Category 2: Industry Excellence in Consulting, Research or Education

Performance of Geopolymer Based Binders in Improving the Expansive Subgrades

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Overview

- Expansive soils exhibit significant volume change due to their ability to absorb water and swell, then shrink when water evaporates. These soils are widely distributed globally and pose a particular risk to lightly loaded structures, such as roads and buildings, because their overburden cannot effectively counteract the swelling pressure.
- Expansive soil stabilization techniques are divided into two primary categories: physical and chemical methods. Chemical stabilization is currently the most popular choice because it enables the use of in-situ soils, saving on hauling costs.
- Portland cement is the most widely used chemical stabilizer globally due to its availability and relatively low cost. However, cement production is energy-intensive and emits approximately one ton of CO_2 per ton of cement produced. It also releases heavy metals, fine particles, and dust during manufacturing. Additionally, using cement to treat sulfate-rich expansive soils can cause sulfate-induced heave due to ettringite formation. These environmental and practical drawbacks have led researchers to focus on identifying new sustainable binders for treating expansive soils.
- One such sustainable binder is the geopolymer, produced by combining precursors (industrial solid waste) with alkaline liquids and silicates. While geopolymers demonstrate satisfactory geotechnical performance, they have three major concerns (over the entire product life cycle):

    1. CO_2 Emissions: Geopolymer treatments have slightly higher CO_2 emissions compared to cement and lime, primarily due to the additional silicate source in the activator, contributing over 50% of emissions.
    2. Unit Cost: The material cost for geopolymer treatment is over five times higher than cement treatment, with sodium silicate being the most expensive component.
    3. Field Implementation: Few field implementations have been done, no design charts, thus limiting commercial acceptance.

- Therefore, this research aims to use an alternative silicate source from industrial waste to develop a commercially viable and eco-friendly geopolymer for expansive soil stabilization.
- Considering feasible industrial waste products, global annual fly ash production exceeds 2800 million tons, with Australia's production estimated at 12 million tons as per the Ash Development Association of Australia. Global rice husk ash production is around 120 million tons annually, posing environmental challenges due to disposal issues. In Australia, rice production from 2019-2023 averages 0.24 million tons annually, generating approximately 17,000 tons of rice husk ash (US Department of Agriculture). RHA disposal causes significant environmental and health problems due to its low bulk density and airborne fine particles.
- Thus, this research will utilize Fly ash as the precursor and Rice husk ash to substitute commercial silicate solutions in developing a sustainable geopolymer for expansive soil stabilization.

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Overview

Overall Problem


Expansive soil distribution in Australia

- 20% of surface soil in Australia is expansive.
- Problems related to expansive soil may be due to soil heave, fractures, desiccation cracks, slope or foundation failures etc.
- Estimated annual cost of damage due to expansive soil ranges from $150 million in Victoria to $15 billion in USA.
- In Australia, 80% of all housing insurance claims compensated are for expansive soil related damages.

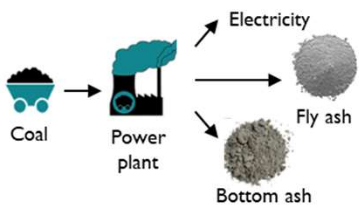
Existing solutions

CEMENT as a Stabilizer → Energy intensive production | GHG emissions | Heavy metals/ dust | Sulphate induced heave

TOWARDS SUSTAINABLE SOLUTIONS → GEOPOLYMER = Precursor + Activator (NaOH + Sodium silicate)

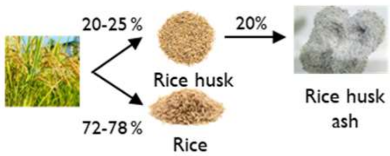
- Geopolymer has indicated 9-16 folds cost increments compared to cement stabilization.
- Sodium silicate is responsible for more than 50% of the total cost.
- CO_2 emissions from geopolymer has found to be doubled compared to cement treatment.
- The main contributor to the global warming potential was verified to be Sodium silicate; 50 – 59%.

Proposed solution



Waste-derived geopolymer-soil treatment

- Use Fly ash as the precursor.
- Use rice husk ash to produce sodium silicate.



(GHG – Greenhouse gas; RHA – Rice husk ash)

Objectives

1. Propose an optimized the mix design for geopolymer stabilized expansive soil activated using NaOH and RHA based silicates using laboratory tests.
2. Investigate the reaction kinetics between geopolymers and expansive soil.
3. Investigate the mechanical and hydraulic characteristics of the geopolymer stabilized subgrade.
4. Investigate the durability characteristics of geopolymer stabilized soil.
5. Evaluate the performance of geopolymer stabilized using a numerical simulation.
6. Assess the environmental impacts of geopolymer-stabilized subgrade construction.

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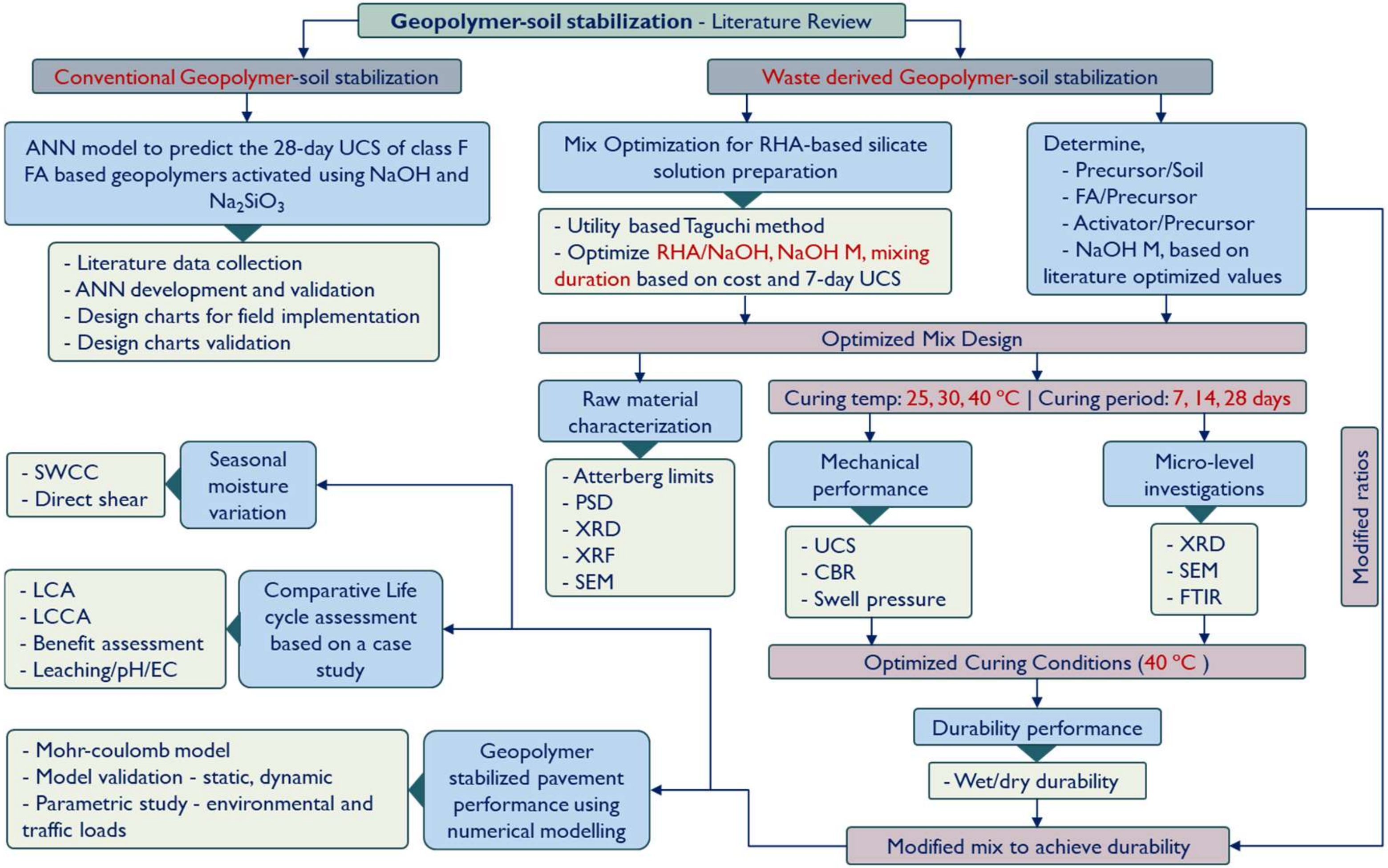
Initiatives Undertaken

- The next slide shows the flow chart of the testing program. Following the literature review the testing program was conducted in two directions. The mix design ratios for the conventional commercial based silicate solution based geopolymers were studied and data were collected from the literature to develop an artificial neural network to predict the 28-day unconfined compressive strength of class F FA based geopolymers activated using NaOH and commercial sodium silicate. As an output of the exercise, a few design charts for the same prediction was derived using the ANN model output.
- Considering the development of the new waste derived geopolymer, initially mix optimization for the preparation of rice husk ash-based sodium silicate solution was carried out. Three parameters, RHA/NaOH ratio, NaOH molarity, and the mixing duration were considered for the mix optimization using the Utility based Taguchi method for multi-response optimization based on cost of raw materials and 7-day unconfined compressive strength. Precursor/soil, FA/Precursor, Activator/Precursor, and NaOH molarity for geopolymer soil stabilization were obtained considering the optimum values used for conventional geopolymer soil stabilization.
- Following the raw material characterization tests, mechanical and micro level investigations were carried out using the optimized mix design considering varying curing temperatures (25, 30, and 40 deg Celsius) for 7, 14, and 28 days to simulate the performance of the new geopolymer under different environmental conditions. Through these tests, the curing conditions that provide the maximum strength was selected for the following wet/dry durability performance test.
- Based on the durability performance the same optimized mix or a modified mix was used to simulate the seasonal moisture variations in soil using SWCC and direct shear tests. A comparative life cycle analysis including a life cycle cost analysis, and benefit, leaching, and pH evaluation was conducted to decide the overall performance of the new waste derived stabilizer considering environmental, cost, social, and strength aspects. Finally, the performance of the new geopolymer stabilized soil was modelled using the ABAQUS software. The model was validated using a field study and a further parametric study was conducted to simulate the performance based on environmental and traffic loads.

Initiatives Undertaken



(ANN – Artificial neural network; UCS – Unconfined compressive strength; CBR – California bearing ratio; PSD – Particle size distribution; SEM – Scanning electron microscopy; XRD – X-ray diffraction; XFR – X-ray fluorescence; FTIR – Fourier transform infrared spectroscopy; SWCC – Soil water characteristic curve; FA – Fly ash; RHA – Rice husk ash)

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Initiatives Undertaken

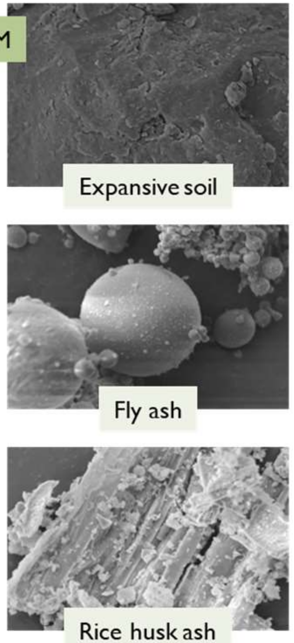
- The expansive soil employed in this study was procured from test excavations conducted within the Central province of Sri Lanka at an approximate depth of 300 mm below the ground surface. Initially, specimens of expansive soil were systematically collected from six distinct geographic coordinates. Preliminary characterization tests: free swell index, free swell ratio, and Atterberg limit test were conducted on all the samples, and the soil displaying the most expansive features was selected to proceed with the study (PI = 33%, LL=66%). The selected soil belongs to the moderate expansive category with as per the AASHTO (T 258–81) classification. Based on the unified soil classification system (USCS), the soil was identified as high-plasticity clay (CH).
- The precursor used in the geopolymer preparation is FA and was obtained from the Lakwijaya coal power plant in Norochcholai. The alkaline activator used is a combination of NaOH and a sodium silicate solution produced via the dissolution of waste RHA in a NaOH solution. RHA utilized for the preparation of the sodium silicate solution was obtained from a local rice mill and was ball-milled and sieved to obtain particles finer than 75 µm only for the silicate production. Despite the fact that smaller RHA particle sizes offer amplified reactivity in the silicate production process, a 75 µm sieve was used in view of the feasibility of the industrial applications.
- According to the XRF results, FA is classified as Class F, as the sum of the total chemical composition of SiO2, Al2O3, and Fe2O3 is >70%, and CaO is <10%. RHA contains approximately 90% of silica, making it eligible waste source for silicate production.
- The morphology of raw expansive soil, FA, and RHA was observed via scanning electron microscopy (SEM) images. Thin sheet-like structures are visible in raw soil, which are characteristic of the expansivity. FA particles are spherical in nature, while more irregular shaped arrangements are dominant in RHA particles. Although the given magnifications have obscured the porous nature of RHA, such honeycombed structures in RHA are responsible for the high surface area leading to their high reactivity (Farooque et al. 2009).
- A significant amount of crystalline materials, including quartz, mullite, and magnetite, were detected in the XRD spectra of FA between 15◦ and 30◦ 2θ along with several additional peaks from 30◦– 45◦ 2θ. On the contrary, no such prominent crystalline phases were noted in RHA. The amorphous phases in FA and RHA are depicted via the wide humps in the diffraction patterns between 15◦ and 30◦ 2θ. Few traces of illite, kaolinite, and montmorillonite were spotted in the XRD spectra of raw expansive soil, where the latter is responsible for the swelling properties.
- The mix design of the geopolymer for expansive soil treatment consists of two distinct components: (1) RHA-based sodium silicate solution preparation, and (2) geopolymer-soil specimen preparation. However, the optimization is carried out only for the RHA-based silicate solution preparation, whereas the mix ratios for the geopolymer-soil specimen preparation are obtained considering the optimum combinations from the previous studies (Onyelowea et al. 2019; Murmu and Patel 2020; Maheepala et al. 2022).
- RHA-based sodium silicate activator has never been utilized for expansive soil treatment; thus, no previous studies recommend optimized mix ratios. Therefore, during the preliminary stage, relying on the current data for RHA-based silicate activator preparation, several random mix ratios were explored for the 7-day unconfined compressive strength (UCS) to ascertain their potential to attain the required strength criteria for subgrade applications. Three process parameters, NaOH/RHA, NaOH molarity, and mixing duration, were considered for the development of the RHA based silicate solution. The preliminary experimental stage led to the selection of NaOH/RHA = 0.6, NaOH = 4 mol/L, mixing temperature = RT (∼25 ◦C), and mixing duration = 20 min as the benchmark for mix optimization through the second phase.
- During the second stage, the experimental design for the RHA-based silicate solution preparation was performed using the Taguchi's L9 orthogonal array for robust design of experiments. The levels of input parameters (in the top right table above) utilized during the second stage were selected based on the ratios obtained via the benchmarked mix from the preliminary stage. The desired responses were: the 7-day UCS of the stabilized soil (higher-the-better) and the unit cost per cubic meter of stabilized soil per 1 MPa of strength gained (lower the better).
- NaOH/RHA = 0.6, NaOH molarity = 3 mol/L, and mixing duration = 40 min yield the optimal performance in terms of UCS and cost for 7-day UCS within the selected range of parameters.

Initiatives Undertaken

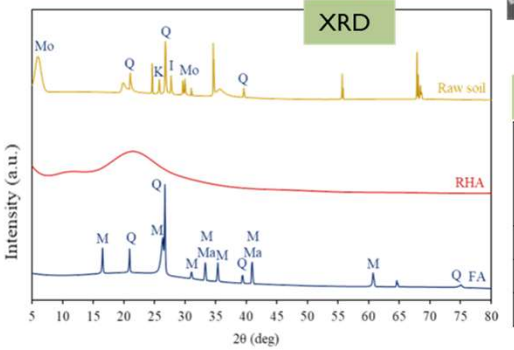
Raw materials

Description	Value
Specific gravity	2.60
Particle size distribution	
Sand	35.18%
Silt	15.50%
Clay	49.25%
Natural moisture content	23.4%
Liquid limit (LL)	66%
Plastic limit (PL)	33%
Plasticity index (PI)	33%
USCS classification	CH

SEM



XRD

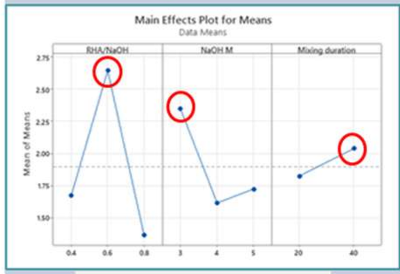


(Q: Quartz; M: Mullite; Ma: Magnetite; Mo: Montmorillonite; I: Illite; K: Kaolinite; C: Crystobalite)

Mix optimization using Utility based Taguchi method

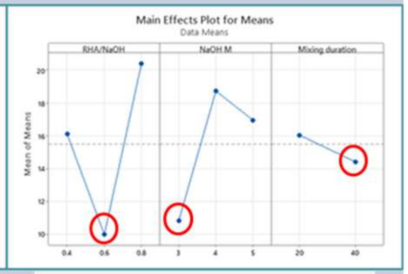
Parameter	Level		
	1	2	3
NaOH/RHA	0.4	0.6	0.8
NaOH M	3	4	5
Mixing duration (min)	20	40	-

UCS - Higher-the- better



Optimization for UCS

Cost - Smaller-the-better



Optimization for cost/m^3/MPa

Optimal ratios ~ NaOH/RHA = 0.6; NaOH M = 3 M; Mixing duration = 40 min.

XRF

Raw material	% Composition									
	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	Cr_2O_3	MnO_2	Fe_2O_3	SO_3
FA	-	29.08	58.54	2.92	0.64	6.61	1.82	0.03	0.08	2.05	-
RHA	1.68	-	90.44	4.96	1.61	0.65	0.02	-	0.10	0.48	0.16
Raw soil	-	14.45	66.29	-	1.56	4.49	0.61	-	0.18	12.13	0.17

(SEM – Scanning electron microscopy; XRD – X-ray diffraction; XFR – X-ray fluorescence; FA – Fly ash; RHA – Rice husk ash; UCS – Unconfined compressive strength; M - Molarity)

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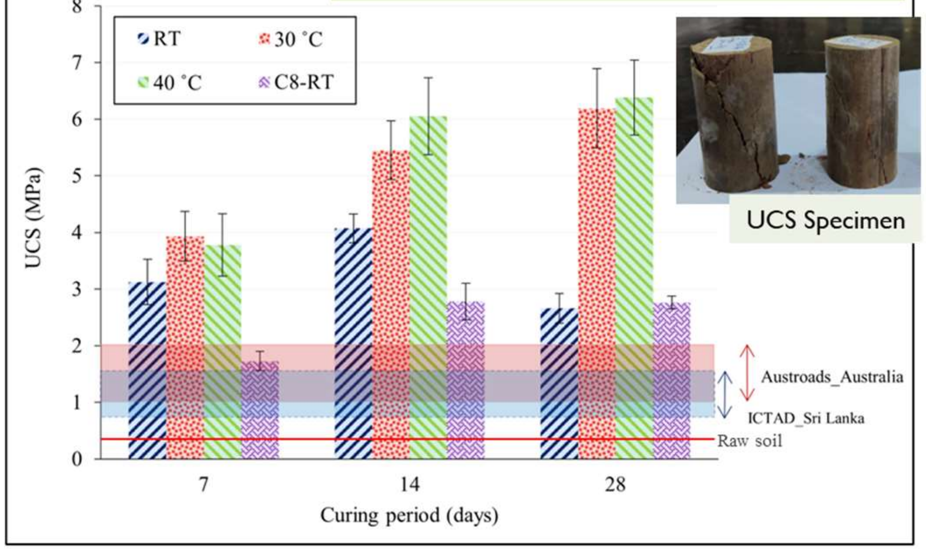
Challenges

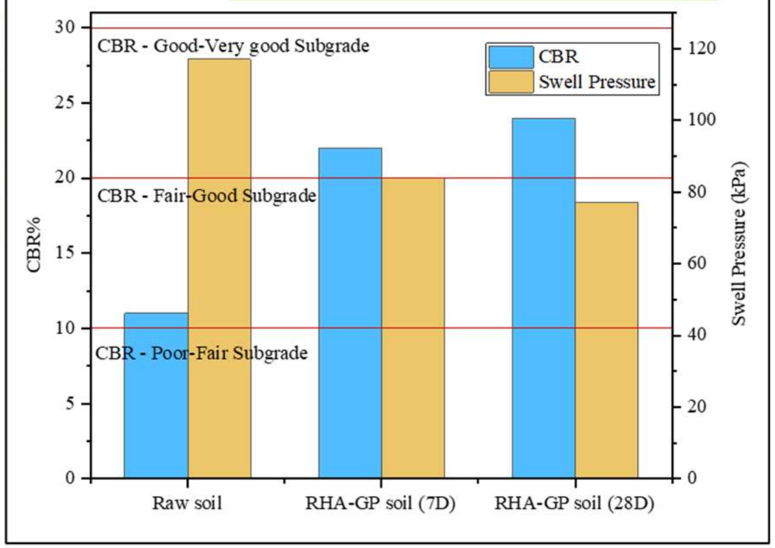
- The UCS test was conducted for stabilized soil samples cured at RT (25 ◦C), 30 ◦C, and 40 ◦C for 7, 14, and 28 days. The temperatures of 30 and 40 ◦C were used to simulate an average heat temperature on pavement subgrades in countries with tropical climates (Phetchuay et al. 2014) and to replicate the extreme heat during summer-time in states such as Australia. In addition, heat is a reaction accelerator for geopolymers, and the beneficial effects of this novel stabilizer could be obtained at higher temperatures. UCS testing was conducted as per BS 1377–7 at a strain loading rate of 1 mm/min.
- A 4-day soaked CBR test was conducted on raw soil and cement and geopolymer-treated expansive soil samples following BS 1377–4.
- The swell pressure test was performed as per IS 2720-Part 41–1977 using the constant volume method.

Challenges

Unconfined compressive strength of RHA-GP soil



CBR% and Swell Pressure of RHA-GP soil



- All samples satisfy UCS criteria.
- At a given curing period, Curing temp. ↑ >> UCS ↑
- After 7 and 28 days of curing the UCS of geopolymer stabilized samples at 40 °C increased from 0.3 MPa (in raw soil) to 3.7 MPa and 6.4 MPa, respectively.
- Higher UCS can be ascribed to better connectivity and the good bonding strength between the geopolymer binder and soil particles.
- With the increasing curing period, the 3D aluminosilicate networks develop further via sialate bonds.

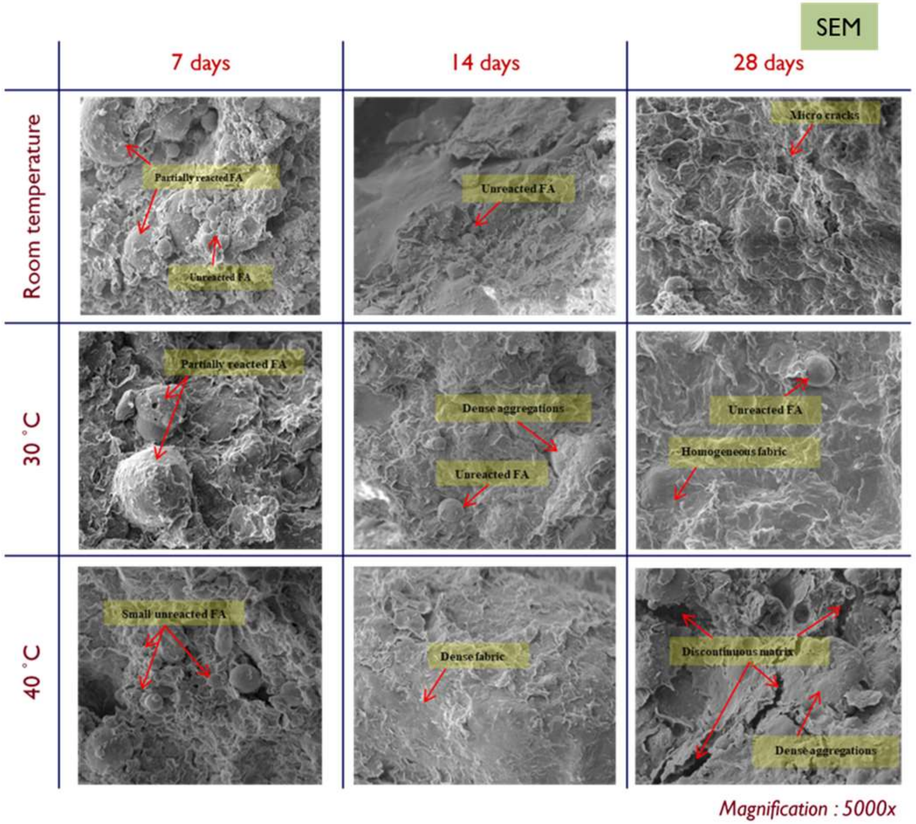
- The CBR of raw soil has increased by approximately 74% (7-day) and 100% (28-day) when treated with the optimized geopolymer, which can be approved to be used under weathering conditions for expansive subgrade stabilization.
- The swell pressure of control soil reduced by 28.2% (7-day) and 34.2% (28-day) following geopolymer treatments.
- This can be linked to the swift exchange of cations between geopolymer and clay minerals which impedes the hydrophilicity of expansive clay minerals.

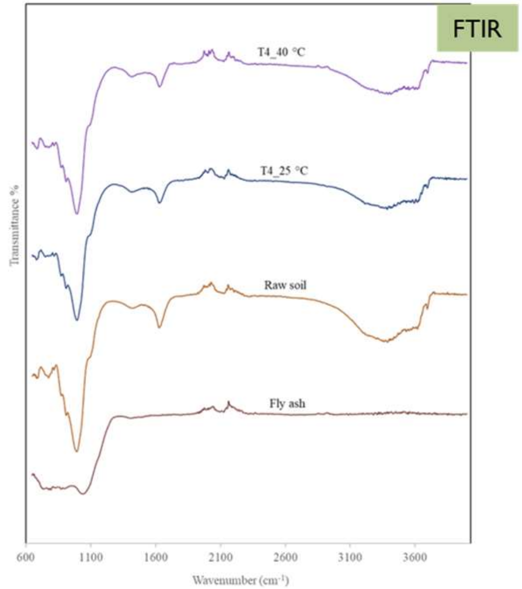
(RHA-GP – Optimized geopolymer treated soil; C8 – 8% cement stabilized soil; RT – Room temperature curing; CBR – California bearing ratio)

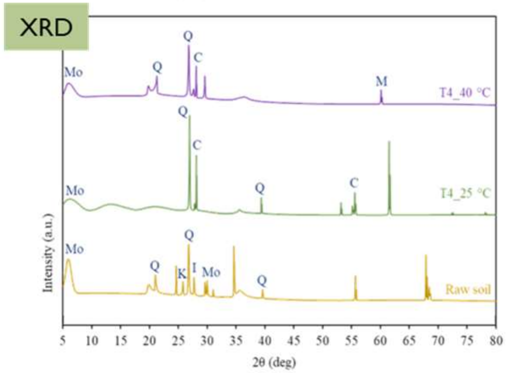
Initiatives Undertaken

- According to SEM images, a larger number of small/large sized partially reacted/unreacted FA particles are visible during room temperature curing after 7 days, which suggests the initiation of reactions, although the morphology of soil-geopolymer mix was not much affected. In contrast, a wide distribution of smaller sized FA particles covered with geopolymer is evident at elevated curing at 40 ◦C. The dissolution of precursors by alkaline activators suggests that the formation of geopolymer products will engulf certain portions of smaller FA particles, thus accelerating the geopolymerization at elevated curing. Dense aggregations and a homogeneous fabric with no significant discontinuities and voids are witnessed with the progression of time up to 28 days. Certain substances observed on the surface of semi reacted FA particles indicate the leaching process of aluminosilicate materials from FA owing to the alkalinity, followed by the precipitation of cementitious products on clay particles, thus offering reinforcement to the clay structure. Clay fabric enhancement with closely linked clay particles bound by fewer voids, geopolymer formation and hardening, and compaction enhancement with curing time produce durable and more stable structures.
- From the XRD plot, it is visible that the Montmorillonite peaks identified at 6◦ and 30◦ in raw expansive soil, reduced and completely disappeared, respectively, with the geopolymer stabilization. In addition, the disappearance of the kaolinite peak in raw soil can be attributed to the formation of flocculated structures owing to the cation exchange reactions during the geopolymerization mechanism (Sharma and Kumar 2020). Several peaks belonging to the original clay minerals were absent in the treated specimens, which indicates the disturbance of their orderly stacked structure during the stabilization procedure (Murmu and Patel 2020), whereas the reduced intensities of several peaks indicate the participation of expansive soil in the stabilization reaction mechanism (Murmu and Patel 2020). Formation of geopolymer binder is implied by the discovery of new peaks at 28◦, 53◦, 61◦, 72◦, and 78◦ 2θ in geopolymer-soil samples cured at RT (T4_25 ◦C), and at 28◦ and 60◦ 2θ in specimens cured at 40 ◦C (T4_40 ◦C). Agunwamba et al. (2021) discussed similar peaks observed at 28◦ 2θ and associated them with crystobalite, indicative of geopolymerization. Besides, a comparison of spectra belonging to geopolymer treated soil at RT and 40 ◦C could detect that most crystalline peaks diminished with increasing curing temperature, thus indicating more materials being utilized in the development of the geopolymer matrix under elevated temperatures (Cristelo et al. 2012).
- The characteristic stretching and bending vibrations corresponding to –OH and H–O–H are observed between 3380 and 3420 cm−1 and at 1629 cm−1, respectively (Murmu and Patel 2020; Murmu et al. 2020) in the FTIR plots. Stretching vibrations bearing weak but sharp peaks are located around 3693 cm−1 in both raw and stabilized soil. These indicate the presence of weakly bonded water molecules (Murmu and Patel 2020; Agunwamba et al. 2021) dominated by the hydrophilic expansive clay minerals, whereas such peaks are absent in FA. The reduction in peak intensities of treated specimens in comparison with raw soil indicates the participation of water in the geopolymerization reaction (Murmu et al. 2019). The bands at 2128 and 2124 cm−1 in treated soil can be assigned to Si–O–Si asymmetric stretching due to unreacted FA particles and crystalline aluminosilicates present in the geopolymersoil matrix (Agunwamba et al. 2021). The shift of strong and sharp peak concentrations from 1032 cm−1 in FA to 995 cm−1 in geopolymer-soil specimens, which represent the asymmetric stretching vibration of Si–O and Al–O, corresponds to the formation of the aluminosilicate matrix (Murmu and Patel 2020; Murmu et al. 2020). As per Agunwamba et al. (2021), they characterize the intense cross-linking of geopolymerization products: sialate and siloxo networks.
- Overall, substantial information from micro-level investigations strongly support the occurrence of geopolymerization within the new RHA-GP treated soil specimen.

Initiatives Undertaken







(Q: Quartz; M: Mullite; Ma: Magnetite; Mo: Montmorillonite; I: Illite; K: Kaolinite; C: Crystobalite)

- More partially and unreacted FA visible under RT conditions.
- Appearance of dense fabric in 14- and 28-days samples compared to 7- and 14-days, respectively.
- Discontinuous matrix visible after 28 days at 40 °C.

(SEM – Scanning electron microscopy; FTIR – Fourier transform infrared spectroscopy; XRD – X-ray diffraction; FA – Fly ash; T4 – Optimized geopolymer treated soil)

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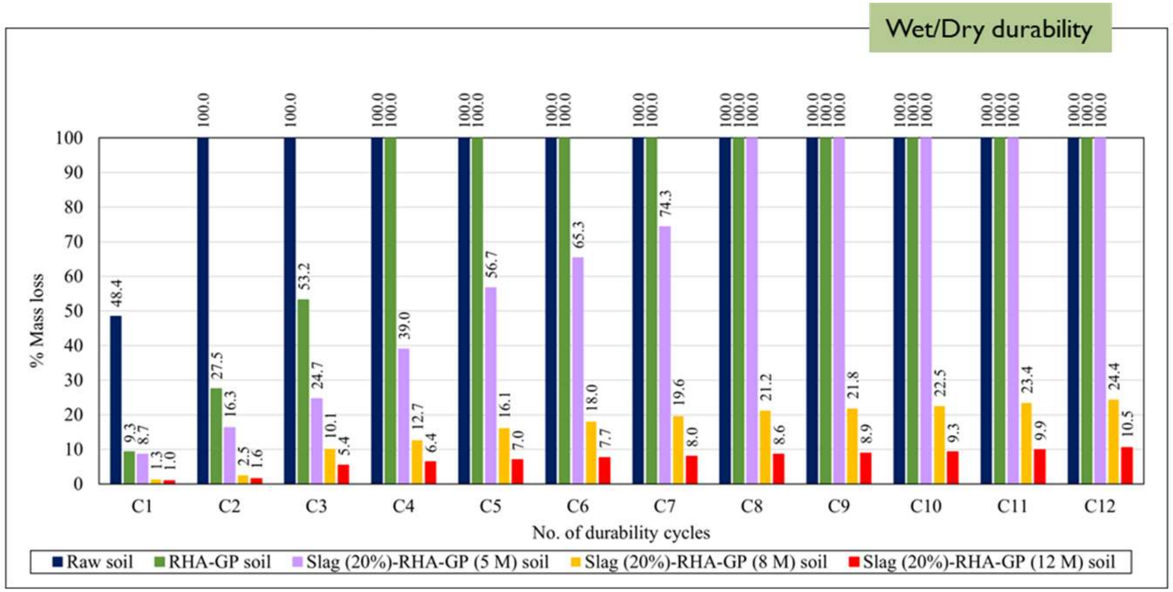
Initiatives Undertaken

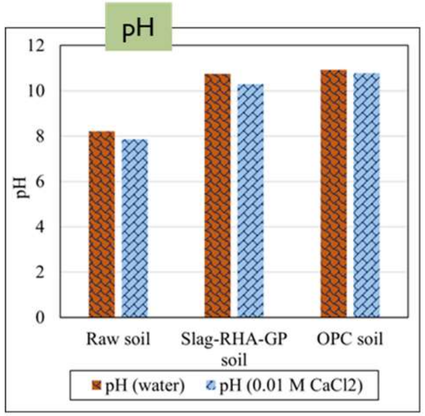
- The wet and dry durability test was conducted based on the standard procedure outlined by ASTM 559 (ASTM 2007). Initially, Wet-dry tests were performed on raw soil and RHA-GP stabilized samples (cured for 28 days at 40 deg). Raw soil sample failed after the first wet cycle as it could not remain in the compacted state. Despite the successful mechanical performance, RHA-GP treated soil lasted only 3 durability cycles. Geopolymerization degradation occurs in geopolymer treated soil samples owing to activator leaching while being submerged in water during the wetting phase, thus deteriorating the binder durability. Ye et al. (2018) stated that the microstructure of the treated soil specimen will be destroyed in the course of drying-wetting cycles, hence resulting in an increased fine particle content. However, beyond a certain number of cycles, formation of micro-fissures will direct to fully developed water flow inside the samples, thereby reaching extensive deterioration.
- Thus, 2 from the original mix ratios (FA/Precursor and NaOH M) derived via the literature review were modified by replacing 20% of the FA with slag (waste product) and maintaining the molarity at 5, 8, and 12 M, in three distinct mix designs (Not changing the optimized RHA based silicate solution preparation ratios). Two modified mix designs with 8M and 12M survived for all the 12 durability cycles.
- However, as stated by the Portland cement association (PCA), the maximum permitted mass loss for cement stabilized soil should be 14% following 12 wet/dry cycles (Hamid and Alnuaim et al., 2023; PCA, 1992). Thus, only the modified mix with 20% slag and 12 M NaOH molarity displayed satisfactory resistance for the durability test, which represents aggressive weather conditions (This mix is referred to as the Slag-RHA-GP (12M) in the slide).
- Following 12 durability cycles, the UCS of slag-RHA-GP-soil specimen was measured and found to be 1.73 MPa, which still satisfies the Austroads criteria for stabilized subgrade applications.
- XRF analysis on slag and OPC confirmed the presence of approximately 35% and 58% CaO, respectively. In addition, increasing the NaOH molarity up to 12 M, also improves the alkalinity in the geopolymer-soil mix. These factors in combination lead to high pH values (10 and 12, respectively). Higher pH favour the dissolution of aluminates and silicates, helping the geopolymerization process. This may have contributed the additional durability gain of the modified Slag-RHA-GP soil mix. The alkalinity differences are well reflected via the pH values depicted in the chart (lower left) as well.
- The findings from the leachate analysis demonstrate that the utilization of the novel Slag-RHA-GP binder for stabilizing expansive soil results in leaching of heavy metals well below the prescribed upper limits established for industrial wastes as per the Environmental Protection Act (EPA), Victoria (2021), hence no environmental risks are reported.

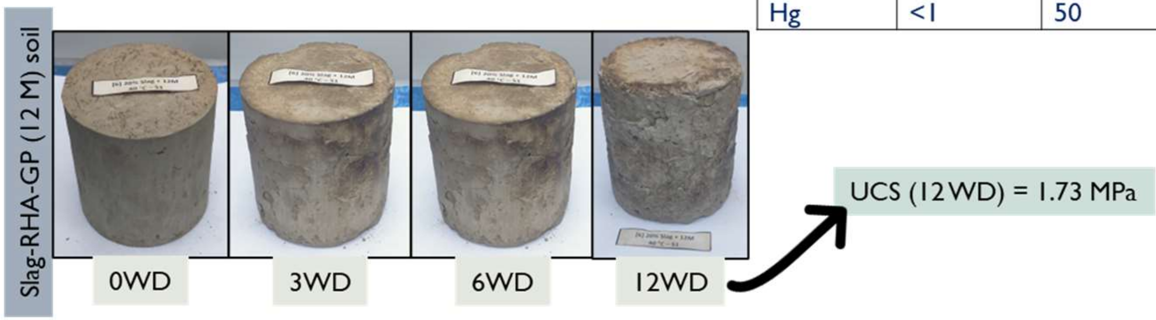
Evidence of Success



Leachate analysis

Leaching element	Concentration (ug/L) (90 days)	
	Slag-RHA-GP	EPA Category D upper limits (Victoria, 2021)
Cr	26.022	2500
Mn	<1	Not given
Co	2.915	Not given
Ni	4.573	1000
Cu	31.649	100000
Zn	4.986	150000
As	5.144	500
Cd	<1	100
Sb	<1	150
Pb	<1	500
Hg	<1	50





(RHA-GP – Optimized geopolymer treated soil; Slag-RHA-GP – Optimized (modified) geopolymer treated soil; OPC – ordinary Portland cement; RT – Room temperature curing; WD – Wet/dry cycle; EPA – Environmental protection authority; UCS – Unconfined compressive strength)

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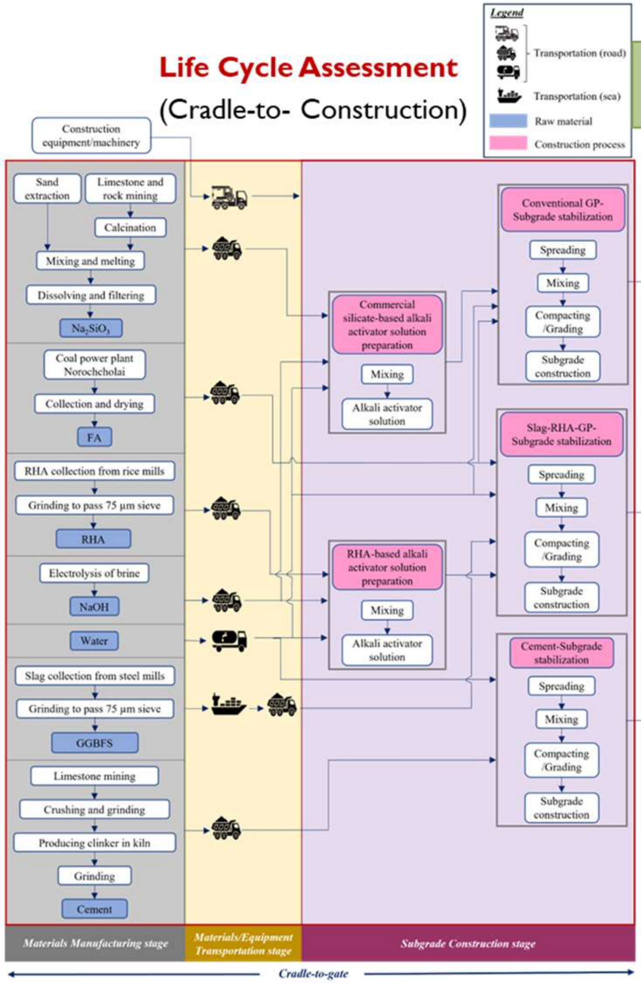
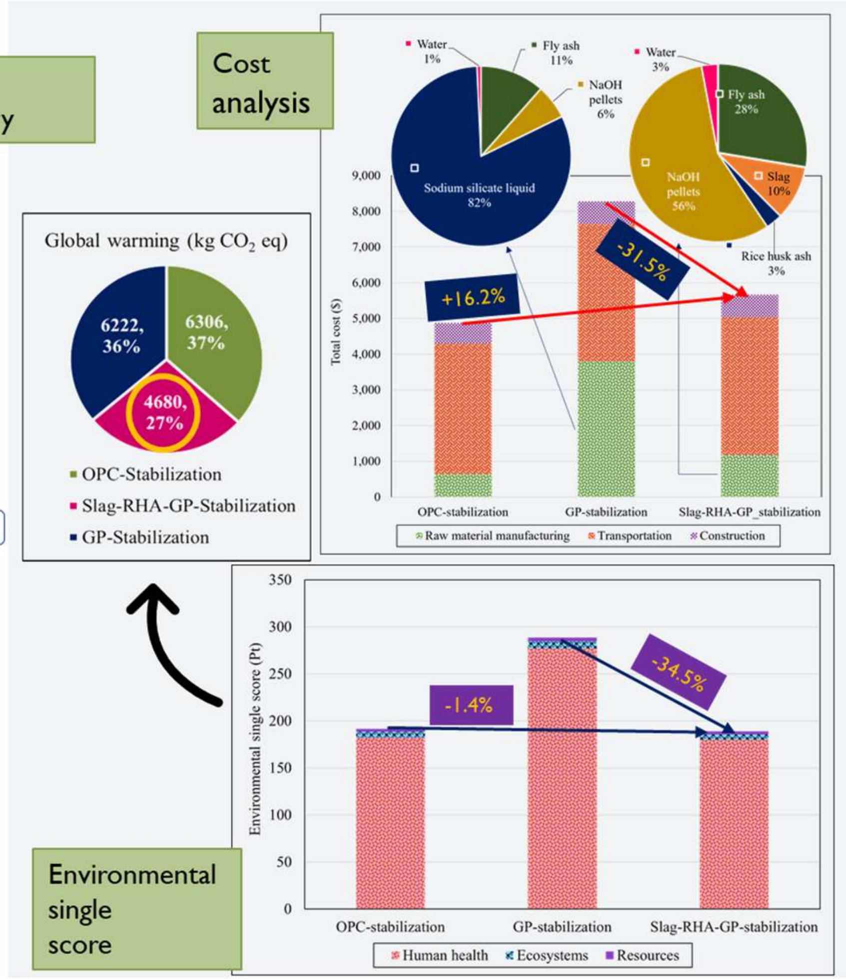
Evidence of Success

- A Life Cycle Assessment (LCA) was conducted to perform a comparative estimation of environmental impacts of three soil stabilizers: (1) Modified Slag-FA-based geopolymer activated using a combination of RHA-based silicate solution and NaOH solution (Slag-RHA-GP); (2) FA-based geopolymer activated using a combination of commercial Na2SiO3 liquid and NaOH solution (GP); and (3) OPC, based on a case study related to stabilized expansive road subgrade construction. The scope of the study is restricted to cradle-to-gate, until the end of the road subgrade construction phase.
- The functional unit used in this study is 50 m length of road section (3 m width, and 0.2 m depth) of stabilized soil. The system boundary encompasses emissions originating from the material manufacturing phase, the transportation of raw materials and machinery to the construction site, and emissions arising from equipment and machinery operation throughout the subgrade construction phase.
- Required data were sourced and integrated from the Ecoinvent v3.9.1 database, compiled as of January 2023, and from previous LCAs. Transportation stage inventory involves the environmental impacts associated with the transportation of raw materials and machinery, from suppliers to the construction site, covering elements such as fuel consumption, vehicle maintenance, emissions, and energy usage. Data on the standard construction equipment selection for the construction stage were acquired through expert knowledge from engineers involved in comparable projects and through vehicle specifications.
- SimaPro software (version 9.5.0) and Microsoft Excel were employed to construct the model, execute calculations. This study utilized the ReCiPe Mid-Point (Europe H) impact assessment methodology. ReCiPe end-point assessment was also carried out to evaluate the environmental impacts considering three categories: human health, ecosystem and resource scarcity. Several mid-point impact categories are grouped together to form these 3 groups during the end point assessment.
- As per the environmental single score based on the end-point assessment, the Slag-RHA-GP method exhibited the lowest total points, which is 1.4% and 34.5% lower than OPC and GP stabilizations, respectively. The predominant impact across all three stabilization methods was on human health, with percentages of 94.2%, 95.6% and 94.5% for Slag-RHA-GP, GP and OPC, respectively.
- Considering the mid-point impact; global warming potential, Slag-RHA-GP has the minimal impact (27%), compared to the 36% and 37% impact by conventional GP and OPC treatments, respectively.
- The overall cost from Slag-RHA-GP treatment is 31.5% lower compared to the traditional GP stabilization, however its 16.2% higher compared to OPC treatment. Na2SiO3 liquid is responsible for 82% of the total material cost in GP stabilization, which was drastically reduced due to the utilization of RHA based silicate in the new binder. Thus, Slag-RHA-GP stabilization can be recommended as a more favourable option compared to conventional geopolymer stabilization.
- In addition, environmental benefits may be forthcoming by utilizing FA, RHA, and slag from the storage sites, which will otherwise be disposed of thus contaminating soil and water sources due to leaching of hazardous elements.

Evidence of Success





(FA - Fly ash; RHA – Rice husk ash; GGBFS – Ground granulated blast furnace slag; GP – Conventional silicate based geopolymer; Slag-RHA-GP – Optimized (modified) geopolymer treated soil; OPC – ordinary Portland cement; RT – Room temperature curing)

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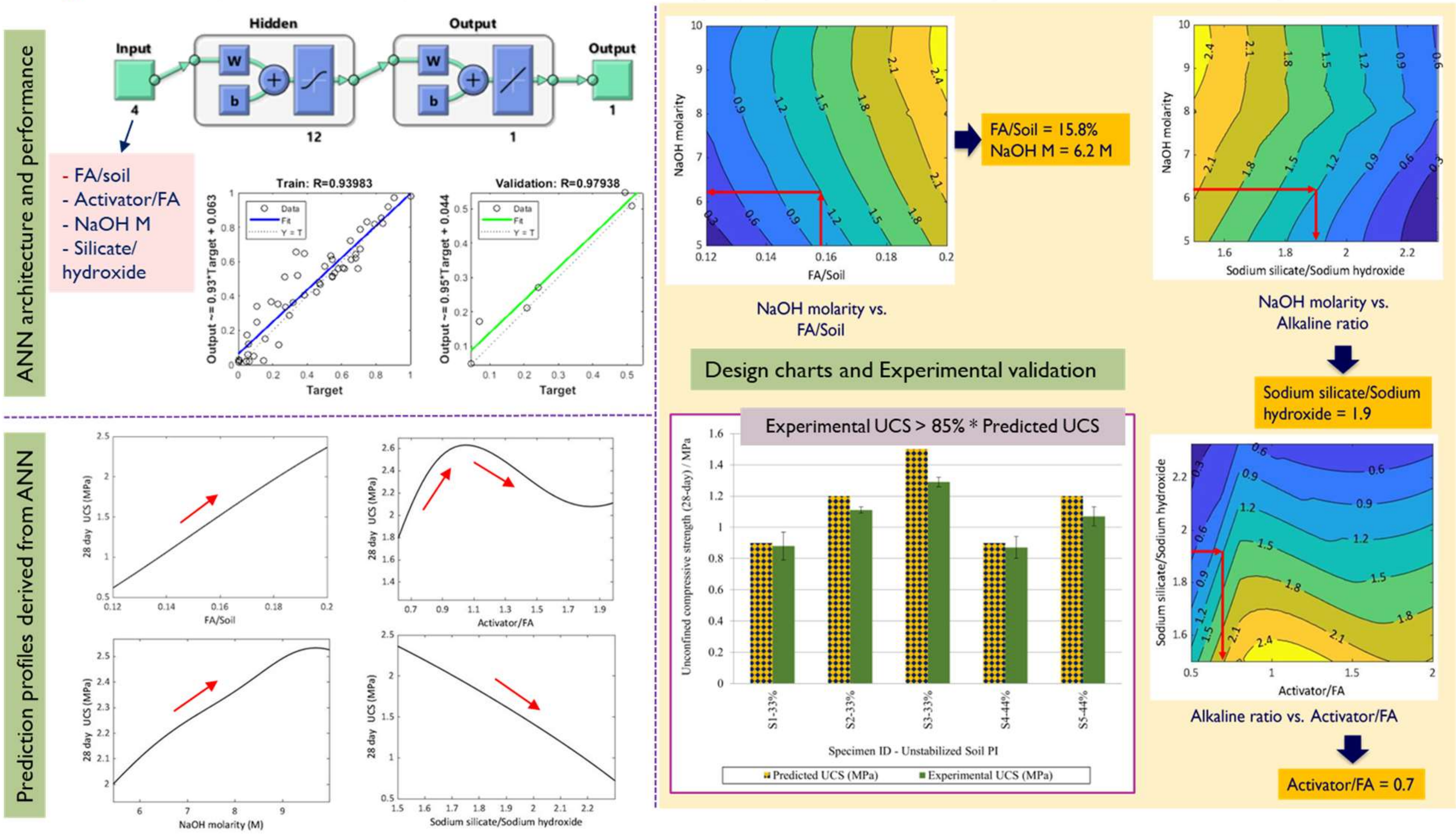
Evidence of Success

- This is with reference to the literature study carried out on conventional geopolymer treated expansive soil.
- Despite the successful performance of Class F FA based geopolymer-expansive soil stabilization that has been studied extensively during previous studies, to date, no efforts have been taken to develop a mixture design guideline or charts to assist the practical implementation of those research findings, which will otherwise require a large number of laboratory tests for the mix optimization. Thus, a machine learning model via artificial neural networks (ANN) was developed using MATLAB software to ultimately produce essential design charts, which can be utilized for obtaining the mix compositions for a targeted range of compressive strengths in highly expansive (PI between 32% – 46%) subgrade stabilization using class F FA based geopolymers activated by conventional activators. Information from this section was particularly useful in obtaining the optimum mix ratios (FA/soil, activator/FA, NaOH M etc.) for geopolymer-soil stabilization. The proposed model was developed on the basis of literature data and has been adopted to propose three design charts with successful validation using in-house lab tests.
- The ANN model predictions for both the training and validation datasets correlate well with the experimental results.
- The lower left figures depict the prediction profiles of the ANN model, which demonstrate the individual effects of FA/soil, activator/FA, NaOH molarity, and the alkaline ratio (Na2SiO3/NaOH) on 28-day UCS, for selected ranges of the respective parameters, chosen based on the range of input data distribution.
- UCS continued to rise as the FA/soil ratio increased from 0.12 through 0.2. This is due to the provision of aluminosilicates by FA, that dissolve in the presence of the alkaline environment, which later polymerize to form long chains to bind the soil particles together.
- Activator/FA > 0.6 offers dramatic UCS improvements up to approximately activator/FA = 1.0, which can be ascribed to the formation of polysialatesiloxo (-Si-OAl-O-Si-O-) structures at higher activator/FA ratios as a result of the abundant availability of soluble silicates (Cioffi et al., 2003), hence producing robust geopolymer-expansive soil configurations.
- NaOH molarities exceeding 5 M progressively increase the 28-day UCS of treated soil.
- Na2SiO3/NaOH = 1.5 produces the maximum UCS at 28 days, beyond which the strength indicated a diminishing trend. Na2SiO3 acts as a nucleating site for hydration points and increases the number of contact points between hydration materials, thus forming a solid microstructure (Van et al., 2018), which also constrains moisture absorption due to the agglomeration and flocculation mechanisms in treated expansive soil. On the contrary, excess Na2SiO3 will increase the total solid particles in the soil geopolymer mix and reduce the free water available for compaction. Thus, more voids will lead to less surface area contacts that ultimately impede the alkaline activation reaction and the UCS.
- The contour plots can be utilized to ensure the design compliance of expansive subgrades with industry standards and guidelines. If the PI of raw soil falls under the scope specified in this study (32% – 46%), and the target 28-day UCS requirement is known according to the standards, the produced contour plots can be appropriately employed in deciding the mix proportions for the subgrade stabilization procedure. According to the results from the in-house experimental validation of the contour plots, overall, all the specimens achieved at least 85% of UCS in contrast to their predicted performance.
- Particularly, plots will facilitate better consumption of available materials. Furthermore, incorporation of swelling characteristics of subgrade soil in the initial pavement design procedure will also curtail the rehabilitation expenses due to expansive soil. In addition, the outputs from this exercise will positively cater to the averseness among the industrial community to adopt geopolymer for expansive soil stabilization applications due to lack of proper guidelines. Hence, this study is a pragmatic approach in the utilization of conventional geopolymeric binders for construction applications.

Evidence of Success

Design charts to predict the 28-day UCS of class F FA based geopolymers activated using NaOH and Na_2SiO_3 using **ANN**



(FA - Fly ash; UCS – Unconfined compressive strength; ANN – Artificial neural network; M – Molarity)

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Key Points of Interest

- A novel RHA-based silicate solution combined with NaOH can be used as an activator to prepare geopolymers for expansive soil stabilization, and the optimum mixture composition for preparing the RHA-based silicate solution for a higher UCS of the stabilized soil includes NaOH/RHA = 0.6, NaOH molarity = 3 mol/L, and mixing duration = 40 min.
- RHA-GP treatment preforms better at elevated curing temperatures (at 40 deg - high strength gain).
- The CBR (7-day) of the RHA-GP treated soil (22%), represents a "very good subgrade".
- Precursor/soil = 0.2, Slag/FA = 0.2, NaOH M = 12 M, Activator/precursor = 0.4 along with the optimized RHA-silicate solution preparation ratios render a geopolymer mix (Slag-RHA-GP) which could restrain aggressive weather conditions, evident by the survival of the 12 wet/dry durability cycles with a mass loss (10.5%), which is below the stipulated criterion by PCA (14%).
- SEM, XRD, and FTIR findings provide substantiating evidence for the formation of a geopolymerization matrix within the geopolymer stabilized soil specimen.
- The leaching of heavy metals from Slag-RHA-GP-treated soil remains substantially below the thresholds established for industrial waste and is compliant with the standards set by the World Health Organization (WHO) for drinking water. Consequently, the utilization of the novel geopolymer stabilizer poses no evident harm to either soil integrity or water sources.
- As per the environmental single score from the LCA, the overall impact on the environment from Slag-RHA-GP treatment is 34.5% and 1.4% lower compared to conventional GP and OPC treatments.
- The waste-derived Slag-RHA-GP treatment demonstrates a cost-effectiveness that is approximately 31.5% lower than conventional GP treatment.
- ANN models can be successfully utilized for reliable predictions of the 28-day compressive strength of conventional class F FA based geopolymer treated expansive soil with plasticity index (PI) varying between 32% and 46%.

Key Points of Interest

The outcomes of this research have been documented in the following publications

- Maheepala, M.M.A.L.N., Nasvi, M.C.M., Robert, D.J., Gunasekara, C. and Kurukulasuriya, L.C., 2022. A comprehensive review on geotechnical properties of alkali activated binder treated expansive soil. Journal of Cleaner Production, 363, p.132488
- Maheepala, M.M.A.L.N., Nasvi, M.C.M., Robert, D.J., Gunasekara, C. and Kurukulasuriya, L.C., 2023. Mix design development for geopolymer treated expansive subgrades using artificial neural network. Computers and Geotechnics, 161, p.105534
- Maheepala, M.M.A.L.N., Nasvi, M.C.M., Robert, D.J., Gunasekara, C. and Kurukulasuriya, L.C., 2024. Mix optimization for expansive soil stabilized with a novel waste material-based geopolymerization approach. Canadian Geotechnical Journal

Publications in drafting

- Life cycle assessment of geopolymer stabilized expansive subgrade incorporating a combination of novel rice husk ask-based silicate solution and sodium hydroxide as the alkaline activator
- Durability characteristics of geopolymer stabilized expansive soil incorporating a combination of novel rice husk ask-based silicate solution and sodium hydroxide as the alkaline activator