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Effects of light crude oil contamination on the physical and mechanical properties of geopolymer cement mortar

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ABSTRACT

Fly ash and oil contaminated sand are considered as the two waste materials that may affect environment. This paper investigated the suitability of producing geopolymer cement mortar using oil contaminated sand. A comparison between physical and mechanical properties of mortar produced using geopolymer and Ordinary Portland Cement (OPC), in terms of porosity, hydration and compressive strength, was conducted. The results showed that heat curing can increase the compressive strength of geopolymer mortar up to 54% compared to ambient curing situation. The geopolymer mortar with 1% of light crude oil contamination yielded a 20% higher compressive strength than OPC mortar containing sand with a saturated surface dry condition. Furthermore, the formation of efflorescence decreased as the level of oil contamination decreased. Moreover, the heat curing method increased the kinetic energy and degree of reaction for geopolymer cement mortar, which cause an increment of the density of the pore system and improving the mechanical properties of the resulting composites. From the results of this study, it was demonstrated that geopolymer mortar has the potential of utilizing oil contaminated sand, and reducing its environmental impacts.

1. Introduction

There is growing public concern about the wide variety of toxic organic chemicals that are either deliberately or inadvertently being introduced into the environment. Petroleum hydrocarbons are a common example of these chemicals because they enter the environment frequently, in large volumes, and in a variety of ways. Leakage from natural deposits is one of the major ways that crude oil affects the environment [1] Co-produced water associated with the production of oil and gas is also another source of oil contaminated sand [2–4]. Intentionally or accidentally, oil spill contamination has detrimental effects on the properties of the surrounding soil and changes its physical and chemical properties [2]. To minimise its effect on the environment, methods of remediation ranging from sand washing, bio-remediation, electro-kinetic sand remediation, and thermal desorption have been implemented, but are not considered to be cost effective [5]. One alternative method of remediation is using contaminated sand for engineering applications. Some researchers have already investigated the use of sand contaminated with oil in road base materials or topping layers in parking areas [6–8]. Furthermore, several studies investigated how oil contaminated sand would affect the mechanical properties of concrete; for example, how used engine oil affect the properties of fresh, hardened and reinforced concrete [9]. These investigations revealed that the oil acted like a chemical plasticizer and improved the fluidity and doubled the slump of the concrete mix, while maintaining its compressive strength. A similar study was conducted by Mindess and Young [10] where engine oil was added to a fresh concrete mix and found that its effect was similar to adding an air-entraining chemical admixture that enhanced some of the durability properties of concrete. Additionally, the potential use of soil contaminated with petroleum in highway construction was investigated by Hassan et al. [11], and they concluded that it could be used for this purpose. Recent study by Ajagbe et al. [3] investigated the effect of crude oil on compressive strength of concrete, and concluded that 18–90% of its compressive strength was lost due to 2.5–25% contamination with crude oil. Abdul Ahad [12] indicated there was a significant reduction in the compressive strength and about 11% reduction in the splitting-tensile strength of concrete soaked in crude oil.

Geopolymer is a combination of reactive material that is rich in silica and alumina, with alkaline liquid [13]. This material has been studied widely and shown to be a promising green substitute for ordinary Portland cement in some applications. It is reported that geopolymer concrete has good engineering properties [14–17] and it reduces the potential for global warming as a result of its ability to replace ordinary Portland cement [18,19]. Geopolymer concrete was developed as a result of research into heat resistant materials after a

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series of catastrophic fires [20], and it has the advantage of not using any Portland cement in its production. Geopolymer research has shifted from being in the field of chemistry to engineering applications and commercial production. Furthermore, the use of fly ash has further environmental advantages because the volume of fly ash produced annually is too high compared to the percentage utilised in a beneficial way. For instance in Australia 14.5 million tonnes of fly ash was produced, of which only 2.3 million tonnes were utilised in useful applications, mainly as a partial replacement for Portland cement [17,21]. The improvement of geopolymer technology and applications will lead to a broader utilisation of fly ash, as the use of fly ash in concrete and other building materials has been observed over the last 15 years.

In order to provide a more cost effective solution, oil contaminated sand can be combined with cement binder that come from industrial waste like geopolymer concrete. Currently, most of the studies focused on combining oil contaminated sand with Portland cement in order to provide a better and more cost effective remediation method. However, the effect of crude oil on the properties of geopolymer and cement mortar such as strength, hydration, polarisation, and porosity is still unknown. This study aimed at investigating a new concept for utilizing the contaminated sand in geopolymer concrete which appears to be the first study in this research area.

2. Experimental program

2.1. Oil contaminated sand

Air dry fine sand was used because of its similarity to the sand in the Libyan Desert where the first author originated. The Particle Size Distribution (PSD) of the sand was determined following AS-1141-2011 [22]. The PSD test showed that the maximum grain size of the sand particle is less than 2.36 mm. Mineral Fork w2.5 motor cycle oil was used to contaminate the sand as this oil has a density and viscosity very similar to that of light crude oil as shown in Table 1. The samples were prepared by mixing the dry sand with eight different percentages of light crude oil (0.5, 1, 2, 4, 6, 8 and 10% by the weight). In addition, uncontaminated (0%) sand was used as a control sample. The sand was mixed manually with the oil and was placed inside a plastic container for 72 h to allow the mixture to attain a homogenous condition. The effect of curing methods on the compressive strength of geopolymer mortar using fine sand with different levels of light crude oil contamination (0, 1 and 10%) was investigated first. These percentages were selected based on the results of the preliminary investigation on the mechanical properties of fine sand contaminated with light crude oil [23]. Zero oil percentage represents the control sample, 1% represents the optimum shear strength and the optimum compressive strength conducted using Ordinary Portland Cement (OPC) and the 10% represents the highest percentage of crude oil contamination attained a comparable result to control sample (0%).

2.2. Fly ash

The fly ash used in this study was Type F (low calcium) fly ash of approximately 15 μm. It was sourced from Pozzolanic Millmerran, Queensland, Australia. The chemical composition of the fly ashes is given in Table 2, and its packing density was found to be 1100 kg/m^3. Generally, amorphous material accounts for 60%–90% of bulk fly ash composition, while crystalline material accounts for the difference [26]. The last author has studied the preparation of Millmerran fly ash for many years, and the design of the composition of these materials were reported in Refs. [27,28].

Table 1
Comparison between light crude oil and Fork w2.5 Motorcycle oil [24,25].

Specifications	Light crude oil	Fork w2.5 Motorcycle oils	Ref.
Density (kg/L)	0.825	0.827	[24–26]
Viscosity (mm^2/s)	5.96	6.74	
Temperature (°C)	40	40	

Table 2
Chemical composition of fly ash (%).

Element	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3
Percentage (%)	51.8	24.4	9.62	4.37	1.5	0.34	1.41	0.26

Table 3
Properties of sodium silicate solution.

Property		Value
Composition	Sodium oxide, (Na2O)	14.7 (%)
	Silicon dioxide, (SiO2)	29.4 (%)
	Water	55.9 (%)
Specific gravity of solution		1.52
PH value		11 to 13
Odour		No odour
Solubility in water		Completely soluble

2.3. Alkaline liquid

A combination of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solutions was used as the alkaline liquid.

2.3.1. Sodium silicate solution

The sodium silicate solution was obtained from PQ Australia. This solution is recommended for use as a detergent ingredient, adhesive, binder, feedstock silica source or industrial raw material. Some of its important properties of the solution are tabulated in Table 3.

2.3.2. Sodium hydroxide solution

The sodium hydroxide solution was prepared in the laboratory by dissolving sodium hydroxide pellets in water. Its specific gravity depended on its concentration expressed by the term molar (M). Generally, the concentration for making geopolymer concrete varies from 8M to 16M. A previous study, conducted by Hardjito and Rangan [29], measured the mass of the NaOH solid by using a different concentration. Based on their investigation, an 8M solution contains 262g of NaOH solid per kg of solution while 10M, 12M, 14M, and 16M contain 314g, 361g, 404g, and 444g, respectively. Thus, the specific gravity of the NaOH solution can be calculated; for instance, the actual weight of a 1 L, 12M solution is $(12 \times 40 \times 1000)/361 = 1329.6$ g, where 40 is the molecular weight of the NaOH, and its specific gravity is $1329.6/1000 = 1.10$. In this study, a 10M solution was prepared. This molarity was selected based on initial trials comparing 10M and 13M, where a 30% higher compressive strength was achieved for 10M than 13 M. The properties of the Sodium hydroxide (NaOH) are given in Table 4.

2.4. Mix design

The mixing was performed manually in the laboratory using Kitchenaid mini mixer (mono phase 5lt). The samples were prepared by

Table 4
Properties of sodium hydroxide solution.

Properties		Value
Compositions (10 M solution)	Sodium hydroxide (NaOH) solid	36.1 (%)
	Water	63.9 (%)
Specific gravity, (10 M solution)		1.10