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Developing a sustainable post-fire soil restoration technique using pulp mill fly ash

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ABSTRACT

This study was conducted to develop a sustainable post-fire soil restoration strategy utilizing pulp mill fly ash (PFA) as soil stabilizer. Wildfire impacts on forest soil properties located in Okanagan region of British Columbia was initially assessed, and efficiency of PFA for post-fire soil stabilization was evaluated in terms of hydro-mechanical properties variations of burnt soil treated with PFA. Detailed microstructural examination of untreated and treated soil samples was also conducted to investigate the underlying stabilization mechanisms. The soil aggregate stability and water retention capacity of burnt soil were substantially improved with 10% PFA dosage after 28 days curing. Formation and deposition of new water stable cementitious compounds, predominantly consisting of calcium-silicate and magnesium bridges, were revealed in soil macropores attributed to soil restoration.

RÉSUMÉ

Cette étude a été menée pour élaborer une stratégie durable de restauration des sols après l'incendie en utilisant les cendres volantes des usines de pâte à papier (PFA) comme stabilisant du sol. Les effets des incendies de forêt sur les propriétés des sols forestiers situés dans la région de l'Okanagan en Colombie-Britannique ont été initialement évalués, et l'efficacité du PFA pour la stabilisation des sols après le feu a été évaluée en termes de variations des propriétés hydromécaniques du sol brûlé traité avec du PFA. Un examen microstructural détaillé des échantillons de sol non traités et traités a également été effectué pour étudier les mécanismes de stabilisation sous-jacents. La stabilité de l'agrégat du sol et la capacité de rétention d'eau du sol brûlé ont été sensiblement améliorées avec une dose de 10% de PFA après 28 jours de durcissement. Formation et dépôt de nouveaux composés cimentaires stables à l'eau, constitués principalement de ponts calcium-silicate et magnésium, dans les macropores du sol attribués à la restauration du sol.

1 INTRODUCTION

The densely forested areas in Canada are at the risk of extremely destructive wildfires during the dry weather. The global climate change can potentially increase the risk of wildfires in the future and ordinary fire management techniques will no longer be effective (Jolly et al. 2015). Wildfires lead to significant negative impacts on soil properties such as aggregate stability, water holding capacity, infiltration rate and hydraulic conductivity (Zavala et al. 2014). The soil degradation and loss of natural soil cover such as vegetation and organic litter during wildfire events increases the sensitivity of burnt sites to post-fire risks including massive erosion, sediment loss, mud flows, and flooding during the subsequent storms (Ben-Hur et al. 2011). These post-fire events often have serious implications on the human life and property as well as the aquatic habitats. The debris and sediments transported by the runoff from burnt areas to downstream have adverse effects on human residence, roads and infrastructure, water reservoirs, etc. Further, the suspension of ash and fine soil particles in the streamflow reduces the drinking water quality and imposes a serious threat on aquatic life as well (Neary et al. 2005). Therefore, the global predictions call attention to urgent need for sustainable restoration techniques to address these post fire effects and associated risks.

1.1 Fire Effects on Mechanical and Hydraulic Properties

The severity of wildfire impact on soil aggregate stability, which is the measure of soil resistance against destructive forces when wet, depends upon the fire intensity as well as inherent soil properties (Francos et al. 2018). The partially decomposed organic matter at lower fire temperatures forms water repellent layer coating around the soil particles, thereby providing protection to soil aggregates against slaking and increasing the aggregate stability (Mataix-Solera et al. 2011). On the other hand, the complete destruction of organic matter following the moderate and high severity wildfires caused a decline in soil aggregate stability (García-Corona et al. 2004; Arcenegui et al. 2008).

The alterations of soil aggregate stability as well as other physico-chemical changes further affect soil water movement, water holding capacity, infiltration rate and rainfall threshold, leading to high erosion potential and debris flow (Lu et al. 2014; Wieting et al. 2017). In low severity fires, partially burnt organics volatizes into wax like gaseous organic compounds; these compounds diffuse into soil, condense at deep layers, coating the mineral surface and result in hydrophobic layer (DeBano 1981). The hydrophobic layer and pores clogged by fine particles result in fire-induced water repellency, low infiltration rates and high flooding potential. On contrary, complete burning of organic matter induces changes in soil aggregation, leading to decrease in water holding capacity and reduction in macropore space (Boyer and Miller 1994). The depth of wildfire impact on forest soil depends primarily on fire severity and duration, as well as soil texture and moisture (Bento-Gonçalves et al. 2012). The changes attributed to burning are greatest in the upper 0-5cm layer and more modest at the 5-10 depth; often no heating is detected below 20-30cm (Certini 2005; Litton and Santelices 2003).

1.2 Post-Fire Soil Stabilization Techniques

Post-fire soil stabilization methods are designed to counteract the effects of wildfire and reduce soil erosion. The most common soil treatments are seeding for rapid restoration of vegetation, mulching to lower the raindrop impact on soil, erosion barriers to collect sediments and chemical soil surface treatments. Further, the different chemical treatment methods including natural soil binders such as gaur and starch, synthetic soil binders such as polyacrylamide (PAM) formulations, etc. are used for long-term improvement and permanent restoration of soil's original quality (Robichaud et al. 2010; Ngole-Jeme 2019). These chemical restoration methods improve soil quality through physicochemical adsorption processes and new bond formation through chemical reactions (Cherian and Siddiqua 2019). However, the organic and synthetic soil binders are not sustainable being very expensive and rapidly degradable (Robichaud 2010). In regard to these concerns, innovative strategies for cost-effective applications of industrial waste materials and by-products for soil amendment are receiving world-wide attention.

The pulp and paper mill fly ash (denoted as PFA), a green waste by-product generated during wood combustion processes in the pulp and paper industries, is considered to be potential candidate for sustainable and eco-efficient soil stabilization applications (Brady and Weil 2008; Cherian and Siddiqua 2019). Due to its high cementitious properties and hydrophilic nature, the chemical treatment of burnt soil using PFA can lead to improved soil aggregate stability and water holding capacity (Graber et al., 2006; Yunusa et al. 2011; Cherian and Siddiqua 2019). Although, literatures reported effective utilization of PFA as a fertilizer and liming agent in agriculture and forestry sectors, soil stabilization agent, binder material in construction, etc. (Pitman 2006; Pandey and Singh 2010; Nurmesniemi et al. 2012). However, the authors are not aware of other studies which considered the application of PFA for post-fire soil restoration.

This paper presents a novel study conducted to evaluate the efficiency of a PFA, generated as a wood combustion by-product during pulp making processes, for improvement of post-fire soil properties and mitigating the risks of soil erosion. For this purpose, the most important and vulnerable hydro-mechanical soil properties including aggregate stability and water retention capacity of burnt and unburnt forest soils were studied by pairwise analysis approach comparing in order to assess the impact of wildfire. Further, the burnt soil was treated using PFA as a chemical additive in order to improve the soil properties and restore to original quality as that of unburnt soil. It is anticipated that valorization of PFA as environmentally and economically sustainable soil amendment would provide efficient ways of fly ash recycling and reuse by the growing pulp and paper industries, thereby reducing the environmental footprints.

2 MATERIALS AND METHODS

2.1 Soil Sampling and Characterization

The burnt soil samples were collected from the pine forests in Peachland, British Columbia, Canada, which was subjected to Mount Eneas wildfire on July 2018. The sampling was done in the top 0-5 cm surface layer where the moderate wildfire effects are most prominent because of soil's poor heat conduction (Bento-Gonçalves et al. 2012). To minimize the variability of inherent soil properties, both unburnt and burnt soil samples were collected from adjacent locations. The precipitation occurred between the time of fire and time of sampling was classified as light rain (Government of Canada 2019). Therefore, the effect of post-fire rainfall was presumed to be insignificant.

The soil samples were thoroughly mixed, air dried, sieved (< 2 mm size) and stored in plastic containers for further analysis. A series of laboratory tests was carried out to determine the physico-chemical, mineralogical and molecular properties of burnt and unburnt soils. Soils were classified according to the unified soil classification system (USCS) based on ASTM (D2487-17) guidelines. The pH and EC of soil were measured in soil suspension corresponding to 1:2 soil/water ratio. Particle surface area (SA_{BET}) and cation exchange capacity (CEC) were evaluated on the basis of Braunauer-Emmett-Teller's multilayer adsorption technique and ASTM (D7503-18) guidelines respectively. Soil organic matter (SOM) content was determined by Loss-on-ignition (LOI) method (ASTM D2974-14).

The physicochemical properties of the soils are listed in Table 1. The changes in particle density and natural moisture content attributed to alteration in chemical composition and due to decomposition of soil organic matter (represented by LOI value) by wildfire (Kolay et al. 2011). The texture became coarser after burning. The chemical properties of soil were determined in terms of concentration of elements (in Wt%) using energy dispersive spectroscopy (EDS) analysis with the aid of an

Oxford Instruments X-Max EDS detector coupled with TESCAN Mira 3 XMU scanning electron microscope (SEM). As presented in Table 1, EDS results indicated that silica was the most dominant element in both soils, followed by alumina, calcium and iron. Ash after wildfire contributed to high relative amount of calcium in burnt soil.

Table 1. Important properties of soils and pulp mill fly ash

Property	Unburnt soil	Burnt soil	PFA
Density (ρ_s), (g/cc)	2.34	2.47	2.77
Moisture content (%)	36.5	11.33	29
Silt size fraction (%)	24.17	28.45	53.4
Clay size fraction (%)	26.97	17.98	21.8
USCS classification	Sandy silt	Silty sand	---
SA_{BET} (m^2/g)	5.21	9.16	39.8
LOI @ 950 °C (%)	10.4	5.8	23.9
pH	5.49	7.26	12.95
EC (µS/cm)	123.63	133.25	96.9
CEC (cmol+/kg)	39.23	31.11	---
Si [a]	31.82	34.62	2.77-11.69
Al [a]	7.11	2.33	1.77-7.61
Ca [a]	1.96	2.49	26.23-27.28
Fe [a]	1.37	1.32	1.51-5.00
Mg [a]			2.78-3.38

— not applicable

[a] Percent by weight values for elements from EDS analysis

2.2 Characterization of Pulp Mill Fly Ash

Pulp mill fly ash (PFA) was procured from a local pulp mill in Kamloops, BC. The physicochemical properties of the PFA is listed in Table 1. PFA consists of 75.2 % fine particles (silt clay) and has high specific surface area. PFA has higher particle density and LOI value as compared to soil. Further, SEM image depicted in Figure 1 shows that PFA contains heterogeneous mixture including some hollow cenospheres, irregular and angular shaped particles with thin layers of crystalline structures. EDS analysis indicates that calcium is the most dominant element in PFA, followed by Si, Al, Ca, Fe and Mg.

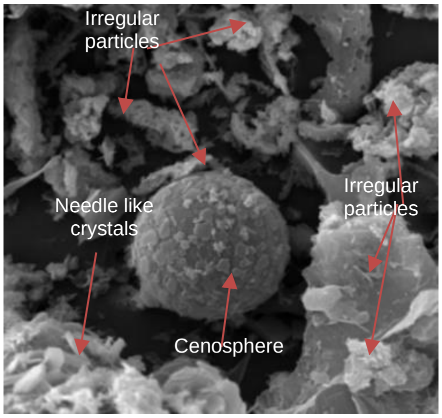


Figure 1 SEM image of pulp mill fly ash

2.3 Preparation and Testing of Pulp Mill Fly Ash Treated Burnt Soil

Different percentages of PFA in the dry form were added by total dry weight of burnt soil (denoted as BS) and mixed well. Then 21% of deionized water corresponding to natural moisture content (approx. 70% of field capacity of the soils) was added to the mixture. After thorough mixing soil was placed in fabricated PVC molds at about 1g/cc which is the typical bulk density for forest soil (Brady and Weil 2008). All prepared soil specimens were immediately transferred to an environmental chamber (with controlled temperature of 22 °C and 80% relative humidity) for short-term curing. After reaching the respective curing time, samples were air dried to standardize the initial conditions before conducting tests. Table 2. presents the soil treatment and test design used in this study.

Table 2. Summary of mixture design details with the experimental module and curing periods

Sample ID	Treatment	Methods	Curing Time
UB	-	F-WS, S-WS, SWCC, SEM-EDS	-
BS	-	F-WS, S-WS	1, 7, 14, 21, 28
		SWCC, SEM-EDS	-
BF1	5%	F-WS, S-WS	1, 7, 14, 21, 28
		SWCC, SEM-EDS	-
BF2	10%	F-WS, S-WS	1, 7, 14, 21, 28
		SWCC, SEM-EDS	-

F-WS: Fast wetting followed by wet sieving; S-WS: Slow wetting followed by wet sieving, SWCC: soil water characteristics curve; UB-Unburnt soil, BS-Burnt soil, BF1-Burnt soil+5% PFA, BF2-Burnt soil+10% PFA. SEM-EDS: scanning electron microscope-energy dispersive spectroscopy.

The performance efficiency of PFA treated burnt soil was evaluated in terms of most important and vulnerable hydro-mechanical soil properties, i.e., aggregate stability and water retention capacity, which are considered to be of primary relevance in soil erodibility.

2.3.1 Aggregate Stability Test

Soil susceptibility to detachment and transport processes can be determined using the macro- and micro-aggregate stability tests, which evaluates the interaction between aggregate stability and soil behavior under simulated disintegration processes such as wetting and mechanical actions (Amezketa 1999; Saygin et al. 2017). Macro-aggregate stability test measures the slaking effect of water on the soil and micro-aggregate stability test of particles produced by aggregate breakdown gives measurement of soil susceptibility to surface sealing (Amezketa 1999).

In the present study, slow wetting (SW) and fast wetting (FW) pretreatments followed by wet sieve method were performed on all mixtures to determine the aggregate stability and slaking effect in accordance with Kemper and Rosenau (1986) using an Eijkelkamp wet sieving apparatus. Some recent studies were followed to optimize this methodology (Heikkinen et al. 2019). For fast wetting, air dried aggregates of 0.850 mm to 2 mm size (equivalent to 4 g bone dry weight) were placed on 0.25 mm size sieve and left to stand for 15 mins in 100 ml of deionized water. In slow wetting, air dried aggregates of 0.850 mm to 2 mm (equivalent to 4 g bone dry weight) were spread on Whatman 42 filter paper placed above a cotton cloth. The edges of cloth were immersed in deionized water and aggregates were allowed to saturate under controlled vacuum. The results are expressed in terms of percentage of water stable aggregates (WSA) and stability index (SI).

Further, the statistical analysis using two-way ANOVA (analysis of variance) was conducted on control and treated soil samples to assess the effect of treatments on aggregate stability of burnt soil. Aggregate stability analysis was conducted in three replicates and replicates were considered as blocks. Data satisfy with all the assumptions of analysis of variance (ANOVA) and no transformations were applied. ANOVA was followed by Fisher's least significant difference test. Minitab version 19.2.0.0 statistical software was used to conduct ANOVA. Results were significant at $p<5\%$, i.e., significantly different from each other at the 95% confidence level.

2.3.2 Soil Water Characteristics

Soil water characteristics curve (SWCC) was determined in accordance with filter paper method (ASTM D5298-16) and compacted soil specimens were prepared using static compaction method. To keep the initial conditions constant and same pore distribution for all specimens, the target water content and dry density selected for compacted specimens were corresponding to 5% on the dry side of respective optimum moisture content (OMC) value. The compaction characteristics were determined corresponding to standard proctor energy. After compaction, volume and mass of each specimen was measured and accepted only if the dry density was ±5% of initially selected dry density. The coefficient of variation of the void ratio was measured to ensure that specimens had same volume of pores. The coefficient of variation was equal to 3±0.5% for all soil mixtures. As per standard guidelines, to avoid any error related to hysteresis and temperature gradient in low suction range, each filter paper was oven dried initially and contact filter paper method was adopted.

The matric suction was calculated from Whatman no. 42 calibration curve in accordance with ASTM D5298 (2016). SWCCs were plotted between volumetric water content (θ) and suction (ψ) corresponding to the water content. Experimental data was fitted to the van Genuchten (1980) model and Fredlund and Xing (1994) model to find the best fit. The root-mean- square error (RMSE) and the coefficient of determination (R^2) were used to choose the model best fit. Field capacity (FC) and permanent wilting point (PWP) were determined as water content corresponding to -30 kPa and -1500 kPa, respectively. Available water content (AWC) was determined as difference between FC and PWP (Obia et al. 2016) and the percentage macropore space was determined as the difference between the volume of water at saturation point and -30 kPa (Boyer and Miller 1994).

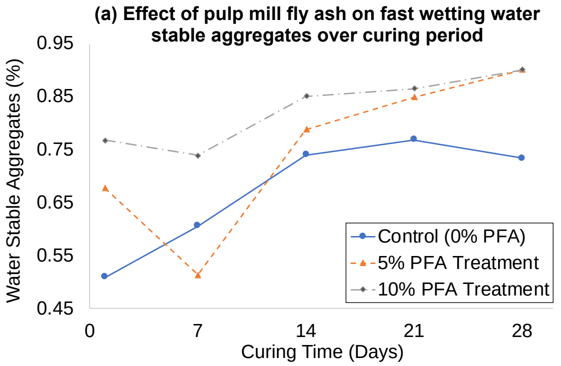
2.4 Microstructural Examination

Micro level investigation was conducted using SEM-EDS analysis in order to comprehend the key stabilization mechanisms and factors contributed to the restoration of soil properties. The variations in the morphology and elemental composition for untreated and treated samples over the curing period were investigated with the aid of SEM-EDS analysis.

3 RESULTS AND DISCUSSION

3.1 Effect of PFA Treatment on Soil Aggregate Stability

To assess the resistance of treated soil to slaking effect, aggregate stability analysis was performed using fast wetting and slow wetting pre-treatment. The most disruptive fast wetting pre-treatment relates the field conditions and it results in slaking of aggregates. On the other side, slow wetting is less disruptive, and it avoids the slaking of aggregates (Amézketa 1999). The effect of PFA on water stable aggregates over the curing time is presented in Figure 2 (a) and (b). The FW WSA ranged from about 50.93% in the control soil at day 1 to 90.09 % in the soil amended with 10% fly ash at day 28. The SW WSA ranged from about 88.48% in the control soil at day 1 to 95.30% in the soil amended with 10% fly ash at day 28. The difference between percentage of FW and SW water stable aggregates confirms occurrence of slaking effect.



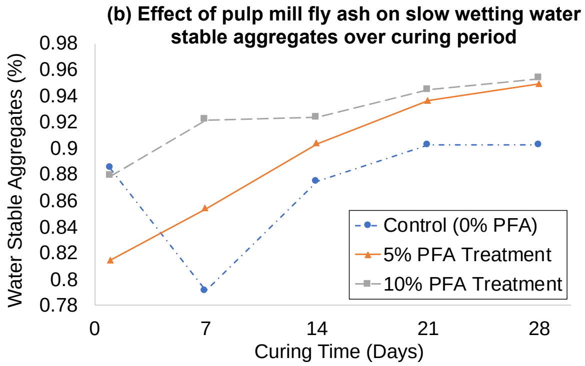


Figure 2 Effect of pulp mill fly ash on percentage of water stable aggregates over curing period: based on (a) fast wetting and (b) slow wetting methods

The percentage of WSA increased in fast wetting pretreatment with increasing amount of PFA application over all curing periods except for 7days curing. For 7 days curing, percentage of WSA aggregates in soil treated with 5% PFA decreased by 15.21% over the control. Similarly, in slow wetting, increase in WSA with amount of PFA can be explained by linear function over entire curing period except day 1. At day 1, WSA decreased by 8% in soil treated with 5% PFA over the control. The difference between the treatments BF1 (5% PFA) and BF2 (10% PFA) to improve WSA aggregates strength is more pronouncing in initial periods and it becomes statistically insignificant at curing time of 21 days and 28 days.

The F values from ANOVA analysis given in Table 3 represents that effect of time is dominating as compared to amount of fly ash and block effect (interaction due to replicates) were insignificant. On the other hand, PFA treatment is statistically significant (p< 5%) over control at curing time of 21 days and 28 days. Therefore, initial unexpected result fluctuations in case of soil amended with 5% PFA may be due to insufficient interaction period and lower amounts of fine particles (clay + silt present in PFA) for reaction with soil particles. Aggregates with BF2 (10% PFA) treatment are more resistant to erosion and slaking effect; similar results were reported by Jayasinghe et al. (2005).

Table 3. Analysis of variance (F values) for factors related to aggregation in treated soil

Source of Variation	WSA (FW)	WSA (SW)	SI
Treatment (amount of PFA)	246.45	63.13	90.43
Curing Time (Days)	274.24	72.41	101.59
FA*Days	32.86	17.84	38.15
CV (%)	16.6	5.3	5.5

F significant at 5 %; Variables analyzed: WSA = Water stable aggregates and SI = Stability Index. CV=Coefficient of variation.

Stability index (SI) parameter directly relates the aggregate stability values of all treated soils and curing time on relative scale of zero to one. Value of SI equals to 1 represents maximum stability and no slaking effect. It occurs when aggregates subjected to fast wetting have no structural degradation in relative to aggregates exposed to slow wetting. SI value equals to zero represents complete structural loss of aggregates. SI values are reported in Table 4, and it ranged from 0.80 for burnt soil to 0.98 for treated soil. SI values increased with increase in PFA amount and time. The difference in treatment BF1 and BF2 became insignificant (p>5%) at 21 days. The effect of treatments BF1 and BF2 was significant (p<5%) over the control for entire period.

In case of unburnt soil, the percentage of WSA for fast wetting and slow wetting were 84.79% and 94.94% respectively. The value of SI index was 0.95 for unburnt soil. In case of treated burnt soil, all the values achieved at 28 days curing time were more than values reported for unburnt soil. Therefore, it represents restoration of burnt soil to original conditions in terms of aggregate stability. The coefficient of variation shows high variation in case of fast wetting pre-treatment due to disruptive forces. While the burnt soil is classified as silty sand, the increase in aggregate stability might be attributed to decrease in aggregate structural loss due to entrapped air pressure (Grant and Dexter 1990; Lu et al. 2014) and cementing of fine soil particles together due to bridge formation by soluble cations (Ca and Mg) present in the PFA (Jala and Goya 2004; Zhang et al. 2005).

Table 4. Stability Index (SI) affected by fly ash amendment (Values in a column followed by the same letter are not significantly different from one another at 5% level of significance).

Treatment FA %	Curing Time (Days)				
	1	7	14	21	28
BS	0.80a	0.90a	0.93a	0.93a	0.91a
BF1	0.92b	0.82b	0.94a	0.96b	0.98b
BF2	0.94b	0.91a	0.96b	0.96b	0.97b

3.2 Effect of PFA Treatment on Soil Water Retention Capacity

The effect of PFA application on the important agronomic properties including field capacity (FC), permanent wilting point (PWP) and plant available water content (AWC) were assessed by comparing soil water characteristics curves of unburnt soil, burnt soil (control), BF1 and BF2 soils. The experimental results based on Fredlund and Xing (1994) model are reported in Figure 3. Fredlund and Xing (1994) model is selected to represent results as it is taking all the model parameters independently and correlated to experimental data over entire suction range. Water drained under short range of suction in all soil mixtures due to coarse soil texture. In the coarse textured soils, less pore air pressure is required to desaturate large pores (Brady & Weil, 2008). A considerable increase in water retention capacity of burnt soil occurred with 10% PFA treatment over the control and 5% PFA treatment.

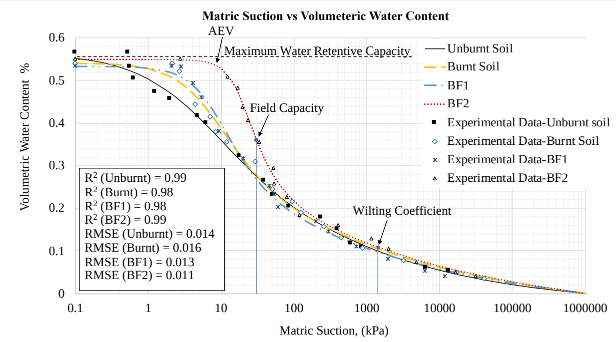


Figure 3. Soil water characteristics curve for all soil mixtures

The water retention capacity at -10kPa, -30kPa, -100kPa and -1000kPa increased as the result of BF2 treatment over the control by 36.7%, 30.6%, 8.9% and 3.6%, respectively. The 10% PFA treatment restored the maximum water retention capacity at saturation, by 55.03% and it is 55.32% in case of unburnt soil. Therefore, increase in water retention was higher around field capacity as compared to permanent wilting point. The 5% PFA treatment resulted decreased water content at field capacity from 27.84% in control to 26.91% in amended soil. Amendment of burnt soil with 5% PFA treatment resulted decline in water content held at PWP by 7.3% over the control. On the other hand, 3.7% rise was recorded at PWP in case of 10% PFA treatment over the control. Similar results were reported in case of agricultural soils in previous studies (Kalra et al. 2000; Yunusa et al. 2011). Similar to literature (Pathan et al. 2003), 10% PFA treatment increased water retention within the range available for plants by 46.5% over the control sample. It could reduce water losses due to erosion and drainage, enhance water use efficiency for revegetation.

A significant decline in macropore space was recorded in 10% PFA treatment over the control and 5% PFA treatment. It declined from 26.14% in control to 18.67 % in 10% PFA treatment. It is also confirmed by air entry value that increased from 2.2 kPa in control to 3.35 kPa and 12kPa in 5% and 10% PFA amendment soils respectively. AEV is inversely proportional to the macropore space (Zhao et al. 2017) and it plays significant role in governing pore size and pore volume.

PFA used for soil amendment is having very high surface area that is equal to 39.8 m^2/g and it attributes to the fineness of particles, high porosity and high irregularity of particles shapes (Cherian and Siddiqua, 2019). SEM image Figure 1 showed that PFA contains Cenoshperes (hollow spherical particles), irregular and angularly shaped inorganic particles with thin layers of crystalline structures. The external and internal surface of these particles contribute to high water retention due to hydrophilic nature and these particles absorb water into their pores by capillary phenomenon (Kumar and Singh 2003; Cherian and Siddiqua 2019). High LOI value improves soil aggregation which is responsible for high water retention (Boyer and Miller 1994). Therefore, high porosity, high surface area and high LOI value of PFA particles has contributed to improve water retention capacity of post-fire soil. The effect of 5% PFA addition in soil was not much significant, and it might be due to insufficient fine particles (silt and clay fractions) added through this treatment.

3.3 Microstructural Evolution After PFA Treatment

The scanning electron micrograph of burnt soil represented by Figure 4 shows detailed micro morphology of soil particles. Burnt soil contains rods, angular and irregular shaped soil particles. The EDS pattern shows dominant peaks of Si, Al and Ca in burnt soil. Figure 5 and 6 represent the SEM-EDS results of soils amended with 5% and 10% PFA after 28 days curing, which illustrated the microstructural evolution of modified soil. As shown in Figure 5 (a) and (b), the hydration reactions of ash and consequent cementation process caused macro aggregation in soil amended with 5% and 10% PFA. It shows weak arrangement of particles with lower amount of fly ash (5%) as compared to soil treated with higher amount of fly ash (10%). It represents that high aggregation ability and high aggregate stability is positively corelated with amount of PFA added in the soil.

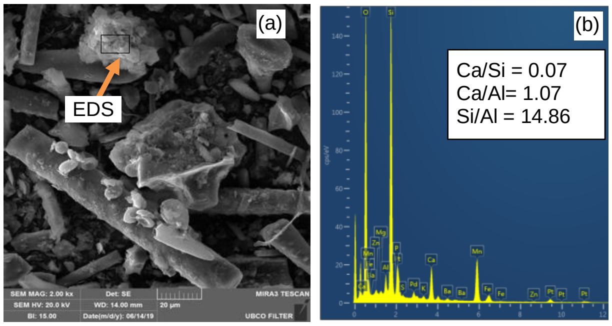


Figure 4. (a) SEM image of burnt soil showing particles of different sizes and shapes (b) EDS spectrum of burnt soil

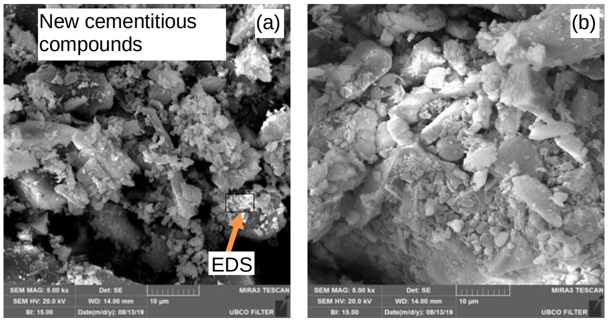


Figure 5. SEM images showing improvement in soil aggregation with (a) 5% and (b) 10% PFA treatment

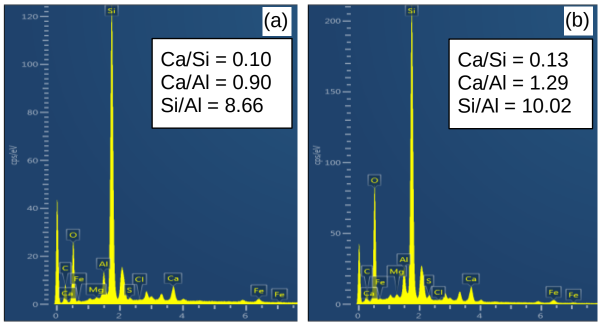


Figure 6. EDS spectra showing alteration in soil chemistry with (a) 5% and (b) 10% PFA treatment

As shown in Figure 6 (a) and (b), based on EDS analysis the relative increase in Ca/Si ratio increased from 0.07 to 0.10 and 0.13 in 5% and 10% PFA treatment, respectively. This is primarily owing to high calcium content of PFA, and formation of calcium-based hydration products which coats soil surface and forms cementitious bridges between the fine soil particles by filling the inter-particle pore spaces. Soils treated with 5% and 10% PFA also showed dominated peaks of Mg which is absent in case of control soil. So, improvement in aggregate stability is attributed to soluble, reactive Ca and Mg cations. The large pores get further reduced in case of 10% PFA treatment as compared to 5% PFA treatment (shown in figure 5a and b on same scale). Therefore, SEM-EDS analysis provided ample evidence to substantiate the underlying mechanisms of burnt soil stabilization by PFA treatment.

4 CONCLUSION

The present study was conducted to evaluate the efficiency of PFA for improvement of post-fire soil quality in terms of mechanical and hydraulic properties, and thereby mitigating the risks of soil erosion. Based on the results of the study, the following conclusions were drawn.

(i) Structural stability of burnt soil aggregates increased with increase in the amount of PFA applied and over the curing time.
(ii) Curing is an important factor for improving the aggregate stability since the hydration reactions of PFA and following cementation processes are time-dependent.
(iii) The difference in the effect of various percentages of PFA became insignificant over the extend of curing time.
(iv) The increase in stability index with increase in percentage of PFA confirms the reduction in slaking effect over time.
(v) The dosage of 10% PFA over 28 days provided the maximum restoration of burnt soil to original pre-fire quality in terms of aggregate stability and water retention capacity.
(vi) SEM-EDS analysis revealed the formation of cementitious bridges between fine soil particles and coating of calcium on the surface of soil particles.
(vii) The combined effect of improved aggregate stability of soil, and high porosity and high surface area of PFA particles contributed to improved water retention capacity.

Hence, this study demonstrated that the green waste PFA can be effectively utilized as chemical stabilizing agent for the restoration and rehabilitation of forest soils subjected to wildfire impacts. Based on the standard practices related to other chemical soil binders, it is recommended to apply PFA by either mixing with water and spraying on the soil surface or by spreading in dry powder/pellet form where it can dissolve in rain (Robichaud 2010). However, future studies must be conducted to identifying the more efficient PFA application techniques for large-scale commercial purposes (Pitman 2006). Overall, the outcomes of this research are anticipated to develop innovative strategies and efficient ways of PFA recycling and reuse thereby reducing the environmental footprints.

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