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A Comparative Review on the Sustainable Utilization of Oil-Contaminated Sand in Concrete

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ABSTRACT

The use of oil-contaminated sand in concrete is essential for sustainability and environmental purposes. The comparative characteristics of oil-contaminated sand are crucial to understand and optimize the use of this material, though several research gaps remain to be addressed. To date, few review papers have included recent comparative studies of the oil-contaminated sand and its effect on concrete. Therefore, this comparative review paper examines the impact of using oil-contaminated sand in concrete production. It focuses on how contamination affects sand, fresh and hardened concrete properties, structural performance, environmental and durability effects, microstructure and fiber impacts, sustainability, real-world and practical applications, challenges and solutions for existing challenges, and current research gaps and future research needs. The review synthesizes findings from experimental studies, theoretical models, and practical applications to provide a comprehensive understanding of the challenges and benefits associated with this practice. Main findings include a reduction in fresh and hardened properties up to a certain limit. Even though the usage of oil-contaminated sand in concrete offers numerous challenges, nevertheless, future research directions and field applications hold promise for overcoming these challenges. Addressing the research gaps, such as performance of hybrid materials, optimized treatment method, and standardization of material quality in the construction industry, can lead to the potential of oil-contaminated sand usage for sustainable infrastructure improvement.

INTRODUCTION

The structural integrity of reinforced concrete (RC) members is crucial for the safety and longevity of infrastructure (Hason & Al-Janabi, 2024; Mohd Apandi et al., 2025). However, the use of contaminated materials, particularly oil-contaminated sand (OCS), in concrete production presents significant challenges. The occurrence of oil contamination in sand due to industrial activities and oil spills has raised concerns about its disposal and management. Understanding the impact of such contamination on the structural

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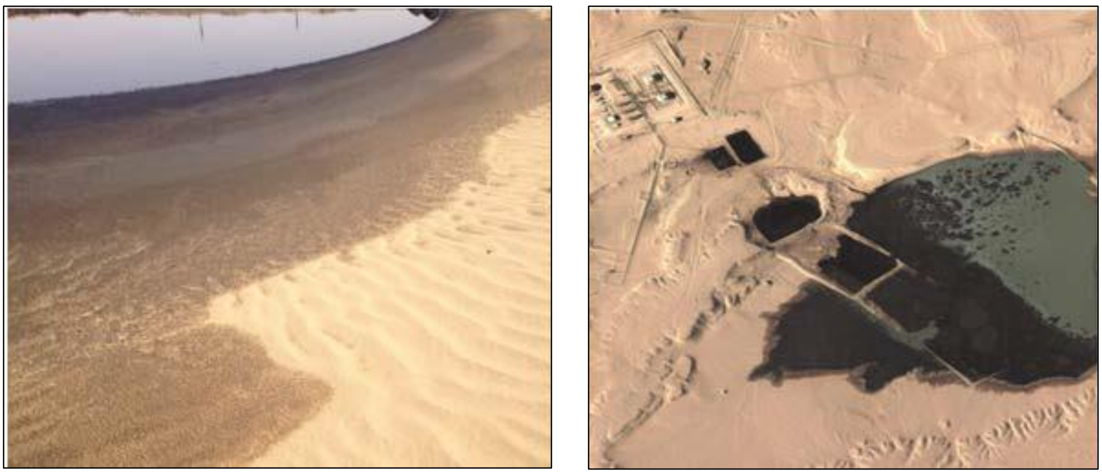
behavior of RC members is essential for ensuring their performance, safety, and durability. RC is a fundamental material in construction due to its versatility, strength, and durability (Hassan et al., 2025). It is used in a wide range of structures, from residential buildings to large-scale infrastructure projects such as bridges and dams. The composite nature of RC, combining the compressive strength of concrete with the tensile strength of steel reinforcement, makes it highly effective in bearing various loads and resisting different forms of stress (Neville, 2011). Oil contamination in sand primarily occurs due to industrial spills, improper disposal of oil waste, and natural oil seepage in sand deposits as shown in Fig. 1(a) and (b). This contamination can significantly alter the sand chemical and physical characteristics, subsequently affecting the quality of concrete made with it. The presence of oil can interfere with the cement hydration development of cement, reduce the bonding between cement paste and aggregates, and increase the porosity of the concrete, leading to compromised structural integrity (Meegoda & Ratnaweera, 1994).

In the world as a whole, waste oil-contaminated sand (OCS) is a serious problem that is mainly found in oil-rich areas. For example, the oil industries annually are believed to produce millions of tons of contaminated sand from drilling, production, pipeline spills, and the like. For example, the oil deposits in Middle East countries generate up to one to 1.2 million tons of oily sand waste per year of production accumulated from years of production, based on recent environmental appraisals. Hence, the occurrence of a substantial amount of sandy soils contaminated suddenly by a major oil spill demands rapid intervention for remediation. Despite these issues, a very small portion of OCS is currently reused or treated effectively. Redirecting even a fraction of this waste for concrete production could provide environmental and economic benefits by reducing landfill disposal, minimizing pollution, and encouraging sustainable construction practices.

(a)



(b)

Fig. 1. Environmental impacts and sand contaminated by oil; (a) Rumaila oil field/Iraq (Al-Halfy et al., 2021) and (b) Ghani field HOO/Libya (Abousnina, 2016).

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The load-bearing capacity is significantly affected by the compressive strength (f'_c), which is considered one of the most critical parameters of concrete (Hanoon et al., 2023). Research has shown that OCS can lead to a decrease in f'_c. For instance, studies have indicated that the compressive strength of concrete decreases as the level of oil contamination increases, due to the formation of a weak interfacial transition zone (ITZ) between the aggregates and the cement paste (Huda et al., 2018). Moreover, the durability of concrete structures made with contaminated sand is adversely affected. Increased porosity and permeability can accelerate the ingress of harmful substances, such as chlorides and sulfates, leading to faster degradation of both concrete and reinforcement steel. This results in reduced service life and higher maintenance costs for structures (Abousnina et al., 2020).

Flexural and tensile strengths are also vital for the performance of RC members, especially in elements subjected to bending and tensile stresses, such as beams and slabs (Abdulhameed et al., 2023; Sharba et al., 2021). The presence of oil in sand can weaken the bond between the concrete matrix and the reinforcement, diminishing the overall tensile strength and flexural capacity of the RC members. Experimental studies have demonstrated that beams made with OCS exhibit reduced flexural strength and increased deflection under load compared to those made with clean sand (Abousnina et al., 2014).

The long-term performance of RC structures is a critical consideration, particularly in harsh environmental conditions. Oil contamination can exacerbate the effects of environmental exposure, such as freeze-thaw cycles and chemical attacks, further compromising structural integrity over time. Understanding these impacts is essential for developing effective mitigation strategies and ensuring the reliability and safety of RC structures throughout their intended lifespan (Pedrosa & Andrade, 2011).

The impact of sand contaminated by oil on the structural behavior of RC members is a complex issue that affects various aspects of material performance and structural integrity. Comprehensive research and thorough understanding are necessary to develop appropriate mix designs, construction practices, and maintenance strategies that mitigate the adverse effects of contamination. Ensuring the structural performance and durability of RC members in the presence of contaminated materials is vital for the sustainability and safety of infrastructure. This review paper provides a thorough examination of the impacts of OCS on the structural behavior of reinforced concrete members, highlighting both the challenges and opportunities associated with this practice.

The present review focuses on the use of OCS in concrete and is compiled and analyzed in this review using a narrative approach. Using keywords like "oil-contaminated sand," "effect of oil-contaminated sand on concrete", "OCS concrete", and similar terms, searches were conducted in scholarly databases to find the scientific literature. Moreover, this comprehensive review encompasses studies conducted over the past two decades, focusing on different types of oil contamination, various contamination levels, and diverse concrete applications. The review synthesizes findings from multiple geographical regions and different environmental conditions to provide a global perspective on OCS utilization. Thus, the main objective of the current study is to conduct a systematic comparative review of the sustainable utilization of oil-contaminated sand in concrete production, synthesizing findings from experimental studies, theoretical models, and practical applications. Another secondary objective is to compare and analyze the physical and chemical property changes in sand due to oil contamination. Besides, to systematically compare the effects of OCS on fresh and hardened concrete properties, in addition to analyzing the influence on concrete durability characteristics and long-term performance. To examine the structural performance of OCSRC members.

MATERIAL PROPERTIES OF OIL CONTAMINATED SAND (OCS)

Physical properties

Oil contamination can significantly change the physical characteristics of sand due to oil coating, impacting its suitability for various engineering and construction applications. These changes, including

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reduced effective size, increased fines content, decreased uniformity coefficient, smoother surfaces, and reduced angularity, accordingly affect the overall mechanical properties of the sand. Understanding these changes is crucial for developing appropriate strategies to mitigate the negative effects of contamination on the concrete.

Grain size

Grain size distribution is a crucial factor in determining the mechanical properties of sand. Oil contamination can cause agglomeration of fine particles and affect the overall gradation, as illustrated in Table 1 and Fig. 2. Oil contamination reduces the effective size of sand grains (overall observation) (Table 1). Research has shown that oil contamination tends to agglomerate fine particles, leading to a shift in the grain size distribution curve. For instance, studies have found that the D10 can decrease by 10% to 20% when sand is contaminated (Khan et al., 2011). Another study reported that D10 decreased from 0.35 mm to 0.28 mm with 3% oil contamination (Panchami et al., 2020). The presence of oil can lead to an apparent increase in fines (particles smaller than 0.075 mm) due to the binding effect of the oil, which can cause fine particles to stick together and form larger agglomerates. This change can increase the fine content by 10-15%. A recent study found an increase from 5% to 6.5% fines with 2% oil contamination (Abousnina et al., 2015b) (Fig. 2). As can be seen from Table 1 and Fig. 2, the Cu, which is the ratio of D60 to D10, is often used to assess the gradation of sand. Cu can decrease by approximately 15% due to the binding effect of oil. A study showed that Cu was reduced from 4.5 to 3.8 with 5% oil contamination.

Table 1. Changes in grain size distribution for different levels of oil contamination (Abousnina et al., 2015a; Ajagbe et al., 2012a)

Oil Content (%)	0%	1.0%	3.0%	5.0%
D10 (mm)	0.30	0.28	0.24	0.20
Fines Content (%)	7.0	7.5	8.0	8.5
Uniformity Coefficient (Cu)	4.5	4.2	3.9	3.8

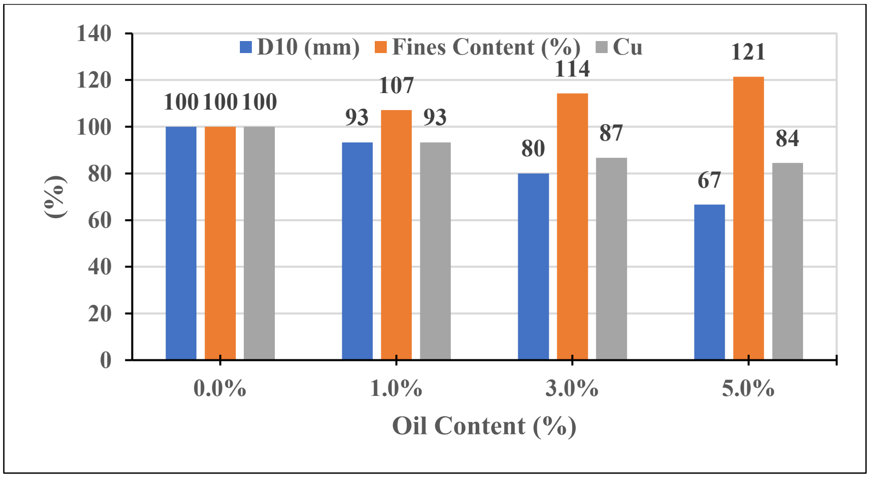

Fig. 2. Impact of oil content on sand grain size (Abousnina et al., 2015a).

The surface texture of sand particles plays a crucial role in the bonding characteristics between the sand and cement paste in concrete. Oil coating significantly impacts the surface roughness and texture (Fig. 3), which can affect the mechanical properties of concrete. Oil contamination tends to smooth the surface of sand particles, reducing the roughness that is essential for good mechanical interlock within concrete. The surface roughness can decrease by up to 30% due to oil coating (Hong et al., 2014). A study found a reduction from 2.0 to 1.4 roughness units with 5% oil contamination (Abousnina et al., 2020). The

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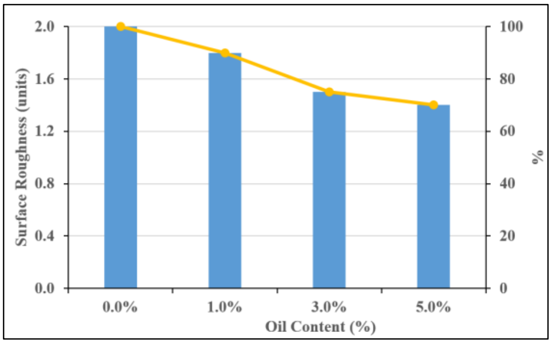
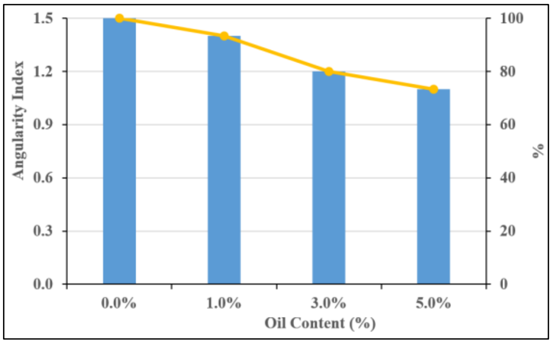
angularity of sand particles, which contributes to better particle interlocking and higher strength, is also affected. Oil-coated sand particles show a notable reduction in angularity, leading to a more rounded particle shape. This change can reduce the angularity index by 20% to 25%, negatively impacting the workability and strength of concrete (Abousnina et al., 2020). In addition to dropping the angularity index from 1.5 to 1.2 with 3% oil contamination. The oil coating on sand particles creates a hydrophobic layer that interferes with the adhesion between the sand and cement paste. This effect can decrease the adhesion properties by approximately 20-25%, which is critical for the development of mechanical strength in concrete. The compaction behavior is crucial in determining the load-bearing capacity and stability of sand in construction applications. Oil contamination affects the compaction characteristics by altering the inter-particle friction and cohesion. The reduction in dry and bulk densities, along with the increase in moisture content (Table 2), highlights the need for careful consideration and adjustment in engineering applications involving contaminated sand. Oil contamination reduces MDD. The MDD can decrease by 5% to 15% (Table 2). For instance, MDD dropped from 1.75 g/cm³ to 1.50 g/cm³ with 5% oil contamination (Ejeh & Uche, 2009). Optimum Moisture Content (OMC): OMC increases with oil contamination. The OMC values can increase by 10% to 25%. For example, OMC increased from 12% to 15% with 3% oil content (Panchami et al., 2020). Bulk Density: Bulk density decreases with increasing oil content. Bulk density can decrease by 5% to 10%. Bulk density dropped from 1.60 g/cm³ to 1.45 g/cm³ with 5% oil content (Meegoda & Ratnaweera, 1994).



(a)



(b)

Fig. 3. Effect of oil content on surface texture of contaminated sand (Hong et al., 2014), (a) surface roughness and (b) angularity index.

Table 2. Changes in compaction behavior and bulk density for different levels of oil contamination (Panchami et al., 2020)

Oil Content (%)	Density (g/cm³)				OMC (%)	%
	MDD		Bulk			
	(g/cm³)	%	(g/cm³)	%		
0	1.75	-	1.60	-	12	-
1	1.70	97	1.55	97	13	108
3	1.60	91	1.50	94	14	117
5	1.50	86	1.45	91	15	125

Chemical properties

Oil contamination in sand affects not only its physical properties but also its chemical properties (Fig. 4 and Table 3) and chemical interactions (Fig. 5), particularly when used in conjunction with cementitious materials. Oil contamination alters the chemical properties of sand, which can affect the environmental and

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engineering performance of contaminated sand, necessitating careful consideration and management in construction and remediation projects.

Oil contamination effect on sand chemical properties

Oil contamination typically lowers the pH of sand, making it more acidic. The pH levels can drop by 1–2 units. For instance, a study found the pH decreased from 7.5 to 6.0 with 5% oil contamination (Mekkiyah et al., 2023). Total organic carbon (TOC) levels increase significantly with oil contamination. TOC can increase by 20% to 50%. A recent study observed TOC levels rising from 0.2% to 0.35% with 3% oil contamination (Abousnina & Allister, 2022). Electrical conductivity (EC) increases with oil contamination, indicating higher ionic content. EC can increase by 15% to 30%. For example, EC values increased from 0.3 $m.S/cm$ to 0.4 $m.S/cm$ with 4% oil contamination (Pedrosa & Andrade, 2011). Oil contamination reduces the CEC of sand. CEC can decrease by 10% to 20%. A study reported a decrease in CEC from 12 $meq/100g$ to 10 $meq/100g$ with 5% oil contamination (Pedrosa & Andrade, 2011). increase with oil contamination, reflecting the amount of oil absorbed by the sand. Total Petroleum Hydrocarbons (TPH) can increase by 100% to 300% depending on the level of contamination. For example, TPH increased from 100 mg/kg to 400 mg/kg with 5% oil contamination (Shahrabadi & Vafaei, 2015). Polycyclic aromatic hydrocarbons (PAHs) are a subset of hydrocarbons that can be particularly harmful. Their concentration also rises with oil contamination. PAH content can increase by 50% to 200%. A study showed PAH levels rising from 10 mg/kg to 25 mg/kg with 3% oil contamination (Abdullah et al., 2020). Volatile organic compounds (VOCs), which include lighter hydrocarbons, show a significant increase in contaminated sand. VOC content can increase by 70% to 150%. For instance, VOC levels increased from 20 mg/kg to 50 mg/kg with 4% oil contamination (Wei et al., 2014).

Table 3. Effect of oil contamination on the chemical and hydrocarbon characteristics of sand (Hassan et al., 2024; Svintsov, 2019)

Oil Content (%)	Chemical properties				Hydrocarbon Content		
	pH	TOC (%)	EC (mS/cm)	CEC (meq/100g)	TPH (mg/kg)	PAHs (mg/kg)	VOCs (mg/kg)
0.0	7.5	0.2	0.3	12	100	10	20
1.0	7	0.25	0.32	11.5	200	15	30
3.0	6.5	0.35	0.35	11	350	25	40
5.0	6	0.4	0.4	10	400	30	50

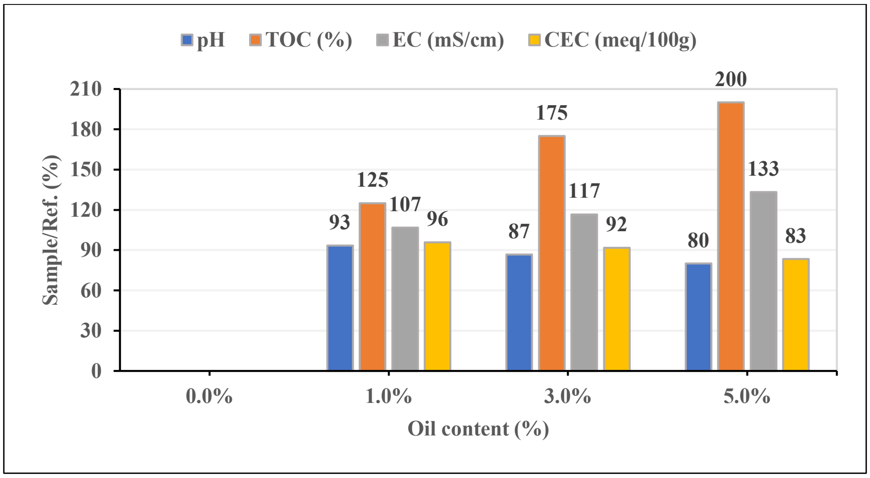

Fig. 4. Oil contamination effect on sand chemical properties (Mekkiyah et al., 2023; Wei et al., 2014).

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Chemical interaction

Oil contamination significantly impacts the chemical interactions between sand and cementitious materials. It primarily inhibits, as shown in Fig. 5, hydration reactions, reduces long-term strength, and increases chloride and sulfate content, which can compromise the durability of concrete structures. Considering these interactions are vital for improving approaches to lessen the deleterious impacts of oil contamination in construction materials. Oil contaminants can react with Calcium Hydrocarbylates $Ca(OH)_2$ (Calcium Hydroxide, which is a byproduct resulting from the cement hydration during manufacturing, to form calcium hydrocarbylates. These compounds are less stable and can negatively affect concrete durability and strength. Formation of calcium hydrocarbylates can reduce the long-term compressive strength by 15% (Ajagbe et al., 2012a; Pedrosa & Andrade, 2011). Oils containing chlorides and sulfates can introduce these ions into the mix, affecting the durability. Increased chloride content can lead to corrosion of steel reinforcement, while sulfates can cause expansion and cracking. A study found that 3% oil contamination increased chloride content by 50% and sulfate content by 40%, leading to a 10% reduction in steel reinforcement lifespan (Abousnina & Allister, 2022).

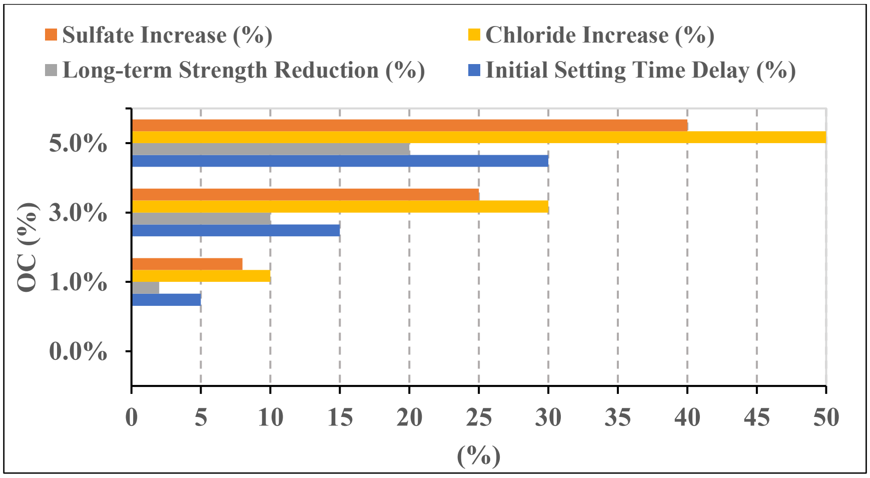

Fig. 5. Effects of oil contamination on cement hydration reactions and concrete properties.

Impact on concrete mix design

Workability

Oil contamination reduces the workability of concrete, primarily by decreasing the slump and increasing water demand. Adjustments such as altering the water-cement ratio, using superplasticizers, and modifying mix designs can mitigate these effects. Table 4 shows the effects and modifications on workability. Understanding these impacts and adjustments is crucial for ensuring the quality and performance of concrete in construction projects. Oil contamination generally reduces the workability of concrete. This is primarily owing to the oil coating of sand particles, which interferes with the bonding between cement paste and aggregates. Oil creates a hydrophobic layer on sand particles, preventing proper mixing and bonding with water and cement. A study showed that with 5% oil contamination, the slump value of concrete decreased by 40% (Mekkiyah et al., 2023). To achieve the same workability as uncontaminated concrete, the water content often needs to be increased. The hydrophobic nature of the oil requires more water to achieve adequate lubrication and flow. Water demand can increase by 10% to 25%. For example, an increase in water content by 15% was required to maintain workability with 3% oil contamination (Ajagbe et al., 2012b).

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Required modification to mix design to achieve the desired workability

To compensate for the loss of workability due to oil contamination in concrete, several mix design modifications can be implemented as outlined in Table 4. The strategy is to increase the water-cement ratio to help restore workability. W/c ratio from 0.45 to 0.55 was found to compensate for up to 3% oil contamination (Mekkiyah et al., 2023). Besides, adding superplasticizers can reduce the negative impact on workability without significantly increasing water content. Superplasticizer dosage of 1.5% by weight of cement improved the slump by 25% with 4% oil contamination (Abousnina & Allister, 2022; Attom et al., 2013). Moreover, adjusting the mix design, including increasing fine aggregate content, can help improve workability. Increasing fine aggregate content by 10% helped maintain the desired consistency in concrete with 2% oil contamination (Abousnina & Allister, 2022).

Table 4. Oil contamination effect on concrete workability and potential adjustments (Al-Lami & Hassan, 2017)

Oil Content (%)	Reduction in Slump (%)	Increase in Water Demand (%)	Superplasticizer Dosage (%)	Increase in Fine Aggregate (%)
0	0	0	0	0
1	10	10	0.5	2
3	25	15	1.0	5
5	40	25	1.5	10

Curing efficiency

Standard curing practices are critical for achieving the desired strength and durability in concrete. However, the presence of OCS can alter the effectiveness of these curing practices, mainly by reducing hydration efficiency, early and long-term strength, and overall durability (Table 5). Adjustments such as extending curing times, improving curing conditions, and using chemical additives can help mitigate these adverse effects. Oil contamination hinders the hydration process of cement, which is vital during the curing period. Oil forms a hydrophobic layer around cement particles, reducing water-cement interaction essential for hydration. Studies show a reduction in hydration efficiency by 20% to 30% in concrete with 5% OCS (Abousnina & Allister, 2022). The early development of concrete strength is adversely affected by oil contamination. Poor hydration leads to lower initial strength gain. A decrease in early compressive strength by 15% was observed with 3% oil contamination (Abousnina & Allister, 2022; Attom et al., 2013). Long-term strength is also compromised due to incomplete hydration. The presence of oil slows down the overall hydration process, leading to lower strength over time. Long-term compressive strength reduced by 25% with 5% oil contamination (Mekkiyah et al., 2023). The durability of concrete is negatively impacted by oil contamination. Poor hydration and incomplete cement bonding lead to a more porous and less durable concrete structure. Durability tests showed a 30% reduction in resistance to chloride penetration in concrete with 4% OCS (Ajagbe et al., 2012b).

Table 5. impact of oil contamination on standard curing practices and potential adjustments (Ajagbe et al., 2012b)

Oil Content (%)	Reduction in Hydration Efficiency (%)	Reduction in Early Strength (%)	Reduction in Long-Term Strength (%)	Reduction in Durability (%)	Extended Curing Time (Days)	Improvement with Additives (%)
0	0	0	0	0	28	0
1	10	5	8	10	35	5
3	20	15	20	25	42	12
5	30	25	30	30	56	15

Adjustment to curing practices

To minimize the negative effects of oil contamination on concrete, adjustments to curing practices can be implemented, such as increasing the curing time can help mitigate some of the adverse effects by allowing more time for hydration. Extending the curing period from 28 days to 56 days improved

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compressive strength by 10% in concrete with 3% oil contamination (Osuji & Nwankwo, 2015). Also, using higher humidity and temperature-controlled environments can enhance hydration. Controlled curing conditions at 90% relative humidity improved hydration efficiency by 15% in oil-contaminated concrete (Abousnina & Allister, 2022). Adding chemical additives like accelerators can counteract the negative effects of oil and improve the early strength by 12% in concrete with 2% oil contamination (Abousnina & Allister, 2022).

SEM analysis

Looking closely at small structures helps us understand how well OCS works in concrete. Research, like the one done by Abousnina et al. (2020) showed that sand particles covered in oil make the area between the sand and cement weaker because they stop the cement from properly drying and sticking together. SEM images showed tinier holes and uncovered cement particles around OCS, which caused small cracks and made the material weaker. Future research should pay more attention to how ITZ works and changes in its structure to enhance the performance of OCS in eco-friendly concrete uses. The SEM analysis (Fig. 6) showed that as the mortar cures, more hydration products are produced that fill the gaps in the material. This helps decrease the overall amount of empty space, or porosity, in the mortar. Also, the area where the aggregate and cement paste meet, as well as how well they stick together, isn't changed by oil contamination up to 2%. In the fog room (FR) curing, compared to water (w) and plastic bag (PB) curings, a thicker calcium silicate hydrate (C-S-H) is seen, and the holes are filled, which is different from other curing methods. This shows why the mortar cured in FR is stronger than the mortar cured in other ways.

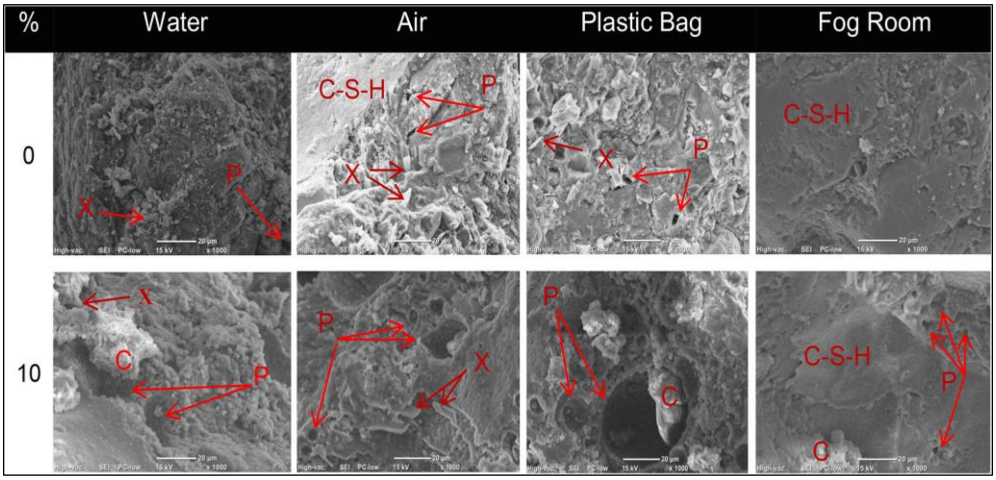

Fig. 6. Comparison of the SEM of concrete that contains contaminated oil sand and concrete that does not (Abousnina et al., 2020).

Mechanical properties of concrete with OCS

Oil contamination in sand significantly reduces the mechanical properties of concrete, including compressive strength, tensile strength, flexural strength, and modulus of elasticity, as shown in Table 6 and Fig. 7. The extent of these reductions depends on the level of contamination, with higher percentages of oil contamination leading to greater decreases in these properties. However, a noticeable variation in the reported effects of OCS on concrete mechanical strength. Some studies have observed slight improvements in compressive or tensile strength at very low oil contamination levels (typically below 2%), which is often attributed to the partial filling of pores by oil residues, resulting in a temporary densification effect. Nevertheless, many studies reported a severe decline in strength when increasing the content of oil contamination (2%–4%). This is properly due to the oil film that coats the sand particles, resulting in a

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decrease in the bond strength between the cement and aggregate, higher porosity, and disturbs hydration. Besides, the various types of oil, sand characteristics, contamination dosages, and mixing procedures are additional factors that contribute to this matter. These facts support the need for test standardization and further examination into the negative and positive effects of using oil-contaminated sands in concrete. A comparative review of recent findings on how OCS impacts key mechanical properties of concrete.

Table 6. Comparison of the effects of oil contamination on different concrete mechanical properties (Attom et al., 2013)

Concrete type	Oil %	$f'c$		ft		fr		Ec	
		MPa	%	MPa	%	MPa	%	GPa	%
Uncontaminated	0%	40	-	4.5	-	6	-	30	-
	1%	38	5	4.3	4.44	5.8	3.33	29.4	2
Contaminated	3%	34	15	4	11.11	5.4	10	27	10
	5%	30	25	3.6	20	4.9	18.33	25.5	15

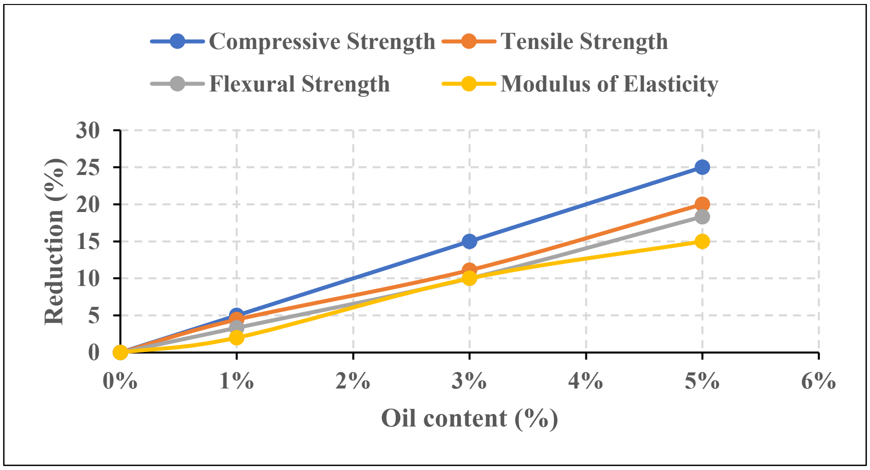

Fig. 7. Mechanical properties comparison of concrete with and without contaminated oil sand (Attom et al., 2013; Osuji & Nwankwo, 2015).

Concrete with oil contamination has lower compressive strength. The hydrophobic nature of oil interferes with the hydration process and bonding of cement paste to aggregates. A study showed that with 5% oil contamination, compressive strength decreased by 25% compared to uncontaminated concrete (Osuji & Nwankwo, 2015). The tensile strength is decreased by oil contamination, affecting the concrete's ability to resist cracking. Poor bonding between cement pastes and oil-coated aggregates results in weaker concrete. Tensile strength reduced by 20% with 4% oil contamination (Hamad et al., 2003). Oil contamination affects flexural strength, which is critical for concrete's bending resistance. Similar to tensile strength, the interference in cement bonding leads to reduced flexural strength. Flexural strength reduced by 18% with 4% oil contamination (Hamad et al., 2003). The modulus of elasticity decreases with increasing oil contamination, affecting the concrete deformation characteristics. The disruption in the microstructure due to oil leads to a less stiff concrete matrix. The modulus of elasticity reduced by 15% with 5% oil contamination (Attom et al., 2013).

Recent studies have explored the use of fibre as an effective strategy to improve the mechanical performance of OCS concrete. The effects of various fibres, such as PP and SF, on the mechanical properties and sustainability of OCS concrete were investigated (Aljuaydi et al., 2024). Their study revealed that the inclusion of fibres enhanced compressive, tensile, and flexural strengths while also reducing crack propagation caused by oil contamination. Moreover, the fibres contributed to improved

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energy absorption capacity and post-cracking behavior, making the concrete more ductile and resilient to external loads (Hason et al., 2021a; Hason et al., 2021b). These findings indicate that the addition of fibers can help lessen the negative impacts of oil contamination on the properties of concrete, providing a practical approach to improving the sustainability of OCS concrete in structural applications. Therefore, future research is encouraged to explore the most effective types and amounts of fibers in OCS concrete, taking into account both mechanical performance and environmental effects.

Durability and resistance to environmental factors

OCS concrete is less resilient to environmental elements like freeze-thaw cycles, chemical attacks, chloride penetration, and other adverse conditions (Table 7). The level of decrease in durability and performance is proportional to the level of oil contamination (Fig. 8). Hence, necessitating careful consideration and potential mitigation strategies when using OCS in concrete applications. Concrete containing OCS shows reduced resistance to freeze-thaw cycles, leading to accelerated deterioration. Oil contamination reduces the bonding strength between cement paste and aggregates, increasing the permeability and susceptibility to freeze-thaw damage. After 100 freeze-thaw cycles, concrete with 5% oil contamination exhibited a 30% decline in compressive strength compared to only a 10% reduction in uncontaminated concrete (Attom et al., 2013). Concrete with OCS is more susceptible to chemical attacks, such as exposure to sulfates and acids. Oil contamination disrupts the formation of a dense, impermeable matrix, allowing chemicals to penetrate and degrade the concrete more easily. Sulfate resistance tests showed a 25% mass loss in concrete with 4% oil contamination after 90 days of exposure, compared to a 10% mass loss in uncontaminated concrete (Attogbe & RizkallaI, 1988). OCS concrete shows higher chloride ion penetration, leading to increased risk of steel reinforcement corrosion. The hydrophobic layer of oil on sand particles creates microcracks and voids, facilitating chloride ingress. Chloride penetration depth increased by 35% in contaminated concrete (5%) relative to control concrete (0% contamination (Attogbe & RizkallaI, 1988).

Water absorption (WA) is crucial for assessing the durability of oil-contaminated sand (OCS) concrete. For instance, a study by Ajagbe and Rabiu (2018) investigated how crude oil-affected sand influences concrete durability, with a specific emphasis on WA characteristics (Abousnina et al., 2016a; Ajagbe & Rabiu, 2018). Their results indicated that OCS concrete demonstrated significantly higher WA rates compared to control samples that used clean sand. This increased WA was linked to oil residues, which modified the sand's pore structure and surface properties, facilitating greater water penetration. As a result, the increase in WA negatively impacts concrete durability, making it more susceptible to cracking, shrinkage, and long-term deterioration from environmental exposure. Therefore, minimizing WA is critical for improving the durability and longevity of OCS concrete in structural applications. Heavy Metal Leaching: Environmental effects and heavy metal leaching are basic considerations when utilizing the OCS concrete. Mahmoud Kassem et al. (2018) conducted a point-by-point examination of the environmental influence of OCS in concrete, highlighting the significance of leaching performance (Kassem et al., 2018). They employed the TCLP test to assess the discharge of heavy metals from the concrete framework. They demonstrated that clean sand attitudes a chance of leaching hazardous substances, whereas OCS appeared to decrease leaching within reasonable limits. They recommended that incorporating OCS in concrete without suitable treatment may lead to natural dangers through groundwater contamination. Consequently, it is basic to evaluate leaching characteristics and apply treatment strategies to moderate dangers some time when utilizing OCS in construction applications. This fact is vital for advancing an all-encompassing feasible approach that considers not as it were mechanical behavior but, moreover, environmental protection.

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Table 7. Comparative impact of various oil contamination levels on the concrete resistance to various environmental factors (Attom et al., 2013; Osuji & Nwankwo, 2015)

Oil Content (%)	Freeze-Thaw Reduction in Compressive Strength (%)	Chemical Attack Mass Loss (%)	Chloride Penetration Depth increasing (mm)
0	10	10	10
1	15	15	12
3	22	20	15
5	30	25	17

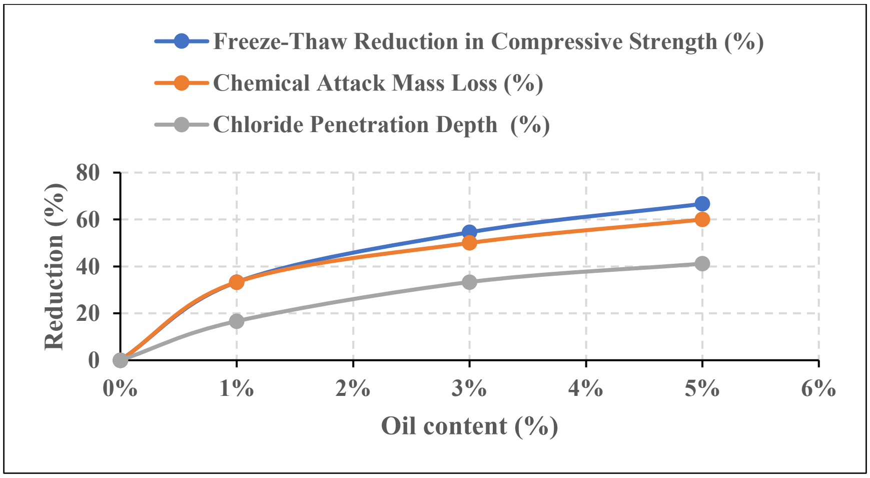

Fig. 8. Effect of oil contamination percentages on various environmental factors (freeze-thaw, chemical attack, and chloride penetration (Attom et al., 2013; Osuji & Nwankwo, 2015).

Structural performance

Abousnina et al. (2018) carried out an experimental examination of RC beams made of sand contaminated with crude oil to investigate the structural and mechanical performances. The evaluation had varying percentages of oil (0, 1, 2, 6, 10, and 20 percent). Two beams measuring 1400 mm in length, 250 mm in depth, and 100 mm in breadth were utilized. One control beam with 0% oil crude and the other beam is contaminated with 6% oil-contaminated sand. The top and bottom 2∅10 bars and the spacing was 100c/c of the ∅6 mm diameter stirrups reinforced the beams. A concrete cover of 25mm was designed using steel spacers between the concrete and wooden bottom side molds. A 6 percent crude oil contamination level was determined to be the optimal level for the beams, and they were compared to an uncontaminated beam (0 percent). After 28 days of curing in a fog room at a temperature of 25 °C and 85% humidity, all specimens (beams and cylinders) were tested. The highest load that the contaminated beam (6 percent) could support during the flexural strength test of the beams was 20% less than the uncontaminated beam (Fig. 9). Besides, when compared to an uncontaminated beam, the oil-contaminated beam's initial crack and yielding duration occurred at a lower weight and over a shorter period of time, respectively (Fig. 10). Nevertheless, For both beams, the initial stiffness stays the same (Abousnina et al., 2018).

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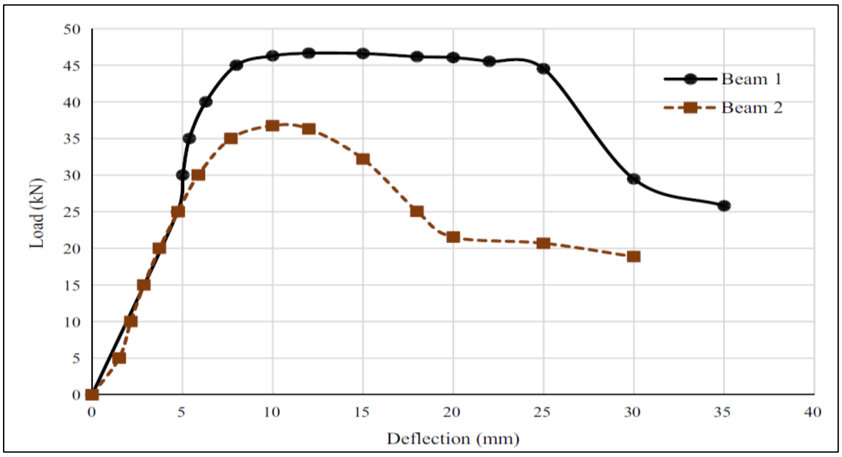

Fig. 9. Load-deflection comparison between contaminated and uncontaminated beams (Abousnina et al., 2018).

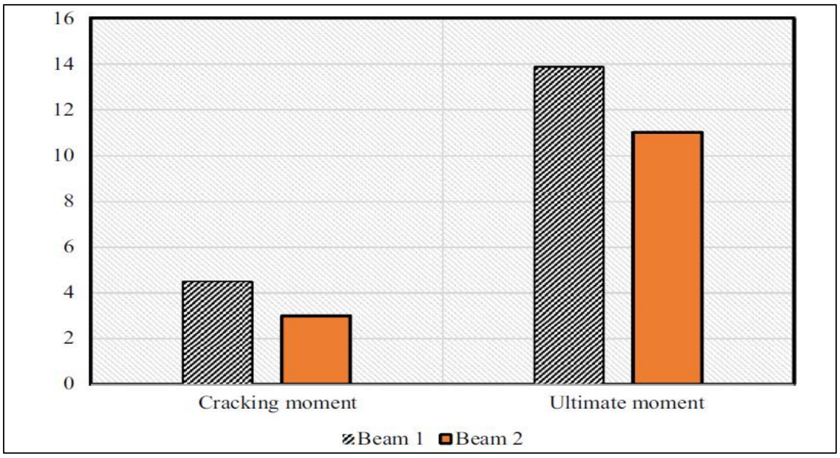

Fig. 10. Comparison between cracking moment and ultimate moment for beam 1 and beam 2 (Abousnina et al., 2018).

Kadhum et al. (2020) conducted a study to examine whether building crude oil tanks with reactive powder concrete (RPC) is a better choice than using normal concrete (NC). After being submerged for 180 days, the influence of kerosene and gas oil on the structural behavior of RPC and NC slab specimens is experimentally studied. 140 MPa and 40 MPa of cylinder compressive strength were selected as the target design strength of RPC and NC, respectively. The samples underwent immersion in a tank containing the designated crude oil product, as did the control group under a similar immersion approach. Both types of RC slabs were subjected to failure at the age of 180 days. With the largest drop of 2.58 percent from its ultimate load following immersion in gas oil product, the test results (Fig. 11) demonstrated that the impact of each type of crude oil product on the load-bearing capacity of RPC slabs was almost insignificant. Conversely, after soaking in kerosene and gas oil, standard concrete slabs lost roughly 10.15 percent and 12.57 percent of the final load, respectively. All of the data suggested that, in comparison to NC slabs, which displayed comparatively linear load-deflection relationships as displayed in Fig. 10, reference and submerged RPC slabs demonstrated more ductile behavior.

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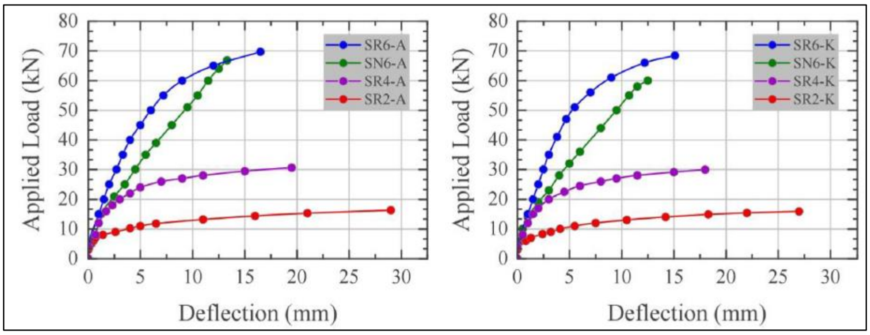
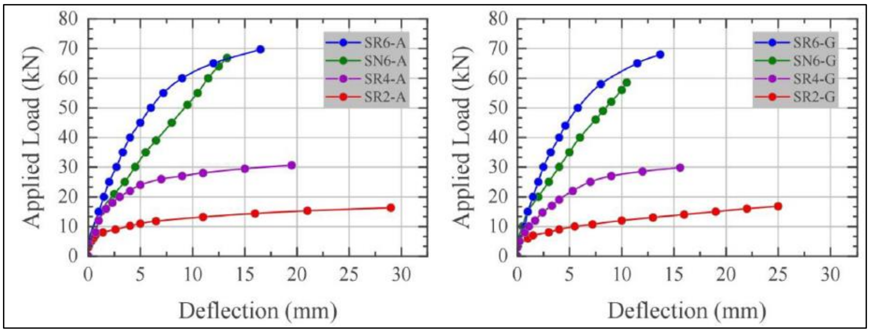


(a)



(b)

Fig. 11. Load-deflection correlation (Kadhum et al., 2020) (a) reference and immersed slabs in kerosene and (b) reference and immersed slabs in gas oil.

CASE STUDIES AND PRACTICAL APPLICATION

Real-world application

The use of OCS in concrete applications demonstrates significant potential for cost savings and sustainability in construction. Real-world applications with proper treatment and innovative approaches (Table 8) can be effectively utilized in OCS. These case studies and practical applications highlight the economic and environmental benefits of incorporating such waste materials into construction practices.

Case studies

Kuwait has abundant OCS due to its extensive oil extraction activities. A highway embankment project utilized this sand to construct base layers. OCS was mixed with stabilizers to improve its properties before use. The project demonstrated that treated OCS could achieve sufficient compaction and stability for highway embankments, with a 20% cost reduction compared to using clean sand (Kassem et al., 2018). An industrial facility in Saudi Arabia used OCS in the concrete for its flooring. The sand was treated with chemical agents to neutralize the oil's adverse effects. The treated sand concrete exhibited adequate compressive strength and durability, with a 15% increase in material recycling efficiency (Abdullah et al., 2020). In Nigeria, a residential building's foundation was constructed using OCS, addressing both environmental concerns and material shortages. Local engineers mixed the contaminated sand with cement and other aggregates to form concrete. The foundation showed a 10% reduction in compressive strength compared to traditional concrete, but was deemed acceptable for low-rise residential buildings, reducing construction costs by 18% (Abousnina & Allister, 2022).

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Practical application

OCS concrete has been effectively used in non-structural elements such as pavements, walkways, and retaining walls. In Bahrain, OCS was used in the construction of a large public park's walkways. The treated concrete provided a durable surface suitable for heavy pedestrian traffic while utilizing waste materials (Abousnina et al., 2015a). This approach promotes recycling and reduces landfill waste, with a 25% material cost saving. OCS has been employed in creating barriers and containment structures for environmental remediation. In Iran, OCS was used to construct barriers around contaminated sites to prevent the spread of pollutants. This innovative use helped in isolating contaminants and reducing the environmental impact (Du & Jiang, 2022). The use of OCS in such projects facilitates the containment of pollutants and supports environmental protection efforts, with a reported 30% decrease in remediation costs. Researchers have developed new materials using OCS to create high-strength, eco-friendly concrete. A study in India experimented with geopolymer concrete incorporating OCS, achieving comparable strength to conventional concrete and enhanced durability under harsh conditions. This method contributes to sustainable construction practices and provides a viable solution for utilizing contaminated materials.

Table 8. Summary of case studies and practical applications

Project Location	Application	Oil Content (%)	Strength Reduction (%)	Cost Reduction (%)	Additional Benefits
Kuwait	Highway Embankment	3	5	20	Enhanced stability with stabilizers
Saudi Arabia	Industrial Flooring	4	8	15	Improved recycling efficiency
Nigeria	Residential Building Foundation	5	10	18	Suitable for low-rise buildings
Bahrain	Public Park Walkways	2	4	25	Durable surface for pedestrian traffic
Iran	Environmental Barriers	3	6	30	Effective containment of pollutants
India	Geopolymer Concrete	5	0	20	High-strength, eco-friendly concrete

SUSTAINABILITY OF RECYCLING CRUDE OIL INFUSED SAND (COIS)

Recycling OCS in concrete production has emerged as a promising strategy for sustainable construction, alongside (Table 9) economic advantages (Fig. 11). This approach not only addresses the environmental challenge of oil-contaminated waste but also contributes to the conservation of natural resources by reducing the demand for fresh sand.

Environmental benefits

Recycling OCS helps to reduce the volume of waste that would otherwise be disposed of in landfills. Studies have shown that incorporating OCS in concrete can divert significant quantities of waste from landfills, mitigating soil and water contamination risks. This practice supports waste management and environmental conservation efforts. Utilizing contaminated sand reduces the demand for natural sand, which is a finite resource. Research indicates that using recycled sand can save up to 20% of the natural sand required for concrete production (Abdullah et al., 2020). This contributes to the sustainable use of natural resources and minimizes the environmental impact of sand extraction. The recycling process can

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lower the overall carbon footprint of concrete production. Life cycle assessments (LCAs) demonstrate that incorporating OCS can reduce the carbon emissions associated with raw material extraction and processing (Mekkiyah et al., 2023). This is in line with international initiatives to lower greenhouse gas emissions and slow down climate change.

Economic benefits

Using recycled sand can reduce the material costs associated with concrete production (Fig. 12). Economic analyses have shown that recycling OCS can lead to cost savings of approximately 10–15% in concrete production (Abdullah et al., 2020). This makes the construction process more economically viable, particularly in regions where natural sand is scarce or expensive. The development of new markets for recycled materials can spur economic growth. Studies suggest that the market for recycled construction materials is expanding, driven by increasing environmental awareness and regulatory support (Attom et al., 2013; Osuji & Nwankwo, 2015). This can create new business opportunities and promote sustainable industry practices.

Table 9. Environmental and Economic Benefits of Recycling OCS (Abdullah et al., 2020)

Benefit	Description	Impact
Waste Reduction	Diverts waste from landfills	Reduces soil and water contamination
Resource Conservation	Reduces demand for natural sand	Sustainable resource use
Reduced Carbon Footprint	Lowers emissions from material processing	Mitigates climate change
Cost Savings	Lowers material costs	Economic viability of construction
Market Potential	Expands the market for recycled materials	Economic growth and new opportunities

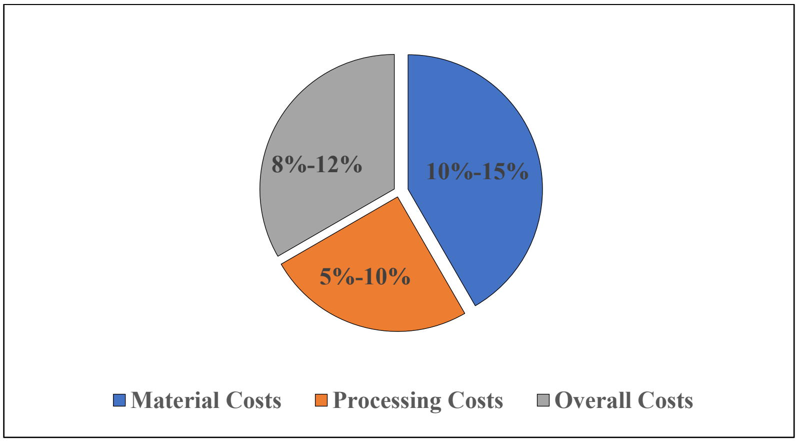

Fig. 12. Cost savings in concrete production with recycled sand (Abdullah et al., 2020).

CHALLENGES, SOLUTIONS, AND FUTURE DIRECTIONS

The use of OCS in concrete for structural members presents several challenges (Table 10), but also opens avenues for more research and innovation. However, future research directions and field applications hold promise for overcoming these challenges (Table 10). Addressing these issues, the construction industry can harness the potential of OCS for sustainable and cost-effective building practices.

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Table 10. Summary of common challenges and future directions

Challenge	Impact	Future Direction	Expected Outcomes
Reduced Mechanical	Compromised structural integrity	Advanced treatment techniques	Improved mechanical properties
Poor Bonding with Reinforcement	Lower load transfer efficiency	Innovative material compositions	Enhanced bond strength
Inconsistent Material Quality	Difficulty in standardization	Standardization and quality control	Consistent and reliable performance
Environmental and Health Concerns	Environmental contamination and health risks	Safe handling and processing methods	Reduced environmental and health impact

RESEARCH GAPS AND AREAS NEEDING FURTHER INVESTIGATION

Although a great deal of progress has been achieved in comprehending the application of OCS in concrete (Table 11), numerous research gaps exist that are essential to be addressed to fully understand and optimize the use of this material (Table 12). Addressing these current gaps and identifying areas requiring further investigation for safer and more effective use of OCS in construction. By advancing research in these areas, the construction industry can better harness the potential of this material for sustainable and resilient infrastructure development.

Table 11. Literature survey matrix

Ref.	Problem	Focus	Method Used	Findings	Limitation
(Abousnina et al., 2018)	Impact of light crude oil on fine sand properties used in concrete.	Investigating the mechanical properties and structural behavior of contaminated concrete.	Experimental analysis of compressive strength, flexural strength, and durability of concrete with varying oil contamination levels.	Oil contamination reduces compressive strength, but slight improvements in workability.	Limited to light crude oil. Does not cover other types of oil contamination.
(Kadhum et al., 2020)	Influence of crude oil on reactive powder and normal-strength concrete slabs.	Comparing the structural performance of reactive powder concrete (RPC) and normal concrete.	Experimental tests on slabs with crude oil contamination and numerical simulations.	RPC showed better resistance to contamination compared to normal concrete.	Limited scope to slab elements; no exploration of beams or columns.
(Abousnina & Allister, 2022)	Sources and remediation methods of oil-contaminated sand.	Reviewing remediation techniques and engineering applications of contaminated sand.	Literature review of remediation techniques and potential applications of treated sand in construction.	Identified multiple remediation methods and proposed sustainable use cases.	Lacks experimental validation of the proposed applications.
(Wasiu, 2013)	Effect of crude oil contamination on concrete properties.	Evaluating how oil impacts concrete's compressive and tensile strengths.	Experimental study of concrete's mechanical properties using oil-contaminated sand.	Found reduction in compressive strength; highlights curing challenges.	Limited to basic mechanical tests; lacks long-term durability analysis.
(Osuji & Nwankwo, 2015)	Impact of crude oil spills on compressive strength of concrete.	Examining how crude oil affects the hydration process and strength development.	Conducted compressive strength tests on concrete made with contaminated sand.	Oil contamination delays hydration and reduces compressive strength.	Focuses only on compressive strength; ignores other structural properties like flexural behavior.

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(Abousnina et al., 2016b)	Overview of oil-contaminated sand's impact and potential engineering applications.	General review of properties, challenges, and potential solutions for using contaminated sand in engineering.	Summarizes challenges of using contaminated sand and highlights opportunities for sustainable use in construction.	Broad overview without specific experimental data.	Limited by the lack of experimental data or case studies to validate its claims. Does not address how regional variations in sand properties or contamination types might influence results.
(Ajagbe et al., 2012a)	Effect of crude oil contamination on concrete's structural and durability properties.	Analyzing the changes in structural integrity and durability of concrete with contaminated sand.	Found significant reduction in both strength and durability; highlighted environmental concerns of using contaminated materials in concrete.	Crude oil contamination significantly reduces both the strength and durability of concrete, highlighting challenges such as delayed setting time and compromised bonding within the concrete matrix.	Does not explore the long-term performance of contaminated concrete under varying environmental conditions, leaving gaps in understanding its practical applications.
(Almabrok et al., 2013)	Characterizing how oil-contaminated aggregates affect cement mortar properties.	Investigating the microstructural changes and mechanical properties of mortar with contaminated aggregates.	Showed that oil contamination alters microstructure, leading to reduced strength and increased porosity.	The study finds that oil contamination alters the microstructure of the mortar, leading to increased porosity and reduced compressive strength, which negatively affects the material's overall performance.	Limited to mortar studies. Lacks analysis of full-scale concrete elements, leaving the broader implications for structural applications unexplored.
(Al-Halfy et al., 2021)	Environmental impact of oil spills on sandy soils in Iraq.	Assessing the contamination levels and proposing remediation measures.	Found high contamination levels in sandy soil and suggested containment and remediation strategies.	Focuses on environmental impact without addressing engineering applications.	Limited by its exclusive focus on environmental impacts, without exploring the potential engineering applications of contaminated sand. Does not address the long-term performance or environmental sustainability of these approaches.
(Ejeh & Uche, 2009)	Investigating the effects of crude oil spills on concrete compressive strength.	Studying how oil contamination disrupts concrete's strength development.	The crude oil significantly reduces strength by interfering with hydration and weakening the bond between cement paste and aggregates.	Emphasizes the need for protective measures; the need to avoid or treat contaminated sand in construction.	Limited to basic mechanical properties. Lacks broader structural analysis.

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Table 12. Summary of research gaps and areas needing further investigation

Research Gap	Areas Needing Further Investigation
Long-Term Durability and Performance	Long-term performance and Durability studies
Optimized Treatment Methods	Development of effective treatment techniques
Mechanistic Understanding of Bonding	Detailed mechanistic studies on bonding
Standardization of Material Quality	Standardization and quality control protocols
Environmental and Health Impacts	Comprehensive environmental and health assessments
Performance of Hybrid Materials	Investigation of hybrid and composite materials

OCS STANDARDIZATION

Because none of the cited standards addresses the OCS, new standards or amendments to current standards are required to guarantee its environmental safety, material quality, and effective application in construction. By reusing contaminated materials, lowering environmental risks, and encouraging eco-friendly building methods, the implementation of such guidelines would not only improve the dependability of OCS in construction but also advance sustainable waste management. Table 13 shows the existing codes and standards relevant to OCS usage.

Table 13. Necessity for OCS standards

Standard	Specifications	Description	OCS
ASTM	C33/C33M	Grading and quality requirements	Require testing and potential modification to meet particle size and contamination limits.
	D512	Chloride ion content	Critical for evaluating the effects of oil contamination
	C618	Usage of supplementary cementitious materials	Could be adapted for stabilizing OCS
ACI	318	Concrete structural design	OCS incorporation must align with these structural performance benchmarks
	201.2R	Durability	relevant for assessing long-term OCS performance
ISO	14040	Life cycle assessment framework	Applicable for evaluating the environmental impact of using OCS in concrete.
	9001	Quality management principles for construction materials	Ensuring consistency in OCS-treated concrete.
BN EN	12620	Aggregates specifications	Required for OCS to meet physical and chemical property limits
	206	Concrete performance, production, and compliance testing	Could be expanded to incorporate OCS-based concrete
EPA	Waste management and safety		Requires hydrocarbon leachability tests and environmental impact assessments before OCS use

CONCLUSION

This review paper provides a thorough comparative examination of the effects of oil-contaminated sand (OCS) on the behavior of concrete, highlighting also the sustainability, economic, and environmental perspectives. Both the challenges and opportunities associated with this practice are illustrated herein. Besides, research gaps and future needs are suggested for further investigations. The following conclusion can be drawn. Oil contamination in sand significantly affects not only its physical properties but also its

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chemical properties and chemical interactions due to oil coating, impacting its suitability for various engineering and construction applications. Oil contamination reduces the consistency of concrete by reducing the hydration efficiency and workability. However, adjustments can be used, such as adding a concern type or amount of superplasticizer and fine aggregate, or adjusting w/c ratio or extending curing time. Besides, the oil contamination in sand significantly reduces the mechanical properties of concrete, depending on the limit of oil contamination, up to 25%.Careful consideration and potential mitigation strategies are needed when using oil-contaminated sand in concrete since it exhibits reduced resistance to environmental factors. Acceptable reduction in flexural strength and maximum load tests of RC beams and RC slabs soaked in oil products (6%) was noticed, of about 20%.

Real-world applications with proper treatment and innovative approaches can be effectively utilized on oil-contaminated sand, such as projects in Kuwait, Saudi Arabia, and Nigeria. The environmental and economic advantages of using the recycled oil-contaminated sand in concrete production have emerged as a promising strategy for sustainable construction. Although the use of oil-contaminated sand in concrete presents several challenges, future research directions and field applications hold promise for overcoming these challenges. Addressing the current gaps in this paper and identifying the areas requiring further investigation will pave the way for future effective usage of OCS in construction. Future investigations may also be considered to develop a schematic summarizing key takeaways, e.g., of how oil affects bonding/hydration, which could be very helpful to better visualize the microstructural impacts of the hydration and bonding of OCS concrete.

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CONFLICT OF INTEREST

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts, and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

Mustafa A. Saeed: Writing, resources, data collection, reviewing. Zarina Itam: supervising, reviewing, editing, and writing, Nazirul Mubin Zahari: waste management, Salmia Beddu: journal proofreading.

DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the author(s) used Microsoft Copilot, LM-based tools, and ChatGPT in order to assist with improving the readability and clarity of the manuscript, particularly to support students who are non-English nationals in expressing academic content more effectively. After using these tools, the author(s) thoroughly reviewed and edited the content as needed and take full responsibility for the accuracy, originality, and integrity of the publication.

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DATA AVAILABILITY/ SUPPLEMENTARY MATERIALS

The datasets and simulation codes used and/or analysed during the current study are available from the corresponding author on reasonable request. All supplementary materials supporting the primary research, including detailed protocols and extended results, can be provided to interested researchers to foster transparency and reproducibility. The authors remain responsible for ensuring the accuracy, accessibility, and integrity of these materials.

ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All simulation procedures and analyses were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Tenaga Nasional (UNITEN). The authors affirm their adherence to academic integrity and ethical standards throughout the conduct and reporting of this study.

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