# Desiccation cracking improvement in an organic soil by using fly ash-based geopolymer

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ABSTRACT
Desiccation cracking is an important phenomenon in geotechnical and geoenvironmental engineering, which can affect the hydrological and mechanical properties of soils. Organic soils are notorious for having high water adsorption capacity, high compressibility, and low strength. In this project, desiccation cracking of a local organic soil from Alberta is first tested by measuring the desiccated area at different moisture contents. Afterward, an effort is made to improve desiccation cracking by reducing the desiccated area through a pulp and papermill fly ash-based geopolymer. The influence of such parameters as geopolymer content, alkaline activator/ fly ash, and sodium hydroxide/ sodium silicate ratios on desiccation cracking have been put to test. The results show that the employed geopolymer leads to a reduction in the soil matrix. However, the shrinkage in the soil and dish boundary area is increased remarkably.

RÉSUMÉ

La fissuration de dessiccation est un phénomène important en génie géotechnique et géoenvironnemental, qui peut affecter les propriétés hydrologiques et mécaniques des sols. Les sols organiques sont connus pour avoir une capacité d'adsorption d'eau élevée, une compressibilité élevée et une faible résistance. Dans ce projet, la fissuration par dessiccation d'un sol organique local de l'Alberta est d'abord testée en mesurant la zone desséchée à différentes teneurs en humidité. Par la suite, un effort est fait pour améliorer la fissuration par dessiccation en réduisant la zone desséchée grâce à un géopolymère à base de cendres volantes d'usine de pâtes et papiers. L'influence de paramètres tels que la teneur en géopolymères, l'activateur alcalin/cendres volantes et les rapports hydroxyde de sodium/silicate de sodium sur la fissuration par dessiccation a été testée. Les résultats montrent que le géopolymère utilisé conduit à une réduction de la matrice du sol. Cependant, le rétrécissement dans la zone limite du sol et de la boîte est remarquablement augmenté.

## 1 INTRODUCTION

Desiccation cracking takes place naturally in all soils with a significant cohesive particle content. This phenomenon can deleteriously affect the mechanical and hydraulic characteristic of the soil. Desiccation cracking also has negative agricultural impacts such as plant water and nutrient stress (Baer et al. 2009), and has such geological impacts as increased sediment entrainment (Tang et al. 2021). Therefore, its measurement is important for soils behavior prediction (Xu et al. 2022) As an organic soil, muskeg is known for extremely high compressibility, low strength, and high moisture content (ElMouchi et al. 2021, 2022).

Soil improvement is an important technique to enable construction in regions with poor soil properties (Abbaspour et al. 2020, Habibi et al. 2021, Narani et al. 2021, 2022, Reza Tabakouei et al. 2022). Efforts have been made in the literature to mitigate soil desiccation by different means. For instance, (Narani et al. 2020) investigated the desiccation cracking of highly plastic and expansive bentonite and its remediation by using waste tire textile fibers. (Tang et al. 2012) proposed desiccation cracking improvement by polypropylene fiber inclusion. Other desiccation cracking mitigation methods include using biochar and biomass (Yang et al. 2020, Zhang et al. 2020, Mei et al. 2021), enzymes (Xie et al. 2020), sugarcane pith (Abd El-Halim 2017), guar gum biopolymer (Acharya et al. 2019), compost (Intharasombat et al. 2007), polyester fibers (Chaduvula et al. 2017), microbially induced calcite precipitation (MCIP) (Liu et al. 2020), and silica fume (Kalkan 2009).

Alkali activated aluminosilicate precursors, also known as geopolymers, are a new stream of green and sustainable binders that are proposed as a decent alternative to ordinary Portland cement (OPC). Different characteristics of geopolymer-improved soils such as compaction, unconfined compressive strength, volume change, compressibility, X-ray diffraction (XRD), energy dispersive X-ray spectroscopy (EDX), and scanning electron microscopy (SEM) have been studied in previous publications (Zhang et al. 2013, Pourabbas Bilondi et al. 2018, Yaghoubi et al. 2020, Wang et al. 2021). Although the improving effect of geopolymer on desiccation cracking has been alluded to in the literature (Khaksar Najafi et al. 2020, 2021, Samuel et al. 2020), there is no comprehensive study on this subject.

In this paper, this gap has been filled by evaluating the influence of fly ash-based geopolymer on the desiccation cracking behavior of an organic muskeg soil procured from Alberta, Canada. The fly ash employed in this paper is produced as a byproduct of pulp and paper mill industry and has shown potential for consumption in construction projects (Cherian and Siddiqua 2021, Naeini et al. 2021, Pokharel and Siddiqua 2021a). The influence of such parameters as geopolymer content and sodium hydroxide/ sodium silicate ratio on the desiccation cracking behavior of the soil were studied.

## 2 MATERIALS AND METHODOLOGY

The organic soil chosen in this study is a muskeg soil obtained from Wabasca region, Alberta, Canada. Basic in situ tests are reported elsewhere (Liu et al. 2018). The muskeg has extremely high intrinsic water content (260±26%), and the organic part makes up to 26±2.1% of the soil. The rudimentary geotechnical characteristics of the muskeg are determined in a previous publication (Pokharel and Siddiqua 2021b) and displayed in Table 1. Based on (Pokharel and Siddiqua 2021a), the muskeg soil consists of 41.01% O, 34.094% C, 10.42% Si, 2.99% Ca, 2.73% Fe, 1.90% Al, 1.33% S, 0.57% K, and 3.91% other elements.

Pulp and paper mill fly ash (PFA) was received from a local company (Domtar, Kamloops, BC, CA). As per the gradation, fly ash consists of 80% particles finer than 0.075 mm, 63% between 0.002 and 0.075 mm, and 17% finer than 0.002 mm. According to XRF tests, PFA consisted of 19.69% CaO, 5.3% $SiO_2$, and 1.57% $Al_2O_3$ (Cherian and Siddiqua 2021, Naeini et al. 2021). Pulp and paper mill PFA has shown potential for being used as a replacement for coal fly ash and cement (Cherian and Siddiqua 2019, Pokharel and Siddiqua 2021a).

Sodium hydroxide (NaOH) and Sodium Silicate ($Na_2SiO_3$) were provided by Fisher Scientific. 12 M solution sodium hydroxide solution was obtained by dissolving the pellets in distilled water.

Table 1. Basic geotechnical characteristics of the muskeg soil

| Parameter | Value |
|---|---|
| Liquid limit (%) | 106 |
| Plastic limit (%) | 84 |
| Plasticity index | 22 |
| pH | 7.5 |
| Grain size distribution (%) | |
| > 0.075 mm | 18 |
| 0.002 – 0.075 mm | 60 |
| < 0.002 mm | 22 |

### 2.1 Specimen preparation

Specimens were prepared in round aluminum dishes with a diameter of 150 mm. About 127.4 g of super saturated muskeg (at its natural moisture content) was poured in the dishes to reach a depth of about 10 mm. In the case of geopolymer-stabilized soils, 10%, 20%, and 30% of the soil was replaced with geopolymer. In order to prepare the geopolymer, the intended alkaline activator composition (NaOH : $Na_2SiO_3$ = 1:0, 1:1, 1:2) was obtained by mixing sodium hydroxide and sodium silicate solutions. The solutions were then thoroughly mixed with the designated amount of fly ash (activator/PFA ratio of 0.8).

After thoroughly mixing the activator with the muskeg soil, samples were weighed and placed directly under a thermal lamp. The height was adjusted to set the temperature at the surface of the soil to 50°C. Samples were monitored for morphological variations and they were weighed and pictures were taken constantly. This process was continued until no further variation is specimen weight was recorded in one-hour intervals. Dishes were then placed inside an oven and dried for 24 hours at a temperature of 110°C. Subsequently, the dishes were weighed again and a picture was taken from the final crack distribution.

Desiccation cracking images were analyzed through ImageJ software. Images were first converted to grayscale and the contrast was adjusted. Afterwards, the images were converted into binary, where the cracks were illustrated in white color, whereas the soil was black. As observed in Figure 1, this process facilitated the cracked area calculation. Respective moisture content of each image was also calculated by using the weights recorded during the tests. In order to quantitatively discuss the effect of geopolymers on desiccation cracking, Crack Intensity Factor (CIF) was calculated by dividing the cracked area by the total area of the samples (Miller et al. 1998, Narani et al. 2020).

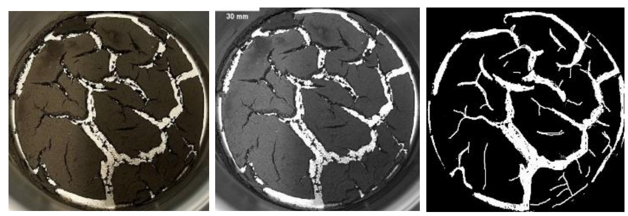


Figure 1. Image processing method: RGB image (left), grayscale image (middle), and binary image (right)

## 3 RESULTS AND DISCUSSION

### 3.1 Quantitative measurements

In order to quantitively assess desiccation cracking, Crack intensity factor (CIF) has been incorporated. For three different stabilized soils, the CIF values are calculated and presented in Figure 2 to Figure 4. For the geopolymer-stabilized soils, three different ratios (1:0, 1:1, and 1:2) of two different activators, NaOH and $Ni_2SiO_3$, were added and the corresponding results are shown in Figure 2 to Figure 4. In all Figures, the results demonstrate that the addition of PFA and activators to the organic soil reduces the initial water content of the soil. Moreover, the more PFA added to the organic soil (from 10% to 30%) the lower water content in specimens has been obtained. Comparing the addition of $Ni_2SiO_3$ and NaOH to the PFA stabilized soils as presented in Figure 2 to 4 suggests that $Ni_2SiO_3$ can lead to better improvement results in terms of crack area reduction. According to figure 2 to 4 the value of crack area changes in stabilized soils in comparison to organic soil can be calculated. Figure 2 shows that the final crack area for PFA10AA1:0, PFA10AA1:1 and PFA10AA1:2 has been increased 72.21%, 62.13% and 40.23% respectively, compared to the plain soil. Although the crack area in plain organic soil is lower than these samples, adding fly ash geopolymer and activators to organic soil leads to decreasing cracks in the middle of samples (soil matrix) and increases the shrinkage in the stabilized soil and dish boundary area, which can result in a uniform soil. As such, if one wishes to exclude the soil shrinkage at the dish-soil boundary, the cracked area is reduced remarkably, reaching to values near zero in the more heavily stabilized specimens. Likewise, in figure 3 the value of increasing cracks is 54.63%, 42.44%, and 28.28% for PFA20AA1:0, PFA20AA1:1 and PFA20AA1:2, respectively, compared to the plain muskeg soil. In figure 4, the value of crack area increase for PFA30AA1:0, PFA30AA1:1 are 18.41% and 8.95% respectively, as compared to the plain organic soil. For PFA30AA1:2 crack area has been reduced by 8.95% comparing to the plain organic soil. Therefore, PFA30AA1:2 only sample that not only is the most uniform sample, but also has the least crack area among all 10 specimens.

### 3.2 Morphological observation

Figure 5 to 8 represent the images of the soil mixtures used in the monitoring of the desiccation cracking process. For the case of unstabilized organic soil (see Figure 5), the monitored cracks are shown to be smooth, with clods randomly distributed over the area of the round dishes. In contrast, the results of Figure 6 to 8 indicate that by stabilizing the soil through PFA and activators addition, the cracks become jagged, and the shrinkage of the soil samples increases. It also shows that by increasing PFA from 10% to 30%, cracked area decreases. Although the organic soil shows less cracked areas in comparison to stabilized soils, the PFA stabilized soils become more compact and the crack in the middle of the samples has been decreased. The underlying reason higher cracked area in stabilized soils lies in the greater shrinkage of the material at the soil-dish boundary. This proves that geopolymer stabilization can make the soil matrix more uniform and the soil particles can adequately adhere to each other. In addition, in all figures substituting NaOH with $Na_2SiO_3$ leads to further reduction in the crack area.

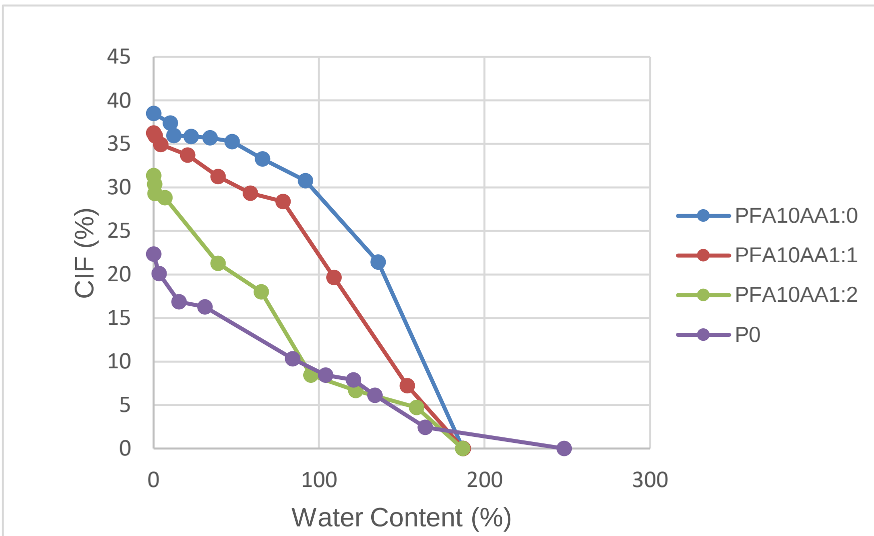


Figure 2. Crack intensity factor against water content for PFA10AA with various activator contents

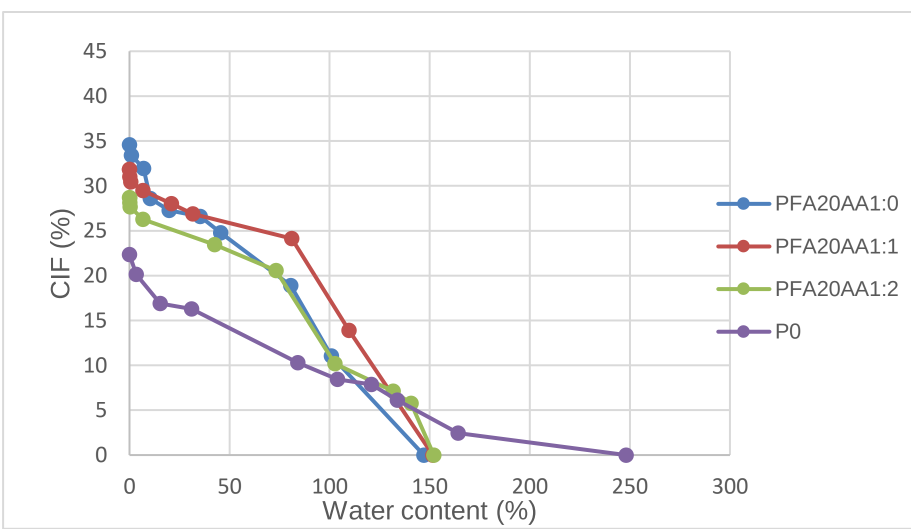


Figure 3. Crack intensity factor against water content for PFA20AA with various activator contents

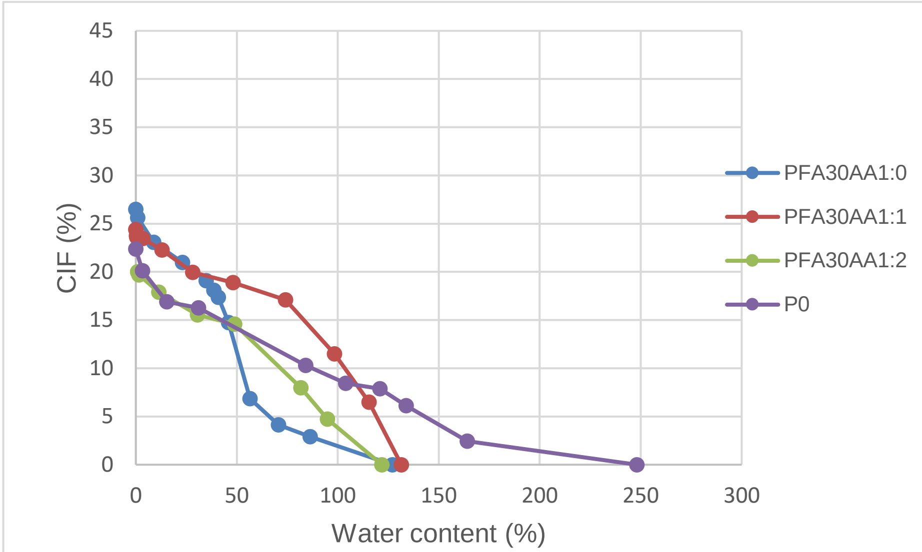


Figure 4. Crack intensity factor against water content for PFA30AA with various activator contents

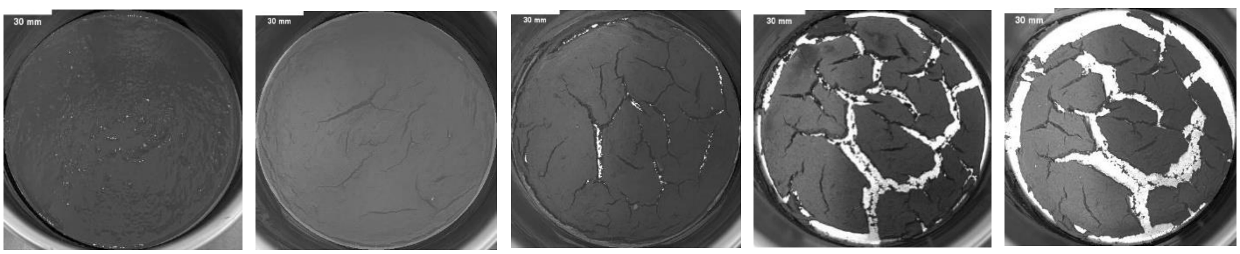

Figure 5. Evaluation of desiccation cracking for P0

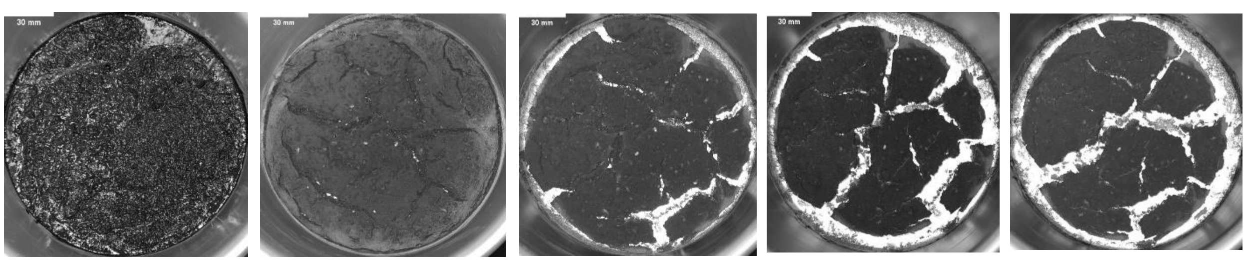

Figure 6. Evaluation of desiccation cracking for PFA10AA1:2

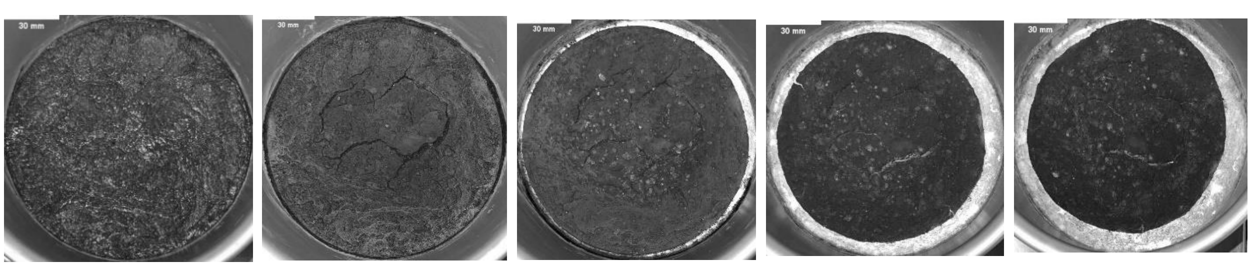

Figure 7. Evaluation of desiccation cracking for PFA20AA1:2

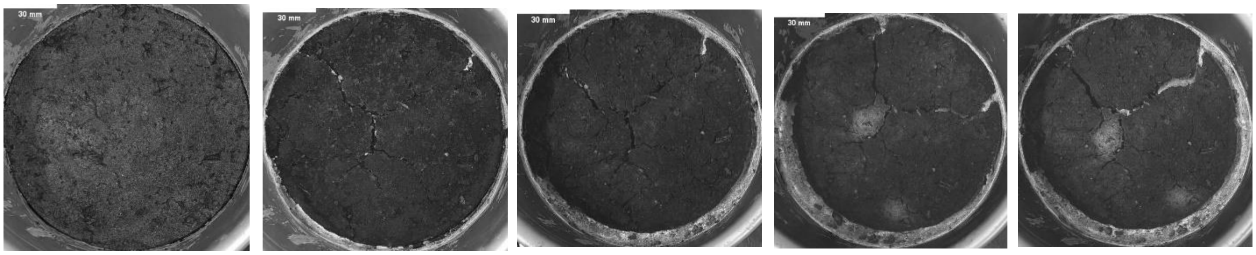


Figure 8. Evaluation of desiccation cracking for PFA30AA1:2

## 4 CONCLUSION

In this paper, laboratory experiments were conducted to evaluate the feasibility of fly ash based geopolymer, sodium hydroxide and sodium silicate employment in desiccation cracking improvement in an organic muskeg soil from Alberta, Canada. Different contents of PFA (10%, 20% and 30%) and different ratios of activators (NaoH: Na2SiO3 = 1:0, 1:1, 1:2) were selected to add into the organic soil. Based on the experiments, it is proven that by adding PFA into the organic soil, samples become more compact and uniform with increasing shrinkage in soil and dish boundary area and reduction of cracks within the soil matrix. Moreover, by increasing the percentage of PFA from 10% to 30%, crack area decreases. In terms of activators, sodium silicate shows higher influence on reducing crack area in comparison to sodium hydroxide. According to these results, fly ash based geopolymers and activators can have a positive effect on having more solid samples while reusing an industrial by-product that is traditionally dumped in the landfills.

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