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Thermo-mechanical properties and microfabric of fly ash-stabilized gold tailings

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HIGHLIGHTS

- Thermal conductivity, temperature, and unconfined compressive strength are studied.
- Microfabric is investigated using mercury intrusion porosimetry (MIP).
- Influential factors are fly ash content, humic acid content, and pore fluid chemistry.

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ABSTRACT

This paper studies the changes in thermal conductivity, temperature, and unconfined compressive strength of gold tailings and fly ash mixtures during the curing period of 5 days. The microfabric of the cured mixtures was investigated with mercury intrusion porosimetry (MIP). The mixture samples were prepared at their maximum dry unit weight and optimum moisture content. Effect of adding fly ash to gold tailings (i.e., 0, 20, and 40% of the dry weight of tailings) was examined, and a comparison was made on samples prepared at the same fly ash content by replacing gold tailings with humic acid (i.e., gold tailings and humic acid ratios of 100:0, 90:10, and 80:20 by weight) or by varying pore fluid chemistry (i.e., water and salt solutions of 1 M NaCl and $CaCl_2$). The results show that the initial thermal conductivity of the samples is sensitive to the mixture proportion and a declination in the thermal conductivity is observed due to hydration of fly ash and evaporation. Inclusion of fly ash and salts into gold tailings improves the unconfined compressive strength but the presence of humic acid in samples leads to the decrease of the strength. MIP results reveal the pore structure changes associated with the packing states of the samples that reflect the influential factors considered.

1. Introduction

Mining operations around the world generate massive residue or tailings after valuable metals and minerals have been extracted from ore. The tailings are the finely ground rocks, and most tailings are stored on site surrounded by tailings dams. To improve geotechnical stability and disposal efficiency of tailings impoundment, several methods have been studied and implemented, such as densification, and co-disposal of tailings and waste rock [1]. Mine tailings can be either reactive (generating acid mine drainage, AMD hereafter) or non-reactive, depending on the mineralogical composition. Effective measures for preventing AMD generation include incorporation of alkaline binding agents such as cement and lime with reactive tailings. Since natural soils are often limited at mine sites, the chemically stabilized tailings can be utilized as construction materials for infrastructures as an integrated approach to tailings management, which can reduce tailings accumulation and limit environmental impacts. Klein and Simon [2] studied the mechanical properties of cemented tailings for backfilling excavated stopes, as related to binder types and content, water content, and pore fluid chemistry. Qian et al. [3] assessed the potential of cemented-stabilized mill tailing as base materials in roadway construction. Galaa et al. [4] examined the variations in stiffness of cemented tailings backfill at early ages and demonstrated that the ultrasonic wave measurement is an effective tool in monitoring the physicochemical reaction process in cemented tailings backfill caused by binder hydration. Fridjonsson et al. [5] observed the pore structure development associated with hydration of cemented tailing backfill. Recently, fly ash, a byproduct from coal-fired electric

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power plants has been applied as a cost effective alternative agent for acidic tailings management [6,7] and its pozzolanic properties provides added advantages for cementation bonding and pore structure refinement of tailings, leading to increasing strength and reducing permeability [8]. Zhang et al. [9] evaluated the feasibility of fly ash and tailings mixtures with geo-polymers as pavement subbase.

The impact of the presence of salts on chemical stabilization of geomaterials has been studied, but contradictory results have been reported. Mehta and Monteiro [10] stated that high concentrations of salts of strong base and weak acids accelerates the hydration of cement minerals, leading to increase of the early strength of hardened cement pastes. Rajasekaran et al. [11] showed that the sodium chloride (NaCl) and calcium chloride ($CaCl_2$) increase the density and strength of lime-stabilized clays and alter their microstructures. In contrast, Onitsuka et al. [12] reported that the presence of salts in solution decreases the strength of cement- and lime-stabilized clay with the removal of salt by leaching. Xing et al. [13] demonstrated that the chlorides in salt-rich soil-cement form Friedel's salt, which prevents strength increase of the soil-cement. In light of previous research results, it is necessary to investigate the influence of salts on engineering properties of tailings stabilized with fly ash.

The addition of organic matter to tailings has been reported to improve physical and chemical properties of tailings by increasing metal immobilization, promoting aggregated structure development, providing nutrients for vegetation, and increasing water-holding capacity [14,15]. Successful application of organic matter in combination with lime and lime kiln dust has been demonstrated for mine tailings [16,17]. Stuczynski et al. [18] reported that adding lime increases soil pH, leading to reduction in the metal solubility and increase in metals adsorption on organic matter. However, the presence of organic matter in tailings may have an adverse effect on the strength development of the tailings stabilized with binding agents, as evidenced on cement-, lime- and fly ash-stabilized organic soils [19–21]. Zhu et al. [22] pointed out that humic acid, a major component of organic matter strongly interferes with the hydration reaction of cement in solidified dredged material. Further study is still needed to estimate the impact of humic acid on geotechnical properties of fly ash-stabilized tailings.

This study investigates gold tailings stabilized with fly ash for beneficial use as structural fill material. The tailings and fly ash used are obtained from a Musselwhite gold mine site and an Atikokan power generating station, respectively, both in Ontario, Canada. The short-term development of thermal conductivity, temperature, and unconfined compression strength of gold tailings and fly ash mixtures is examined, which are known to be significantly related to the hydration process at early age of the mixtures. The microfabric of the cured mixtures is also studied in terms of the pore size distribution. The composition of the samples is altered to explore the roles of fly ash, organic matter (e.g., humic acid), and salts (e.g., NaCl and $CaCl_2$) on the thermo-mechanical properties and pore structure of the gold tailings.

2. Materials

Fig. 1 shows the particle size distributions of the gold tailings and coal fly ash. Both materials are well graded and primarily silt-sized particles, non-plastic, classified as ML according to the Unified Soil Classification System (USCS). The specific gravity of the tailings is 3.28, which is greater than that of most soils due to predominant amphibole minerals with high specific gravity, and that of the fly ash is 2.69. The mineralogical and geochemical properties of the tailings and fly ash are summarized in Table 1. The tailings primarily consist of Si, Fe and Al oxides as indicated by SiO_2 (50.82%), Fe_2O_3 (28.97%) and Al_2O_3 (8.87%). The tailings also contain high concentration of heavy metals and sulphide that will be susceptible to oxidation and acid generation. Minerals identified from X-ray diffraction (XRD) analysis from the tailings include quartz, illite, chlorite, amphibole and pyrrhotite. The mineral pyrrhotite ($Fe_{1-x}S$, $0 < x < 0.125$) is the major sulphide in Musselwhite gold tailings, which are readily oxidized and release iron and other heavy metals into the water, resulting in the generation of AMD. The major compositions of the fly ash are SiO_2, Al_2O_3, Fe_2O_3, CaO, and Na_2O, which account for a mass ratio of 93%. Among these, the CaO (lime) and Na_2O provide the beneficial effect to control and mitigate the generation of AMD from the tailings as well as to

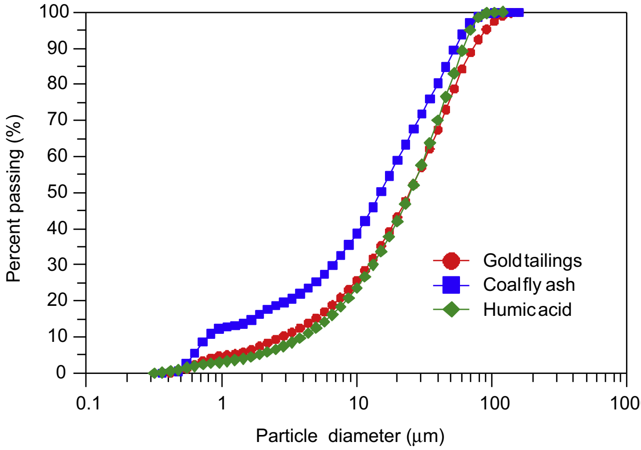

Fig. 1. Particle size distributions of the materials used.

Table 1
Chemical compositions and minerals of Musselwhite mine tailings and Atikokan fly ash.

	Mine tailings	Fly ash
(a) Major oxide (wt.%)		
SiO_2	50.82	37.99
Fe_2O_3	28.97	6.17
Al_2O_3	8.87	19.92
MgO	3.39	3.52
CaO	3.19	15.66
K_2O	0.84	0.62
TiO_2	0.45	0.68
MnO	0.36	0.03
P_2O_5	0.15	0.39
Na_2O	0.02	9.30
Cr_2O_3	0.02	0.00
Loss on ignition	0.05	0.84
Total	97.13	95.12
(b) Minor and traces (ppm)		
Arsenic	159.00	7.20
Boron	–	1400.00
Cobalt	9.50	9.00
Copper	79.00	68.70
Manganese	234.00	163.00
Nickel	36.00	0.78
Lead	105.00	12.30
Selenium	–	<15.00
Silver	<0.10	1.68
Sulphide	1.21	0.79
(c) Minerals (%)		
Quartz	37	Trace
Mica/Illite	26	–
Chlorite	4	–
Amphibole	30	–
Pyrrhotite	3	–
Dolomite	0.41	0.71
Calcite	0.80	0.58