Formulation of a sustainable geopolymeric binder based on pulp mill fly ash for subgrade stabilization

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ABSTRACT
In this study, an inorganic geopolymer binder based on non-hazardous pulp mill fly ash was developed for sustainable soil stabilization using alkali-silicate activation method. The formulation of fly ash-geopolymer was optimized in terms of maximum strength development, with considering key influencing parameters such as ash dosage, activator chemistry (NaOH molarity, and NaOH/Na_2SiO_3 ratio), activator/ash ratio, and curing period. The optimum conditions for achieving higher rate of fly ash geopolymerization was determined to be 20% ash and 5 molar NaOH in 1:1 activator/ash and NaOH/ Na_2SiO_3 ratios. Microstructural examination using SEM-EDS analysis revealed the formation of uniform and dense geopolymer network on soil surface and pores with high calcium and silica concentration, causing significant subgrade strength improvement.

RÉSUMÉ
Dans cette étude, un liant géopolymère inorganique basé sur les cendres volantes non dangereuses des usines de pâte à papier a été développé pour une stabilisation durable du sol en utilisant une méthode d'activation alcaline-silicate. La formulation du géopolymère de cendres volantes a été optimisée en termes de développement de résistance maximale, en tenant compte des paramètres d'influence clés tels que le dosage des cendres, la chimie de l'activateur (molarité NaOH et rapport NaOH/Na_2SiO_3), le rapport activateur/cendres et la période de durcissement. Il a été déterminé que les conditions optimales pour atteindre un taux plus élevé de géopolymérisation des cendres volantes étaient de 20% de cendres et 5 molaires de NaOH dans des rapports 1:1 activateur / cendres et NaOH/Na_2SiO_3. L'examen microstructural à l'aide de SEM-EDS a révélé la formation d'un réseau géopolymère uniforme et dense sur la surface du sol et les pores avec une concentration élevée en calcium et en silice, entraînant une amélioration significative de la résistance du sol.

1 INTRODUCTION

The "pulp mill fly ash" (denoted as PFA), a wood combustion by-product generated in boilers during pulp manufacturing process, is an environmentally massive inorganic waste mostly discarded in industrial landfills (Cherian and Siddiqua 2019; Quina and Pinheiro 2020). Due to increasing concerns of environmental pollution and growing scarcity of land, pulp and paper industries are actively seeking innovative technologies and strategies for environmentally and economically sustainable use of PFA with circular economy as a key driver. Although the utilization of class C and class F coal ashes for various engineering applications has been established and well documented, there is limited research conducted on beneficial uses of PFA. Few studies demonstrated that PFA can provide potential raw materials for various applications such as fertilizer and liming agent in agricultural sector (Etiégni et al. 1991; Hannam et al. 2016), cementitious binder in construction (Chowdhury et al. 2015; Oliveira et al. 2017), and adsorbent for contaminant remediation (Malakootian et al. 2008; Laohaprapanon et al. 2010). However, only less than 25% of PFA is recycled and used as beneficial alternatives for natural and non-renewable resources in Canada. This is owing to the implementation of stringent environmental regulations and lack of standards and guidelines for utilization of PFA in the wide range of commercial applications (Hannam et al. 2016).

As Portland cement and coal ashes have been used as commercial binders for road construction and maintenance applications, it is anticipated that the utilization of green waste PFA as a sustainable and eco-efficient alternative can address the global warming issues currently posed by the construction and infrastructure sector. By formulating a suitable chemical additive from PFA to improve the properties of locally available weak soil can also reduce the cut-and-fill costs and allay the need of further maintenance.

Some recent research reported that PFA-based treatment can upgrade the mechanical and durability properties of pavement subgrade to withstand the anticipated traffic load and resist the damages attributed by seasonal climate/moisture variations (Zhou et al. 2000; Arm et al. 2014; Zumrawi 2015; Škels et al. 2016; James et al. 2018). Further, few latest studies have explored newer areas such as transforming as-received ash into an inert geopolymer product with enhanced pozzolanic activity, and engineering properties suitable for specialized applications (Pachumuthu and Thangaraju 2016; Leong et al. 2019).The ash-based geopolymer is most efficiently synthesized through chemical activation method in high temperature conditions using strong alkaline environments (with NaOH or KOH solutions) and supplementary silicate sources such as Na_2SiO_3 or K_2SiO_3 (Cristelo et al. 2012; Leong et al. 2019). However, the key challenge in developing environmentally and economically sustainable PFA-geopolymers is attaining desirable improvement with eco-friendly activators (i.e. low concentrations and dosages) in ambient conditions (i.e. low temperature).

In view of the above, the present study was conducted to develop a new sustainable geopolymer binder for subgrade stabilization based on an inexpensive, easily accessible and non-hazardous PFA under ambient conditions. The inorganic PFA-geopolymer was formulated using alkali-silicate activation method, and optimum formula was determined in terms of mechanical improvement of treated subgrade. The key influencing parameters such as ash dosage, activator chemistry, activator/ash ratio, and curing period were considered as variables in this study. It is anticipated that the implications of these research findings will facilitate the development of standards and guidelines for beneficial use of PFA and secondary products in commercial applications. It will also significantly contribute towards the reduction of stockpiles of this waste product and its impacts on the environment and public health.

2. MATERIALS AND METHODS

As aforementioned, the multicyclone PFA by-product collected from the boiler unit of a local Kraft pulp mill was used as precursor for the geopolymer formulation. A well-graded silty sand subgrade material with poor strength properties encountered in the interior region of British Columbia (BC) was used for the experimental studies.

2.1 Characterization of Pulp Mill Fly Ash

A better knowledge of the physicochemical, mineralogical, and leachate characteristics of PFA is essential for their eco-efficient utilization. In regards to this, the most relevant properties of PFA were evaluated for determining its suitability as chemical binder for subgrade stabilization applications.

2.1.1 Physicochemical properties

The specific gravity (G) was determined using water pycnometer method as per ASTM D854-14 and natural moisture content (NMC) as per ASTM D2216-19. The particle fineness and grain size distribution (GSD) was obtained based on laser diffraction method, and the plasticity properties were determined as per ASTM D4318-17e1. The particle surface area (SA) was determined using Braunauer-Emmett-Teller's (BET) multilayer adsorption technique, using a TriStar II Plus, Micromeritics apparatus. The pH and electrical conductivity (EC) were measured in soil suspensions prepared using de-ionized water (corresponding to 1:2 soil/water ratio). Total carbon content was determined based on the loss-on-ignition (LOI) method as per ASTM D2974-20e1.

Table 1 presents the physicochemical properties of PFA. It is the lightest component of solid residues generated during wood combustion with specific gravity 2.78. The high NMC of 29% was attributed by its hydrophilic nature; it also leads to particle agglomeration. The particle size ranged from 0.3 to 150 µm, and surface area was 39.98 m^2/g. These physical properties are closely matching with that of ordinary Portland cement.

Table 1. Important characteristics of pulp mill fly ash

Property	Value
Specific gravity, G	2.78
Natural moisture content, NMC (%)	29
SA_{BET} (m^2/g)	39.98
Particle size range (µm)	0.3-150
Fineness, D_{50} (µm)	16
Clay-size fraction (< 2µm), %	21.8
Silt-size fraction (2µm-75 µm), %	53.4
Plasticity index (%)	Non-plastic
Loss on ignition, LOI @ 900˚C (%)	24.3
pH @ 20˚C	13
Electrical conductivity, EC @ 20˚C (µS/cm)	96.9

The key determinants of fly ash chemistry are the wood species combusted, nature of combustion process and conditions at the application site (Naik and Kraus 2003). The total carbon content of PFA determined in terms of LOI was 24.3%. The average LOI of wood ash is 20 to 30%, and the value ranges between 5 to 60 % depending on the wood type and combustion conditions (Cherian and Siddiqua 2019). PFA also had high alkaline pH of 13, which was mainly attributed to addition of lime as causticizing material in the pulping process.

2.1.2 Microstructural properties

The morphological properties of PFA were determined using TESCAN Mira 3 XMU scanning electron microscope (SEM) employing a field emission gun, and elemental composition was determined in the percent range using an Oxford Instruments X-Max EDS (energy dispersive spectrometer) detector. Further, the X-ray diffraction (XRD) analysis was performed using a Bruker D8 Advance Bragg-Brentano diffractometer (equipped with Co-Kα source), and relative mass proportions of different mineral phases in PFA were calculated using semi-quantitative phase analysis (QPA).

SEM image of PFA depicted in Figure 1 exhibited a heterogeneous mixture of irregular and angular shaped inorganic particles. These irregular particles are essentially hydrophilic in nature and absorbs water into the pores by capillary action simultaneously with hydration of oxides. There are many agglomerated cloudy particles and few spherical particles (also termed as cenopshere). Some particles have porous cellular form which are remains of unburned or partially burned wood. According to EDS spectrum, PFA comprises high amount of Ca, which imparts the desirable cementing properties. The particle fineness, high surface irregularity and porous nature also make of this waste a potential adsorbent material for removal of metals or organic pollutants.

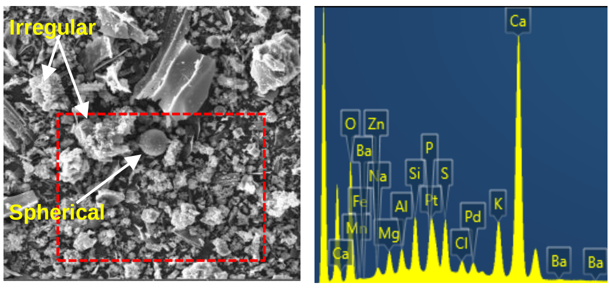


Figure 1. SEM image and EDS spectrum of pulp mill fly ash

Figure 2 revealed that PFA predominantly constituted crystalline phases such as Calcite (64.6%), Syngenite (14.6%), Portlandite (10.5%), Quartz (5.9%), and Hydrocalumite (4.4%). As aforementioned, the high proportion of calcium minerals and presence of other reactive aluminosilicate contents as well as some glassy phases imparts self-cementitious property to PFA which is beneficial for several applications such as stabilization of weak subgrades (Naik and Kraus 2003; Grau et al. 2015).

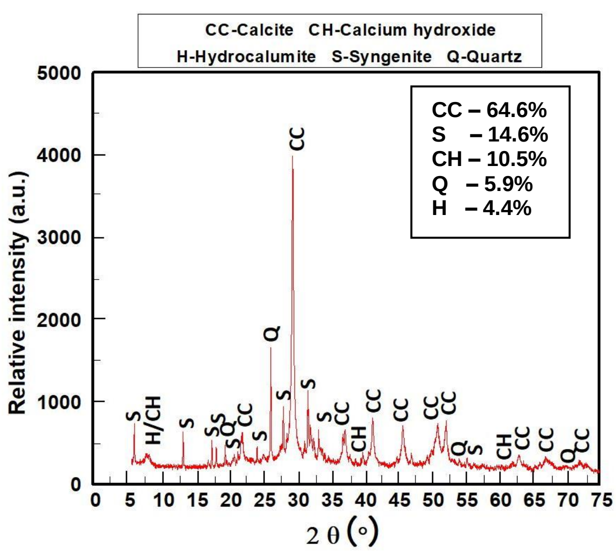


Figure 2. Mineral composition of pulp mill fly ash obtained from XRD analysis

2.1.3 Environmental impact assessment

In order to understand the potential contamination by hazardous heavy metals present in PFA, the environmental impact assessment was done by evaluating PFA leachate characteristics (Zhou et al. 2000; Camberato et al. 2011). Powdered and oven-dried PFA was digested in aqua-regia (concentrated acid medium) at high temperature. An aliquot of clear suspensions from digested samples was diluted and analyzed using Agilent 8900 Triple Quadrupole ICP-MS (inductively coupled plasma-mass spectrometry) for determining trace element concentrations in PFA. In addition, water-based dissolution procedures were followed to analyze water-soluble metal concentrations. Table 2 summarizes the obtained results of environmental risk analysis.

Table 2. Trace element concentrations of pulp mill fly ash

Concentration of trace elements in PFA (mg/kg)			Provincial standard (mg/kg)
	Acid digestion in aqua regia	Batch dissolution in de-ionized water	
As	19.7	<0.01	75
Ba	476	0.22	N/P
Cd	3.0	<0.01	20
Co	3.5	<0.01	150
Cr	16.8	0.45	1060
Cu	67.6	0.01	2200
Mo	6.1	0.56	20
Ni	12.1	<0.01	180
Pb	56.5	0.05	500
Se	1.32	0.02	14
V	15.7	<0.01	N/P
Hg	3.5	0.21	5
Zn	1186	0.12	1850

Note: N/P- not provided

The various trace elements concentrations in the PFA leachate obtained from acid digestion as well as batch-dissolution processes were well below permissible limits according to BC Soil Amendment Code of Practice (SACoP 2020). Based on these results, PFA can be considered as a non-hazardous material and it can be safely utilized for sustainable environmental applications.

2.2 Characterization of Subgrade Soil

Table 3 presents the important index and engineering properties of subgrade soil. The soil consisted of 25.8% of silt and clay fractions, 66% sand and 8.2% gravel. Most importantly, it showed poor plasticity properties, attributed by a low clay content. The compaction characteristics of soil was determined using miniature Proctor compaction test (Sridharan and Sivapullaiah 2005); the optimum moisture content (OMC) and maximum dry unit weight (Υ_{dmax}) were 16.7 % and 17.3 kN/m^3, respectively.

Table 3. Important properties of subgrade soil

Property	Value
Specific gravity, G	2.60
Natural moisture content, NMC (%)	9.1
Particle size distribution (%)	
Silt and clay fractions (< 75 µm)	25.8
Sand fraction (75 µm - 4.75 mm)	66.0
Gravel content (> 4.75 mm)	8.2
Plasticity properties (%)	
Liquid limit, LL	20.6
Plastic limit, PL	19.8
Plasticity index, PI	0.8
Compaction characteristics	
Optimum moisture content, OMC (%)	16.7
Maximum dry unit weight, γ_{dmax} (kN/m^3)	17.3

2.3 Formulation of Fly Ash-Geopolymer Binder

Geopolymerization is an established fly ash valorization technique which forms amorphous three-dimensional aluminosilicate materials termed as geopolymers (Palomo et al. 1999; Rios et al. 2018). During this treatment, the high hydroxyl (OH^-) concentration in the medium breaks down structural silica and alumina bonds. The dissolved free Si and Al ions react with alkaline cations (viz. Na+ or K+) to form intermediate products that precipitate and reorganize into more stable and ordered polymeric aluminosilicate compounds, characterized by improved physicochemical properties and better reactivity (Cristelo et al. 2013). In this study, as-received PFA was transformed into an inorganic geopolymer compound using different combinations of NaOH and Na_2SiO_3 as alkali-silicate activator solution.

For this purpose, the optimum PFA dosage was initially determined based on 28-day unconfined compressive strength (UCS) variations of virgin PFA treated soil. For preparing UCS samples, the as-received ash was oven-dried, pulverized and passed through 75µ sieve to obtain a uniform and representative material. The soil was air-dried and passed through 2mm sieve for obtaining uniformly-graded material. The dry soil and ash were first homogeneously combined and further moistened with de-ionized water corresponding to OMC of respective mixtures (viz., 10%, 20% and 30% PFA).

The addition of PFA caused increase in OMC (from 16.7 to 25.6 % for 30% PFA) and decrease in γ_{dmax} (from 1.62 to 1.51 for 30% PFA). The decrease in γ_{dmax} was a result of partial substitution of soil particles with lighter fly ash particles, whereas increase in OMC was attributed by hydrophilic nature of PFA. As shown in Figure 3, the optimum PFA dosage for achieving geopolymerization efficiency was determined to be 20% by dry weight of soil, which could mobilize the desirable strength (i.e. 450 to 600 kPa) required for a flexible pavement subgrade layer as per the U. S. Transportation Research Board guidelines (Hopkins 1994).

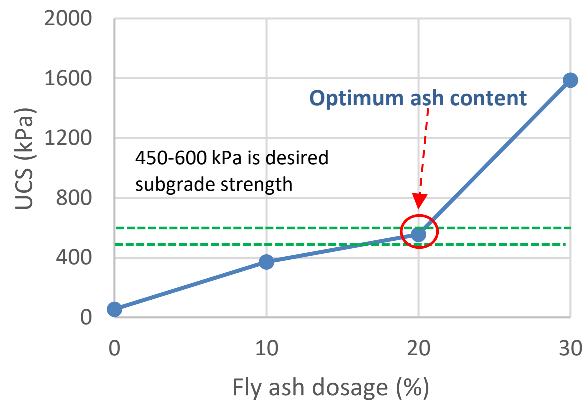


Figure 3. UCS variations for pulp mill fly ash-treated subgrade after 28 days curing

Further, the activator chemistry was varied in the 80% soil + 20% PFA mix design using different NaOH molarity, Na_2SiO_3/NaOH ratio, and activator/ash ratio. Table 4 summarizes the total design mixes considered in this study. The NaOH molarity of 5M and 10M were considered based on previous literature (Pachumuthu and Thangaraju 2016; Muhammad and Siddiqua 2019). The concentrated NaOH provided highly alkaline environment for facilitating the maximum dissolution of reactive alumino-silicates in soil and PFA, which acted as the precursors for geopolymerization reactions. Likewise, Na_2SiO_3 compound was added in 2:1, 1:1 and 0.5:1 Na_2SiO_3/NaOH ratio, respectively. It acted as a source of supplementary reactive silica for accelerating the rate of geopolymerization reactions. For comparing the effect of additional silica source, one set of treatment was also carried out in the absence of Na_2SiO_3 (i.e. Na_2SiO_3/NaOH ratio of 0:1).

Table 4. Mix designs for pulp mill fly ash-geopolymer treated subgrade

Treatment type	Ash %	Activator chemistry		Activator/ash ratio
		NaOH (M)	Na_2SiO_3/ NaOH	
Untreated	0	-	-	-
Virgin ash	20	-	-	0:1
Alkali-silicate activation	20	5	0.5:1	0.5:1
	20	5	0.5:1	1:1
	20	5	1:1	1:1
	20	10	2:1	1:1
Alkaline activation	20	5	0:1	1:1
	20	10	0:1	1:1

2.4 Sample Preparation and Strength Evaluation

To prepare the different design mixes, the dry components (soil + 20% PFA by dry weight of soil) were homogeneously combined and further moistened with activator solution corresponding to optimum moisture content (OMC~21%). For comparative evaluation, the untreated soil samples (~

0% PFA) were also prepared corresponding to its OMC (~16.7%). The prepared different mixtures were immediately compacted in three layers to reach maximum density. The cylindrical specimens of 38mm diameter * 76 mm height were cast and cured under ambient conditions (~ 22°C and 80-85% relative humidity) in order to simulate the natural field conditions for 7, 14, 21 and 28 days. After curing, the specimens were tested for evaluating the mechanical performance in terms of UCS variations.

2.5 Microstructural Examination of Treated Subgrade

The post-treatment alterations of microstructure in the chemically stabilized soils have a predominant influence on its engineering properties. Therefore, it is crucial to perform a micro-level investigation of the fly ash treated subgrade and obtain substantiating evidence for the macro-level changes. In view of this, the treated and cured subgrade samples were examined using SEM-EDS analysis and the morphological and compositional characteristics of geopolymer compound formed by alkali-silicate activation of PFA, as well as the new cementitious compounds were determined.

2.6 Leachability Test of Treated Subgrade

The leachate characteristics of PFA-geopolymer treated subgrade was determined in terms of variations in the trace metal concentrations, using batch-dissolution experiments (Sack et al. 1981). The representative samples of specimens after 28 days curing was oven-dried and crushed into fine powder followed by mixing with de-ionised water (at a liquid to solid ratio of 5) and continuously agitated in an orbital shaker for 48 hours. Later, all solutions were filtered and analysed using Agilent 8900 Triple Quadrupole ICP-MS. The obtained results were analysed for assessing any potential contamination of environment by hazardous heavy metals leached from PFA and other impurities in the products during their implementation and service life.

3 RESULTS AND DISCUSSION

3.1 Improvement in Mechanical Properties

Figure 4 shows the UCS variation of subgrade material treated with PFA, and alkaline activator corresponding to different activator chemistry (NaOH molarity and Na_2SiO_3/NaOH ratio) and constant activator to ash ratio of 1:1. The results revealed that a lower NaOH molarity and lower Na_2SiO_3/NaOH ratio instilled more efficient PFA geopolymerization and significantly high compressive strength. The maximum UCS of 1280 kPa was exhibited by mixture having 5M NaOH and Na_2SiO_3 in 1:1 ratio when compared to mixture having 10M NaOH and Na_2SiO_3 in 1:2 ratio. On contrary, mixtures having no supplementary silica source (i.e. Na_2SiO_3/NaOH ratio of 0:1) developed 28-day UCS values of 700 kPa and 180 kPa only, respectively for 5M and 10M NaOH, which was lower than that of 20% virgin PFA-treated soil. This might be attributed to the curtailment of geopolymerization reactions caused due to the lack of surplus reactive silica precursor in the medium.

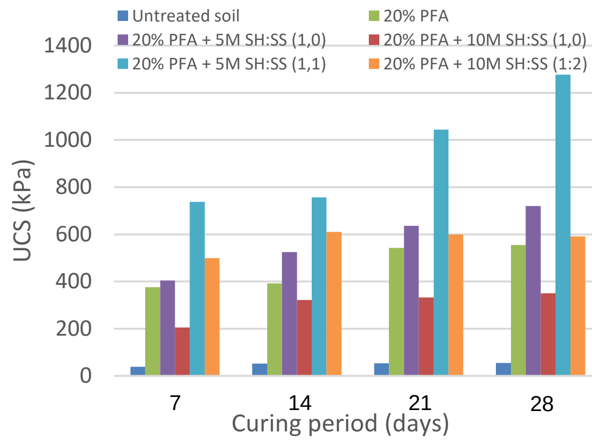


Figure 4. Variation in subgrade UCS with different activator chemistry and constant activator to ash ratio

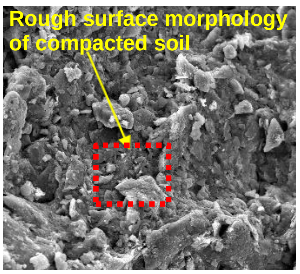
In the next step, further lower Na_2SiO_3/NaOH and activator/ash ratios were tried with optimized 20% FA and 5M NaOH combination, in view of the potential economic benefits. Table 5 summarizes the development of UCS in the various design mixes tested after 7 days curing. All design mixtures corresponding to alkali-silicate activation could mobilize significant strength improvement after a short-term curing process (by approximately 10 to 15 times as that of untreated soil). The 7-day strength achieved was also higher than the minimum highway subgrade strength requirement (i.e. 450 kPa). Therefore, the mixture having 5M NaOH, Na_2SiO_3/NaOH ratio of 0.5:1 and activator/ash ratio of 0.5:1 is considered as the most eco-friendly soil stabilizer. Another noteworthy observation is that the activator dosage has a non-linear relationship with the mechanical performance of treated subgrade.

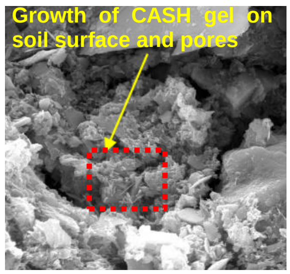
Table 5. Development of compressive strength in fly ash-geopolymer treated subgrade

Activator chemistry		Activator/ash ratio	Compressive strength (kPa)	
NaOH (M)	Na_2SiO_3/ NaOH		7-day UCS	Strength increment
Untreated				
-	-	-	38.12	-
Virgin fly ash				
-	-	0:1	375.92	337.80
Alkali-silicate activation				
5	0.5:1	0.5:1	549.01	510.51
5	0.5:1	1:1	520.97	482.85
5	1:1	1:1	737.20	699.08
10	2:1	1:1	498.71	460.59
Alkaline activation				
5	0:1	1:1	404.38	366.26
10	0:1	1:1	204.74	166.62

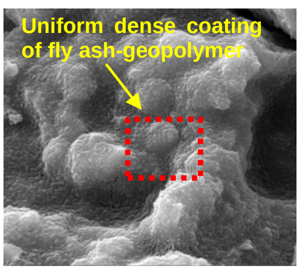
3.2 Microstructural Evolution

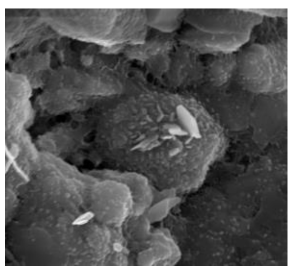
Figure 5 presents the SEM images of untreated and PFA-treated subgrade specimens. The untreated specimen exhibited even and homogeneous texture with dark contrast, whereas new microstructural formations of lighter contrast were visualized in 20% PFA treated specimen. The lighter contrast in SEM imaging indicated the presence of calcium-rich compounds, with high electron interactions on sample surface. These compounds are probably the cementitious calcium-aluminate-silicate-hydrate (CASH) gel which formed and deposited on soil surfaces and pore spaces as a result of soil-fly ash interactions.



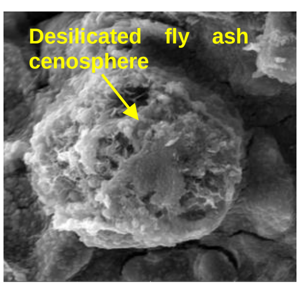


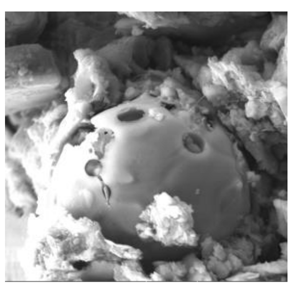
(a) Untreated soil (b) 20% PFA





(c) 20%PFA+5M NaOH (0.5,1) (d) 20%PFA+10M NaOH (2,1)

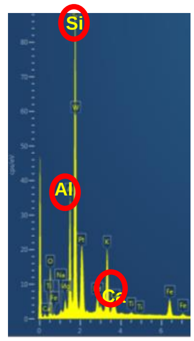


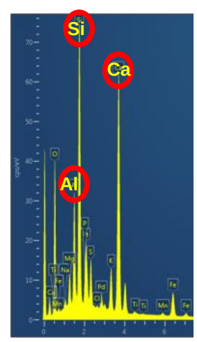


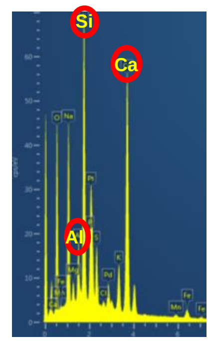
(e) 20%PFA + 5M NaOH (1,0) (f) 20%PFA +10M NaOH (1,0)

Figure 5. SEM images of subgrade treated with different fly ash-geopolymer formulations after 28 days curing

The EDS analysis was conducted on selected regions of interest in the SEM images (highlighted using red windows in Figure 5) to determine chemical composition of new microstructural formations. Figure 6 presents the spectra and average elemental composition of scanned regions in terms of variations in Si/Al, Ca/Si and Ca/Al ratios. When compared to untreated subgrade, the overall Ca concentration significantly increased after 20% PFA treatment which was attributed by Ca-rich nature of PFA. This excess amount of free calcium was utilized for maintaining the chemical reactions and formation of stable compounds (such as CSH and CASH) in PFA-treated subgrade. Further, the PFA-geopolymer network developed by alkali-silicate activation process had highest Ca/Si and Ca/Al ratios, which reinstates its high stability.







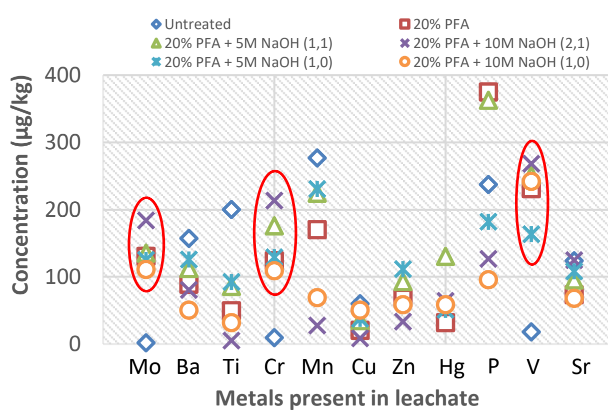
	(a) Untreated soil		(b) 20% PFA		(c) 20%PFA+5MNaOH (0.5,1)
Si/Al	2.36	Si/Al	2.22	Si/Al	3.57
Ca/Si	0.06	Ca/Si	1.22	Ca/Si	1.37
Ca/Al	0.14	Ca/Al	2.71	Ca/Al	4.88

(a) Untreated soil (b) 20% PFA (c) 20%PFA+5MNaOH (0.5,1)

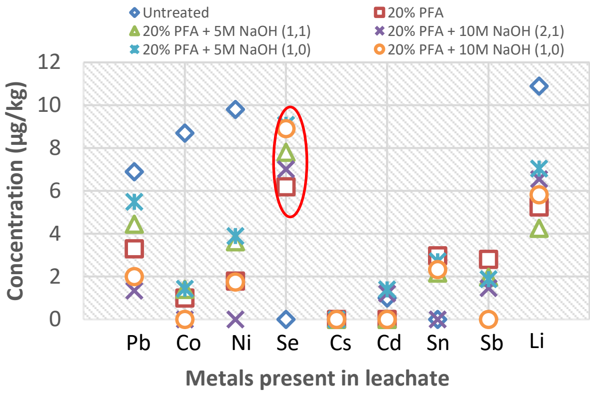
Figure 6. SEM images of subgrade treated with different fly ash-geopolymer formulations after 28 days curing

3.3 Ecotoxicological Effects

Figures 7 (a) and (b) present the leachable concentrations of hazardous elements which are only available in trace levels (in µg/kg or ppb, parts per billion). These concentrations are much lower than the permissible limits as per BC provincial water quality standards for agricultural requirements. Hence, it was verified that the fly ash-geopolymer is environmentally safe and sustainable raw material for soil amendment applications. It is important to note that most of the metal concentrations (except Mo, Cr, V, Se) were lower in all PFA-treated subgrades when compared to untreated counterpart. This indicated that PFA treatment also resulted in the encapsulation of hazardous impurities, in addition to mechanical improvement. The relatively high concentration of Mo, Cr, V, and Se in PFA when compared to silty sand has caused small hike in their values in treated subgrade material.



(a)



(b)

Figure 7. (a) and (b) Leachate characteristics of PFA-geopolymer treated subgrade

It is also noteworthy that pH of the various fly ash treated subgrade materials increased with increasing fly ash dosage, which was obviously due to high alkalinity of PFA (~ pH 13). The alkaline condition (> pH 9) is indispensable for maintaining the essential conditions required for pozzolanic reactions. With addition of 20% PFA, subgrade pH increased from pH 7.9 to pH 11.9. Further, for all PFA geopolymer-treated subgrades, pH was maintained to be around 11.9 to 12.5. Hence, it is confirmed that PFA high pH buffering capacity and small dosages of it can be sufficient for liming applications in acidic agricultural soils (Etiégni et al. 1991; Qin et al. 2015).

4 SUMMARY AND CONCLUSIONS

There is a growing motivation for recycling and reuse of inorganic wastes from pulp and paper industries for several beneficial applications with environmental and economic sustainability as main drivers. The present study aimed to develop and assess a novel waste-to-product technology for valorizing the green waste PFA, with low energy consumption and less carbon footprint, as eco-friendly binder for subgrade stabilization. The as-received PFA from a local pulp mill was transformed into a geopolymer binder for the stabilization of a weak silty sand, by using the alkali-silicate activation method under ambient curing conditions. The performance efficiency of PFA-geopolymer was assessed in terms of UCS variation in the treated subgrade, with considering the ash dosage, activator chemistry (NaOH molarity, and NaOH/sodium silicate ratio), activator/ash ratio, and curing period as variables.

The major findings of the study are following.

(i) PFA is a non-hazardous waste material with suitable physicochemical and engineering properties for utilization as sustainable soil stabilizer.

(ii) Efficient PFA-geopolymerization was achieved at ambient temperature with alkali-silicate activation using NaOH and Na_2SiO_3 compounds.

(iii) All design mixtures achieved the desirable strength (i.e. 450 to 600 kPa) required for a flexible pavement subgrade after a short-term curing process.

(iv) Maximum subgrade strength was developed with 20%PFA and activator chemistry of 5M NaOH/ Na_2SiO_3 and activator/ash ratio of 1:1.

(v) Optimum formulation of PFA-geopolymer to obtain the most eco-friendly soil stabilizer was considered to be 5M NaOH, Na_2SiO_3/NaOH ratio of 0.5:1 and activator/ash ratio of 0.5:1.

(vi) Alkaline activation without supplementary silicate source (Na_2SiO_3/NaOH ratio of 0:1) did not develop stable geopolymer compound for efficient stabilization.

(vii) PFA-geopolymer treatment caused encapsulation of hazardous impurities, and hence, promises an environmentally sound soil stabilization process.

Further studies are being conducted using sustainability assessment tools (such as life cycle assessment and cost-benefit analysis) in order to demonstrate the environmental and economic benefits of PFA-geopolymer as alternative soil stabilizer compared to conventional materials. Moreover, the ongoing research related to upcycling of PFA also focuses on developing value-added products for various other potential applications such as nutritional soil amendment, alternate cement for building construction, as well as adsorbent for pollutant removal.

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