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Effect of SiO_2 Nanoparticles and Cement on the Performance of Stabilized Ni-Contaminated Clayey Soils

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ABSTRACT: This study investigates the capability of cement-SiO_2 nanoparticles (CNS) mixture to the promotion of stabilization/solidification (S/S) process of heavy metal (HM) contaminated soils. For this purpose, artificially contaminated soil samples were first prepared by mixing kaolinite with nickel (Ni) and then a set of tests were performed to assess the effectiveness of the CNS treatment. The results indicate that the addition of cement markedly increases the HM retention of soil; however, the TCLP tests show that leaching of cement treated samples leads to return a part of pollutants to soil pore fluid. The cement and Ni interaction has a destructive impact on particles solidification which adversely affects the strength development and compressibility of the cement-stabilized specimens. At same condition, the CNS blend is more efficient in immobilizing Ni and modifying the soil engineering properties as compared to sole cement. Based on the physicochemical, XRD and SEM tests, the better performance of CNS agent is mainly associated with the more and faster growth of cement compounds, reducing the adverse effect of heavy metal precipitation on the hydration reactions and increasing the particle density. The study concluded that with the consideration of EPA criteria, an optimum cement content of 0.5 wt% per one cmol/kg.soil of HM within 28 days of curing can successfully remediate the Ni contaminated soils. The incorporation of SiO_2 nanoparticles into the binder system improves the microstructure and geomechanical performance of stabilized materials and causes a significant reduction in the cement consumption (up to 35%) and time of curing (up to 3 times).

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1- Introduction

In recent years, due to rapid urbanization and a range of different industrial activities, a large number of sites are polluted with a wide range of contaminants [1-3]. Soil contamination has been a serious problem worldwide presenting a health risk to humans [4]. Several methods were applied to treat contaminated site soils [2]. Among them cement-based solidification/stabilization (S/S) technologies have been widely employed as efficient, cost-effective, versatile and low risk remediation method which began in the early 1970s [1]. S/S involves mixing binders and contaminated soils to reduce the mobility of heavy metals (HMs) and enhance the strength by physical and chemical means [3]. The commonly used agents in S/S process are high alkali materials, such as cement. However, previous studies have indicated that cement may show limited efficiency in some applications [2]. In addition, the cement production is known to be highly energy consuming and releases up to 10% CO_2 during its production [3]. The above disadvantages are leading researchers to develop alternative agents or additives, especially those that are more effective and less costly, for the S/S treatment [1]. Under the drive of sustainability, industrial by-products are drawing people's attention recently. In this case, the amorphous structure, large specific surface area and small particles make the nano-SiO_2 (NS) reactive to the alkali product to produce cementing phase, which is expected to show advantages in terms of mechanical capacity and durability of the composite cementing system. While the positive effects of nano-SiO_2 as a supplementary cementitious material in concrete technology and soil modification are most well-known, there is a lack of detailed studies on different aspects of the NS performance for the S/S treatment of clayey soils. Thus, the present research was conducted to address the efficacy of NS combination with cement to remedy Ni-contaminated soil and enhance the S/S possess with reduction in the cement consumption and decrease in the time of curing, as evidenced by macro and microstructure experiments. Moreover, the required dosage of binder to meet the full needs of HM immobilization is determined; however, it has not gained enough consideration in the literature [1-4].

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2- Materials and methods

2- 1- Materials

This research was performed on the Ni-contaminated kaolinite at the laboratory scale. To characterize the soil sample, its properties were determined according to ASTM [5] and EPA [6] methods and were presented in the Table 1. Nickel (Ni) represents one of the most common HMs found in the contaminated lands [7], hence, nickel nitrate (Merck, Germany) was used as the source of heavy metal to prepare the HM-contaminated soil samples. The source chemical of Ni was selected in the form of nitrate because it is inert for the cement hydration reactions [4].

Table 1. Physicochemical characteristics of soil sample

Characteristics	Quantity measured
Mineralogy	Mainly kaolinite (>80%)
XRD peak, Å	7.13
CEC, cmol/kg	12.5
SSA, m^2/g	25
Soil pH	8.82
Plasticity index, %	19
Soil classification	CL
$\gamma_{d\text{-}max}$, gr/cm^3	1.56
ω_{opt}, %	28.5

The chemical compositions of the used Portland cement and nano-SiO_2 were determined by the XRF analysis and were presented in Table 2.

Table 2. Properties of used cement and nano-SiO_2

Characteristics	Quantity measured	
	Cement	nano-SiO_2
Maine elements	CaO=63.2, SiO_2=21.5 Al_2O_3=4.9, Fe_2O_3=3.8, MgO=1.5	SiO_2=97.1, Al_2O_3=0.9, CaO=0.8, MgO=0.5, Fe_2O_3=0.2
EC, mS/cm	11.1	0.07
pH (In 1:20 ratio)	12.9	7.2
SSA, m^2/g	30	450
Particle size	---	< 75 µm

2- 2- Samples preparation and experimental methods

To achieve the objectives of this study, cement and cement-nano-SiO_2 (CNS) at wide ranges (2 to 20% by mass) were separately mixed with Ni-contaminated soil. The mixes were then blended with the required amount of water for each test and the specimens were cured in a warm humid chamber at temperature 22±1°C and with a relative humidity of 85%. At the end of each curing, the soil samples were used in different tests including batch equilibrium, compression strength (UCS), the toxicity characteristic leaching procedure (TCLP), scanning electron microscope (SEM) and X-ray diffraction (XRD) powder analyses. The all tests were performed according to ASTM [5] and EPA [6] methods.

3- Results and Discussion

The results of Ni toxicity leaching for the cement and CNS treated samples after 7 and 28 days of curing are presented in Figure 1. As can be seen, the S/S products showed lower amounts of leached Ni as compared to untreated soil sample. This can be attributed to a more formation of cementing products [1, 8], which strongly binds the soil particles, and thus increases encapsulation of HM resulting in a lower Ni content in the pore fluid. On the other hand, at same level of binder, the CNS blend is more efficient in immobilizing Ni. Such behavior could be explained by the higher pozzolanic activity of CNS mixture and the formation of denser microstructure at presence of CNS, as evidenced by the XRD patterns and SEM micrographs.

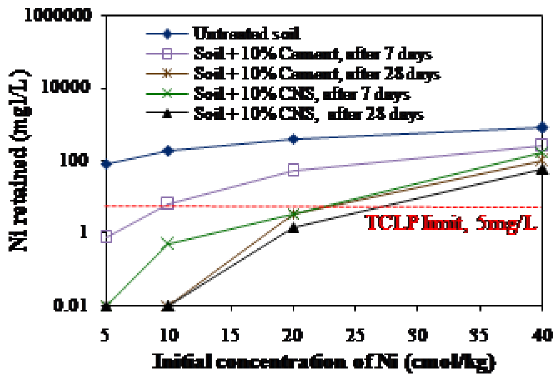

Figure 1. Effect of S/S process on the HM leachability

Figure 2 shows the UCS of soil with different dosages of binder. The results indicated that an increase in the HM content adversely affects the strength development. This is because the cement-Ni interaction can hinder the hydration kinetics [3-7] which has a destructive impact on the soil strength.

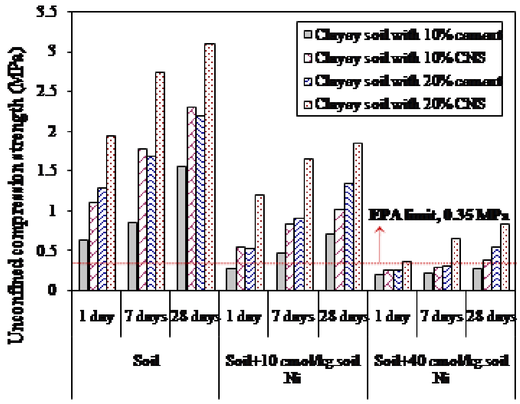

Figure 2. Effect of S/S process on the soil strength

According to the results presented in Figure 2, the soil strength upon CNS treatments is higher than that of the cement-treated samples. Such behavior is mainly due to the consumption of free lime liberated during the cement hydration by nano-SiO2 particles, giving additional cementing products which can increase the soil strength [4-8], as shown in Figure 2.

4- Conclusions

- The results indicated that the addition of 10% cement markedly increases the HM retention capability of soil; however, the TCLP tests show that leaching of cement treated samples leads to return a part of pollutants (by nearly 30%) to pore fluid.
- The cement and Ni interaction has a destructive impact on solidification of particles which adversely affects the

strength and compressibility of the stabilized soil. On the other hand, CNS is more efficient in immobilizing Ni and modifying the engineering properties in comparison to cement treatment.

- With the consideration of EPA criteria, an optimum cement content of 0.5 wt% per one cmol/kg.soil of HM at 28 days can be use for the effective S/S treatment of Ni-contaminated soils. The incorporation of nano-SiO2 into the binder system improves the performance of S/S products and causes a reduction in the cement content (to about 35%) and time of curing (up to 3 times).

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