Journal of Engineering and Sustainable Development
https://jeasd.uomustansiriyah.edu.iq/index.php/jeasd
https://doi.org/10.31272/jeasd.27.6.6

Vol. 27, No. 06, November 2023
ISSN 2520-0917

Original Research

A LABORATORY MODEL FOR THE TWO-PHASE FLOW CONTAMINANT TRANSIENT IN MULTI-POROUS MEDIA

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Received 28/01/2023 ***Revised 26/04/2023*** ***Accepted 09/05/2023***

Abstract: The environmental behavior of rock and oil pollutants in soil has long been a focus of environmental protection research. In this research, a laboratory model was established to study the oil pollutant transfer process in two stages. Two samples from porous media of sandy soil and agricultural soil (organic) were used with oil as a pollutant. The oil is pumped through a system consisting of two pipes with a length of 4 m and a diameter of 0.07 m. Each pipe is assigned to a specific type of soil. The results showed that the organic soil needs a long time for the pollutants to travel over greater distances, while the sandy soil showed its ability to absorb and drain the pollutants and get rid of them faster. However, it was also found that both soils contain a small percentage of the pollutant after the water washing process, which lasts for more than (5 hours). The remaining oil percentage is estimated at about (0.1 ml), which is a very small percentage, and it is possible to get rid of it by increasing the washing time. It was found that the physical properties of the soil such as permeability and porosity have a significant effect on slowing down the speed of the pollutant and its transmission through the porous medium.

Keywords: *Immiscible liquids; kerosene; migration oil in soil; multiphase flow; oil-water mixing in soil*

1. Introduction

Immiscible two-phase flow in porous media occurs when two immiscible fluids compete for the same pore space [1]. It is a challenging engineering process to model multiphase flow in porous media. Agriculture, geotechnical engineering, hydrogeology, biotechnology, medical engineering, and petroleum engineering are just a few of its many disciplines. Air and water movement in soil; gas, oil, and saltwater in crushed stone; blood and solid solutions in tissue; chemical solutions in porous plastic; and ink soaked in paper are all examples of multiphase motion in porous media that demand expert knowledge in their respective domains [2]. Research into porous media aims to characterize the two-phase immiscible flow at chain sizes, i.e., at scales where the porous medium may be considered a continuum. Accelerating progress in our knowledge of two-phase immiscible flow results from technological breakthroughs in experimental methods and a rise in computing capacity [3]. The characteristics of multiphase and single-phase flows are vastly different for many reasons. These include viscosity differences between fluids, capillary forces at the interface, testability, and system geometry. Drainage is the flow that occurs when a non-wetting liquid displaces a wetting liquid, while absorption is the reverse phenomenon. When one fluid replaces another, high-viscosity fluid shows a stable displacement front. In contrast, low-

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viscosity fluid displaces high-viscosity fluid in a porous medium during drainage, resulting in a wide range of finger patterns [4]. The system can reach a steady state after an initial transient subsides by continually injecting both fluids into the porous medium. It is shown that in the capillary-dominated mode, the equilibrium two-phase flow rate deviates from the linear Darcy law. In contrast, it was delivered to rely power-law-like on the overall pressure decrease [5]. To date, studies of dynamic effects continue continuously on a continuous scale using experimental [6], theoretical [7], and numerical methods on a constant scale. Diamantopoulos and Durner [8]. In petroleum engineering, more attention is paid to oil-water / gas systems in deep and narrow reservoirs. In addition to continuous-scale studies, their work briefly considers microscale models of physical pore networks [9], numerical models of pore networks, and computational fluid dynamics (CFD) simulations [10-15].

Diamantopoulos and Durner's [16] Conducted a study of dynamic non-equilibrium factors in soil water flow which were thorough and sufficient in soil science and hydrology. Their studies were published almost ten and twenty years ago. Thus, they did not consider any advancement relevant to our research purpose in the intervening time. In addition, Li et al. [8] briefly summarized the most current review without providing any more contexts, concentrating on the dynamic effects of the ultra-low permeability confined reservoir. Consequently, there is a lack of a state-of-the-art evaluation, especially in geotechnics. Several decades ago, geotechnics introduced unsaturated soil studies to Agriculture, which greatly enriched our understanding of how water seeps through and is retained by the soil. The geomechanics was later improved by studying unsaturated soil hydrology, particularly in shear strength, effective stress, and deformation [17-20]. Unsaturated soil mechanics relied on studying unsaturated soil hydrology, but geotechnics seldom incorporated new results from soil hydrology, such as the dynamic consequences of transient seepage.

Unsaturated soil and deep reservoirs are only two examples of geological materials whose hydro-mechanical behavior is analyzed in geotechnics. Soil hydrology developments need a shift from the equilibrium state of transient seepage flow to a non-equilibrium state. In addition, Bordoni et al. [19] and Tian et al. [20] have recently identified more substantial dynamic impacts in low permeable reservoirs and natural slopes, respectively [20]. In light of this, it is plausible that considering dynamic non-equilibrium effects, which are often ignored in geotechnics, may lead to a deeper comprehension of the factors that contribute to unsaturated soil suction and shear strength decrease. In addition, it will help with the temporal predictions of geohazards (such as shallow slope failure, dam failure, etc.) caused by excessive rainfall and floods. Reservoir geotechnics may also be benefit from more accurate estimates of deep reservoir production achieved by incorporating dynamic impacts into the planning and execution of reservoir development projects [9].

Based on the concerns above, this research aims to examine the migration process of one of the most prevalent insoluble pollutants in nature, oil, via its transmission in various porous media and to determine the adsorption, migration, and breakdown processes. Pollutants' ability to travel through oil is influenced by how many other contaminants, soil types, and qualities they encounter along the distance.

The consistency of cohesive soil depends to a large extent on the structure of soil particles which may be arranged in two systems; dispersed or flocculated. The presence of salts or acids between the soil particles will alter the arrangement of particles by affecting the attractive and repulsive forces[21]. Oil contaminant is possible to travel in a planar diffusion motion with the flow of water or to migrate to the deep soil layer rather quickly, but the fraction adsorbed on the particles does not move much as long as the soil layer is not damaged. For petroleum pollutants, gravity plays a significant role in allowing them to travel parallel to the soil's depth, whereas capillary force is primarily responsible for movement in the transverse direction.

The movement of particles is caused mainly by capillary force, while the transport of petroleum contaminants along the direction of soil depth is primarily influenced by gravity. The particles' absorption capacity is low. There are not a ton of petroleum pollutants already in the soil, but the soil will wash some of them deeper and speed up their adsorption. However, given enough time, hydraulics, gravity, diffusion, and mixing will cause these contaminants to evolve into a more stable state [22].

In general, hydrodynamic thrust and surface oiling are both enhanced by increasing the water's surface. Penetration fronts might approach the water table if oil contaminants spread through the soil and pollute it further.

Significant transverse migration and diffusion of oil pollutants will be seen in capillary zones close to the water table. Increases in this direction of growth will be most noticeable perpendicular to the water table and groundwater flow path [23].

3. Material and Method

3.1 Laboratory Model

The transport of contaminants through porous media, their adsorption, and their subsequent filtration or washing are all processes that can be studied in detail using a laboratory setup dedicated to porous media. The system consists of two polyethylene (PE) pipes, each 4 m long and 8 cm in diameter. All pipes are displayed on an iron stand 1.5 meters high. In addition to the pipes, there are three plastic tanks in the system. One tank for storing oil before transferring it to the pipes with a capacity of 90 liters is placed at the beginning of the physical Model. The second tank has a capacity of 250 liters; it is also of 250 liters is also at the front of the physical model and is used to pump water into the Pipes. The third tank is with a capacity of 250 liters; it is placed at the end of the system to collect oil and water after leaving the pipes. As shown in Fig. 1, 2, and 3, each tube has holes evenly spaced 50 cm apart, with a hole diameter of 1 cm, and each tube is equipped with a small tube of 3 cm for collecting samples and measuring pressure. A cotton filter was placed at the beginning of these openings to prevent leakage of soil with the water coming out of these openings.

Figure 1. Main polyethylene pipe.

Figure 2. Laboratory model.

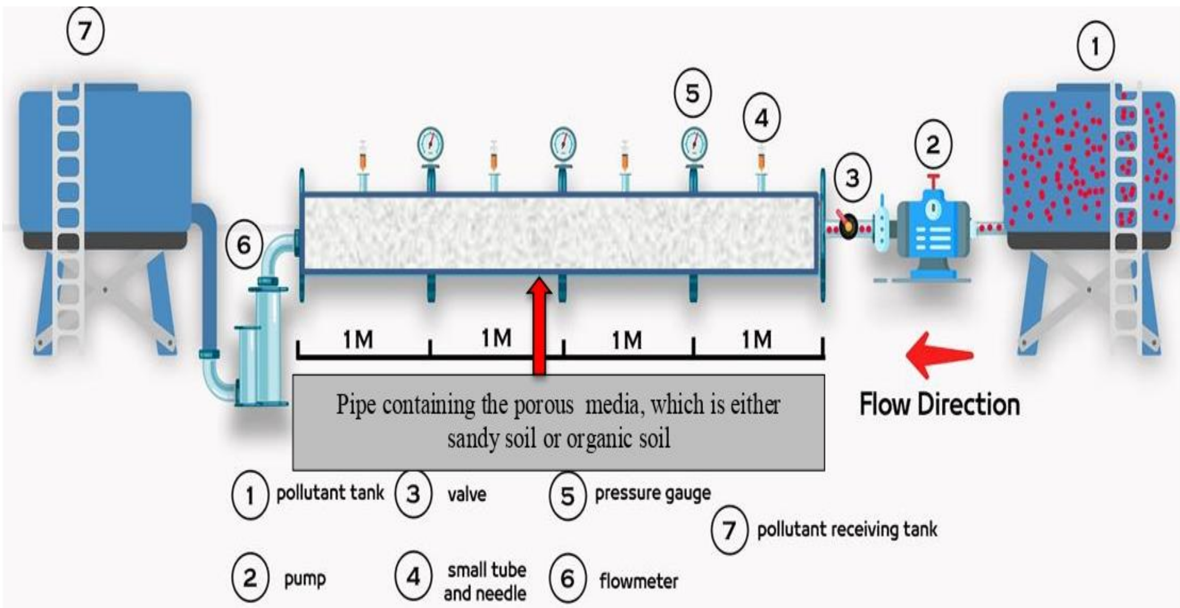

Figure 3. General system representation of the physical model.

3.2 Pollutant Tank

Oil is considered light if its density is low. On the other hand, it is classified as heavy if its density is large. Density is measured according to the specific density scale, according to the American Petroleum Institute, and it has a mathematical formula for calculating the specific density. According to it, oil is classified as "light" if its value is greater than 31.10, "average" at values between 22.30 and 31.10, and "heavy" when its API density is less than 22.30 [24]. In the experiment, kerosene was used because it is lighter, has a lower density, easier to flow into the soil and it does not cause blockages in the soil or problems in the laboratory system

More than 200 liters of oil were consumed due to filtration, wastage of oil, and other process problems. Several pumping experiments were conducted to obtain more accurate results for each type of soil, see Fig.4.

Figure 4. Pollutant tank.

3.3 Porous Media

Two distinct kinds of soil make up the porous medium. Sandy soil is the first type, consisting of sand with gradations ranging from 9.52 millimeters to 0.074 millimeters. The second soil type is agricultural soil, consisting of an equal mixture of sandy soil, alluvial clay soil, and organic soil, represented by peat moss soil with gradations ranging from 2.0 millimeters to 0.074 millimeters. These percentages were then mass-produced to be sieve-analyzed at the Central Soil Laboratory. The two types of medium carried out the required laboratory tests, which included sieve analysis, porosity, bulk density, and permeability.

3.4 Experimental work

In the beginning, the soil was stuffed into the two pipes so that each pipe contained one type of the two mediums. The mediums were stacked with a hand-made tool inside each pipe so that no voids were formed between the soil particles, thus impeding the flow and absorption of pollutants (see Fig. 5). After it was confirmed that the soil was well pressurized, water was pumped into the models for an adequate period until the porous medium was saturated. Water began to exit from the pipe's ends into the collection tank placed at the end of each pipe. Then, the water pumping was stopped, and the pollutant began to be pumped (pollution stage). Samples were taken along the pipes for certain distances and at different times. After making sure that the oil reaches the last point and begins to be collected in the external tank, the pumping of the pollutant is stopped and returned to the water pumping stage (washing stage). At this stage, the samples continued to be withdrawn at different times along the pipeline. Pollutant levels were gradually measured at all points, and discharge was calculated as a percentage of total discharge.

Figure 5. Filling and compacted process.

4. Results and Discussion

4.1 Results of Permeability, porosity, and bulk density

Laboratory experiments were performed for bulk density, porosity, and falling head permeability tests. These soil properties were essential properties of the porous medium. Porosity was evaluated for all soil types to see how it affects soil washing and oil loss from the soil. The rate at which a soil solution or water moves through soil particles depends on porosity. This affects how quickly oil is lost from the soil by making the water flow through the soil larger and faster.

In contrast, when the porosity is low, water moves slowly, lengthening the bonding time between water and soil particles. As a result, the pollutant's likelihood of losing its concentration is higher than the likelihood of adhering to the soil. Table 1 lists the results of the permeability**,** porosity, and bulk density for the two pours media Fig. 6 and Fig.7 show the permeability measurement model and sieve analysis results of the two used media.

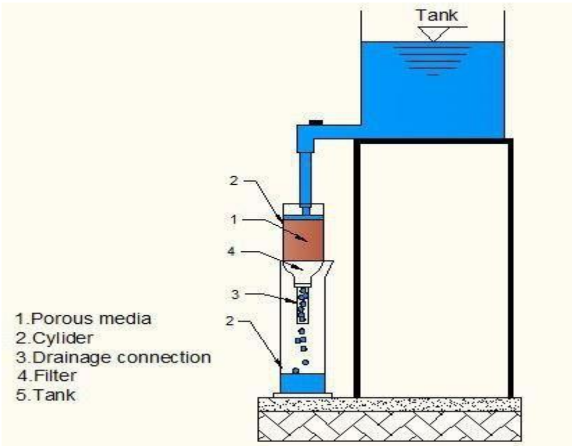

Figure 6. Permeability Measurement Model

Table 1. Results experiments of soil.

Properties	Mediums	
	Medium 1 Sandy soil	**Medium 2 Organic soil**
Permeability (m/s)	2.07E-05	2.48E-05
porosity	0.35	0.25
Bulk density (g/cm^3)	1.59	1.52

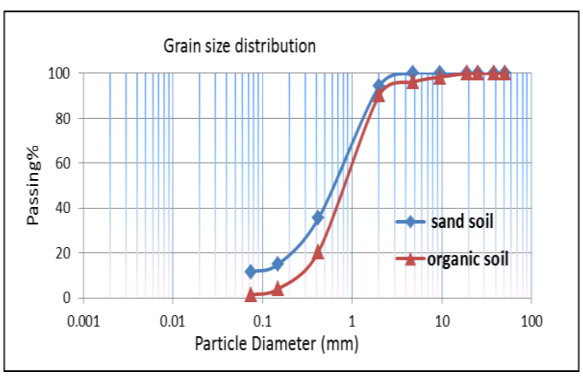

Figure 7. Sieving analysis results of the two media.

4.2 Physical Model Results

Water pumping continued through the pipes until the soils were perfectly moistened. Then, the water pumping was stopped, and the oil started being pumped into the two pipes. The system operation continued for a period ranging from 14 to 18 hours, which included the soil wetting stage, pollutant pumping stage, and washing stage. The results were obtained at the pumping stage. The pollutant concentrations at various points along the pipe showed that the speed of pollutant transmission in organic soil is slower than in sandy soil. This slow transmission is due to the difference in soil porosity, transmission rate, and absorption. However, it was later found that the transmission speed slows down and becomes equal with increasing distance in both soils, either in the washing stage, which is to stop pumping pollutants and start pumping water directly to wash the soil and begin losing the pollutant. The results revealed that the washing speed and the loss of pollutants in sandy soil were faster than in organic soil. The process of withdrawing samples from the porous media was carried out over time utilizing a needle inserted in the center of the tubes through the openings installed along the tubes at known distances. After that, the samples were emptied through small graduated cylinders as shown in Fig. 8 which represents the process of withdrawing and calculating samples, and then finding the percentage of oil in each sample by using the following formula:

$$Oil\ percentage = \frac{volume\ of\ oil}{total\ volume\ (oil + water)} * 100\%$$

4.2.1 Contamination stage

The contamination stage is when the oil begins to be pumped into the system after the soil is saturated with water. It continued until the oil pumping stopped, and the water was pumped again. Fig. 8 shows the results of the percentage oil ratio along the pipe during the contamination stage for organic soil. Fig. (9,10) shows the results of the organic and sandy soils.

Figure 8. Withdrawal of the pollutant from the soil

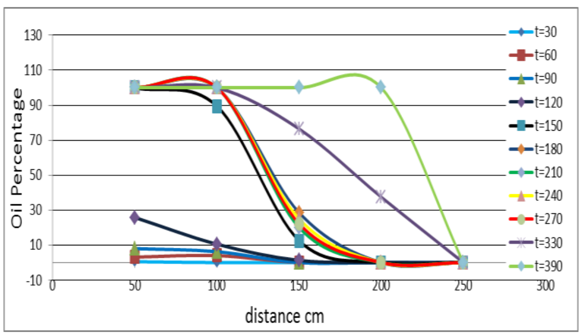

Figure 9. Percentage oil in organic soil after pumping oil (contamination stage).

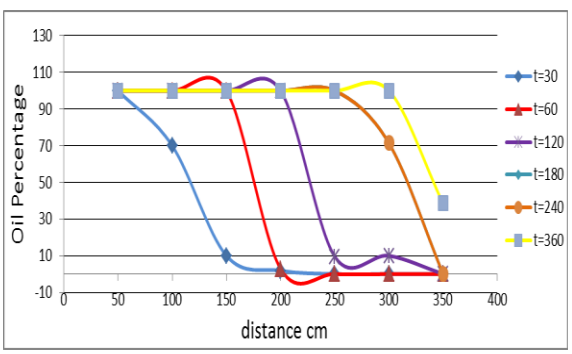

Figure 10. Percentage of oil in sand soil after pumping oil (contamination stage)

From the results mentioned above, it is clear that it takes longer for pollutants to reach the first sampling points in organic soils than in sandy soils. Likewise, the transmission of the pollutant from one point to the next increases gradually in the organic soil as we go further into it and move away from the source of the pollutant. In comparison, the arrival time of the oil at points in the organic soil ranges between 1.5 and 3 hours. For the sandy soil, the time when the pollutants reach the first points close to the source of the pollutants is shorter, ranging between 15 and 45 minutes. This short time is due to the porosity, permeability, and flow velocity differences between the two media. In addition, it is due to the increase in soil compaction, the particles' proximity to each other, and the small distance between them. The small distances reduce the soil's permeability to the pollutant and slow the flow velocity with increasing soil depth.

Fig.11 to Fig.15 show how the results of both soils were the same but at different stages of contamination.

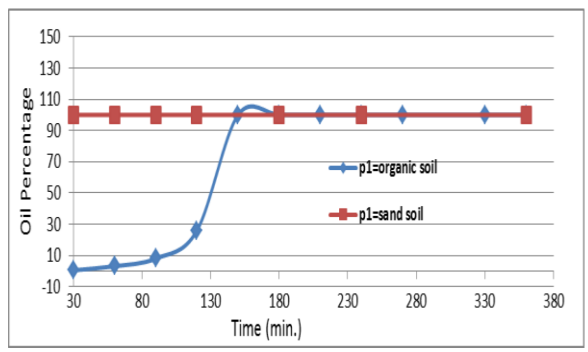

Figure 11. Percentage of oil in the organic and sandy soils at the first point (contamination stage)

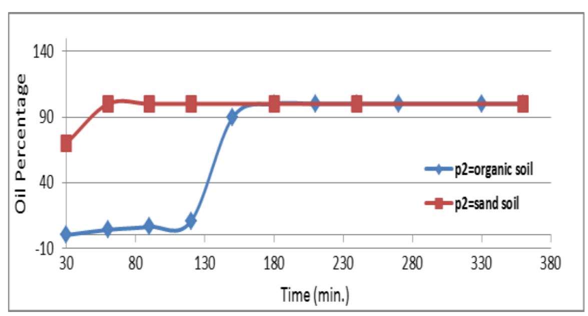

Figure 12. Percentage of oil in the organic and sandy soils at the second point (contamination stage)

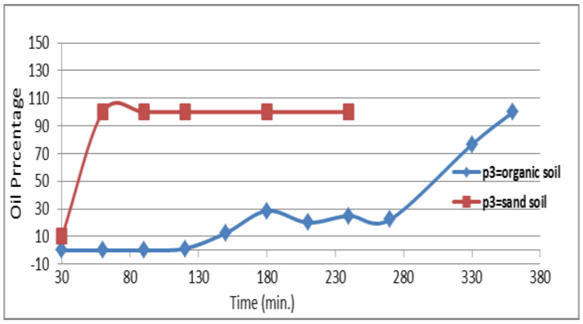

Figure 13. Percentage of oil in the organic and sandy soils at the third point (contamination stage)

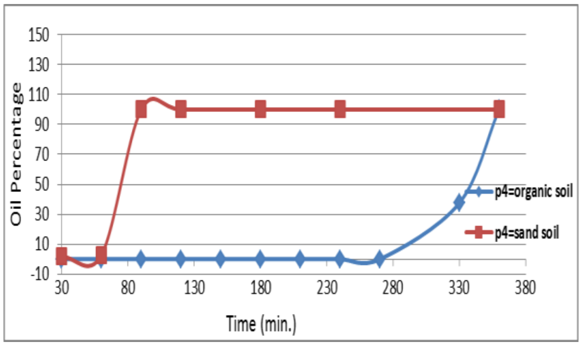

Figure 14. Percentage of oil in the organic and sandy soils at the fourth point (contamination stage)

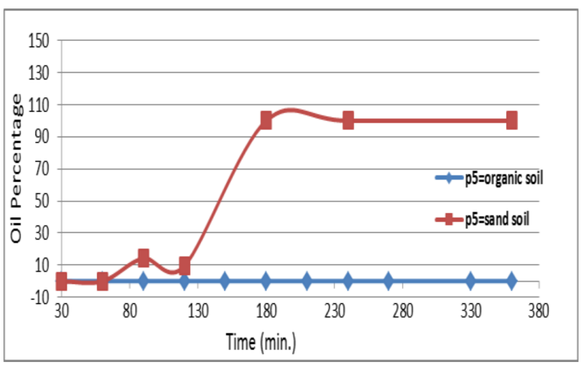

Figure 15. Percentage of oil in the organic and sandy soils at the fifth point (contamination stage)

4.2.2 Washing stage

The washing stage is when oil pumping stops and water pumping returns to the system again, as a representation of the end of the pollution period and the beginning of the treatment period. Fig. 16 shows the results of the percentage oil ratio along the pipe during the washing stage for organic soil, while Fig. 17 shows the results for sandy soil.

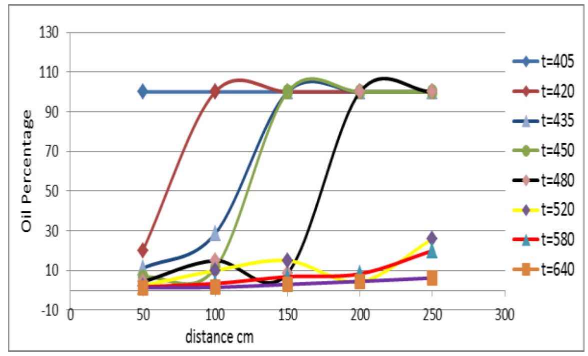

Figure 16. Percentage oil in organic soil after pumping water (washing stage).

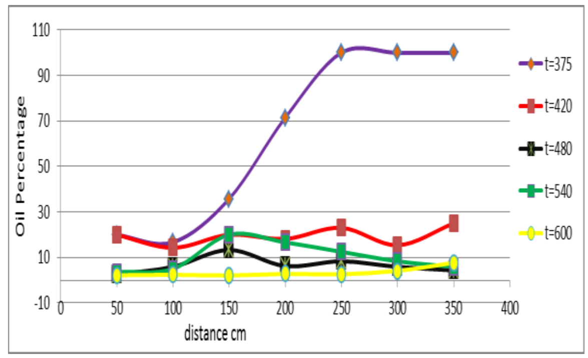

Figure 17. Percentage oil in sandy soil after pumping water (washing stage).

From the previous results, we note that the time for washing the soil and getting rid of the pollutants is faster in the sandy soil because of its smooth structure, light texture, and large grain size, which leads to the presence of openings or gaps that contribute to water leakage. Sandy soil takes a shorter time to wash, especially at the first points where the water reaches faster. The pollutant particles are gradually pushed into the collection basin and replaced by water particles. Fig. 18 to Fig. 22 compare results in both soils at different washing stages but at the same point.

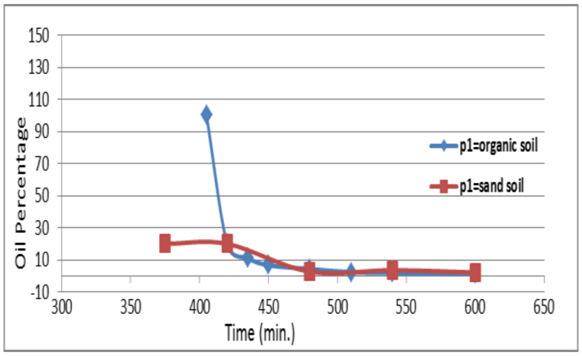

Figure 18. Percentage of oil in organic and sandy soil at the first point (washing stage)

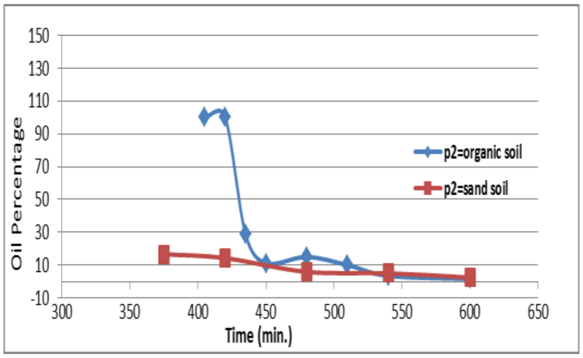

Figure 19. Percentage of oil in organic and sandy soil at the second point (washing stage)

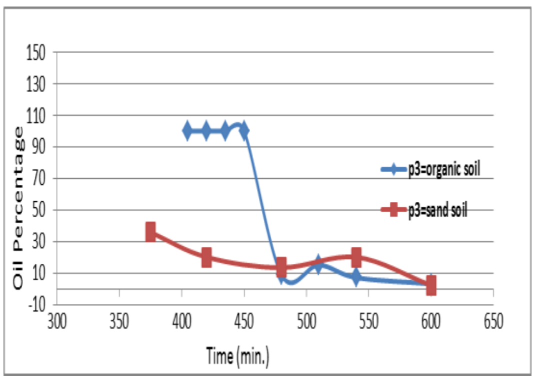

Figure 20. Percentage of oil in organic and sandy soil at the third point (washing stage)

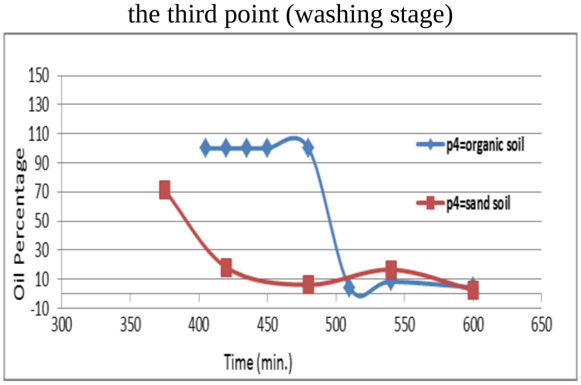

Figure 21. Percentage of oil in organic and sandy soil at the fourth point (washing stage)

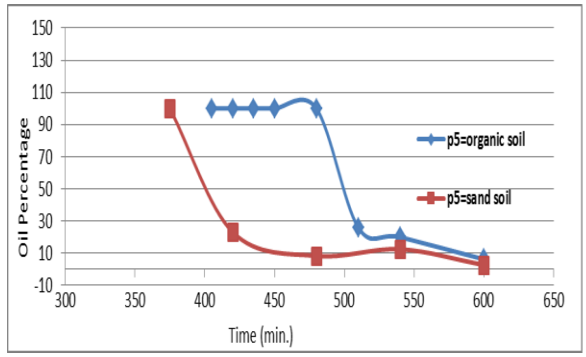

Figure 22. Percentage of oil in organic and sandy soil at the fifth point (washing stage)

Fig.23 to Fig.26 represent another results presentation for the contamination and washing stages for both soils but at each point.

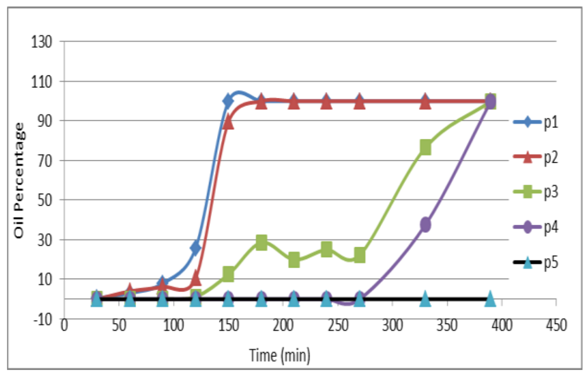

Figure 23. Percentage of oil in organic soil at each point in the contamination stage.

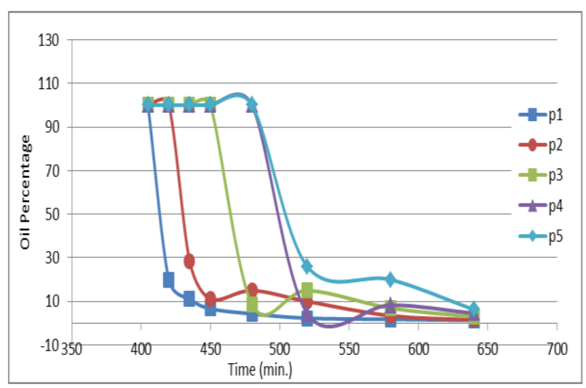

Figure 24. Percentage oil in organic soil at each point in the washing stage.

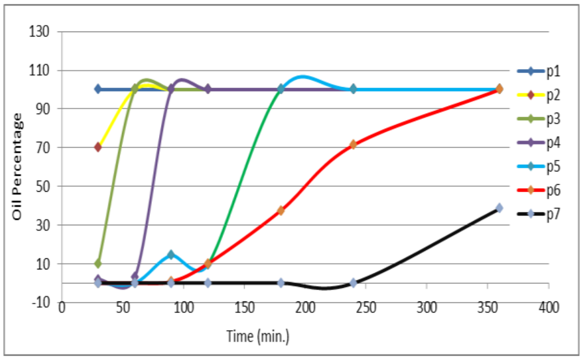

Figure 25. Percentage of oil in sandy soil at each point in the contamination stage.

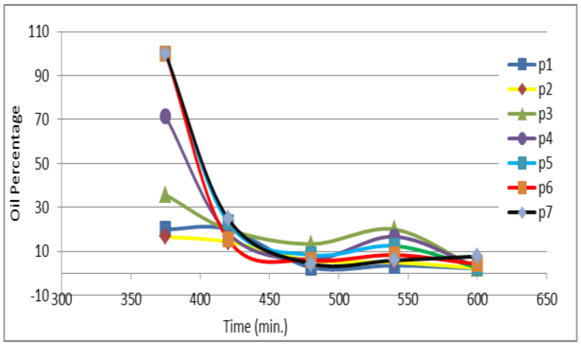

Figure 26. Percentage of oil in sandy soil at each point in the washing stage.

Fig.18 to 22 show the percentage of pollutants at each point. It gradually changes with time, whether in the pollution stage or even in the washing stage. The amount of pollutants gradually increases, and the percentage of water decreases at each point as the contamination stage changes. The opposite occurs in the washing stage. The water percentage increases with the decrease in pollution at each point over time.

5. Conclusions

Pollutant transmission in the soil, whether at the stage of contamination or leaching, depends mainly on the soil type, composition, and physical properties. These properties include porosity, permeability, grain gradation, and the closeness of the particles to each other, as the structure of the soil affects the speed of pollutants' transmission through it. The increase in the friction velocity leads to a loss in pollutant transmission speed. Thus, the speed of its flow through the porous medium decreases, and it needs a longer time to penetrate the soil. The process of pollution and leaching in sandy soil is faster because it is characterized by higher permeability and porosity than organic soil. The transmission speed of the pollutant is higher since the holes in sandy soil are mostly of the wide type due to the large size of their grains. As a result, they are suitable for drainage and aeration, unlike organic soils, which have narrow holes because their granules are small and precise, resulting in less drainage and aeration. The first withdrawal points close to the source of pollution contained a larger amount of oil than the next points, and practical experiments also showed that the lower the oil's weight and density, the faster its flow and transmission in the soil.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Zahraa Akram Thijeel is a master's student, and Sadiq Salman Muhsun is the thesis supervisor.

Acknowledgment

The authors would like to acknowledge colleagues from our various Universities of affiliation and research centers for their help and advice during this review.

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