Chapter

Oil Contaminated Sand: Sources, Properties, Remediation, and Engineering Applications

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Abstract

Oil leakage during the exploration, production, and transportation of crude oil is a significant issue worldwide because crude oil spills severely impact the physical and chemical properties of the surrounding soil. A range of remediation methods for oil-contaminated soil is recommended, consisting of sand washing, bioremediation, electro-kinetic sand remediation, and thermal desorption; however, none are cost-effective. To find a suitable alternative remediation method, oil-contaminated sand utilisation in construction was considered. Several researchers found that oil contamination generally has an adverse effect on the mechanical properties of sand, but certain levels of contamination have beneficial effects on some of the important properties of the sand and its produced concrete. This chapter reviews the main sources of oil contamination and the existing remediation methods for this waste material. It analyses the different factors that affect the properties of oil-contaminated sand and concrete, including the type of crude oil and permeability of sand, like its properties, absorption, chemical composition, and spillage quantity. Furthermore, the intensive evaluation results of light crude oil effects on the geotechnical properties of fine sand, cement mortar and concrete were presented. Potential applications for oil-contaminated sand were also identified for the re-use of this material in engineering and construction.

Keywords: contaminated sand, produced water, remediation, mechanical properties, construction

1. Introduction

Sand contaminated with crude oil has become a major environmental concern worldwide. This problem poses threats to human health, the ecosystem, and the properties of the surrounding sand. Due to the prohibiting cost of the existing remediation methods, a more cost-effective way of utilising oil contaminated sand is warranted. Mixing oil contaminated sand with cement and using this mix as alternative construction material is considered an innovative approach to reduce its environmental impact.

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 frequently enter the environment in large volumes and in a variety of ways. Leakage from natural deposits is one way that crude oil affects the environment [1] and oil wastewater associated with the production of oil and gas is another source of oil contaminated sand [2–4]. Intentionally or accidentally, oil spill contamination impacts on the properties of the surrounding sand 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 is using contaminated sand for engineering applications; indeed, some researchers have already investigated its use in that area and concluded that sand contaminated with oil can be used for road base materials or topping layers in parking areas [6–8]. However, the successful use of waste materials in concrete depends on the mechanical properties developed by the end product. While some studies investigated the effects of oil contamination on concrete, these studies only focused on heavy crude oil and engine oil [3, 9, 10] as well as hydrocarbons [10–12]. For instance, Almabrok et al. [13] investigated the effect that incorporated mineral oil has on the cement solidification process, and its consequent effect on the fresh and hardened properties of mortar. Almabrok et al. [14] further investigated oil solidification using a direct immobilisation method. Furthermore, the effect of kerosene impacted sand on the compressive strength of concrete in different conditions was investigated by Shahrabadi and Vafaei [15]. In this study, different percentages of kerosene (0, 0.5, 1, 2, 4, 6 and 8%, by weight of sand) was used to evaluate the effect of kerosene-soaked environment on compressive strength of concrete. They concluded that using contaminated sand adversely affects the compressive strength of concrete and hence, a reduction up to 27% in the concrete compressive strength occurred when samples with 2% of kerosene contamination were used. In a similar study by Attom et al. [16], the effect of 0.5, 1 and 1.5% of kerosene and diesel by dry weight of sand was investigated. They noted a reduction of up to 42% in the compressive strength as the level of contamination increased. Recently Shafiq et al. [17] investigated the effects of used engine oil (UEO) on the slump, compressive strength and oxygen permeability of normal and blended cement concrete. They concluded that engine oil caused variations in the compressive strength in the range of ±20% compared to the control mix. However, the UEO caused a reasonable reduction in total porosity and the coefficient of oxygen permeability of all concrete mixes compared to the control mix which can help this type of concrete achieve a high performance. Recently a study conducted by Abousnina et al. [18], the author investigated the effects of light crude oil contamination on the physical and mechanical properties of geopolymer cement mortar. The results showed that geopolymer mortar has the potential of utilising oil contaminated sand and reducing its environmental impact.

This shows the high potential of oil contaminated sand as sustainable material in building and construction. However, understanding the physical and mechanical properties of contaminated sand and its effect on produced mortar and concrete is very important in order to determine their end-use application [19]. Once achieved, this will potentially solve the issues of oil contamination in oil producing countries because the cost of this method will be cheaper compared to the existing remediation methods. Therefore, in this chapter the authors presented an extensive investigation to evaluate the effect that light crude oil has on the mechanical properties and microstructure of concrete. The succeeding sub-sections provide a better understating of the main sources, properties, existing remediation methods, and the beneficial use of oil contaminated sand in engineering and construction.

2. Petroleum contaminants

Over the last few decades there has been an increased public awareness of environmental issues, particularly when the contamination of sand, water, and air is involved. Worldwide, scientists and environmentalists are faced with the challenge of overcoming the detrimental effects of the contamination of sand, air, and water. The spillage of crude oil onto sand, leakages from pipelines, underground and surface fuel storage tanks, indiscriminate spills, and careless disposal and management of waste- and other by-products of society, constitute the major sources of petroleum contamination. **Figure 1** shows the final stage of produced water and the contaminated sand around the discharge disposal point, while **Figure 2** shows the oil spillage in one of the Libyan oil fields.

2.1 Sand contaminated with oil

One of the most critical environmental impacts of the oil industry is the spillage of crude oil, which severely contaminates the sand. Remediating contaminated sand takes longer and costs much more than it does for water contaminated with oil. Hence, it is very important to investigate the properties of sand contaminated with oil [21] because crude oil has a significant effect on the physical and chemical properties of surround sand [22]. However, the severity of the effect is based on several factors such as the sand type and quantity of the crude oil spillage. **Figure 3** shows who the crude oil migrates down to the groundwater causing partial saturation of the sand and the pathway of the hydrocarbons as shown in **Figure 3**.

Several studies have already investigated the effect of crude oil on the geotechnical properties of the sands. For instance, Cook et al. [24] experimentally investigated the compaction, compression, and strength properties of uniformly graded sands contaminated by crude oil. They reported that although oil contamination had no significant effect on the compaction characteristics, it decreases the friction angle and considerably increases the compressibility of the sand. Similar results were obtained by Puri [25] and Meegoda and Ratnaweera [26] for sandy and clayey

Figure 1.
Oil contaminated sand caused by produced water Ghani field HOO [20].

Figure 2.
Oil contaminated sand caused by oil spillage Ghani field HOO [20].

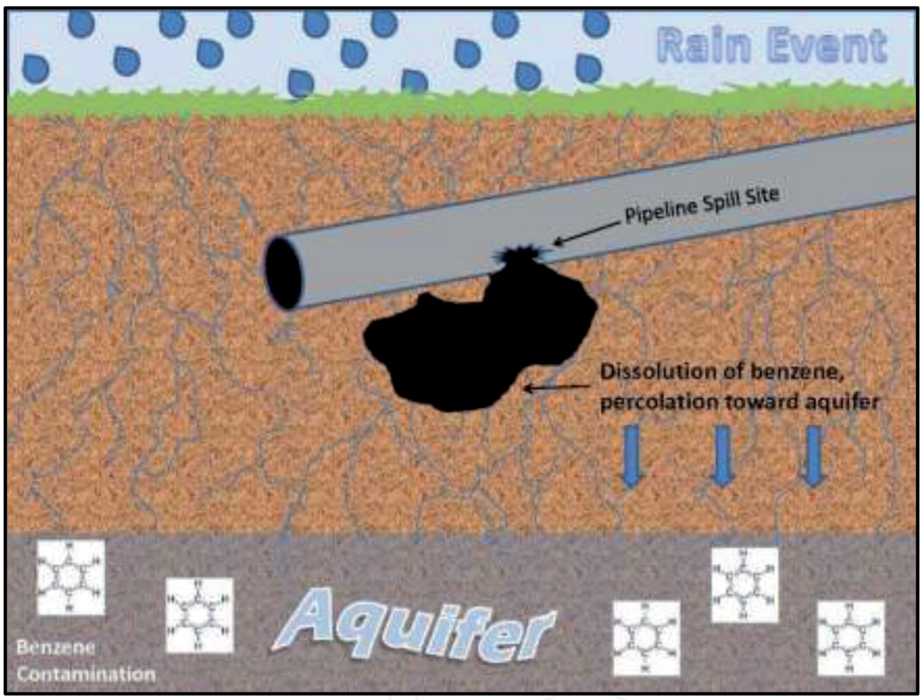

Figure 3.
Crude oil spillage and the leaching of light hydrocarbons to the aquifer [23].

sands, respectively. Studies on the geotechnical characteristics of fine-grained sands have just recently gained momentum. Khosravi et al. [2] studied the geotechnical properties of the oil-contaminated clayey and sandy sands and found a reduction in strength, permeability, maximum dry density, optimum water content, and Atterberg limits of these sands. Singh et al. [27] found an increase of 35–50% in the consolidation settlement of fine-grained sands upon contamination with petroleum hydrocarbons. From the previous studies in can be considered that the uniformly graded sands, clayey sands, fine-grained sands showed similar results however, when clayey and sandy sands was used the strength, permeability, maximum dry density, optimum water content, and Atterberg limits were decreased. Although none of the previous studies were investigated the absorption test of crude oil, it is expected that the type of sands may play a great role properties of oil contaminated sand.

Hydrocarbon contamination has a direct effect on the erodibility of sand and water infiltration and may also cause fire on the ground. Furthermore, the aggregation of fine particles, and the fusing of minerals, may lead to a reduction in the stability of the sand-organic matter aggregate. Whereas fire-induced or fire-enhanced sand water repellence has often been cited as the major cause of post-fire enhanced runoff and erosion [28], hydrocarbon contamination can also affect the physio-chemical characteristics of sand [29].

A previous study by Rahman et al. [30] has shown that is not only the ecosystem that can be affected by the spillage of crude oil, but the safety of the civil engineering structures as well. Cleaning up contaminated sand is a complicated job due to the long period of time needed, and the high cost and limitations of disposing the excavated sand. Furthermore, proper environmental regulations are not available due to the lack of proper management in many developing counties such as Libya, which then leads to disused oil and illegal dumping of other hydrocarbon components, which could have helped to tackle the environmental issue, as well as the economy, in the form of construction materials such as sand. Moreover, oil contamination can adversely affect plants as well as contaminate ground water resources for drinking or agricultural purposes [31].

2.2 Mechanical properties of oil contaminated sand

Sand is a naturally occurring material, which is considered to be an engineering material. Thus, its physical characteristics can be determined by experiments, which then may enable these properties to be used to predict their expected behaviour under working conditions, which in turn raises the possibility for its potential beneficial use to be determined [32]. The advantages of examining the mechanical properties of sand are that it permits a greater accuracy of measurements, so that any changes in conditions can be simulated to represent the conditions during and after construction, and the sand parameters can be derived within a reasonable time scale. Therefore, understanding mechanical properties of sand is beneficial to an engineer in terms of reducing the uncertainties in the analysis of foundations and earth work and the creation of structures, and in the use of sand as a construction material. In this application, the mechanical properties such as shear strength is investigated.

2.2.1 Shear strength

The shear strength of sand is one of the most important parameters in civil engineering applications. The safety of any mechanical engineering structure is based on the shear strength of the underlying sand [33]. All constructions, when in or on the land, impose loads on the sand that supports the foundations of that particular construction or building. The load imposed on the sand may cause shear failure of the underlying sand, which occurs when the shear stress imposed on the sand mass exceeds the maximum shear resistance (shear strength) that the sand can offer [34]. The shear strength of the sand is considered to be an important aspect in many foundations, such as in the bearing capacity of shallow foundations and piles, the lateral earth pressure on retaining walls, and the stability of slopes of dams [35]. Hence, understanding the shear strength can play a great role in terms of the entity classification of the sand [36], which in turn can assist engineers to derive the critical aspects of the overall sand mechanics in a specific environment.

The shear strength of common engineering materials, such as steel, from a continuum mechanics viewpoint, is governed by the molecular bonds that hold the material. The higher the shear strength of a material, the stronger the molecular structure [35]. Nevertheless, the shear strength of sand operates under a different set of principles. Sand is a particulate material, so shear failure occurs when the stresses between the particles are such that they slide or roll past each other. Due to the particulate nature of sand, unlike that of a continuum, the shear strength depends on the interaction of anti-particles (is it a particle of the opposite charge), rather than the internal strength of the sand particles themselves [36]. Sand derives its shear strength from two sources: cohesion between particles and frictional resistance between particles. Cohesion is the cementation between sand grains or the electrostatic attraction between sand particles [34].

2.3 Stabilisation of oil contaminated sand by mixing with cement

Several studies have investigated the mechanical properties of concrete utilising oil contaminated sand and have evaluated their potential use in construction. These studies are presented in this section, as well as the current usage of oil contaminated sand in construction.

2.3.1 Effects of oil contamination on the properties of mortar and concrete

Hamad and Rteil [37] revealed that oil acted like a chemical plasticiser, improved the fluidity, and doubled the slump of the concrete mix, while maintaining its compressive strength. A similar study was conducted by Hamad et al. [10] who added engine oil to a fresh concrete mix and found that its effect was similar to adding an air-entraining chemical admixture, which enhanced some of the durability properties of concrete. Additionally, the potential use of sand contaminated with petroleum in highway construction was investigated by Hassan et al. [38], and they concluded that it could be used for this purpose.

In a recent study by Ajagbe et al. [3] the effect of crude oil on compressive strength of concrete was investigated, and they concluded that 18–90% of its compressive strength was lost due to 2.5–25% contamination with crude oil. Ahad and Ramzi [9] indicated that there was a significant reduction in the compressive strength and about an 11% reduction in the splitting-tensile strength of concrete soaked in crude oil. **Table 1** summaries the effect of oil contamination on the mechanical properties of concrete. Nevertheless, there are still disagreements about the effect of crude oil and its produced content on the properties of produced concrete.

As it can be seen in **Table 1** that most of these researchers disagree on the effect of crude oil on the behaviour of concrete. The inconsistency of some of the factors such as type of crude oil, permeability of sand, sand properties, absorption, chemical composition, and spillage quantity [22, 39–41] were considered as the main reason beyond this lack of agreement. Thus, there is a need to further investigate the properties of oil contaminated sand and its effect on produced mortar and concrete.

2.3.2 Beneficial use of mortar and concrete containing oil contaminated sand

Range of remediation methods for sand contaminated with oil have been recommended but they are not cost effective [5]. The possibility of an end-use scenario of treated material or contaminated sand was addressed, based on the results of the compressive strength. For instance, less strength is required for landfill but a higher compressive strength is required to make bricks or for some other structural objectives. Based on the United States Environmental Protection Agency (USEPA)

Test	Petroleum hydrocarbon	Effect	References
Compressive strength	Engine oil	Maintained	[3]
	Oil, phenol, trichloroethylene (TCE) and hexachlorobenzene (HCB)	Decrease	[4]
	Hydrocarbon (phenol)	Maintained	[5]
	Low % of mineral oils	Maintained	[3]
	Crude oil	Decreased (18–90%)	[6]
	Soaked in crude oil	Decreased (11%)	[7]
Workability	Engine oil	Increased	[3]
Durability		Increased	

Table 1.
Effect of oil contamination on the properties of mortar/concrete properties.

guidelines, the recommended compressive strength, at 28 days, for landfill disposal material is 0.35 MPa, while it is 1.0 MPa in France and the Netherlands [42]. A higher compressive strength of 3.5 MPa in a sanitary landfill is required according to the Wastewater Technology Centre (WTC) in Canada [43]. Based on the British standard for precast concrete masonry units (BSI, 1981) a higher compressive strength is required for blocks and bricks, of 2.8 and 7 MPa, respectively. Additionally, a minimum of 7 days cube compressive strength, which should vary between 4.5 and 15 MPa, is required for subbase and base materials, as regulated under the department of transport in the UK. This shows that there is high potential in using oil-contaminated sand in construction. However, an understanding of the details of its physical and mechanical properties is warranted.

3. Results and discussion

3.1 Effect of light crude oil contamination on shear strength

The effect of oil contaminated sand with different percentages (0, 0.5, 1, 2, 4, 6, 8, 10, 15, and 20%) on shear strength was determined using the cohesion and frictional angle of fine sand contaminated with light crude oil, using the Mohr-Coulomb equation. **Figure 4** shows the sand shear strength as function of light crude oil contamination at an applied normal stress of 50 kPa. It can be deduced from the figure that light crude oil contamination affects the shear strength of fine sand.

The shear strength increased for fine sand with 1% oil contamination, which was due to the significant increase in the apparent cohesion of the fine sand contaminated with light crude oil [41]. In contrast, at a high level of crude oil contamination, the shear strength decreased significantly with a further addition of oil content beyond 1% of crude oil content in contaminated sand. Thus, it can be inferred that the presence of a high percentage of oil increased the viscosity, and as a consequence the sand particles started to be coated by the crude oil. By increasing the amount of oil content in particular sand, the chance of inter-particle slippage will also increase, and subsequently the shear strength of soil, will decrease [44]. This indicates that higher

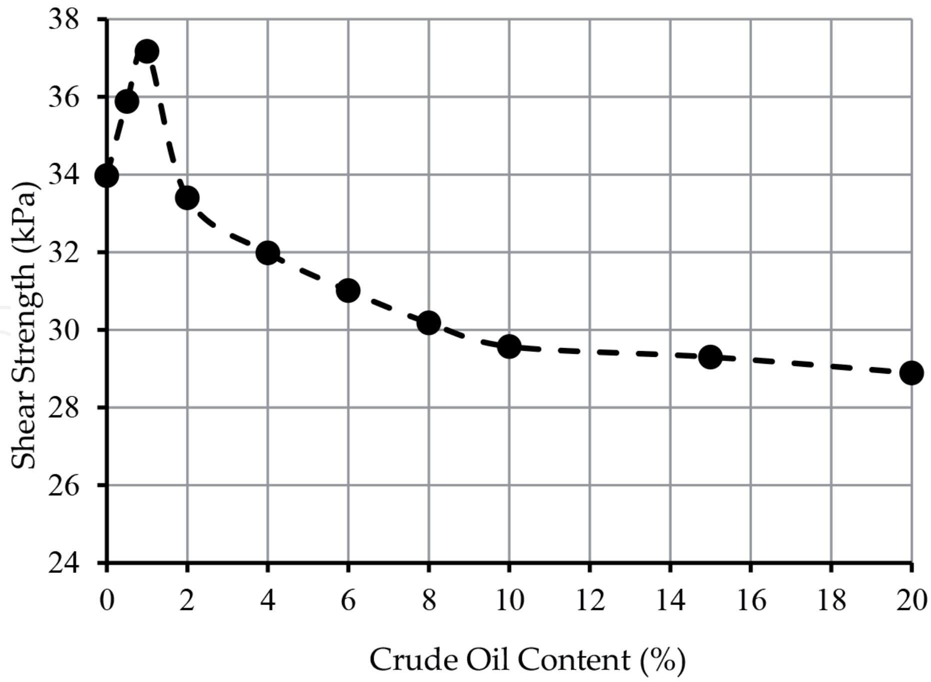

Figure 4.
Shear strength of contaminated fine sand at 50 kPa normal stress.

oil contamination resulted in lower shear strength values. Nevertheless, these results are contradicted by Khosravi et al. [2] finding, who concluded that the shear strength of kaolinite (clay) is not significantly influenced by gas oil. Furthermore, Puri [25], Shin and Das [45] both concluded that the shear strength of sand can be adversely affected by oil contamination. Moreover, Rahman et al. [44] have investigated the effect of hydrocarbons components on two types of soil, granitic soil and sedimentary soil. They concluded that the shear strength values of both soils significantly dropped from 0 to 4% of hydrocarbon content. Then, the shear strength values decreased slightly beyond 4% of hydrocarbon content. This implies that the sample will easily be slipped or sheared with higher oil content when the shear strain is applied. Moreover, Mashalah et al. [46] concluded in their study of the effect of crude oil contamination on three types of soils Lean clay, Silty sand and Poorly-graded sand (CL, SM and SP), that the shear strength decreased by increasing the crude oil content.

3.2 Effect of crude oil on the compressive strength of mortar and concrete

The effect of different percentages of light crude oil (0, 0.5, 1, 2, 4, 6, 8, 10, 15, and 20%) on the mechanical properties of mortar and concrete was investigated. A comparison between the compressive strength of cement mortar and concrete with different levels of light oil contamination is presented in **Figure 5**. In this figure, the percentage (%) increase or decrease in the compressive strength was calculated, based on the strength of the uncontaminated samples (0%). It is worth noting that the overall trend was similar with a higher value of the compressive strength, as obtained in mortar compared to concrete. This is despite the total volume of light crude oil being less for concrete than for cement mortar, due to the addition of coarse aggregates, even though the mix percentage of oil contamination by weight of sand is the same. At 1% of crude oil contamination, the cement mortar exhibited a 24.4% higher compressive strength than uncontaminated samples, while only an increase of 7.49% was shown by the concrete. At 2% of crude oil contamination, the mortar

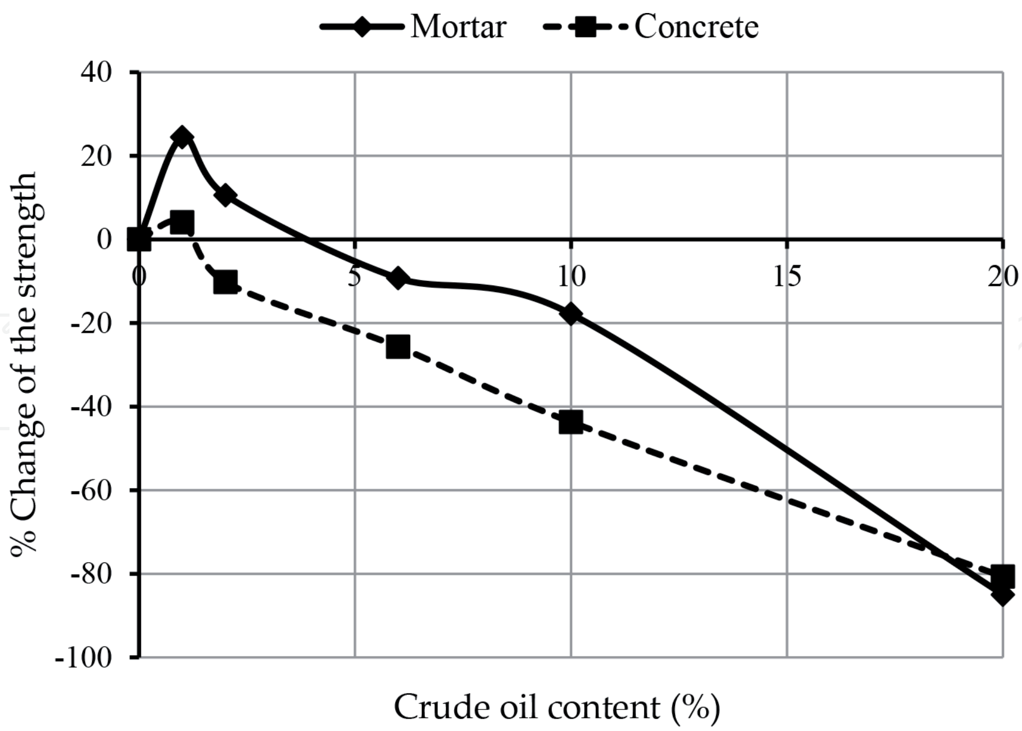

Figure 5.
Normalised compressive strength between mortar and concrete containing light crude oil contamination.

still has a 10.5% higher compressive strength than uncontaminated samples, but the compressive strength of concrete decreased by 10%. Up to 9 and 17% lower compressive strength was observed for mortar with 6 and 10% light crude oil contamination, respectively, whereas the decrease in concrete was as much as 25 and 43%, respectively. At 20% light crude oil contamination, the reduction of compressive strength was almost the same for both mortar and concrete, which was around 80%.

The higher reduction in compressive strength of the concrete with oil contamination, compared to cement mortar, was due to two main reasons: (1) lower cement binder to aggregates ratio (C: A); and (2) bigger aggregate size. Decreasing the amount of binder reduces the ability of the cement to fully cover the aggregates, hence yielding a void structure that forms a path for water permeation. It can be noted that the total volume of the fine sand used with cement mortar was around 75% (1:3), while the combination of fine and coarse aggregates for concrete accounted for almost 85% (1:3:3). This can be related to the internal structure of a pervious concrete, which is relatively less compact due to the insufficient amount of binders which produce the voids [47]. In addition, the presence of crude oil in high percentages hinders the bond formation between the cement to the large surface area of the coarse aggregates, resulting in more segregation in concrete than in mortar [48]. As a result, the compressive strength was lower for concrete compared to mortar. Furthermore, as the aggregate size increased, the water permeability of concrete increased. It is worth mentioning here that the connected porosity increased as the aggregate size increased. Previous studies conducted by Fu et al. [47], Chang et al. [49] showed that the compressive and splitting tensile strengths increased as the amount of binder increased, and they decreased with an increase in aggregate size.

The higher strength exhibited by the cement mortar than the concrete, under different percentages of crude oil content, may also be due to an increase in the contaminated surface area of the aggregates. In the concrete mix, the surface area of the

0% - Uncontaminated aggregates

20%-Coarse aggregate coated by crude oil

Figure 6.
Surface area of the coarse aggregate under different crude oil contaminations.

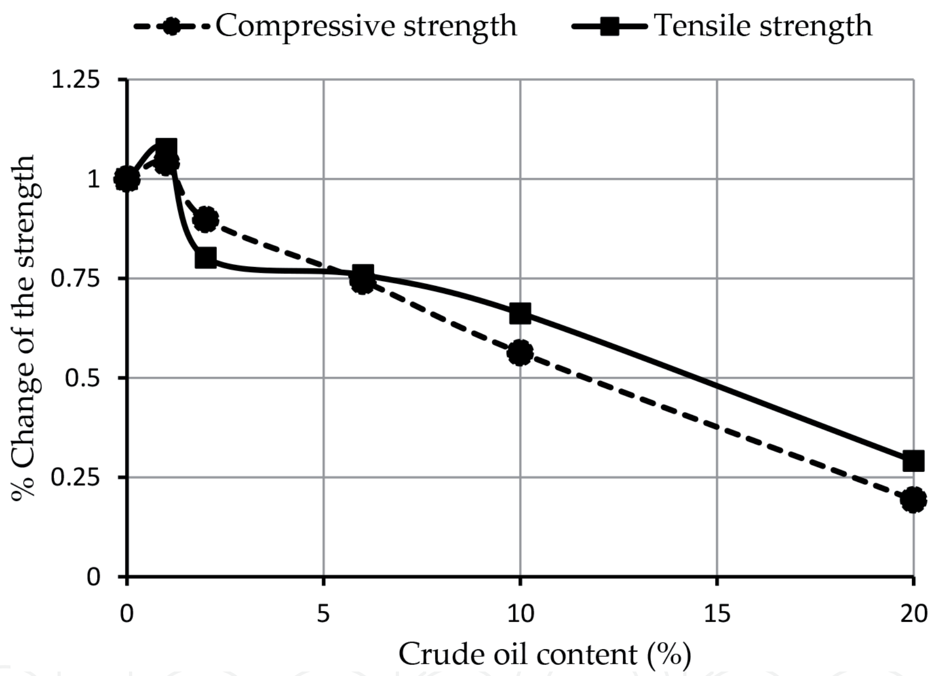

Figure 7.
Normalised relationships between the tensile compressive strength with different crude oil contaminations.

coarse aggregate is also coated by crude oil, as shown in **Figure 6**, especially at a high level of crude oil content of 10 and 20%. As a consequence, the total surface area of aggregate achieved damp or wet status (saturation status). Achieving the saturation status of aggregate by crude oil means extra free water will remain in the mix. This hindered the bond formation between cement and the coarse aggregates, resulting in more segregation for concrete than for mortar [48]. As a result, the compressive strength was lower for concrete compared to mortar.

3.3 Compressive and tensile strength relationship

Figure 7 shows the normalised effect on the compressive strength and splitting tensile strength of concrete containing fine sand with oil contamination. The behaviour of the splitting tensile strength shows a similar pattern to that of compressive strength, but with the percentage of reduction less than for compressive strength. Jasim [50] have attributed this behaviour to the inconsistency of the effect of crude oil contamination between the tensile and compressive properties. Kovler [51] has indicated that adding some waste materials, such as superabsorbent polymers (SAP), to concrete can improve the tensile strength to a higher extent than the compressive strength. This can be related to the fact that tensile strength is sensitive to cracking, so any improvement of cracking resistance is expected to be beneficial in terms of tensile properties. This indicates that the viscosity of oil had a significant effect on the splitting tensile strength of concrete, compared to its compressive strength.

4. Conclusion

The effect of crude oil on the mechanical properties of sand and its concrete were reviewed to evaluate their suitability for engineering applications and the following conclusions can be drawn:

- Sand contaminated by light crude oil is considered to be one of the most important environmental issues compared to medium and heavy crude oil because it contains a high percentage of light hydrocarbons that quickly spreads the crude oil into the surrounding soil.

- The highest value of cohesion was 10.76 kPa and it was observed at 1% of light crude oil contamination. This increase was due to the increased surface wetness of the fine sand particles. However, increasing the crude oil content from 2% up to 20% caused a significant reduction of cohesion value due to the sand particles being fully coated with crude oil, which reduced the interaction between sand particles.

- The compressive strength was enhanced by the crude oil up to the certain amount of crude oil level. At 1%, the oil contamination increased by 4.09% compared to the uncontaminated samples. However, the concrete containing fine sand with 2–6% of light crude oil contamination exhibited up to 25% lower compressive strength than uncontaminated samples and failed due to splitting failure. Increasing the crude oil from 10 to 20% resulted in significantly lower strength than the uncontaminated concrete.

- The optimum value of the splitting tensile was also observed at 1% of crude oil contamination, which was 7% higher compared to uncontaminated samples. On the other hand, increasing the crude oil content above 2% caused the fine sand to exceed the equilibrium condition, and the oil also contaminated the surface of the coarse aggregates.

- Oil contamination has a more detrimental effect on the mechanical properties of concrete than cement mortar. Up to 7 MPa lower compressive strength was obtained in concrete compared to mortar.

- Generally, it can be concluded that the properties of oil contaminated sand and its concrete were found to be suitable to use as some construction materials up to certain amount of level. Similarly, the results indicated that even the mortar and concrete using fine sand contaminated with higher crude oil contamination (15 and 20%) can be used for low load bearing engineering application such as landfill layering and production of bricks.

5. Proposals for future research

The following aspects need to be further studied in more detail to determine the end use application of cement mortar and concrete containing oil contaminated fine sand, and to pave the way for the development of structural components for civil engineering applications:

- The decrease in the mechanical properties of cement mortar and concrete containing oil contaminated fine sand could be enhanced by adding fibres into the mix. The appropriate forms of the fibres and the optimal dosage, which will result in properties equal or higher than the uncontaminated samples, need to be determined. Moreover, the maximum level of light crude oil contamination that will not severely impact on the bond between the cement and the fibres needs to be determined.

- The initial results of the effect of the light crude oil on the mechanical properties of geopolymer mortar showed a high potential to combine some of the major waste products, namely oil contaminated sand and fly ash, and to use them in building and construction. Therefore, further investigation on the effect of different percentages of oil contaminated sand on the mechanical and durability behaviour of the geopolymer concrete is recommended.

- The effect of crude oil on reinforced concrete is a new area of research that could be conducted to investigate the effect of crude oil on steel bars through the resistance of corrosion. Understanding the bond between reinforcement and concrete, and the behaviour of reinforced concrete structures containing oil contaminated sand warrants further exploration with regards to their potential beneficial use in civil engineering and construction applications.

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Conflict of interest

The authors declare that they have no conflict of interest.

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