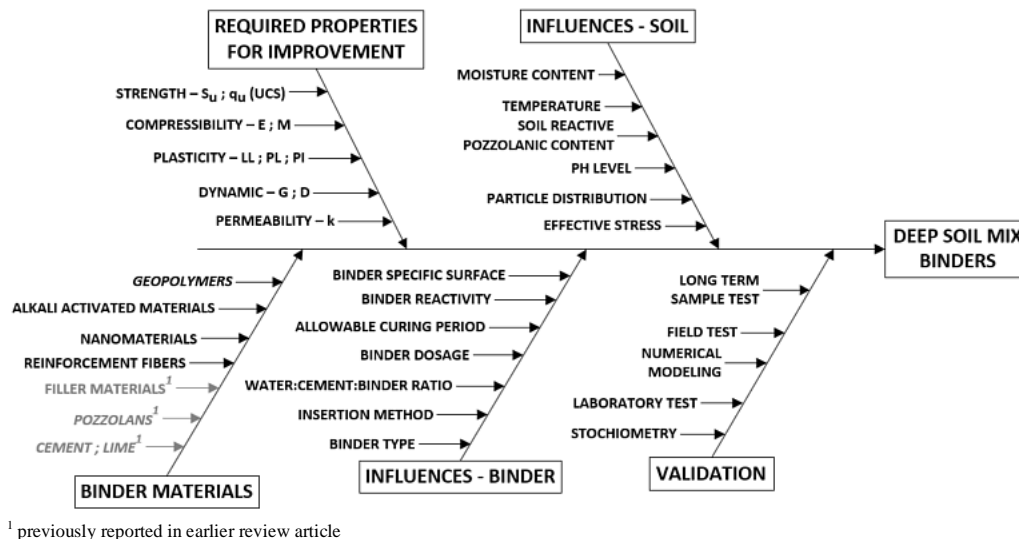


Figure 1. DSM Binders methodology

Reinforcement fibres (natural or synthetic), by mechanical means, improves the stability, increase tensile strength and reduce settlement / lateral deformation of soil [1].

Nanomaterial binders enhance the reaction efficiency of their macro scale counterparts due to the extremely high specific surface areas and surface charges on the binder nano particle [2].

Alkali-activated binder materials utilize a different chemical reaction pathway altogether which does not rely on calcium to develop strength gain [3]. They can be mixed in slurry, utilized in the wet mixed method of DSM as a medium to reach lower soil strata [4].

Finally, Geopolymers are a class of synthetic inorganic alkali aluminosilicate materials with its 3D network polymeric structure which overcomes possible long-term stability shortcomings of alkali-activated materials.

2. Reinforcement Fiber Materials

Adding /mixing of reinforcement fibers offers a mechanical process as opposed to the chemical process of cementitious / pozzolanic binders to improve the properties of soil. The reinforcement binders can be either natural or synthetic in origin.

- Natural fibers are derived from plant-based or cellulosic materials – e.g. barley straw, jute, palm, sisal, bamboo, coconut fibers etc.;
- Synthetic fibers can be any form of man-made plastic, mineral or metal-based material. Examples researched and applied have included polyvinyl alcohol (PVA), polypropylene (PP), polyester (PET), polyethylene (PE), nylon (NL), steel (ST) etc. some of which, can also be derived from waste industrial materials.

Research and studies have been conducted on the contribution of fibers (with varying fiber length (L) and diameter (d), either applied solely or in conjunction with chemical process binders for soil stabilization. Comprehensive reviews were recently conducted for natural and synthetic fibers describing the history, development and applicability to soil stabilization [1, 5]. However, the long-term / permanent requirements of DSM columns may preclude the usage of natural fibers due to their organic and bio-degradable nature. If fibers are applied with DSM methods, it would need to be pre-mixed with a binding agent (typically cement with water) to form in a slurry for injection under pressure into the soil.

Conventionally, polypropylene fibers have been used for control of thermal and shrinkage induced cracks with dosage ranges from 0.6 to 0.9 kg/m³ when added to concrete mixes for crack control [6,7].

Laboratory studies on soil stabilization using OPC as a binding agent and polypropylene fibers on peat soils showed a clear trend that addition of fiber also increased unconfined compressive strength (UCS) in comparison with soil-cement mix alone [6].

Research study on rapid stabilization of weak soils for road and airfield applications compared PP, PET and PVA fibers either alone or with chemical stabilizers in clay. Increased soil strength and toughness was encountered up to a maximum dosage of ~ 1% dry weight. Thereafter, mixing became difficult with soil. Longer fibers increased strength, but the addition of fibers alone was insufficient to meet strength requirements. When combined with other stabilizers (e.g. cement / lime) and in secondary role, the shorter fibers contributed to increased toughness whereas improved

compressive strength was determined by the primary chemical stabilizer. Dispersion of fibers influenced UCS as it may have introduced pockets of weakness/failure planes [8].

Arasan et al. (2015) studied the feasibility of utilizing polymers as a binder for rapid stabilization of sandy soils with DSM by conducting UCS tests on different ratios of polyester-soil mix. UCS was observed to increase with increasing polyester ratio, effective diameter, relative density and curing period. The highest UCS achieved was with 0.6-1.18 mm grain size, 30% polyester ratio and 40% relative density respectively [9].

Laboratory studies testing on fiber reinforced soil cement (FRSC) samples of clay soils in Bangkok, Thailand were conducted to investigate effect on flexural performance (bending strength @ $L/150$ deflection, f_{150}^D) improvement [10]. It was observed that PP fiber performed better than steel fibers – the fully crimped shape of PP fibers achieved greater bond strength than straighter steel fibers. Hence, brittleness in cement-based binders in deep soil mix columns could be improved with fiber reinforcement which increases toughness. Some recent research is listed below:

Table 1. Research on reinforcement fiber materials

Research	Soil (USCS)	Reinf. Fiber / Sec. Binder	Effect AS % Nano Material Increases		Opt. Mix / Max. UCS / Other Improvements
			Increase	Reduce	
John Paul & Sneha (2016) [11]	Black Cotton Soil q=6.9 kPA	<ul style="list-style-type: none"> Bamboo L=25 mm; d=0.45mm; 0.25–1 % wt. FA Fly Ash (FA) (class F) 15–25 % wt. soil 	UCS	OMC MDD	<ul style="list-style-type: none"> 1% fiber + 20% FA ~ 100% improvement
Sharma et al. (2017) [12]	Sand	<ul style="list-style-type: none"> Jute L=20 mm; d=0.3-0.45mm; 0.5–2 % wt. soil 	UCS	OMC MDD	<ul style="list-style-type: none"> 1.5% fiber 382 kPA
Cai et al. (2006) [13]	Clayey soil q=90 kPA c = 90 kPA; $\phi = 19.1^\circ$	<ul style="list-style-type: none"> Polypropylene L=12 mm; d=0.034mm; 0.05–0.25 % wt. soil Lime (CaO) 2–8 % wt. soil 	UCS c ϕ	Shrinkage (%) Swelling (%)	<ul style="list-style-type: none"> 0.25% fiber + 5% lime 880 kPA (28 d) c = 292.7 kPA; $\phi = 45^\circ$
Estabragh et al. (2011) [14]	Silty Clay (CL) q=131 kPA @ 13.5% strain $\phi = 27^\circ$	<ul style="list-style-type: none"> Nylon L=4 mm; d=0.4mm; 10–30 % wt. 	UCS Excess pwp Cc Φ	Pre-consol. Pressure	<ul style="list-style-type: none"> 30% fiber 241 kPA @ $\epsilon=20.2\%$ $\phi = 44^\circ$
Kalantari and Huat (2008) [6]	Peat q=28.5kPA CBR=0.78%	<ul style="list-style-type: none"> Polypropylene L=12 mm; d=0.018mm; 0.1–0.25 % wt. soil Cement (OPC) 15–50 % wt. soil 	UCS CBR	–	<ul style="list-style-type: none"> 15-50% OPC 77–490 kPA (28 d) CBR=19–35% (90 d) 0.15% fiber + 15-50% OPC 94–528 kPA (28 d) CBR=23–39% (90 d)
Sukontasukkul and Jamsawang (2012) [10]	Clay (Bangkok) Su =15.6 kPA q=31.2 kPA	<ul style="list-style-type: none"> Polyprop. (PFSC) L=58 mm (L) Steel fiber. (SFSC) L=60 mm (L) 35 mm (S) @ 0.5,0.75 & 1 % vol. Cement (OPC) 10–20 % wt. soil 	Flexural strength PP better than steel Short fiber better than long fiber	–	<ul style="list-style-type: none"> 20% OPC @ MC=70% 1.25 MPa (28 d) $f_{150}^D=0.20$ MPa (PFSC-L1.0) $f_{150}^D=0.14$ MPa (SFSC-S1.0) $f_{150}^D=0.11$ MPa (SFSC-L1.0)
Xiao et al. (2013) [15]	Clay (Singapore marine)	<ul style="list-style-type: none"> Polyprop. PP6 PP12 L=6 mm 12 mm Polyvinyl alcohol PVA6 PVA12 L=6 mm 12mm 0–0.32 % vol. soil Cement (OPC) 20–50 % wt. soil 	UCS Ductility	–	<ul style="list-style-type: none"> 50% OPC@100% WC + 0.32% fiber @ 7 d 1494 kPA (PVA6) 1240 kPA (PP6) 1445 kPA (PVA12) 1354 kPA (PP12)

3. Nanomaterials (nM)

3.1. Reaction Mechanism

Nanomaterials are defined as physical substances with at least one dimension from 1 to 150 nm ($1 \text{ nm} = 1 \times 10^{-9} \text{ m}$) [16]. Nanomaterials can be produced through the following approaches:

- “Top Down” approach whereby larger particles are scaled down in size to nano range of dimensions whilst maintaining original properties without resorting to “atomic scale level of control or manipulation (e.g. electronics industry miniaturization of computer chips). Nano scale versions of pozzolans can be produced mechanically with pulverizing techniques using high energy ball milling [17];
- “Bottom Up” approach (known also as molecular nanotechnology) whereby materials are assembled from singular atoms or molecules.

Nanomaterials have been proven to enhance the performance of concrete [18, 19] – e.g. with the addition of nano-silica (nS), concrete compressive strength can increase by up to 30% [20]. Improvements in the flexural strength and elasticity (Young’s modulus, E) can be achieved by introducing Carbon nanotubes (CNT) [21].

The application of nano materials has been considered as a potential binder material in soil improvement [2, 22]. The primary characteristics from nanomaterials that induce soil improvement can be described below [23]:

- Particle size – As the particle size approaches or decreases to less than light wave wavelength (De Broglie wave), the periodic boundary condition of the particle is destroyed, and surface atomic density decreases, leading to different physical properties from that at the micro or macro scale;
- Microstructure – which can be categorized into 2D structured nano tubes and 3D structured nano particles. The two categories induce different improvement effects on the soil;
- Particle surface area – likewise, the specific surface area of the particle increases, which leads to greater ion exchange capacity and increase interaction with other particles.

Furthermore, since the nanomaterial will need to be mixed in some form of solution prior to injection into the soil, the rheological suspension properties in solution will have also an influence on dispersion and enhancement effect into the soil. Nanomaterials applications and understanding of it is still in its infancy – it has only been recently researched as a potential additive for concrete and many developments would still be under commercial consideration [21]. Some examples of recent research are compiled in Tables 2 to 4.

3.2. Carbon Nanotubes (CNT)

Carbon nanotubes (CNT) are tube-shaped carbon materials where the diameter of the tube is measured in the nanometer scale [16]. CNTs can be up to several millimeters in length and can be arranged in one-layer walls (known as Single-wall carbon nanotubes – SWCNT) or multi-wall structures (known as Multi wall carbon nanotubes – MWCNT). In general, CNTs have 5 x Young’s modulus (E) and 8 x the strength of steel at 1/6 the density of steel. This strength is due to the covalent sp² bonds formed between the individual carbon atoms. Thus, there can be potential gains in increased flexural strength and improved control of crack propagation with CNT enhanced concrete and by extension, to soil treated with a combination of a primary binder (e.g. cement) and CNT.

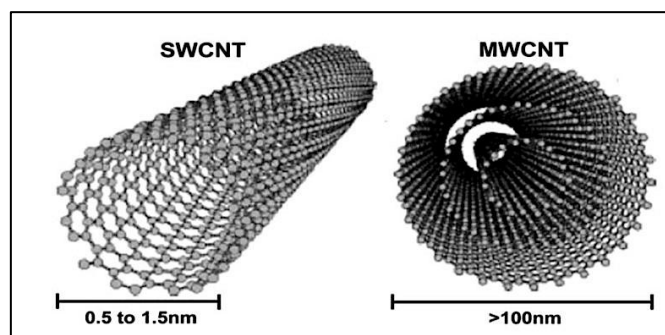


Figure 2. Schematic Structure of SWCNT and MWCNT [24]

Due to the size and fineness of CNTs, it is possible to distribute/disperse on a finer scale within concrete than for micro reinforcement fibers, thus CNT infused composites can achieve greater compressive and flexural strengths. A comparison on flexural and compressive strengths achieved from the research by Kahidan and Shirmohammadian [25] showed up to 19% compressive and 25% flexural improvement. This is supported by Sáez de Ibarra et al. [26] who reported 80-90% increase in E_{concrete} with the addition of only 0.10-0.20% MWCNT/SWCNT by cement weight and Cwirzen et al. [27] reporting 50% improvement in compressive strength with 0.045 – 0.15% MWCNT by cement weight.

Direct addition of nanocarbon filaments to sandy soil mixed with bentonite in proportions ranging from 0.05 to 0.2% of total dry weight of soil resulted in dry density increase and subsequent decrease in soil shrinkage / expansive strains [28, 29]. This is compared with fiber reinforcement addition to soil which also reduced soil cracks but increased hydraulic conductivity. It is suggested by Taha et al. [30] that the better dispersion of the CNT additives

would provide the potential to overcome these desiccation cracks in soil associated when using fiber reinforcement and binder.

The potential for utilizing CNT together with binder material as deep soil mixing supplement has not been explored at depth. The present high expense of carbon nanotubes may have a deterring effect from the application in this field [21]. In addition, challenges faced with consistent dispersion of the CNT needs to be overcome when applied to soil stabilization [30]. Correia and Rasteiro [31] reported adding a surfactant to the blended solution of MWCNT/ OPC in improving the dispersion and achieving higher UCS and Youngs Modulus (E).

3.3. Nano Titania (nTiO₂) / Nano Fly Ash (nFA)

Nano Fly Ash enhances the activation of pozzolanic reaction and further densifies concrete like its non-nano counterpart [32]. Babu and Joseph [33] conducted research to study the effect of Nano Titanium Dioxide (nTiO₂) and Nano Fly Ash (nFA) on properties of soft soil (Silty clay of USCS classification CH-MH). With increasing nano material additive (from 0% to 2%), the following improvements were observed:

- Atterberg limits – decreased LL;
- Compaction – increased MDD and decreased OMC;
- Strength – increased shear strength (and consequently, UCS);
- CBR and Settlement – improved CBR values and reduced settlement.

3.4. Nano Clay (nC)

Nano Clays (nC) can be defined as nanoparticles of layered mineral silicates also commonly known as phyllosilicates. Some Nano Clays are:

- Montmorillonite Nano Clays – this is the most common Nano Clay, consisting of ~ 1 nm thick aluminosilicate layers with lateral dimensions ranging from few hundred nM to ~ 10 μm, combined into large stacks;

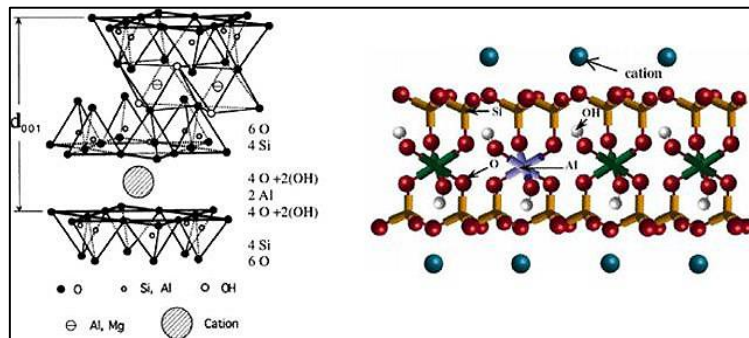


Figure 3. Schematic Structure of Montmorillonite Nano Clay [34]

- Halloysite Nano Clays – naturally occurring aluminosilicate nanotube with a wall thickness of 10-15 atomic aluminosilicate sheets, an outer diameter averaging 50 nm, an inner diameter of 12–15 nm, and length of 0.5–1 μm.

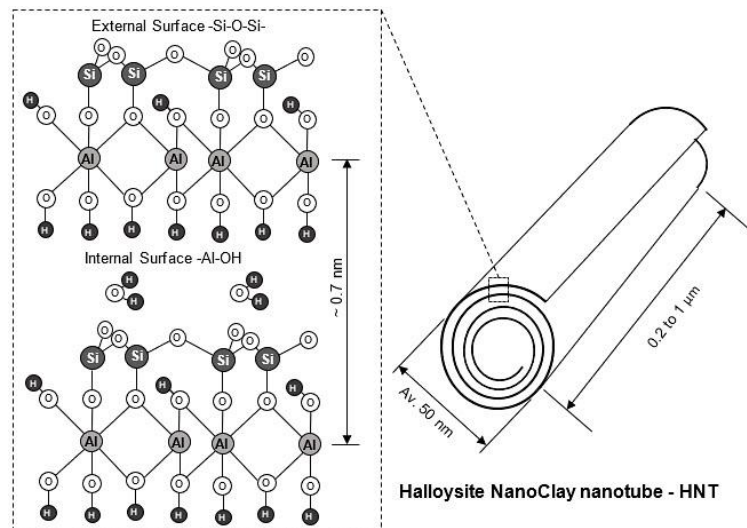


Figure 4. Halloysite Nano Clay nanotube structure

Ali et al. [35] studied the potential use of nC (montmorillonite) to increase the strength of contaminated soil. Soil contaminated with kerosene experienced reduction in UCS down to 61% of original UCS depending on kerosene %. However, the addition of nC up to 2% for contaminated soil and 1% for uncontaminated soil increased the bearing capacity of the soil. Increase in LL, PL and shear strength of silty soils was observed by Bahari et al. [36] with the addition of up to 2% by weight nC (montmorillonite) to silt. A linear correlation for shear strength was observed from direct shear tests conducted.

Table 2. Research on nano materials – CNT, NanoClay

Research	Soil Type (USCS)	Nanomaterial / Secondary Binder	Effect AS % Nanomaterial Increases		Opt. Mix / Max. UCS / other improvements
			Increase	Decrease	
Correia and Rasteiro (2016) [31]	• Silt q=143 kPa E ₅₀ =15.8 MPa	• CNT (MWCNT) 1% dry wt. OPC • Cement (OPC) @ 175 kg/m ³ + surfactant 1. Amber 4001 2. Glycerol	• Greater dispersion of MWCNT → stronger and stiffer soil skeleton matrix formed OPC • Max. E ₅₀ attained with 1% Amber 4001 surfactant		• 175 kg/m³ OPC + 0.001% CNT 237.5 kPa E ₅₀ =38.7 MPa
Alsharif et al. (2016) [28]	• Residual / clayey sand (SC)	• CNT (MWCNT); CNF 0.05 – 0.2 % CNT 0.1, 0.2 % CNF • Distilled water	• MDD*	• Specific gravity • OMC • porosity • Soil permeability (k)	–
Taha (2018) [22]	• Clay (CL/CH)	• CNT; CNF 0.05–0.2 % dry wt. soil • Bentonite 10 & 20 % dry wt. soil + ultrasonication	• PI • MDD	• Soil shrinkage/expansive strains • Desiccation cracks are suppressed	–
Ali et al. (2016) [35]	• Clay (CL) q=40.9 kPa	• Nano-Clay (nC) 1–2 % dry wt. soil –	• UCS • Empirical function developed to model curing time (D, day) vs UCS	–	• 1% nC 194 kPa
Bahari et al. (2013) [36]	• Silt (ML/MH)	• Nano-Clay (nC) 0.5–2 % dry wt. soil –	• MDD* • PL; LL • Su; • φ	–	–
Majeed et al. (2014) [37]	• Org. Clay (OL) q=90 kPa • Silty Clay (CH) q=42.6 kPa	• Nano-Copper (nCuO) 0–1 % dry wt. soil • Nano-Clay (nC) 0–0.30 % dry wt. soil • Nano-Magnesium (nMgO) 0–0.4 % dry wt. soil	• UCS* • MDD*	• LL, PL, PI • Linear shrinkage of soil	• 0.7% nCuO 150 / 330 kPa (OL/CH) • 0.2% nC 159 / 325 kPa (OL/CH) • 0.3% nMgO 101 / 188 kPa (OL/CH)
Mohammadi and Niazi (2013) [38]	• Clay q~50 kPa	• Nano-Clay (nC) 0.5–2 % dry wt. soil –	• UCS* ; Su • CBR* • PL; LL	• PI	• 1.5% nC 170 kPa @ ε=0.02

* Until optimum % thereafter decreases

3.4. Nano Silica (nSi)

Nano Silica (nSi) is silicon dioxide in nano particle size form. It can directly be produced from bio waste e.g. rice husk ash (RHA) aerosol-gel method, electric arc method, precipitation method etc. [39].

Chemically, nSi particles would react with calcium hydroxide (Ca (OH)₂) to develop more of the strength contributing C-S-H material in concrete. In addition, concrete workability, increased resistance to water penetration and reduced leaching of calcium has also been encountered with nSi. The effective surface area plays a large part in influencing the improvement and nSi was reported to be more effective than micron-sized silica e.g. Silica Fume due to the exposed surface area to the pozzolanic reaction [18]. Improvement from nSi addition is affected by water/binder ratios [40].

Table 3. Research of nano materials – nano Fly Ash, nano Silica

Research	Soil Type (USCS)	Nanomaterial / Sec. Binder	Effect AS % Nanomaterial Increases		Opt. Mix / Max. UCS / other improvements
			Increase	Decrease	
Babu and Joseph (2016) [33]	• Silty Clay (CH-MH) q=27.5 kPa	• Nano Titania (nTiO₂) • Nano Fly Ash (nFA) 0.5–2 % dry wt. soil –	• Su* • MDD	• PL; LL; SL • OMC	• 0.5% nTiO₂ 51.5 kPa • 1% nFA 46 kPa
Prabhu et al. (2017) [41]	• Clay (CH) q=254 kPa	• Nano Fly Ash (nFA) • Fly Ash (FA) 10–30 % dry wt. nCem • Nano Cement (nCem) • Cement (Cem) 2–10% dry wt. soil	• OMC • UCS • Nano particle equivalent achieves 1.2 times UCS than non-nano particles	• LL • MDD • UCS • Soil permeability (k)	• 10% nFA+10% nCem 1416 kPa (7 d) • 10% FA+10% Cem 1175 kPa (7 d)
Khalid et al. (2015) [42]	• Clay (CI) q=231kPa φ =29°	• Nano Soil (nSoil) 0–4 % dry wt. soil –	• UCS • PL; LL • φ • UCS*	• PI –	• 4% nSoil 283 kPa φ =34° • 0.4% nS + 6% OPC 1287 kPa (28 d) • 0.4% nS + 8% OPC 2000 kPa (28 d) • 6% OPC 534 kPa (28 d) • 8% OPC 593 kPa (28 d)
Bahmani et al. (2016, 2014) [43,44]	• Residual Soil (CH) q=322 kPa	• Nano Silica (nSi) 15, 80 nm particle size 0–1 % dry wt. soil • Cement (OPC) 6, 8 % dry wt. soil	• Higher UCS achieved with smaller particle size nanomaterial. • SEM analysis shows formation of secondary C–S–H gel in reactions between hydration products and SiO ₂ nanoparticles.	–	• 0.7% nS 1.18 MPa @ ε=7.8% C=42.3 kPa; φ=28° E50=14.5 MPa • 1% nS 1.16 MPa @ ε=6.15% C=45 kPa; φ=29.5° E50=19 MPa
Changizi and Haddad (2017, 2016) [45,46]	• Clay (CL) q=760 kPa @ ε=11% C=36.6 kPa φ=14.3° E50=10.3 MPa	• Nano Silica (nSi) 11–13 nm particle size 0.5–1 % dry wt. soil –	• Su*; UCS* • C*; • φ* • MDD*; E ₅₀ • Peak UCS occurs at lower strain than for untreated soil → treated soil is more brittle, and failure triggered by tension cracks	–	• 4% nS + 6% OPC 0.98 MPa (28 d) • 8% nS + 6% OPC 1.12 MPa (28 d) • 12% nS + 6% OPC 1.02 MPa (28 d)
Choobasti and Kutanaei (2017) [47]	• Sand	• Nano Silica (nSi) 0–12 % dry wt. soil • Cement (OPC) 6% dry wt. soil • Distilled water	• UCS* • Adding nanoparticles (up to optimal %) promotes hydration process especially at early curing times and changes the unhydrated CH crystal needles into C–S–H gel. • Beyond optimal %, increasing further nS % prevents suitable CH crystal growth. This leads to increased micro-cracks and reduced UCS • UCS increases as curing time increases	–	• 4% nS + 6% OPC 0.98 MPa (28 d) • 8% nS + 6% OPC 1.12 MPa (28 d) • 12% nS + 6% OPC 1.02 MPa (28 d)
Lin et al. (2016) [48]	• Clay (CL) q=32.5 kPa PI=8.8	• Nano Silica (nSi) 2 % dry wt. soil • Sewage sludge ash (SSA) SSA/OPC = 1:1, 2:1, 3:1, 4:1 • Cement (OPC) 15 % dry wt. soil	• UCS • OMC; • CBR • Volumetric swelling	• PI • Soil permeability (k) • MDD ^A	• 15% OPC; 1:1 SSA/OPC 364 kPa (28 d) PI=0 (28 d) • 2% nS + 15% OPC; 1:1 SSA/OPC 410 kPa (28 d) PI=0 (28 d)

* Until optimum % thereafter decreases | A decreases until optimum % thereafter increases again

3.5. Nano Alumina (nA)

Nano Alumina (nA) may come in the form of nearly spherical nanoparticles or as oriented / undirected fibers. As nano fibers, manufacture can be by [49]:

- Selective oxidation of aluminum on the surface of the molten Ga–Al in a humid atmosphere at a temperature of 20 to 70 °C (Method of IPCE RAS);
- Synthesis of nano structural aerogel AlOOH from molten Ga–Bi and Al–Al (Inst. of RF IPPE).
- Growing fiber nano oxide of aluminium on the surface of the aluminium melts (ANF Technology).

When blended with concrete, it results in higher tensile and flexural strength (up to 2% replacement of cement with typical particle sizes of 15 nM) [50]. León et al. (2014) achieved increased abrasion and fracture resistance in cement mortars blended with nA [51].

Pozzolanic binders (CaO and CaO-MK binder mix) when combined with of nSi and nA, have been reported with enhanced properties such as increased compressive strength in conjunction with reduced porosity values [52]. This is due to denser microstructure, decreased carbonation and water absorption. nA did not contribute to the development of C-S-H compounds which are the main contributors to strength. Decreased carbonation was encountered, due to nA which had a negative effect on compressive strength, porosity and water absorption. However, this is on a smaller scale compared to the nSi reaction.

Naval and Chandan (2017) researched the effect of nano MgO (nMg) and nA when added to kaolinite clay and demonstrated improvements in soil properties such as Atterberg limits (e.g. reduced LL, PL and PI of soil), swelling potential decrease and maximum dry density increase [53].

Both Luo et al. (2012) and Lin et al. (2016) investigated using nA from sewage sludge ash/cement mix to stabilize clay soil. The optimum 1% nA achieved UCS 4.2 times higher than untreated soil after 7 days. Improved CBR values and reduced volumetric swelling was also observed [48, 54].

3.6. Nano Lime (nCaO)

Nano-sized lime particles (nCaO) have recently been considered to overcome some limitations of traditional lime binders, e.g. difficulties in achieving complete carbonation. This may be addressed by the much smaller particle size and greater surface area for reaction of nCaO.

Improvements were reported in Atterberg limit properties (e.g. decreases in liquid limit and plasticity index), maximum dry density decreases/increase in OMC as well as compressive strength increase by using nCaO / nSi when compared to conventional particle size lime and silica binder in silty clay [55]. Permeability was also recorded to be reduced by a factor of 10 in comparison to non-nano sized additives of silica and lime. In addition to greater reactivity because of surface area, it is proposed that nano particles can effectively fill in the pores of soil particles due to greater fineness.

The strength contribution of nCaO becomes more apparent with increasing curing time [56]. The effect of nCaO exhibits both positive (aggregation and pozzolanic reaction increasing C-S-H content and creating alkaline environment with more OH-/Si ratio) and negative effects (cement hydration is impeded when Ca (OH)₂ concentration becomes too high and excessive Ca (OH)₂ crystallization leads to strength decrease). Wang et al. (2016) therefore concluded that there was insufficient justification to utilize nCaO in lieu of common CaO. Comparison is made with other nanomaterials whereby nSi is considered more effective, nCaO being comparable to nA but better than nTiO₂ which exhibited negative effects [56].

Table 4. Research on nano materials – nano Alumina, nano Lime, nano Magnesium

Research	Soil Type (USCS)	Nanomaterial / Sec. Binder	Effect AS % Nanomaterial Increases		Opt. Mix / Max. UCS (q) / other improvements
			Increase	Decrease	
Luo et al. (2012) [54]	• Clay (CL) q=40 kPa pH=6	<ul style="list-style-type: none"> • Nano Alumina (nA) 0–3 % dry wt. soil • Sewage sludge ash (SSA) SSA/OPC = 1:1, 2:1, 3:1 • Cement (OPC) 15 % dry wt. soil 	<ul style="list-style-type: none"> • pH • OMC • UCS* • CBR & Volumetric swelling • Optimum % for nA at 1%. 	<ul style="list-style-type: none"> • Max. Unit weight • LL; PL; PI • Soil permeability (k) 	<ul style="list-style-type: none"> • 1% nA + 15% OPC; 1:1 SSA/OPC 185 kPa (28 d) 235 kPa (90 d) pH=12.5 (3% nA)
Naval and Chandan (2017) [53]	• Clay-Kaolinite (CH)	<ul style="list-style-type: none"> • Nano Alumina (nA) • Nano Magnesium (nMgO) 0–2 % dry wt. soil 	<ul style="list-style-type: none"> • OMC* • MDD • Optimum % for nA at 1%. • Optimum % for nMgO at 0.5%. 	<ul style="list-style-type: none"> • LL; PL; PI 	–
Eswaramoorthi et al. (2017) [55]	• Clay (CH) q=254 kPa	<ul style="list-style-type: none"> • Nano Lime (nCaO) 2–10 % dry wt. soil • Nano Silica (nSi) 5–15 % dry wt. soil • Silica (SiO₂) 5–15 % dry wt. soil 	<ul style="list-style-type: none"> • UCS* • OMC • Nano particle equivalent achieves 1.2 times UCS than non-nano particles • Nano particle equivalent achieves greater effects than non-nano particles • Optimum % for nS at 5%. 	<ul style="list-style-type: none"> • MDD; LL; PI • Soil permeability (k) 	<ul style="list-style-type: none"> • 5% SiO₂ + 10% nCaO 493 kPa (7 d) • 5% nS + 10% nCaO 589 kPa (7 d)

Wang et al. (2016) [56]	<ul style="list-style-type: none"> • Soft Clay (ω_r) = 50% 	<ul style="list-style-type: none"> • Nano Lime (nCaO) 0–20 % wet wt. soil • Cement (OPC) 0–20 % wet wt. soil 	<ul style="list-style-type: none"> • UCS* • Brittleness modulus* • Nano silica (nS) is superior to nA, nCaO for strength gain. nTiO₂ has negative effect 	–	<ul style="list-style-type: none"> • 15% OPC 2.09 MPa (28 d) 3.21 MPa (60 d) • 10% nCaO + 15% OPC 2.62 MPa (28 d) 3.83 MPa (60 d)
Govindasamy et al. (2017) [57]	<ul style="list-style-type: none"> • Clay (CL) $q=138\text{kPa}$ Water content (ω_r) = 12% 	<ul style="list-style-type: none"> • Nano Lime (nCaO) 0.2–1 % dry wt. soil • Lime (CaO) 5 % dry wt. soil 	<ul style="list-style-type: none"> • UCS* • Original soil UCS has high sensitivity towards the remolded water content (ω_r). Higher ω_r leads to lower UCS. • Nano particle equivalent achieves greater UCS than non-nano particles. This is due to a higher ability of nCaO to flocculate and agglomerate. • Longer curing period → higher UCS gain. • Optimum % for nCaO at 0.5%. 	–	<ul style="list-style-type: none"> $\omega_r = 12\%$ • 5% CaO 385 kPa (28 d) • 0.5% nCaO 453 kPa (28 d) 634 kPa (56 d)

* Until optimum % thereafter decreases | ω_r = moisture content soil

4. Alkali-Activated Materials (AAM)

The development of alkali-activated binder materials has been claimed to have commenced from ancient binders used for the pyramids to recent applications utilizing Palm Fuel Oil ash (POFA) precursors with NaOH / KOH alkali [5, 58, 59 and 60]. AAM has also been utilized to produce alkali-activated cements with lower CO₂ / energy requirements compared to conventional cement types (OPC) [61].

Alkali-activated material (AAM) binders react with any amorphous mineral aluminosilicates source either in the soil or introduced with alkali (Na or K base) or alkali earth metals (typically Ca). The process mechanism requires a source material for the Si-Al raw material, namely the prime material or precursor together with corresponding alkali activators (which can be a liquid or solid, but which requires water to dissolve – e.g. NaOH, KOH etc.) [58]. The AAM binder is formed from the Si-Al raw material that has dissolved in a solution of alkali activators to form a mixture of gels and crystalline compounds which then hardens to a new, strong matrix amorphous condensed structure. It involves [58, 62]:

- Dissolution (breakdown) and hydrolysis (consuming water) of the mineral aluminosilicates in a strong alkaline solution – leading to breaking of covalent bonds between the Si, Al and O atoms ;
- Transport, orientation and creation of oligomer species $[\text{SiO}_4]^{-4}$ and $[\text{AlO}_4]^{-5}$ comprising polymeric bonds of Si-O-Si and /or Si-O-Al precursor ions into monomers;
- Condensation and stabilization phase whereby these Al and Si components form extensively into cross-linked networks eventually hardening into a 3-D, amorphous Si-O-Al and Si-O-Si mineral structures.

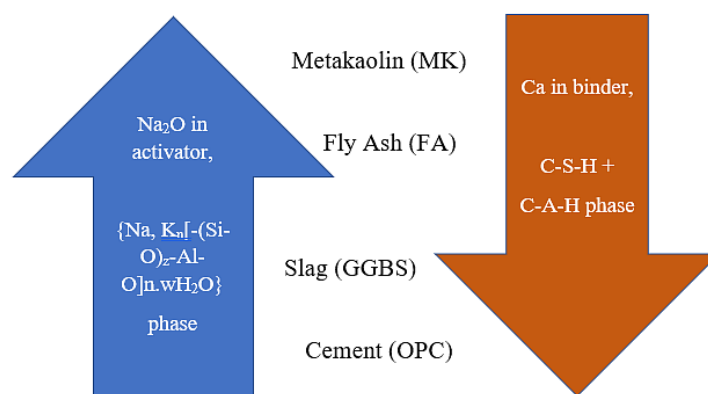


Figure 5. Composition of various alkali activated materials [64]

Škvára (2007) [64] defined alkali-activation materials as a whole range alumino-silicate binder types activated by stronger alkali agents with progressive replacement of C-S-H / C-A-H phase with $\text{Mn}[-(\text{Si} - \text{O})_z - \text{Al} - \text{O}]_n \cdot w\text{H}_2\text{O}$ phase (where M is alkali cation e.g. K, Na or Ca; z is 1, 2 or 3 and n is degree of geopolymerization) [3]. Two (2) alkali-activation models are established [61, 65]:

- Where, Ca is significant, activation with Si + Ca precursor (e.g. GGBS, OPC, lime etc.) in mild alkaline solution, yields C-A-S-H / C-S-H as the main reaction products;

- Where Ca is insignificant or absent, Si + Al precursors (MK, FA etc.) may react with a medium to highly alkaline solution (either NaOH or KOH). Activation produces a polymeric structured material. It is noted that the requirement for calcium in any part of the alkali-activated structure is bypassed in the second model (in the case of A-S-H) [4].

Where Al is prevalent, the reaction is as follows:



Where Si is prevalent, the following reactions are included:



In the case of alkali activation using Si + Al rich precursors ; for metakaolin (MK), a suggested optimum ratio to achieve strength was reported at Si/Al and Na/Al in the range of 3.5- 3.8 for the former and 1.2 for the latter respectively [66]. For Fly Ash (FA) precursors, Si/Al at 3.9 and Na/Al at 1 are the observed optimum ratios [67].

Studies also indicated that by increasing the amount of silicon, it results in more Si–O–Si bonds, which are stronger than Al–O–Al and Al–O–Si bonds [62, 63] . Hence, the strength of the alkali-activated binder would increase with the Si/Al ratio since Si–O–Si bonds density increases as the Si/Al ratio increases.

The stabilization of organic peat soil with sodium silicate system grout with a combination of sodium silicate with calcium chloride/aluminium sulphate acting as a reactor/accelerator was studied by Moayedi et al. (2012) whereby UCS of stabilized soil increased to 270% untreated organic soil [68].

The effect of alkaline activation using Fly Ash with Portland cement as a binder was researched using sodium silicate / sodium hydroxide as the alkaline activator solution [4, 69]. Fly Ash as a binder was utilized to achieve long-term strength gain in stabilized soil. Optimum levels of sodium hydroxide concentration were established together with the influence of solution/ash ratio. Fly ash was selected as more cost effective than metakaolin (MK).

Work done similarly on fly ash with sodium silicate + sodium hydroxide on silty sand achieved up to 2.8 MPa @ 28 days and 5.2 MPa @ 90 days UCS [70, 71]. Sargent et al. (2013) experimented with sodium silicate / sodium hydroxide precursors and FA / GGBS / red gypsum binder on soft alluvial soil. The stabilized soil exhibited higher UCS but higher brittleness over untreated soil. Highest strength gains were gained, using alkali activated GGBS binders [72].

Pourakbar et al. [60] experimented with sodium hydroxide and potassium hydroxide together with Palm Oil Fuel Ash binder material and revealed the main factors for determining the strength of stabilized soil being 1) quantity of source binder 2) type of alkali activator 3) water content of soil 4) curing conditions.

Alkali-activation reactivity depends on the amorphous content of silica and aluminium [58, 59]. The reactivity is linked to the material structure, being higher for higher amorphous content. Provis (2018) has recently discussed the utilization potential of AAM as a replacement for OPC in construction practices [73]. The disadvantage and hazards associated with difficult to handle concentrated alkali activator solutions may be resolved with recently developed one-part alkali-activated materials. One-part AAM which involves a dry mix of the solid aluminosilicate precursor, solid alkali source and other admixtures would only require water added.

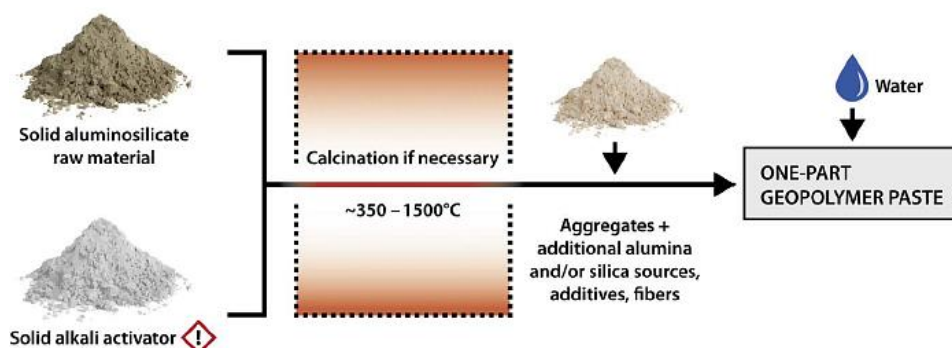


Figure 6. Production of one-part AAM [74]

Similar end-products (N-A-S-H and K-A-S-H gels) are produced from one-part AAM reactions. These include instantaneous dissolution of the solid alkali activators and slower reactions involving aluminosilicates like two-part AAM [74]. Some examples of recent research (mainly focused on strength) are as follows:

Table 5. Research on alkali-activated materials

Research	Soil	Alkali Activator (AA) Mol/L(M) Main Stabilizer/Precursor	Effect AS AA Concentration (M) And/ Or Precursor % Increases		Opt. Mix / Max. UCS / other improvements
			Increase	Decrease	
Pourakbar et al. (2016) [60]	• Clay (CH) q≈12 kPa	<ul style="list-style-type: none"> • KOH • NaOH (5–15 M) • Palm Oil Fuel Ash (POFA) 15–30 % wt. 	<ul style="list-style-type: none"> • UCS • Scaled laboratory model of treated column groups (diam = 23mm / length = 200mm) tested for UCS – replacement area ratios of 9.9, 11.9 and 15.82% • Curing time at 7, 14 and 28 days – higher strength gain at later stages observed 		<ul style="list-style-type: none"> • 10 Mol KOH / 20% POFA 1.2 MPa (28 d)
Moayedi et al. (2012) [68]	• Organic Soil q=10 kPa	<ul style="list-style-type: none"> • Hydrous Na₂SiO₃ – (3 M); • CaCl₂ / Al₂(SO₄)₃ – (0.1 M); • Kaolinite found in soil 	<ul style="list-style-type: none"> • UCS • Improved UCS (up to 270%) with increasing Na₂SiO₃ up to 3 mol/L Al₂(SO₄)₃ • improved UCS at lower Na₂SiO₃ concentrations 		<ul style="list-style-type: none"> • 3 M Na₂SiO₃ 22 kPa (14 d) • 3 M Na₂SiO₃ + 0.1 M CaCl₂ 27 kPa (14 d) • 3 M Na₂SiO₃ + 0.1 M Al₂(SO₄)₃ 25 kPa (14 d)
Cristelo et al. (2011,2013) [4,69]	• Sandy Clay q=558 kPa	<ul style="list-style-type: none"> • Na₂SiO₃ + NaOH (Na₂SiO₃: NaOH = 2:1) (10M, 12.5M, 15M) (AA/Binder material = 0.4 to 0.45) • Cement (OPC) 0.5–1 W/C 20–40 % wt. • Fly Ash (class F) 20–40 % wt. 	<ul style="list-style-type: none"> • UCS • AA + FA stabilization requires a longer curing period to achieve same UCS as cement. • Strong dependency between the AA / FA ratio and mechanical strength. A lower ratio leads to higher strength • NaOH concentration is important – practical limit of 12.5 due to difficulties in mixing beyond that. • Beyond 90 days curing, AA / FA ratio more critical than AA concentration. 		<ul style="list-style-type: none"> • 12.5 M AA + 40% FA 7.1 MPa (28 d) 17 MPa (90 d) 44 MPa (1 yr.) • 30%, 1 W/C OPC 11.6 MPa (28 d) • 12.5 M AA + 30% FA 5.2 MPa (28 d)
Rios et al. (2016, 2017) [70,71]	• Silty Sand (CL) q≈300 kPa (M01)	<ul style="list-style-type: none"> • Na₂SiO₃ + NaOH (Na₂SiO₃: NaOH = 1:2) (7.5 M) (AA/Binder = 0.781) • Fly Ash 15, 20, 25 % wt. total wt., soil + binder mix 	<ul style="list-style-type: none"> • UCS • Compaction is more important than FA quantity / activator type. • The strength of soil-cement tapers off after 28 days whereas strength for AA stabilized soil continues to improve • Very high internal angle of friction and cohesion intercept values also achieved from triaxial tests. • Scaled laboratory model of treated column groups (diam = 23mm / length = 200mm) tested for UCS – replacement area ratios of 9.9, 11.9 and 15.82% • Curing time at 7, 14 and 28 days – higher strength gain at later stages observed 		<ul style="list-style-type: none"> • 11.7% AA + 15% FA (M1) 2.3 MPa (28 d) 4.8 MPa (90 d) c = 287 kPa; φ = 65°
Vitale et al. (2017) [75]	• Clay (Kaolin)	<ul style="list-style-type: none"> • Na₂SiO₃ (AA/Binder = 0.5) • Cement (OPC) 20–40 % wt. • Fly Ash 20–40 % wt. 	<ul style="list-style-type: none"> • Yield stress 	<ul style="list-style-type: none"> • Soil compressibility 	–

5. Geopolymers (GP)

Geopolymers are a class of synthetic inorganic alkali aluminosilicate materials. They are produced by the reaction of a solid aluminosilicate with a highly concentrated alkali hydroxide/alkali silicate solution. The resultant geopolymer product from reaction is a generally amorphous, polymeric Si-O-Al framework binder material with potential in soil stabilization [76]. Feng et al. (2004) defined a geopolymer as basically a 3D aluminosilicate mineral polymer formed by several amorphous to semi-crystalline phases [77]. Geopolymers are formed by dissolution of aluminosilicate solids in a solution of alkali or alkali salts producing a mixture of aluminosilicates, aluminates and silicates in solution. With sufficient concentration, the solution solidifies through several gel phases and undergoes polymerization that hardens into a 3D aluminosilicate framework.

Like AAM, geopolymer materials have advantages over traditional cement binders in that the production process imposes less demands on energy consumption and produces less greenhouse gasses (CO_2) [3]. Raw materials for polymers can be sourced from a wide range of industrial waste materials which contain silicate and/or alumina – e.g. natural pozzolans such as fly ash, ground granulated blast furnace slag, agricultural / construction waste materials with high silica/alumina content such as RHA, palm oil fuel ash (POFA), red clay brick waste and metakaolin [78].

Improved sulphate resistance properties of geopolymer concrete (prepared from blended Waste Fuels Ash precursor and sodium silicate alkali activator) was observed [79].

Du et al. (2017) investigated the physical, hydraulic and mechanical properties of clayey soil stabilized by geopolymer composed of a GGBS precursor and sodium silicate/ calcium carbide residue alkali activator [80]. The lightweight geopolymer stabilized soil (LGSS) developing greater water absorption, permeability (k of LGSS being $10 \times k$ of LCSS) and material strength (q_u LGSS = $2\text{-}3.5 q_u$ LCSS) when compared to benchmark lightweight cement stabilized soil (LCSS). C-S-H content in LGSS was ~ 2 times found in LCSS.

The effectiveness of soil-geopolymer stabilization and comparison between Fly Ash and GGBS based geopolymer types were made by Singhi et al. (2016) [81]. Alkali activator solution used selected was sodium hydroxide and sodium silicate. The unconfined Compressive strength from slag based geopolymer stabilized soil (~ 11 MPa @ 20%) was found to be much higher than that with Fly Ash-based (~ 0.3 MPa @ 20%). The difference in UCS between the two geopolymer base types starts to increase beyond 8% content of source geopolymer stabilization material in the soil.

Study by Zhang et al. (2013) on the effectiveness of metakaolin based geopolymer (MKG) soil stabilization on clay soils showed UCS values of MKG stabilized soils being much higher than for original soil as well as 5% cement stabilized soil at MKG contents $> 11\%$. There was also an improvement in shrinkage strains at MKG concentrations $> 8\%$. UCS values of MKG is not significant between 7 and 28-day strengths indicating predominantly fast reactions leading to early strength gain – this may be due to the precursor completing geopolymerization and strength development within 7 days [82]. Improvements in soil Young's Modulus were also recorded, but still, less than 5% cement stabilized soil.

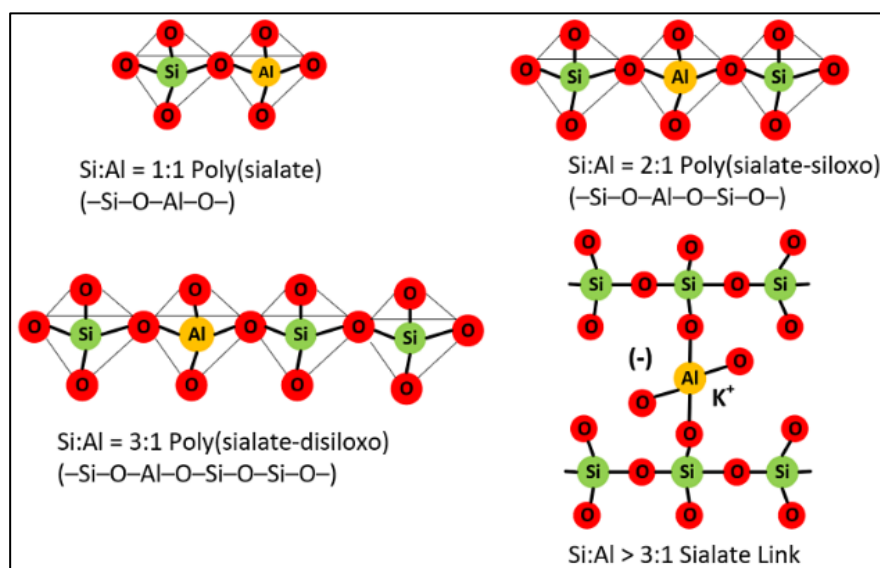


Figure 7. Geopolymer systems – adapted from Al Bakri Abdullah et al. [83]. Geopolymers with Si: Al = 2 have low CO_2 emissions and energy demand during manufacture (e.g. geopolymer cements and concretes) [84]. Cement curing requires only room temperatures [85].

However, Davidovits (1994) [84] asserts that geopolymers (GP) should be separated from AAM in definition, as both belong to different chemistry systems. Although conceptually following a similar reaction mechanism for creation, Davidovits [3, 84] differentiates GP from AAM by restricting geopolymer definition to only those obtained by pure metakaolin precursors and with end products derived, namely, through polycondensation to a 3D K-poly(sialate-siloxo) polymer excluding N-A-S-H / K-A-S-H previously included by earlier research [84]. The interchangeable interpretation of AAM and geopolymers are due to similarities between alkali-activation and first step of geopolymerization. For geopolymers, the first step should instead be termed alkalination instead of alkali-activation.

AAM type cements (e.g. Alkali-activated Slag cement) have a disadvantage to geopolymers due to the generation of leachates leading to potential long-term stability problems although AAM type cements generally achieve higher initial strengths over geopolymer cements. Geopolymer (GP) cements are now being developed in the form of 1) slag-

based; 2) rock-based 3) fly ash-based and 4) ferro-sialate-based types. The manufacture of GP type cement can generate up to 80% less CO₂ and requires far less energy than portland cement [86].

Table 6. Research on geopolymer materials

Research	Soil	Activator %Mol/L(M) / Geopolymer (Gp)	Effect AS Geopolymer % Increases		Opt. Mix / Max. UCS / other improvements
			Increase	Decrease	
Zhang et al. (2013) [82]	• Clay (CL) q=780 kPa	<ul style="list-style-type: none"> • Na₂SiO₃ + NaOH • Metakaolin geopolymer (MKG) 3–15 % dry wt. soil • Cement (OPC) 5 % wt. dry wt. soil 	<ul style="list-style-type: none"> • UCS • E 	<ul style="list-style-type: none"> • Volumetric strain • Brittleness • Shrinkage strain 	<ul style="list-style-type: none"> • MK 11% 2.9 MPA (28 d) • MK 15% 3.8 MPA (28 d) • OPC 5% 3.35 MPA (28 d)
Du et al. (2017) [80]	• Clay (CL)	<ul style="list-style-type: none"> • Na₂SiO₃ + Calcium Carbide Residue (CCR) • Cement (OPC) • GGBS • LGSS CCR: Na₂SiO₃: GGBS = 1:1:8 • LCSS CCR: Na₂SiO₃: GGBS = 1:1:8 Mixed with 385, 430, 475, 520 kg/m³ soil to achieve 900, 1000, 1100, 1200 kg/m³ density stabilized soil mix 	<ul style="list-style-type: none"> • Higher density mixes achieve higher UCS • LGSS permeability (k) is 10x higher than LCSS • C-S-H % achieved in LGSS is 2x higher than LCSS 		<ul style="list-style-type: none"> • LGSS (1200 kg/m³ density) 1.35 MPa (28 d) • LCSS (1200 kg/m³ density) 0.65 MPa (28 d)

6. Discussion

Being a mechanical process of improvement to the soil, reinforcement fiber materials have an immediate effect without curing in comparison to other binders which require curing time due to the hydraulic / chemical reaction process. Review of laboratory research results on reinforcement fiber materials demonstrated improvements in treated soil shear strength and axial strain to failure. However, if acting by itself, the level of compressive / shear strength improvement was still inferior to other binder materials. A higher tensile strength which defines the brittle to ductile post-peak behaviour transition in the improved soil due to the embedded fibers was clearly observed [5]. This can be important in the case of soils subjected to cyclic / dynamic loading.

The mixing of reinforcement fibers in soil also encountered difficulties in compaction and subsequent maximum dry density reduction with increasing dosage. Consistent and effective mixing of the fibers (possibly affecting viscosity in the slurry and hence limited to WDSM approach), application and distribution in soil may be difficult to achieve for DSM in the field. It may be more practical to pair with chemical based binder – e.g. cementitious, pozzolanic, alkali-activated types etc. This could lead to a synergistic combination of improved compressive and tensile strength.

Due to smaller dimensions, nanoparticles increase rate of improvement compared to their micron / macro sized counterparts. With a different order of magnitude on the specific surface, reaction of the same materials, albeit on a nano vs micro scale, is more rapid and effective. Moreover, lesser amounts of nanomaterials can produce significant enhancements in soil improvement. Different nanomaterials lead to different effects – e.g. CNT potentially increases flexural strength and control crack propagation whereas nano-versions of lime and silica increased compressive strength. The use of nanomaterials for ground improvement is presently hindered by high cost and the requirement to install via a slurry media (hence by the wet method) to ensure effective dispersion into the soil. The challenges of effective field mixing and dispersion into soil again needs to be resolved in DSM ground improvement.

Whilst cementitious and pozzolanic binders rely on Ca based reactions, AAM and GP binders undergo a different reaction pathway (Si/Al-based) without reliance on calcium, to improve soil properties. Research to date has shown the potential of alkali-activated binders to match or surpass the compressive strength gain compared to traditional cementitious binders. However, the strength gain comes at the cost of increased curing period (beyond 28 to 90 days) compared to short curing period of soil-cement mixtures (7 to 28 days). This is due to the faster dissolution rate of the calcium-type glassy material, forming the C-S-H gel that can be found in cement hydration [70]. However, this is compensated by greater benefits in environment reduction in CO₂ emissions (due to reduced usage of cementitious binder materials) and better resistance to aggressive soil environments, due to sulphate, chloride and acid exposure.

The difficulties and hazards associated to on-site handling of highly alkaline aqueous solutions can be largely avoided with development of one-part alkali activated materials which already comes pre-mixed in dry powder form like cement, requiring only addition of water. This allows the possibility of dry method DSM in high moisture content soils.

A recent development is the potential application of geopolymers to ground improvement. Research conducted on geopolymers produced from fly ash and metakaolin source materials have demonstrated the clear advantages of geopolymers over other binders in toughness and durability whilst further improving mechanical strength. Geopolymers are also more stable than AAM as they are not subject to potential leachate generation in AAM binders in the long-term.

High early strength for type 1 alkali -activated Fly Ash geopolymers (Si: Al ratio of 1 to 2) can be achieved with curing at optimum temperature range of 40 °C to 90 °C [85, 87]. It may be possible to achieve this from exothermic reaction with sufficient dosage of lime. Another possibility would be a combined approach, when both Ca and alkali activated types of reactions are allowed to take place – calcium-based reactions leading to C-S-H / C-A-H phase and through activation of suitable silica/ alumina rich materials by strong alkali agents to produce alumino-silicate geopolymers (UCS potentially reach up to 160 MPa [64]). In the combined approach, it is noted that cementitious calcium-based reactions are also exothermic. A combined mix incorporating primary calcium-based reactions supplemented by pozzolanic secondary and alkali-activated/geopolymer tertiary reactions is also recommended for further research. In addition, type 2 slag / fly ash-based GP cements (Si: Al ratio of 2) which may harden at room temperatures and which do not require toxic solvents can also be applied.

7. Conclusions

The background and reaction mechanism behind alternatives to cementitious and pozzolanic binders and its application to DSM ground improvement have been covered in this review. Of these alternatives, both alkali-activated materials (AAM) and Geopolymer materials (GP) present an effective alternative chemical process pathway to soil improvement. Hazards associated with handling of alkali activator chemicals on site - e.g. Na_2SiO_3 , NaOH, KOH may be largely avoided by using one-part pre-blended AAM or GP cements. This leads to research opportunities on the applicability of this hybrid implementation in real geotechnical solutions such as:

- A systematic investigation using various combinations of calcium-based (which may include both cementitious and pozzolanic materials) and alkali activated alumino-silicate based binders and the effectiveness and specific improved properties for different soil conditions. The optimum proportions for combined binder types which can work synergistically for application to DSM can be determined;
- Methods in mixing of these combined binder materials and effective dispersion into the soil;
- Deriving a predictive constitutive improved soil model of 1) calcium based 2) alkali-activated / geopolymer as well as 3) hybrid combination in deep soil mix methods design for various soil types;
- Application geopolymer cement as a binder;
- As strength of the improved soil in DSM columns increase to higher compressive strengths approaching conventional concrete, the geotechnical model now transitions from improved ground to that of ground with rigid inclusions like unreinforced piles. Research is needed to establish the crossover point.

8. Acknowledgements

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9. Conflicts of Interest

The authors declare no conflict of interest.

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