

Impact of Petroleum Products on the Compressive Strength of Concrete

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Abstract

Background: Concrete is pivotal in construction due to its strength, affordability, and versatility. However, concerns persist regarding the impact of petroleum products like benzene, kerosene, and diesel on concrete strength. This study evaluates their influence on concrete compressive strength and compares their effects with non-contaminated concrete.

Objectives: The study aims to investigate the effects of benzene, kerosene, and diesel on concrete strength. Additionally, it compares different curing methods, specifically immersion in contaminants versus traditional water curing, on concrete strength.

Methods: 327 standard concrete cubes (150mm x 150mm x 150mm) were cast and divided into four groups based on curing methods. Compressive strength tests were conducted on both control and contaminated samples. Statistical analysis using SPSS software was employed.

Results: All compressive strength values exceeded 100% of the designed concrete compressive strength of K-300. Curing in contaminants positively impacted concrete strength compared to water curing, with kerosene immersion showing the most significant increase. Statistical analysis confirmed the significant positive impact of pollutants on concrete strength.

Conclusion: This study underscores the importance of considering petroleum product contamination in concrete construction. Further research is warranted to elucidate the mechanisms underlying the increased compressive strength, potentially linked to the hydrophobic-plasticizing effect of petroleum products.

Keywords: Compressive Strength; Concrete; Benzene; Kerosene; Diesel

1. Introduction

Concrete is widely regarded as the primary material in the construction industry due to its myriad advantages, including its robust strength, straightforward production process, economic viability, compatibility with adjunct materials like steel, and commendable durability, particularly in harsh environmental conditions. Structural integrity in concrete-based

construction necessitates the capacity to withstand designated loads (Mohammed, 2024). Nevertheless, concrete elements' longevity and operational lifespan hinge upon various factors, notably the material's permeability, water absorption traits, and adherence to appropriate construction methodologies (Bahmani et al., 2025). Numerous components can influence the compressive strength of concrete, encompassing the water-to-cement ratio, mix design proportions, degree of compaction, cement composition, aggregate granularity, water quality, formulation specifications, mixing and curing techniques, and impurities (Sharifzad, 2023). Generally, the constituents employed in concrete production must remain uncontaminated by oil-based substances.

Concrete structures often encounter exposure to petroleum hydrocarbon products, either through deliberate containment in tanks designed for storage or inadvertent contact stemming from leakage at gas stations, garages, service centers, or spill incidents (Narayanan et al., 2023). This exposure increases hydrocarbon content within the surrounding soil. Various petroleum hydrocarbon products, such as kerosene, benzene, and diesel, can adversely affect concrete (George et al., 2024). The contamination created can be separated into external and internal exposure. External contamination occurs when the concrete is exposed to products derived from hydrocarbons after the concrete has set; internal contamination is defined here as being caused by the concrete containing sand that was loaded with hydrocarbon products prior to setting.

Many researchers have examined the effect on concrete properties of using sand that has been contaminated with hydrocarbon products (Ezeokpube et al., 2022). Although research studies are exploding as scientists try to understand the behavior of solidified concrete after being exposed to hydrocarbon petroleum products, a complete clear and complete explanation of the mechanisms is still lacking, warranting more studies.

The ultimate objective of the present study was to assess the effect of curing concrete with several petroleum hydrocarbon products, specifically diesel, kerosene, and benzene on development of compressive strength in concrete, and to compare the compressive strength of curing with the products with the compressive strength from curing the concrete with potable water. Outcomes are discussed from a laboratory testing program that was developed to test the compressive strength impacts of hydrocarbon products on concrete.

2. Literature Review

Concrete is widely considered to be one of the most important materials for construction given its flexibility, long-lasting, and low-cost nature. The frequency of concrete construction in a variety of infrastructures is due to the material's many inherent properties, including high compressive strengths, ease of production and mixing with other materials, like steel, and its resistance to harmful environmental impacts. However, the strength and durability of concrete can be impacted by a handful of constraining factors like exposure to contaminants, petroleum products, to name one.

2.1. Impact of Petroleum Products on Concrete

Concrete materials are often subjected to petroleum hydrocarbon products when used for containment tanks, or when spills occur from a gas station, garage, or industrial site. Such hydrocarbon contaminants include products such as benzene, kerosene, and diesel (Anigilaje et al., 2024). The presence of these products has been shown to have deleterious effects on various concrete properties, leading to reduced durability and structural integrity.

Research has focused on the effects of petroleum products on concrete. Assessment on the compressive strength of concrete containing sand contaminated with crude oil (Abdelhalim et al., 2022). The authors showed significant reductions in compressive strength as contamination with oil increased. Likewise, assess the geotechnical properties of Kuwaiti contaminated sand to determine the effects on the properties of soil, which could lead to reduced performance of concrete material placed on top of the contaminated soil (Ota, 2023).

2.2. Specific Petroleum Products and Concrete Interaction

The effects of the most common component of petroleum products, benzene, have been studied with a focus on the performance of concrete due to exposure to mineral oil containing benzene (Cordiano et al., 2022). Their performance analysis of the compressive strength of concrete demonstrated that compressive strength would decrease with increased exposure to the oil (Mujedu et al., 2021). However, specific mechanisms of interaction of benzene in the context of concrete research needs to be addressed.

The impacts of kerosene on concrete properties, specifically workability and compressive strength of high-performance concrete when contaminated with kerosene versus gasoline. The work showed a clear negative impact on workability and compressive strength; they recommended limiting exposure to effective construction contaminated with contaminants.

The research work has targeted diesel effects on concrete properties despite the study on compressive strength of concrete that involved sand contaminated with crude oil products (Abousnina & Allister, 2022). The experiment on work using diesel as a substitute discovered that the compressible strength was lower in comparison to normal and uncontaminated concrete. The authors assume there should be boundaries concerning the content of diesel in concrete during the construction process.

2.3. Environmental Impacts of Petroleum Contamination on Concrete Structures

Civil engineers are concerned with the impact of petroleum pollution on the environment and concrete buildings (Pauzi & Shah, 2022). Whenever a petroleum product spills or leaks, the entire ecosystem, and human health are contaminated as the products are transferred to the near-surface soil and groundwater (Adeniran et al., 2023). It has been shown that, under conditions of a concrete structure that has been subjected to petroleum hydrocarbons, degradation of mechanical properties of concrete may occur. Moreover, even long-term impact of petroleum contamination of concrete buildings that can affect environmental cleanup operations, policing or policy variables are also under consideration.

2.4. Emerging Trends in Mitigating Petroleum Contamination in Concrete

Recently, materials science and materials engineering have produced new methods to address problems of petroleum contamination of concrete (Douglas et al., 2022). The approaches presented in the literature make use of other pozzolan cementitious materials such as fly ash and slag which are more resistant to concrete - such as chemical attack and permeability. Moreover, new nanotechnologies like silica nanoparticles have also performed well in enhancing the performance and durability of concrete in a diseased environment (Vijayan et al., 2023). Lastly, the digital technologies such as remote sensing and machine learning have more advanced, which provide remote sensing and machine algorithms of spatial/temporal and real-time detection of petroleum contamination in concrete, and are also likely to remediate the concrete.

2.5. Strategies for Mitigation

These several mitigation strategies have been proposed about petroleum products and the harm that they cause in real terms. Proper storage and management of petroleum products at construction and operation stages will help minimize spillage risks and avoid pollution. Also, commonly available and cheap impermeable barriers and protective surfaces over contamination of concrete structures are available to ensure integrity and performance over time.

2.6. Current Gaps and Future Directions

Although a large amount of research has been conducted, there are still many unknowns regarding the interaction of petroleum products with concrete (Hong et al., 2023). More research will be necessary to fully understand the specific mechanisms of how contaminants affect concrete properties, including microstructure, hydration rates and long-term durability (Udumulla et al., 2024). New and improved testing methods and analytical techniques can offer more information on concrete behavior in actual field conditions to aid in designing better resilient infrastructure systems.

3. Methodology

3.1. Concrete Mix Design

The mix design process is important for determining the properties of concrete including its strength and suitability for specific applications. For this study the mixed proportions were based on typical practices for housing construction. The design was to yield concrete strength used for structural elements in Kuwait such as columns, beams, slabs, and footings. The concrete grade for this study was K-300 OPC (Ordinary Portland Cement) which is often used in the construction industry in Kuwait. The design mix used in this research is shown in Table 1.

Table 1: Concrete Mix Design

SL. NO.	Components	Units	Mix Proportions	Design
1	Cement (OPC)	kg/m ³	400	
2	Sand	kg/m ³	640	
3	Aggregate (3/4")	kg/m ³	770	
4	Aggregate (1/2")	kg/m ³	-	
5	Aggregate (3/8")	kg/m ³	380	
6	Water	Liter/m ³	190	
7	Admixture/Rheobuild 858	Liter/m ³	4.2	
8	W/C Ratio	-	0.48	
9	Required Slump	Cm after (60) mins	(16 ± 4)	
10	Required Compressive Strength	Kgf/cm ²	300	

3.2. Selection of Petroleum Products

For this study, three petroleum products—kerosene, diesel, and benzene—were chosen as contaminants because of their extensive use in construction site environments in Kuwait, such as from gasoline filling stations, power plants, and pumping stations. The petroleum products collected and stored in air-tight steel containers to avoid contamination and loss, were obtained from the Kuwait National Petroleum Company (KNPC) station.

3.3. Characterization of Petroleum Products

Table 2 presents the physical and chemical properties of kerosene; a common petroleum product used in industrial applications. Kerosene is a clear, colorless amber liquid with a boiling point exceeding 150°C and a freeze-melting point of -32°C. It has low vapor pressure, moderate volatility, and low viscosity and is slightly soluble in cold water. Its specific gravity is 0.82, and it has a distinct hydrocarbon odor. Its autoignition temperature is 380°F.

Table 2: Physical and Chemical Properties of Kerosene

Type of Contaminant	Kerosene
Appearance	Clear, colorless to amber, volatile liquid
Boiling Point	>150°C (>302°F)
Freeze-Melt Point	-32°C (-26°F)
Vapor Pressure	<0.3 kPa (<2 mmHg)
Volatility	825 g/l VOC (w/v)
Vapor Density	3.0 – 4.0
Viscosity (At 40°C)	< 1
Solubility in Water	Very slightly soluble in cold water
Specific Gravity	0.82
pH Value	N/A
Odor	Hydrocarbon odor
Auto Ignition Temperature	380° F
Evaporation Rate	Not determined

Table 3 shows diesel's physical and chemical properties as a petroleum-derived liquid fuel. Diesel is an oily liquid with a clear appearance and light-yellow color, with a neutral pH value of 7. It has a melting/freezing point below 0°C, a boiling range of 150 to 390°C, and a flash point exceeding 55°C. It is flammable within specific concentration limits, less dense than water, and insoluble in cold and hot water.

Table 3: Physical and Chemical Properties of Diesel

Type of Contaminant	Diesel
Physical State	Liquid [Oily liquid]
Appearance	Clear
Color	Yellow [Light]
Odor	Characteristic
Odor Threshold	Not available
pH Value	7
Melting Point/Freezing Point	< 0°C
Initial Boiling Point and Boiling Range	150 to 390°C
Flash Point	Closed cup: >55°C [ASTM D93]
Rate of Evaporation	Not available
Flammability (solid, gas)	Not applicable
Upper/lower flammability or	Lower: 1%

explosive limits	Upper: 6%
Vapor Pressure	0.4 kPa [20°C]
Vapor Density	Not available
Relative Density	0.84
Solubility	Insoluble in the following materials: cold water and hot water
Dispersibility Properties	Very slightly dispersible in the following materials: hot water. Not dispersible in the following materials: cold water.
Partition coefficient: n octanol/water	Not available
Auto-ignition Temperature	>225°C
Decomposition Temperature	>225°C
Viscosity (40°C)	<5 cSt
Explosive Properties	Not applicable
Oxidizing Properties	Not applicable

Table 4 shows the physical and chemical properties of benzene; a volatile hydrocarbon compound used as a solvent and chemical producer. Benzene has a bright, clear appearance, a characteristic odor, and a neutral pH value. Its boiling range is 25 to 220°C, with a pour/melting point below -50°C. Its flash point is below -40°C, indicating its flammable nature. Its autoignition temperature exceeds 400°C, and its relative density is lighter than water.

Table 4: Physical and Chemical Properties of Benzene

Type of Contaminant	Benzene
Physical State	Liquid
Color	May be colored
Appearance	Bright and clear
Odor	Characteristic
pH Value	Neutral
Boiling Range, °C	25 - 220
Pour/Melting Point, °C	< -50
Flash Point, °C	< -40 (ASTM D56)
Auto flammability/ignition, °C	> 400
Upper explosion limit	7.6 % vol. air (oil base)
Lower explosion limit	1.4 % vol. air (oil base)
Vapor pressure, 20 °C, kPa	35 - 100
Viscosity, kinematic, 40 °C, mm ² /s	< 1
Relative density, 15 °C	0.72 – 0.79
Water Solubility	0.005 % m
Partition coefficient, n-octanol/water	2 - 7
Other data	Vapor Density (air = 1): > 3

3.4. Curing Procedures

Curing time affects cement hydration, affecting concrete qualities, especially strength. Adequate curing involves maintaining a warm and moist environment to facilitate hydration and reduce porosity in the cement paste, thereby increasing concrete density. Cube samples for strength testing were de-molded after 16 to 72 hours, typically 24 hours after adding water and other ingredients. These cubes were cured in a water tank until the testing date or transferred to contamination curing tanks. Control cube specimens were cured in clean water for various durations (7, 14, 28, 60, 90, and 240 days) and tested for compressive strength at each age.

3.5. Contamination Curing Procedure

The cubes subjected to petroleum product contamination, specimens were initially cured in clean water for 7, 14, and 28 days without transfer to non-water tanks. Subsequently, they were transferred to benzene, kerosene, or diesel tanks and immersed for durations matching the control curing periods (7, 14, 28, 60, 90, and 240 days).

3.6. Testing Environment

All laboratory testing was conducted at room temperature, maintained between 20 to 25 degrees Celsius.

3.7. Testing Program

The testing program was structured into groups based on curing conditions and durations. Group (1) comprised control cubes cured solely in clean water. In Group (2), cubes underwent contamination curing after 7 days in clean water, while in Group (3), contamination curing commenced after 14 days in clean water. Group (4) was subjected to contaminated curing for 28 days in clean water. This organized process made it possible to assess the effects of the various petroleum products and the duration of curing on the compressive strength of the concrete with sufficient detail to assess the impacts of petroleum contamination on concrete properties over time.

4. Results

Figure 1 demonstrates that the compressive strength of concrete in petroleum products was typically greater than that of the control. This was true for the three contaminants, showing a significant increase in compressive strength in comparison to standard curing in water. The average compressive strength values in the samples with contaminants continued to exceed that of the control, indicating that petroleum products had a useful impact on concrete strength.

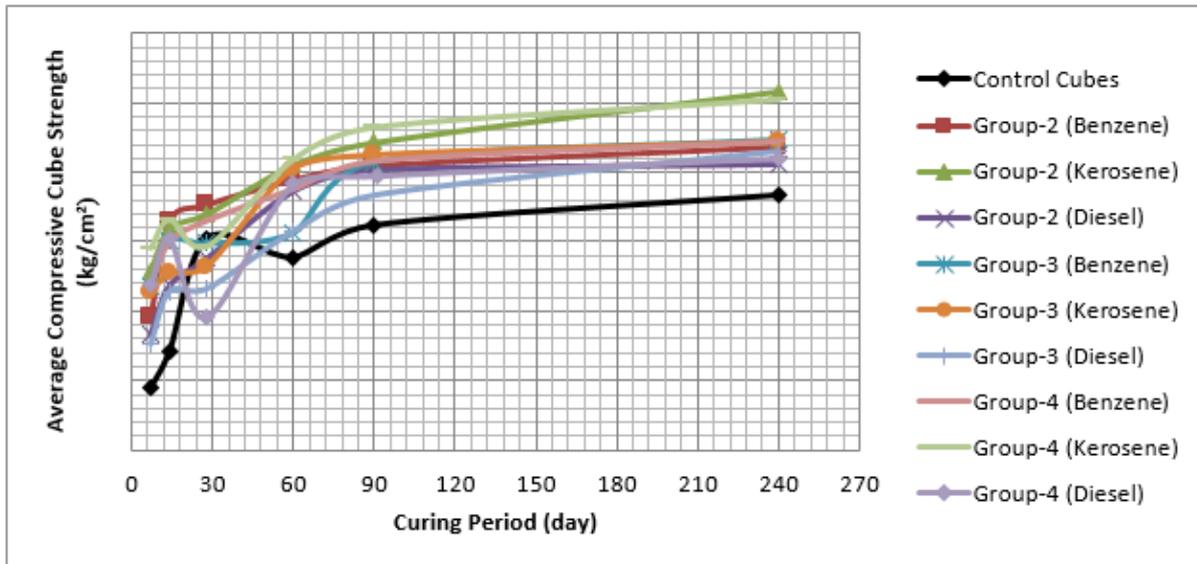


Figure 1: Testing Results Summary

Figure 2 shows the effects of benzene on concrete compressive strength. The results reveal a significant increase in compressive strength in concrete samples under the exposure of benzene compared to the control samples. This improvement indicates that benzene may be beneficial to the mechanical performance of concrete due to its hydrophobic properties and ability to decrease water loss during curing. The mean compressive strength of samples exposed to benzene was higher than that of the control samples indicating an improvement in strength.

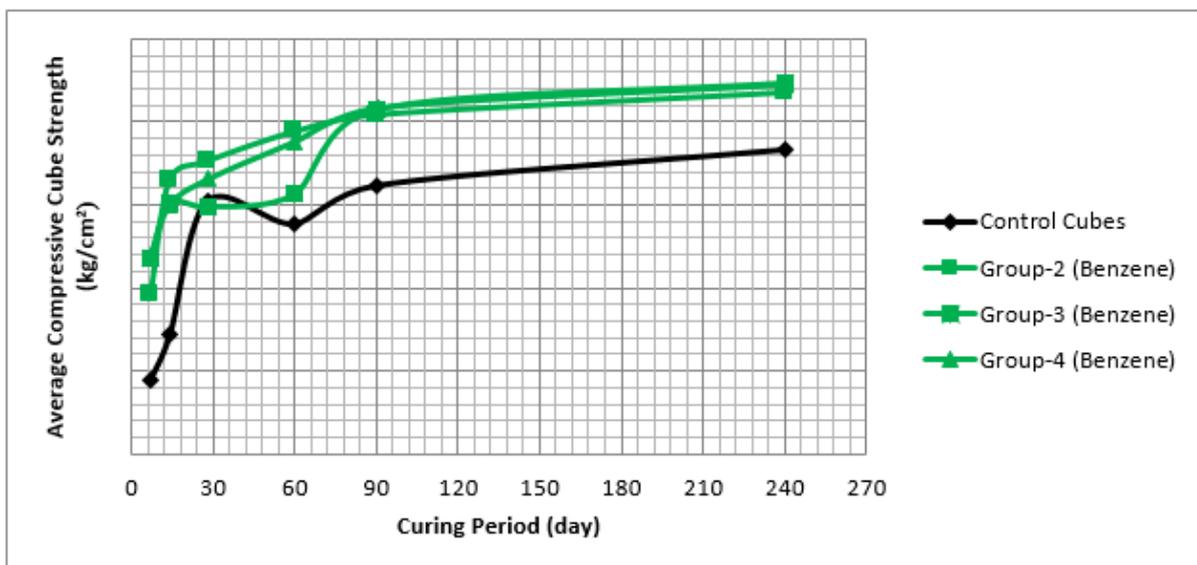


Figure 2: Testing Results Summary of Benzene Impact

The impact of kerosene on compressive strength (f_c) of concrete is presented in figure 3. Concrete specimens subjected to kerosene show an increased compressive strength compared to the control. The improvement in compressive strength of samples immersed in kerosene could be due to the hydrophobic nature of kerosene causing a reduction of the loss of water which creates a denser microstructure of concrete as it cures. The average compressive strength

of the samples subjected to kerosene exceeds that of the control group, indicating improved overall compressive strength.

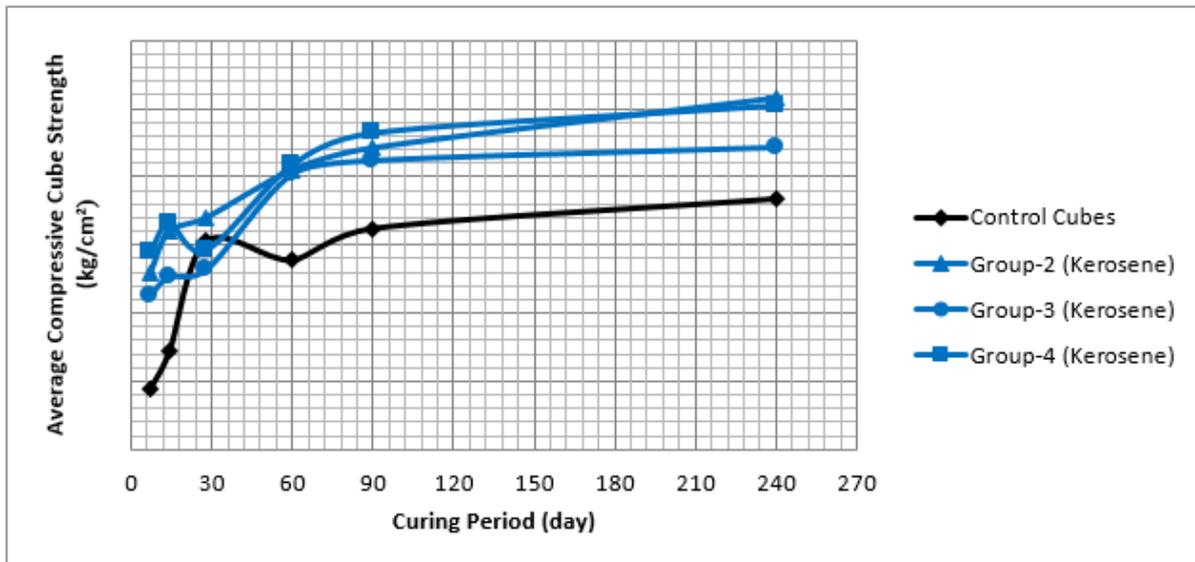


Figure 3: Testing Results Summary of Kerosene Impact

The effect of diesel on concrete compressive strength is shown in Figure 4. Concrete samples that were exposed to diesel also exhibited increased compressive strength compared to the control group. This increase suggests that diesel may have a similar beneficial effect as benzene and kerosene on concrete's mechanical properties. These beneficial effects on properties may be due to the reduced water loss that occurs during the curing process promoting densification of the cementitious matrix. The average compressive strength for samples that were exposed to diesel was greater than the control group, contributing to evidence that petroleum products show beneficial effects on the strength of concrete mixtures.

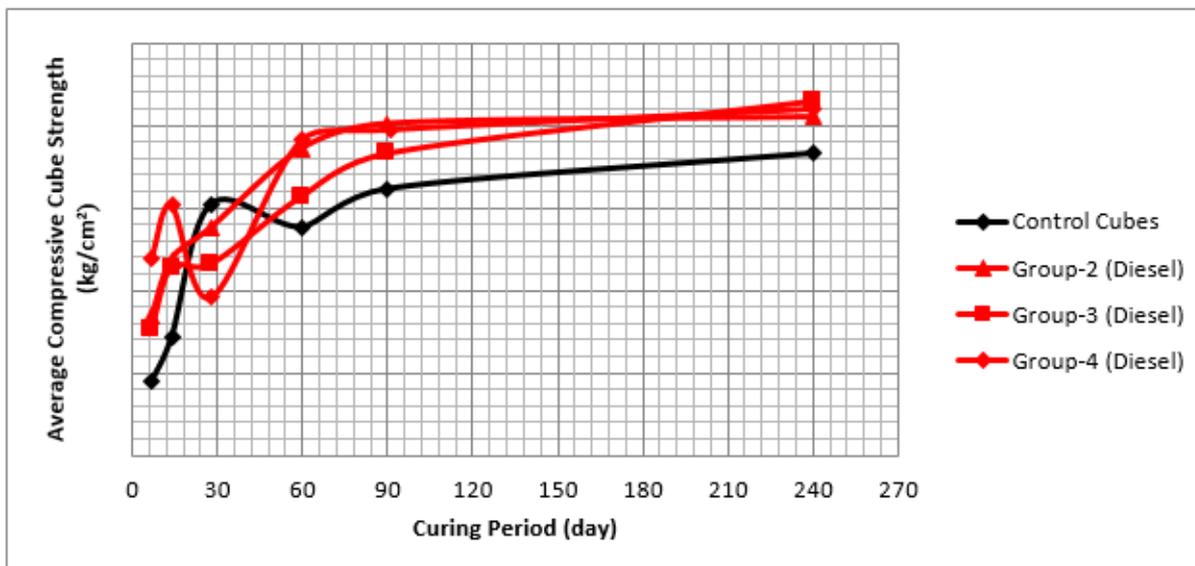


Figure 4: Testing Results Summary of Diesel Impact

The histogram of compressive strength data presented in Figure 5 shows a slight left-skew of the values. Most of the compressive strength values presented are within expected compressive strength values, and there is a long tail towards the lower range of compressive strength values. This distribution of concrete compressive strength suggests that while most of the concrete samples tested were performing adequately with their compressive strength results, they still provided evidence of some sample with lower compressive strength, theoretically the result of a range of specified curing conditions and material properties. In summary, informative distribution of compressive strength is useful data that shows the variability of concrete testing.

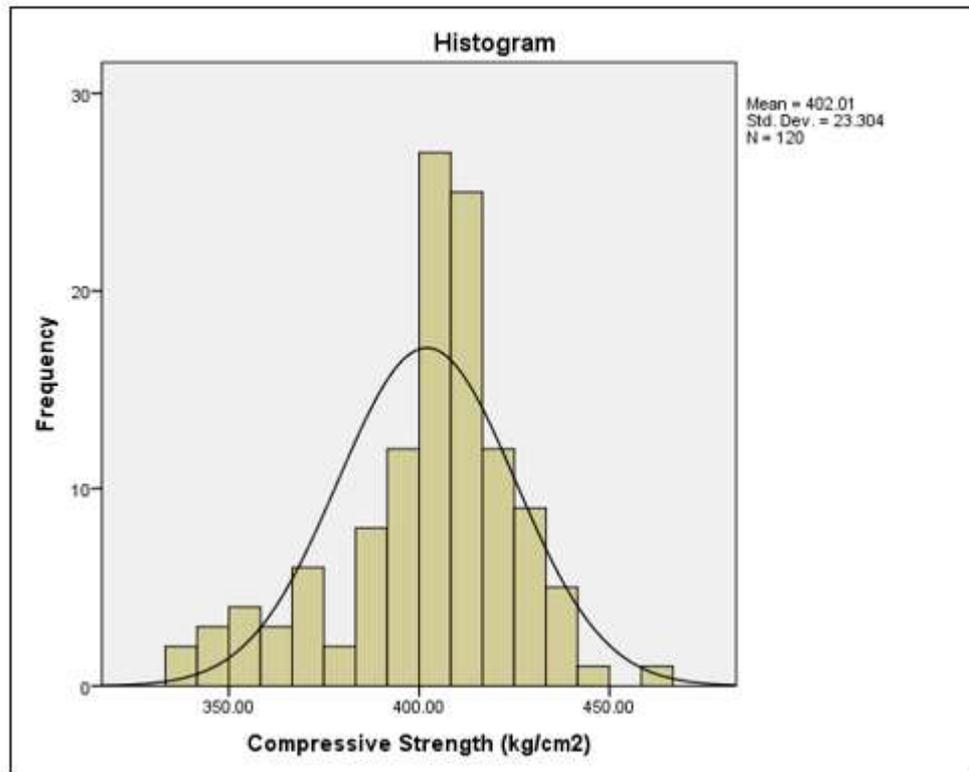


Figure 5: Histogram of Concrete Compressive Strength Results

The results of this study indicate that immersion of concrete specimens in benzene, kerosene, or diesel can lead to improvements in compressive strength compared to conventional curing in water. These enhancements may be attributed to the hydrophobic properties of petroleum products, which can facilitate the densification of the concrete microstructure during curing. However, further investigation is warranted to elucidate the underlying mechanisms and validate these findings through chemical analysis and additional experimentation.

5. Discussion

The findings of this study confirm the conclusion of previous studies that indicated petroleum products, including benzene, kerosene, and diesel, can affect the compressive strength of concrete. In these previous studies, they observed a decrease in compression with increased levels of oil contamination, which is noticeably different than the previous findings of the study (Obisesan et al., 2023). However, it is important to acknowledge the varying experimental procedures and conditions in each of the studies, that likely changed the outcome to some degree; whereas previous studies focused on the effect of crude oil and mineral oil on concrete,

the current study evaluated the effect of benzene, kerosene, and diesel on concrete, and the addition of these specific petroleum products may yield different results.

Likewise, the harmful effects of kerosene and gasoline on concrete workability and compressive strength in both previous studies would cause caution in using the contaminants, due to concrete mixing, curing, and storing expectations in the construction process. Findings in the current study indicated a significant increase in compressive strength on concrete specimens containing kerosene, which opposes the detrimental effects of previously cited studies (Hossain et al., 2024). The clear difference in findings highlights the complexity of the interaction of petroleum products with the workability and compressive strength of concrete. This emphasizes the potential to change the workability and compressive strength of concrete, may depend on various factors such as the curing conditions, environmental factors, and concrete mixture design (Ziolkowski, 2025).

The compressive strength of the concrete with sand contaminated with crude oil product (diesel) was tested. The findings indicated that compressive strength was poor compared to pure concrete. A different part of the analysis, however, presented results indicating that the increase in compressive strength was achieved in concrete samples contaminated by diesel versus control (concrete without contamination) (Yu et al., 2023). The difference in test results indicates that there is no cause not to carry out controlled research that would help to understand the different compressive strength achieved after exposure to petroleum products.

The links between the concrete compressive strength in this experiment and the modes of contamination of petroleum products are significant questions to be considered in terms of constructions and environmental remediation. It indicates the use of benzene, kerosene and diesel as contaminants in enhancing the mechanical properties of concrete, possibly due to the hydrophobicity of these oils, which delay the loss of water during the curing and densifying of the cement matrix (Yu et al., 2023). Nevertheless, care must be taken before practical applications are explored, as there are not yet proven durability and performance of concrete, when subjected to petroleum products.

The mechanisms that accompany the delivery of greater compressive strength remain open to future studies since the hydrophobic-plasticizing impact of petroleum items on the mechanics of hydration of concrete has been established. The performance-relevant physicochemical methods such as scanning electron microscopy (SEM) and x-ray diffraction (XRD) should be added to the future studies because they are necessary to examine the impact of petroleum products on the microstructure and hydration products (Bangaru et al., 2022). Further chemical studies of the correlation between the by-products of petroleum may provide additional information about the molecular mechanism processes discussed.

The research contributes to our general knowledge of the effects of petroleum on concrete and compressive strength. Although the adverse impact of petroleum products on concrete is well documented, the paper provides new evidence of a beneficial impact of benzene, kerosene, and diesel on concrete compressive strength. This is valuable information in terms of construction practice, remediation systems, and risk management and regulation systems in the context of environmental and structural impacts of petroleum products on concrete reclamation.

In future studies, researchers can develop a better understanding of the nuances between petroleum products and concrete properties by learning about the mechanisms that lead to the observed improvements in compressive strength (Ismagilov et al., 2021). Investigating this on a molecular level through techniques such as Fourier-transform infrared spectroscopy (FTIR)

and nuclear magnetic resonance (NMR) spectroscopy would provide insight into the chemical interactions between petroleum contaminants and cementitious materials, which would help clarify the exact pathways in which hydrocarbons affect concrete hydration and the development of the microstructure (Kumaar & Mageswari, 2021).

The implications of the research on the study conclusions extend beyond academic research to the construction industry, mitigation agencies and environmental remediation. Another thing that construction practitioners can find worthy of their time is to learn that exposure to petroleum products can be beneficial to concrete properties and, consequently, may develop or explore new designs to maximize the design of concrete mix, curing techniques and/or quality control processes in a petroleum-polluted environment (Kleiner et al., 2021).

The study may also guide regulatory and industry sectors in their efforts to come up with or enhance engineering principles and standards regarding petroleum contamination in construction sites (Li et al., 2024). Further, they may be more efficient when measurement of concrete properties and performance was also included in regulatory frameworks which may result in regulation that was less prescriptive of concrete placements and methods with a chance to more sustainable construction all reduced environmental risks or hazards to the population and ensured protection of public safety and reliability of infrastructure systems (Xue et al., 2022).

Novel analytical methods are a phenomenal chance to analyze degradation into the molecular and microstructure of concrete caused by a petroleum pollutant, both of which are paramount to the association of petroleum products in the context of concrete characteristics (Brostrøm et al., 2020). Scanning the electron microscope (SEM) using energy-dispersive X-ray spectroscopy (EDS) can provide additional detail to morphological features and elemental compositions of petroleum product-contaminated concrete samples and visualize the distribution of hydrocarbons within the concrete sample (Ismagilov et al., 2021). SEM-EDS allowed the researchers to gain further evidence of contaminated concrete properties about the effects experienced on properties compared to the pore structure, hydration products, and aggregate-paste interfaces (Bahmani & Mostofinejad, 2022).

An analysis of the crystalline phases and mineralogical changes of the contaminated concrete are possible using the x-ray diffraction (XRD) analysis of the concrete samples (Huang et al., 2023). The XRD patterns of the contaminated and uncontaminated concrete samples will enable the researchers to assess the alterations in calcium silicate hydrate (C-S-H) and calcium hydroxide (CH) hydration products that are vital in the assessment of concrete strength and durability performance (De Matos et al., 2022). To obtain a more comprehensive picture of chemical bonds and functional groups that are found in petroleum-polluted concrete and the mechanism of interaction of hydrocarbons and cementitious materials, Fourier-transform infrared spectroscopy (FTIR) can be used.

Further studies of the concrete contaminated petroleum should focus on collaboration with other disciplines and conduct in-field studies that will verify the laboratory outcomes and monitor a range of performance parameters (Jalilifar & Sajedi, 2020). Along with formulating effective recommendations and guidelines on mitigation, it will be wise to create research and regional, or national, regulatory organization. Moreover, the studying and testing of new concepts on mitigation of contamination employing developments in materials science and engineering must consider the utilization of digital technologies and substitute cementitious substances. In addition, supporting educational and training initiatives on coordinating

construction firms and workforce development needs will improve the knowledge of construction professionals (Shirani et al., 2024). Lastly, collaboration of research efforts with their applicability and to develop more sustainable infrastructure regarding assessment of petroleum contaminated concrete is warranted.

6. Strengths and limitations

This study contributes to our understanding of the effects of petroleum products such as benzene, kerosene, and diesel on concrete compressive strength. These findings are essential for construction practice, regulatory agencies, and environmental remediation. It is an interdisciplinary study that examines the complexities of petroleum contaminants interacting with concrete properties.

Generalizability beyond Kuwait, lack of consideration for long-term durability, simplifications regarding contamination conditions, and lack of an expert understanding of how or why compressive strength was improved after exposure to petroleum products were limitations of this study.

7. Conclusion

In conclusion, this study confirms that all compressive strength values meet or exceed 100% of the designed concrete compressive strength of K-300, with curing in petroleum contaminants showing a significant positive impact on strength compared to water curing. The duration of water curing before contaminants immersion is like the results. Kerosene immersion particularly enhances compressive strength, surpassing control samples by an average of 18.90%. The significant positive impact of contaminants on concrete strength was found in this study. These findings underscore the importance of considering petroleum contamination in concrete construction, suggesting opportunities for optimizing mix designs and curing methods. Further research is needed to elucidate underlying mechanisms and explore practical applications, with implications for sustainable infrastructure development and environmental remediation efforts.

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Conflict of interest

The author(s) declares no conflict of interest.

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