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Effect of Curing Methods on the Mechanical Properties of Cement Mortar Contaminated with Heavy Crude Oil

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Abstract. Crude oil contamination poses significant environmental issues, particularly in regions where oil spills affect soil and groundwater. Utilising damaged materials in construction offers a cost-effective rehabilitation strategy that repurposes waste and reduces pollution. This study examines the effects of curing methods and heavy crude oil contamination on the mechanical properties of cement mortar. Mortar samples with different amounts of heavy crude oil (0%, 2%, and 10%) were cured using air, water, and sealed plastic. Water curing attained the highest compressive strength across different pollution levels by maintaining moisture for complete hydration. In contrast, air curing resulted in the lowest strength, especially for uncontaminated and 2% oil samples, due to rapid drying that limited hydration and increased porosity. Curing techniques did not affect the strength of samples with 10% heavy crude oil, perhaps due to oil saturation impeding hydration. Increased oil contamination, particularly with heavy crude, significantly enhanced porosity and reduced compressive strength. The high viscosity and complex molecular structure of heavy crude oil form a dense coating around cement particles, hindering hydration and undermining the integrity of the cement matrix. The findings suggest that selecting an appropriate curing procedure for low-level crude oil may facilitate repurposing materials contaminated with heavy crude oil as sustainable, cost-effective alternatives for specific civil engineering applications, offering a viable option for oil-contaminated sand.

Key words: Heavy crude oil, contamination, hydration, remediation, mechanical properties.

Introduction

Sand contaminated with crude oil and other hydrocarbons has emerged as a global environmental challenge. Such contamination risks human health, disrupts ecosystems, and alters the physical and chemical properties of the affected sand (Kuppusamy et al., 2020; Ore & Adeola, 2021). Traditional remediation methods for oil-contaminated sand are often costly and complex, necessitating more innovative and cost-effective solutions (Ajagbe et al., 2012; Hamad & Rteil, 2003). One promising approach is to repurpose contaminated sand by mixing it with cement and using this mixture as an alternative construction material. This method addresses disposal issues and mitigates environmental impact (A.Mohammed, 2000; Almabrok, 2011). Recent research in Australia has highlighted that light crude oil impacts fine sand's physical and mechanical properties and the quality of mortar and concrete produced with contaminated sand. Studies indicate that higher oil contamination levels decrease water absorption, permeability, contact angle, frictional angle, and cohesion. Notably, a 1% oil contamination level resulted in the highest cohesion (10.76 kPa) and a 10% enhancement in shear strength, demonstrating the potential of using such waste material in construction (Abousnina et al., 2018). Further analysis revealed that cement mortars incorporating oil-contaminated sand achieved up to 19% higher compressive strength when cement and water were mixed prior to adding the sand due to improved cement hydration. Mortars cured in a fog room exhibited up to 45.6% higher compressive strength than those cured under other conditions, such as water, air, or plastic bags. Scanning electron microscopy showed fog room-cured mortars had lower total porosity, smaller capillary pores, and denser calcium silicate hydrate formations (Abousnina et al., 2016).

An investigation into concrete containing oil-contaminated sand revealed that density decreased with increasing crude oil content due to higher surface voids and total porosity. Concrete with 1% light crude oil contamination achieved the highest compressive and splitting tensile strengths due to optimal sand cohesion. However, strength properties declined with contamination levels above 1% as the bond between cement paste and aggregates deteriorated. Concrete beams with 6% oil contamination only showed a 20% reduction in moment capacity compared to beams made with uncontaminated concrete. In contrast to light crude oil, heavy crude oil has a higher density and specific gravity, potentially enhancing the cohesion between sand particles and reducing total porosity (Abousnina et al., 2018). This improvement may positively affect the properties of concrete properties and decrease water absorption during mixing, thereby enhancing the cement hydration process (Aljuaydi et al., 2024). Given that Petroleum Development Oman (PDO) generates approximately 53,000 tons/year of petroleum-contaminated soil (PCS), which poses disposal challenges due to inadequate waste management facilities, repurposing heavy oil-contaminated sand could offer a sustainable alternative (Jamrah et al., 2007).

This study explores the impact of various concentrations of heavy crude oil on the properties of cement mortars, comparing these effects with those observed with light crude oil. It examines how different curing methods—ambient, plastic bags, and water—affect mortars with oil contamination levels of 0%, 2%, and 10%, focusing on changes in the concrete's physical and mechanical properties. This research further examines heavy crude oil's impact on cement mortar's microstructural characteristics, focusing specifically on alterations in porosity and the hydration process. The findings reveal how crude oil presence disrupts typical microstructural formation, affecting the density and durability of the mortar. Based on these insights, the study suggests possible applications for oil-contaminated sand within the construction industry, emphasizing its potential as a sustainable alternative building material. Repurposing contaminated sand could mitigate environmental damage while offering a resource-efficient solution for construction.

2. Materials and methods

2.1. Sample preparation

This study utilised dried fine sand, and its Particle Size Distribution (PSD) was analyzed according to AS-1141-2011 [22]. To prepare samples, dry sand was manually mixed with heavy crude oil at concentrations of 2% and 10% by weight, with uncontaminated sand (0% oil) as the control. The sand-oil mixtures were stored in plastic containers for 72 hours to ensure thorough homogenization (Figure 1).

Fig. 1. Preparation of the samples

Oman Petroleum Development (OPD), through Sultan Qaboos University, supplied the heavy crude oil used as the contaminant in this experiment. The crude oil's detailed specifications are provided in Table 1 below.

Table 1. Specification of heavy crude oil used in this experiment (Total Energies Trading & Shipping, 2020).

Heavy crude oil	Properties
Density at 15°C, kg/m3	868.7
°API	31.3
Bbl/mt	7.253
Acidity, mg KOH/g	0.64
Sulphur, wt%	1.410
Hydrogen Sulphide, mg/kg	<1
Mercaptan Sulphur, mg/kg	160
Viscosity, cSt at 10 °C	51
Viscosity, cSt at 50 °C	10
Pour Point °C	-36
Total Nitrogen, wt%	0.121
Wax, wt%	-
Wax Appearance Temperature	-
RVP at 37.8 °C, kPa	16
Water, vol%	0.1
NaCl, mg/kg	59.0
Nickel, mg/kg	10.1
Vanadium, mg/kg	10.1
Iron, mg/kg	4.0
Mercury, µg/kg	2.0

2.2. Preparing and Casting of Mortar

The study examines the curing methods for cement mortar specimens, including air, water, and plastic bag curing (Figure 2). The mortar mix was prepared according to AS 2350.12 (2012), and specimens were subjected to various curing conditions for up to 28 days. The methods aim to prevent oil leaching and maintain consistent oil content throughout curing.

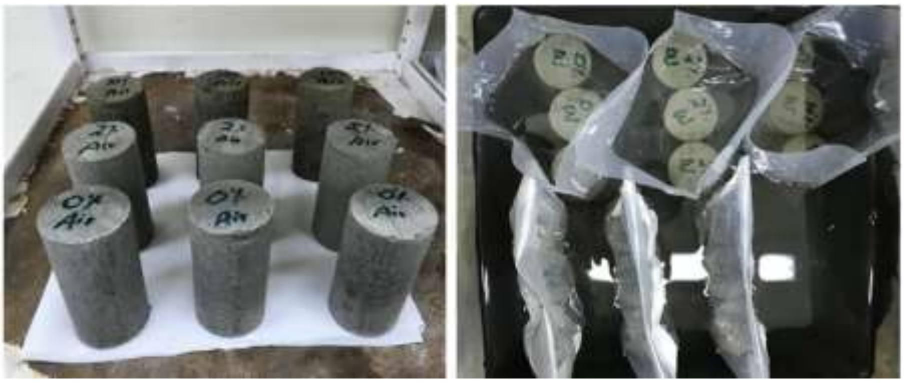

Fig.2. Curing methods used

2.3. Compressive Strength Testing

Compressive strength assessments were performed on all specimens after a 28-day curing duration. Each specimen underwent failure testing with a 2-channel Automatic Cube and Cylinder Compression Machine (CT340-CT440) at a 1.5 kN/min loading rate. To guarantee equal weight distribution, the ends of the cylindrical specimens were polished, and rubber caps were affixed to provide a consistent surface for testing (Figure 3).

Figure 3 Compressive strength machine

2.4. Porosity

The internal structure of the specimen sections was analysed under a microscope at 65x magnification, as seen in Figure 4. The TBitmap programme was used to examine resin colour, facilitating the distinction of pixels associated with pores in the pictures. The porosity examination was conducted immediately after the compression testing, after a 28-day curing period.

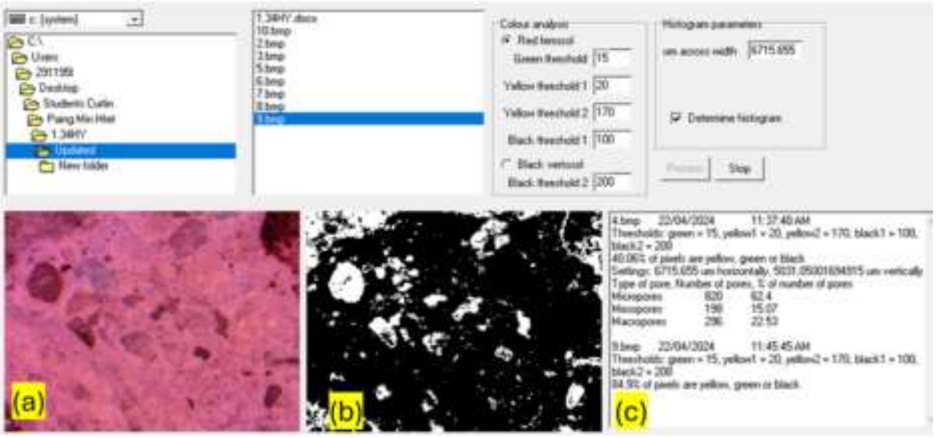

Fig. 4. Example image of specimens' surface showing pores ((a) natural colour of the surface and (b) the readable image by the software) (c) TBitmap software used.

3. Results and discussions

3.1. Effect of heavy crude oil content on the mechanical properties

Figure 5 illustrates the mean compressive strength of mortar with differing crude oil concentrations across various curing settings. For uncontaminated samples (0%), water curing produced the maximum compressive strength of 19 MPa. The compressive strength decreased by 9.7% with plastic bag curing and by 22% under ambient circumstances. In samples with 2% heavy crude oil contamination, the compressive strength was almost equivalent under ambient and plastic bag curing conditions, reaching 12.4 and 12.3 MPa, respectively. Water curing yielded the most significant strength at this amount of pollution, averaging 17 MPa. Nonetheless, as crude oil contamination rose to 10%, the impact of curing procedures on compressive strength became insignificant. The average strength of the ambient plastic bags and water curing with 10% crude oil contamination was 8.8, 9, and 8.9 MPa, respectively. The superior compressive strength of mortar cured in water, as opposed to ambient and plastic bag techniques, is due to enough moisture during curing, facilitating the completion of the hydration process. This outcome signifies the need to maintain high and consistent humidity for the specimens throughout curing to achieve the appropriate moisture level required for the hydration process. This conclusion is corroborated by Taylor (2013), who demonstrated that sustained curing at a relative humidity of 90% enhances hydration in cement and promotes red microstructural growth. Moreover, Wang and Park (2017) asserted that elevated humidity may improve hydration even at the same temperatures. The diminished compressive strength in mortar cured at high temperatures is due to the fast production of hydrates, leading to increased porosity and decreased final strength [18]. Furthermore, Ezziane et al. (2007), demonstrated that the compressive strength of concrete cubes cured in water at 7 and 28 days exceeds those cured in air. The enhancement in compressive strength and other mechanical characteristics of concrete resulting from water curing is attributed to the enhanced gel/space ratio inside the concrete (Neville, 1981).

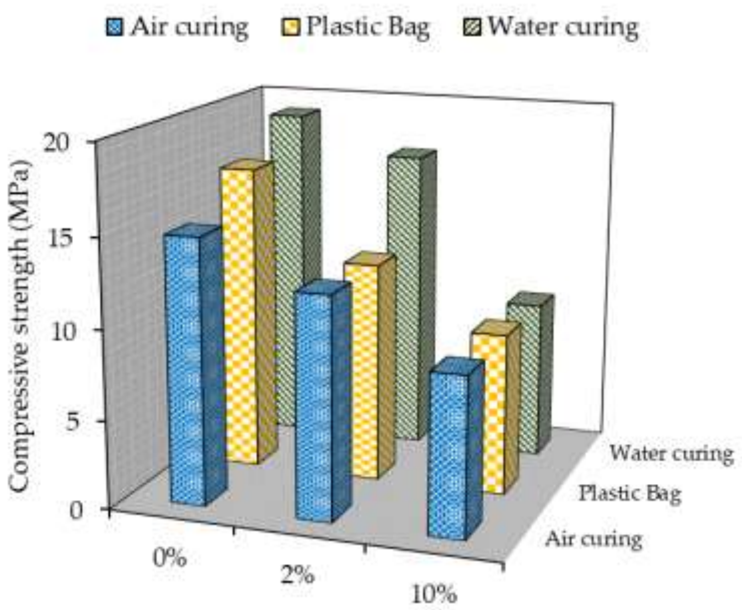

Fig.5. Effect of heavy crude oil contamination on the mechanical properties of mortar

3.2 Effect of Curing Method on Heavy Crude Oil-Contaminated Concrete Properties

The mortar cured at ambient temperatures had the lowest compressive strength among the uncontaminated samples (Figure 6). Ambient curing, especially under arid or variable conditions, yields insufficient moisture for cement hydration, establishing links among cement particles (Joshaghani et al., 2018; Taylor, 2013). Insufficient moisture leads to incomplete hydration, resulting in a compromised microstructure and diminished compressive strength. Temperature fluctuations, particularly when temperatures drop below optimal levels, influence the hydration process, leading to uneven shrinkage and cracking, which further compromises the integrity of the mortar (Bentz, 2007). Incorporating heavy crude oil into the mix design has impacted the compressive strength of all curing techniques, including ambient, plastic cover, and water curing. At 2%, the compressive strength decreased by 10%, 28%, and 16%, respectively. Other studies (Kocaman et al., 2011; Mehta, 1986; Neville, 1995) have also found that curing methods affect compressive strength. This study's conclusion about how curing methods affect the compressive strength of mortar with 0% and 10% crude oil contamination backs this up. Despite this outcome, the research indicated that 2% crude oil contamination, regardless of varying curing conditions, did not significantly impact the compressive strength. Incorporating heavy crude oil into mortar mix designs often diminishes compressive strength since the oil interferes with the hydration process of the cement, which is crucial for strength development. The oil forms a barrier on cement particles, restricting water penetration and inhibiting complete hydration. Furthermore, oil droplets may compromise the adhesion between cement paste and sand particles, diminishing their total cohesiveness. The effect depends on the method of curing; ambient curing may be more susceptible to interruptions. In contrast, water curing may somewhat alleviate the adverse effects but does not eliminate them (Almabrok et al., 2019). In contrast, an earlier investigation on light crude oil contamination in concrete indicated that crude oil concentrations of up to 2% did not significantly impact the mechanical qualities of the concrete. The study revealed that 2% crude oil contamination did not substantially affect compressive strength. Incorporating crude oil into dry sand enhanced the hydration process, leading to this result. When light crude oil enhanced the wettability of dry sand, the sand absorbed less water.

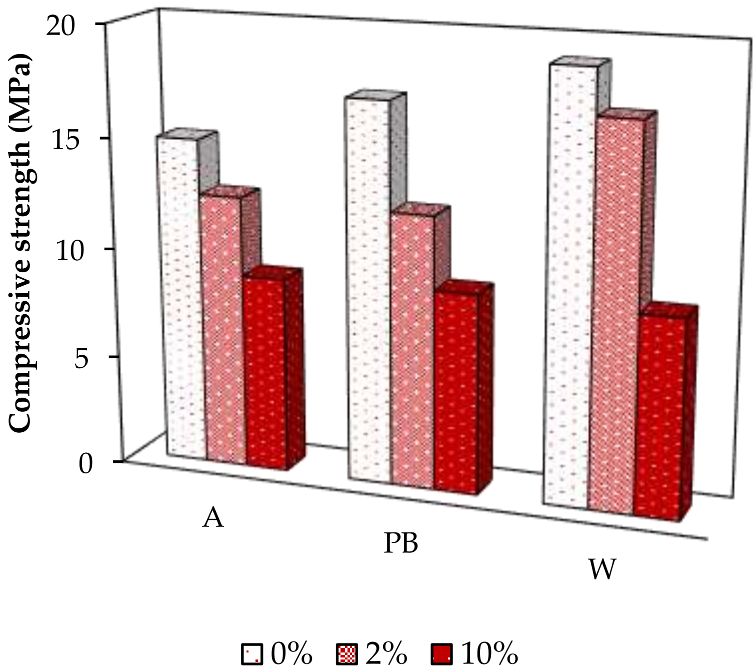

Fig. 6. Effect of curing methods on the mechanical properties of mortar containing heavy crude oil

3.3 Effect of Total Porosity on Mortar with Heavy Crude Oil

Figure 7 depicts the surface porosity of mortar samples with and without heavy crude oil contamination. The figure indicates that bigger air holes exist in a mortar with sand polluted by 10% light crude oil, in contrast to samples with 0% and 2% contamination. Furthermore, while loading, specimens contaminated with 10% crude oil did not produce any cracking noises, even until failure occurred. This may be ascribed to the moisture retained inside these specimens post-failure. Samples with 10% crude oil contamination retained more residual oil than those with 2% contamination or control samples. Figure 9 shows the total Porosity of Mortar with Varying Heavy Crude Oil Contents (a) 0%, b) 2%, and c) 10%) and Curing Methods. Higher porosity was observed when the specimens were cured with A and plastic cover compared to W curing methods for uncontaminated samples and with 2%. In contrast, the lowest percentage of total porosity at the same percentage (0% and 2%) was observed with specimens cured in water. However, when 10%

of heavy crude oil was used, the porosity was the highest and quite similar for the three curing methods. The saturation state of the sample, with 10%, significantly affected the property, and as a consequence, the strength decreased regardless of the curing method used.

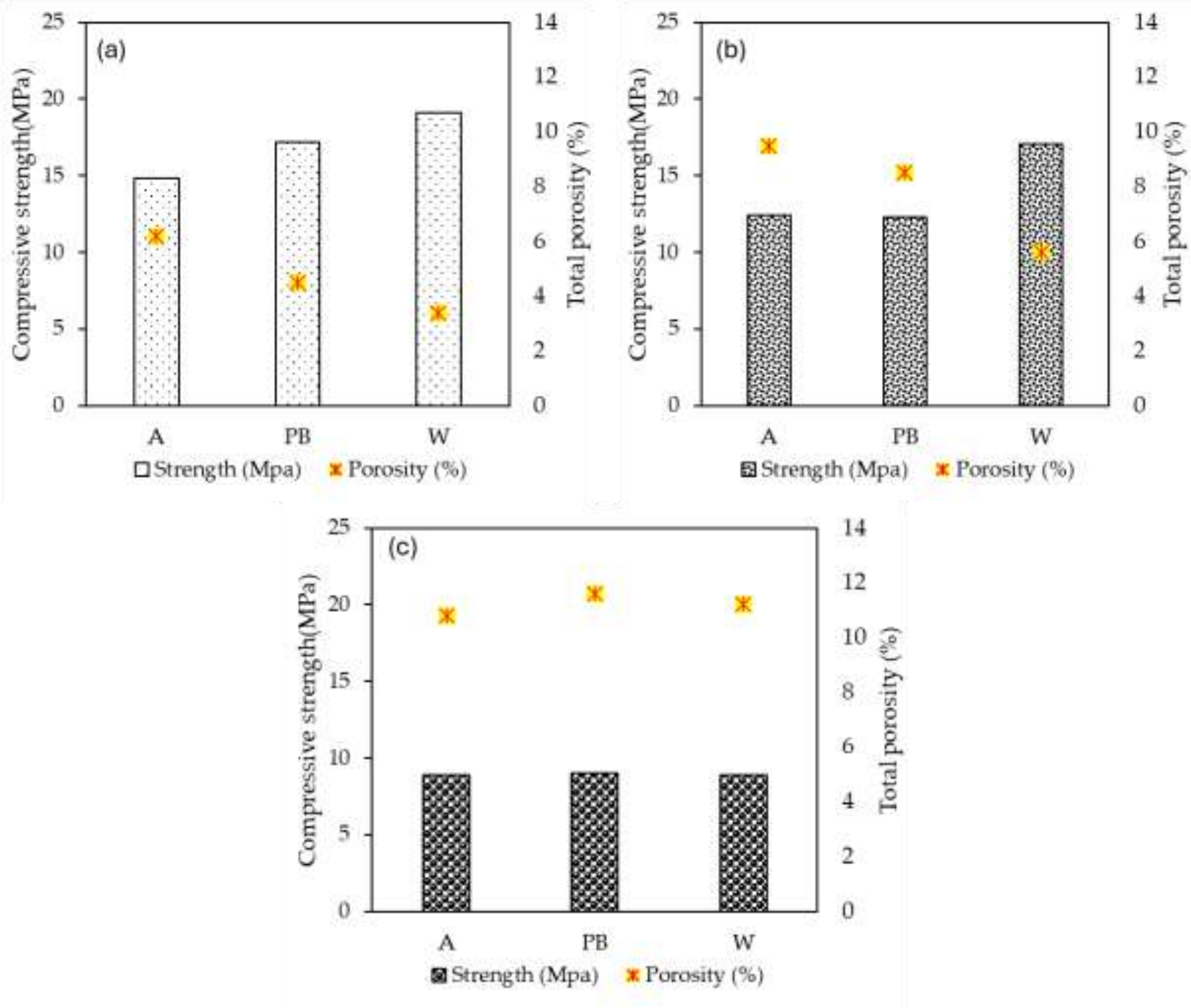

Fig. 7. Total Porosity of Mortar with Varying Heavy Crude Oil Contents (a) 0%, b) 2%, and c) 10%)and Curing Methods

The plastic cover curing method resulted in lower porosity and higher strength than ambient curing. These findings contrast with previous studies on the effect of light crude oil on concrete's mechanical properties (Abousnina et al., 2018). The primary difference can be attributed to temperature conditions; in this study, testing occurred at Sultan Qaboos University in Oman during summer, where average temperatures reached approximately 40°C. Such high temperatures likely accelerated sample drying, slightly impacting hydration, increasing porosity, and, consequently, influencing the material properties. In addition, among all the different curing methods, the specimens treated in water (W) had the best compressive strength and the lowest total porosity. The constant availability of moisture during the curing time, which facilitates complete hydration of the cement particles, is believed to be responsible for the lower porosity found in specimens that were cured using water. As a result of this continuous hydration, the creation of pores within the matrix is reduced, resulting in a denser and more cohesive structure. Compared to other curing techniques, the compressive strength of water-cured specimens is much higher than that of other specimens. This is because the matrix is well-hydrated and has a low porosity. On the other hand, the porosity dramatically increased across all curing techniques when the heavy crude oil concentration increased to 10%. This was most likely caused by interference with cement-water processes, which either delayed or prevented the complete hydration of cement particles (Abousnina et al., 2020; Lavagna & Nisticò, 2022). The presence of heavy crude oil contributed to the increase in porosity and the decrease in compressive strength. Et al. [4] observed that extensive oil contamination in concrete significantly affects compressive strength. They attributed this impact to crude oil coating cement particles interrupting hydration.

4. Conclusion

Among the tested curing methods—air curing, water curing, and sealed plastic curing—water curing consistently yielded the highest compressive strength in uncontaminated samples and those with 2% heavy crude oil contamination. This strength is due to sufficient moisture retention, which improves the mortar's mechanical properties. Conversely, air curing resulted in the lowest compressive strength, particularly in uncontaminated and 2% oil-contaminated samples. This is likely due to the high ambient temperatures (around 40 °C), which accelerate drying and increase porosity, thereby weakening the structure of the mortar. At 10% heavy crude oil contamination, the curing method choice had minimal impact on strength, suggesting that high oil content obstructs further mechanical improvement. Increased oil contamination, especially at 10%, substantially raised porosity, reducing the mortar's compressive strength due to the crude oil's interference with the cement matrix. Heavy crude oil forms a film around cement particles, impeding bonding and creating a porous, less cohesive structure. Additionally, heavy crude oil has a more detrimental impact on mechanical properties than light crude oil at similar concentrations. Its higher viscosity and complex molecular structure create a thicker barrier around cement particles, further limiting interactions and cohesion. These findings underscore that, with appropriate curing, oil-contaminated sand could serve as a sustainable, low-cost material for specific civil engineering applications despite its limitations at higher contamination levels.

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