Interfacial interactions between hydrocarbon liquids and solid surfaces used in mechanical oil spill recovery

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Abstract

The goal of this research was to study wetting and adhesion processes between various petroleum products and solid surfaces. When a liquid interacts with a solid surface, wetting, spreading and adhesion processes determine its behavior. These processes are of great importance for understanding oil spill response as well as oil spill behavior on land and in near shore environments, and oil extraction from the reservoir rock. The current study aimed at analyzing oil affinity and adhesion to surfaces used in the mechanical recovery of oil spills. A number of crude oils and petroleum products were tested with the surface materials that are used or may potentially be used to recover oil spills. Through the study of contact angles and recovered mass, it was found that the behavior of the oils at the solid surface is largely determined by the roughness of the solid. For smooth solids, contact angle hysteresis is a good indicator of the ability of the solid to retain oil. For rougher elastomers, the advancing contact angle can be used to predict wetting and adhesion processes between oil and solid. This study showed that oleophilic elastomers (e.g., Neoprene and Hypalon) have higher oil recovery potential than smooth polymers.

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1. Introduction

Mechanical recovery is the most commonly used oil spill response technique [1]. This technique physically removes oil from the water surface. The main disadvantage of mechanical cleanup is the recovery rate. When employed on a large scale, it may be very time consuming and expensive. It may require a large amount of personnel and equipment, and every additional hour of cleanup time can significantly increase the cost of recovery. A more efficient recovery device can thus reduce the cost significantly and reduce the risk of oil reaching the shoreline.

An adhesion (oleophilic) skimmer is one of the most common types of mechanical recovery equipment. It is based on the adhesion of oil to the skimmer surface. The rotating surface lifts the oil out of the water to an oil removal device (e.g., scraper, roller, etc.). The adhesion surface is the most critical element of the recovery equipment as it largely determines its efficiency. Aluminum and common use plastics are currently being used on recovery units. This original material selection was not based on the adhesion properties, but rather on price, availability and historical practice. This research aimed to study the interfacial processes between various oils and solid surfaces in order to identify methods and criteria that would help to select the most efficient material for the recovery unit.

Contact angles of liquids on solid surfaces are widely used to predict wetting and adhesion properties through calculation of the solid–vapor surface tension. This method has been discussed in the earlier literature [2–6]. When a drop of liquid is deposited on the solid surface, a contact angle \( \theta \) is formed. The affinity of a solid for a liquid increases with decreasing \( \theta \). The size of this angle is determined by the equilibrium of surface forces including liquid surface tension (\( \gamma_{lv} \)), solid surface energy (\( \gamma_{sv} \)) and surface tension at liquid–solid interface (\( \gamma_{sl} \)). This relationship is described by Young’s equation [7]:

\[
\gamma_{lv} \cos \theta = \gamma_{sv} - \gamma_{sl}.
\]

The theory of contact angle measurements is based on the equilibrium of an axisymmetric sessile drop on a flat, hori-
horizontal, smooth, homogeneous, isotropic, and rigid solid. Static contact angle devices measure a contact angle at a single point of contact between liquid and solid. In practice, a static contact angle does not give a correct representation of the wetting and spreading processes. Using the Wilhelmy plate technique and measuring a dynamic contact angle provides a more accurate description of the dynamic behavior of a liquid on a solid. The dynamic contact angle (DCA) measures the contact angle over a large surface area, not a single point of contact. This eliminates the effect of local compositional and textural imperfections on the value of the measured angle. The DCA analyzer operates by holding a plate in a fixed vertical position attached to a microbalance and moving a test liquid contained in a beaker at constant rate up and down past the plate. The microbalance measures the force exerted by the moving contact line in the advancing and receding directions.

The forces acting on the plate consist of the weight of the plate, the buoyancy of the submerged part of the plate, and the surface tension of liquid in contact with the plate. This can be expressed as [8]

\[ F = (\rho_p l w t) g - (\rho_l h w t) g + 2(w + l) \gamma_l \cos \theta, \]

where \( F \) is the force measured by DCA, \( \rho_p \) is the density of plate, \( w \) is the width of plate, \( l \) is the length of plate, \( t \) is the thickness of plate, \( g \) is the acceleration due to gravity, \( \rho_l \) is the density of liquid, \( h \) is the length of submerged part, \( \gamma_l \) is the surface tension of liquid, and \( \theta \) is the contact angle between liquid and plate.

The first term in Eq. (2) is eliminated by zeroing the balance after the plate is attached to it. The second term can be neglected because the force exerted on the microbalance by the moving line, measured as the plate advances through the liquid, is extrapolated to find the force acting on the plate at the moment when only the lower edge of the solid is in contact with the liquid. At this point, the plate is not affected by buoyancy. The only force acting on the plate is the surface tension of the meniscus. This is illustrated in Fig. 1. For this case, Eq. (2) can be simplified to

\[ F = 2(w + l) \gamma_l \cos \theta. \]

Knowing the force \( (F) \) exerted by a meniscus on the plate and the surface tension of the liquid, the contact angle can be found by the following relationship:

\[ \cos \theta = F / 2(w + l) \gamma_l. \]

Equation (4) is also called the modified Young’s equation or Wilhelmy equation [9]. This equation assumes that the solid surface is smooth and nonporous.

The advancing angle captures the affinity between the liquid and solid surface; the smaller the angle, the higher the spreading. A 180° angle represents complete non-wetting, 0° angle represents complete wetting. When the test surface recedes from the liquid, the receding contact angle is measured. If the solid and liquid have a high affinity, a film of liquid remains on the surface, adding to the total weight recorded by the microbalance and affecting the measurement of the receding contact angle. For such cases, the receding angle is assumed to be 0° representing complete wetting. The difference between advancing and receding contact angles is the contact angle hysteresis. This parameter characterizes the ability of the solid surface to retain molecules of liquid during the receding phase, or adhesion.

This research aimed at studying the use of the dynamic contact angles and contact angle hysteresis to predict the recovery efficiency of various materials that can be used for oil spill cleanup with mechanical recovery units.

2. Materials

2.1. Solid surfaces

About 30 different materials, metals, polymers and elastomers, were evaluated during the preliminary phase of this study. The materials were screened for their oleophilicity, durability, and swelling rate. The swelling of the materials selected for further study was less than 3% by weight after being submerged 24 h in oil. It was observed that antistatic polyurethane and Teflon had a very low affinity for oil. A very uneven oil film remained on the surface of these materials once they were withdrawn from oil, leaving some parts of the surface oil-free. These two materials were removed from further study due to their low affinity for oil, since they are unlikely to be used on oleophilic skimmers. Some other elastomers, such as ethylene propylene diene methylene (EPDM) rubber had a high affinity for hydrocarbons, but exhibited significant swelling which would make them unusable for oil spill recovery. The following materials were selected for the detailed study based on their durability and oil recovery potential:

(1) Hard polymers and metals: stainless steel, aluminum, low density polyethylene (LDPE), polypropylene (PP).

(2) Elastomers: ozone resistant Hypalon rubber, styrene–butadiene rubber (SBR), epichlorohydrin rubber (ECH), Neoprene rubber.

Industrial grade materials were tested in this study, since they are likely to be used to manufacture oil spill response equipment in practice. All test polymers and metals were purchased from McMaster-Carr (P.O. Box 54960, Los Angeles, CA 90054-0960; http://www.mcmaster.com/) in sheets with a thickness of 1.6 mm and cut to equal test strips of 25 × 25 mm. An endmill was used to remove edges damaged by the shearing process. The roughness of the samples was measured with a Wyko Optical Profilometer (Wyko NT2000). The root-mean-square roughness (as measured at 50× magnification) of the
Fig. 2. Surface texture of different materials at 50× magnification. Left to right: neoprene, steel, and low density polyethylene.

<table>
<thead>
<tr>
<th>Material</th>
<th>Surface energy (mJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>45[^b]</td>
</tr>
<tr>
<td>Steel</td>
<td>41[^a]</td>
</tr>
<tr>
<td>Neoprene</td>
<td>38[^c]</td>
</tr>
<tr>
<td>Hypalon</td>
<td>37[^c]</td>
</tr>
<tr>
<td>Epichlorohydrin</td>
<td>35[^c]</td>
</tr>
<tr>
<td>Styrene–butadiene rubber</td>
<td>33[^c]</td>
</tr>
<tr>
<td>LD Polyethylene</td>
<td>31[^d]</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>29[^c]</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>32[^d]</td>
</tr>
<tr>
<td>Teflon</td>
<td>19[^d]</td>
</tr>
</tbody>
</table>

[^a] Radelczuk et al. [32].
[^d] Extrand [27].

The surface of the plastic samples was less than 100 nm. The root-mean-square roughness of elastomers was on the order of 100–2000 nm. Metals had a very specific surface structure (Fig. 2). The surface of steel was relatively smooth, but had some space between grain boundaries. These surface features were included into roughness measurements by the Wyko software, which led to an overestimated steel roughness. Although the surface texture of metals was similar to that of hard polymers, their surface roughness was estimated to be on the order of 500 nm. The surface energies of tested surfaces are presented in Table 1, based on literature values as indicated.

Prior to measuring contact angle or adhesion, all samples were (1) cleaned in warm water with liquid detergent, (2) rinsed in deionized water, (3) rinsed in ethanol, (4) rinsed with deionized water, (5) blow-dried using nitrogen, (6) placed in a sterile container, (7) left for 12 h in the temperature controlled room to achieve thermal equilibrium. Fresh oil samples and new test surfaces were used for each test. Samples were not reused except for steel and aluminum. Used metal samples were pre-cleaned using chloroform, followed by heptane and methylene chloride to remove all traces of oil. Then the metal test strips were subjected to the standard cleaning process described above.

2.2. Hydrocarbon liquids

HydroCal 300 (hydrotreated naphthenic medium grade lube stock), IFO-120 (Intermediate Fuel Oil), Cook’s Inlet and Pt. McIntyre (both are Alaskan crude oils) were used in this study. Various oils were used to determine the effect of chemical position, viscosity, surface tension, and weathering degree on oil spreading and adhesion properties. The crude oils were used fresh and weathered.

To obtain weathered fractions of the crude oils, Cook’s Inlet and Pt. McIntyre crudes were evaporated using a rotavapor (RE111, Buchi). The oil was heated using a water bath at 90 °C. Vacuum was applied to the system to facilitate removal of the lighter fractions and to transfer them into the condensation chamber. Lighter fractions were condensed in a glass container that was cooled down using refrigerated water (at 2 °C; closed cycle). A small part of the lighter fractions that was not condensed at 2 °C was trapped using a cold vapor trap cooled down to −110 °C in order to prevent air contamination and ensure complete mass balance. All vapor fractions condensed at this temperature.

To simulate weathered oils, each crude oil was heated in the evaporator and weighted every 30 min until 15% (±1%) loss of sample weight was observed. This weathered oil sample, which had lost 15% of the lighter fractions was then slowly cooled down and stored in a temperature controlled room in a sealed container, to be used in further studies.

2.3. Density, viscosity and surface tension of fresh and evaporated oils

All measurements were carried out in a temperature controlled room at either 25 or 15 °C (±1 °C). Oil density was measured using a standard Specific Gravity Bottle for viscous fluids according to ASTM D70 and D1429 [10,11]. Surface tension of the oils was measured using a dynamic contact angle (DCA) analyzer (Cahn Radian 315, Thermo Electron Corporation) using a Du Nouy ring. At least 5 measurements were performed to ensure the accuracy of the data. Oil viscosity was measured using a programmable viscometer (DV-II+ Pro, Brookfield). At least 3 measurements were performed to ensure the accuracy of the data. The properties of fresh and weathered oils are presented in Table 2.

The composition of crude oils with respect to their carbon, hydrogen and nitrogen content is presented in Table 3. The analysis was performed using an Organic Elemental Analyzer—CHN (CEC 440HA, Control Equipment Corp).

2.4. Research method

A dynamic contact angle (DCA) analyzer that utilizes the Wilhelmy plate technique (Cahn Radian 315, Thermo Electron
Table 2
Properties of fresh and weathered test oils

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Density (kg/m³)</th>
<th>Viscosity (mPa s)</th>
<th>Surface tension (mN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cook’s Inlet</td>
<td>862</td>
<td>847</td>
<td>9.6</td>
</tr>
<tr>
<td>Pt. McIntyre</td>
<td>886</td>
<td>871</td>
<td>24</td>
</tr>
<tr>
<td>HydroCal 300</td>
<td>921</td>
<td>905</td>
<td>342</td>
</tr>
<tr>
<td>IFO-120</td>
<td>965</td>
<td>949</td>
<td>1540</td>
</tr>
<tr>
<td>Weathered Cook’s Inlet 15% weight loss</td>
<td>898</td>
<td>882</td>
<td>32</td>
</tr>
<tr>
<td>Weathered Pt. McIntyre 15% weight loss</td>
<td>923</td>
<td>907</td>
<td>95</td>
</tr>
</tbody>
</table>

Table 3
Elemental analysis of test oils

<table>
<thead>
<tr>
<th>Sample</th>
<th>Weight percent</th>
<th>C/N ratio</th>
<th>C/H ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cook’s Inlet fresh</td>
<td>75.50</td>
<td>10.59</td>
<td>0.60</td>
</tr>
<tr>
<td>Weathered Cook’s Inlet</td>
<td>80.77</td>
<td>11.40</td>
<td>0.54</td>
</tr>
<tr>
<td>Pt. McIntyre fresh</td>
<td>77.56</td>
<td>11.82</td>
<td>0.55</td>
</tr>
<tr>
<td>Weathered Pt. McIntyre</td>
<td>82.52</td>
<td>11.34</td>
<td>0.45</td>
</tr>
<tr>
<td>IFO-120</td>
<td>85.71</td>
<td>10.71</td>
<td>0.73</td>
</tr>
<tr>
<td>HydroCal 300</td>
<td>87.00</td>
<td>12.44</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Corporation) was used for these tests. This equipment is capable of measuring with high accuracy adhesion-related parameters such as dynamic contact angle, surface tension, surface free energy, and amount of adhered oil. The DCA has been successfully used by other researchers studying wetting and adhesion properties of various surfaces [12,13]. All the experiments were carried out in a temperature-controlled room at 25 ± 1 °C to simulate warm conditions and at 15 ± 1 °C to simulate an oil spill in temperate regions.

In addition to measuring the dynamic contact angle, the DCA was used to measure the amount of oil adhered to the sample surface after it was withdrawn from the beaker with the test liquid. Oil recovery was measured as the weight of adhered oil per unit surface area. This pick-up technique was used in two previous studies of oil adhesion to various materials by Jokuty [14] and Liukkonen [15]. The DCA automates this method and achieves more consistent and reliable results.

The contact angle measurement process can be summarized as follows:

The size of the test surface (≈ 25 × 25 × 1.6 mm) is measured using an electronic micrometer with a precision of ±0.1 mm. Then, the sample is placed in the test chamber above the test liquid (oil or water), making sure that its lower surface is parallel to the liquid surface. The sample is automatically submerged into the test liquid until 20 mm are submerged, and then the test surface is withdrawn at the same speed. An advancing rate of 80 μm/s (default speed recommended by the DCA manufacturer) was used for smooth metal and polymeric samples. A 20 μm/s advancing rate was used for rougher elastomers as it takes a longer time for the contact line to equilibrate when it is moving along rough surfaces.

The DCA measures the force exerted on the test surface throughout the entire process: as it enters the liquid, is submerged and is then retracted. The software calculates the corresponding advancing and receding angles as well as the amount of residual oil on the surface at the end of the experiment. Five to ten measurements were made for each test liquid–test surface combination to ensure the accuracy of the data. Only the advancing contact angle and the amount of recovered mass calculated by DCA was considered in the analysis. The receding contact angle was considered to be equal to 0° in all cases, since an oil film remained on the surface after it was withdrawn from the oil, indicating complete wetting.

3. Results and discussion

Fig. 3 shows the correlation between the dimensionless capillary number and the advancing contact angle for tested materials. The capillary number, Ca, characterizes the relative effect of viscous forces and surface tension acting across an interface between a liquid and a gas, and it is calculated using the liquid’s viscosity (μ), surface tension (σ), and advancing velocity (V) [3,16]:

\[ Ca = \frac{\mu V}{\sigma}. \]  

A low capillary number implies that viscous forces are relatively unimportant in comparison to capillary forces. This dimensionless parameter has been used by a number of researchers studying the relative effect of surface tension, viscosity and advancing velocity, on the dynamic contact angle [16–21].

Using the capillary number, one can compare the results obtained for all tested oils at all speeds and distinguish the effect of material type on the advancing contact angle. The four upper lines in Fig. 3 correspond to the elastomers, which have relatively higher roughness compared to the smoother polymers and metals. Although they are presented on the same figure for comparison, the results can be meaningfully compared only within the same roughness group. For both groups, smooth and rougher materials, the lower the line is the higher affinity the material has toward the tested petroleum products as indicated by the lower value of an advancing contact angle. In the elastomers group, petroleum products have higher affinity for Neoprene and Hypalon and lesser affinity for styrene–butadiene rubber and Epichlorohydrin. The hard polymers and metals tested had smooth surfaces and a high affinity for oil. These materials were wetted completely by oil under quasi-static conditions as indicated by a zero contact angle at low capillary numbers.

Good [2] and Mittal [3,4] predicted that a given liquid will spread more readily on a surface with higher surface energy. This trend is observed in the case of the rough elastomers (Fig. 3 and Table 1). Neoprene and Hypalon have higher surface energies than styrene–butadiene rubber or Epichlorohydrin. A similar trend was observed for aluminum, steel and polypropylene in the group of smooth materials. However, the affinity of the tested oils to polyethylene was higher than it would be predicted from a surface energy analysis. This can be explained by the similarity in chemical composition between polyethylene and light nonpolar oil components. Oil molecules absorb onto the
polyethylene surface forming a film preceding the bulk of the oil in the moving contact line. This was observed as an increase of the test surface mass detected by the DCA in the vicinity of the liquid surface just before contact. Formation of the film changes the surface properties of the solid in the vicinity of the contact line, facilitating oil spreading and reducing the measured value of the advancing contact angle. The formation of the molecular region in the closest proximity of the three-phase contact line and the effect of this precursor film on the dynamic contact angle was discussed by Karakashev et al. [22], Pérez [23], and Voinov [24].

Hoffman [25] predicted that \( \theta \) should be proportional to \( \text{Ca}^{1/3} \). However, the experimental results indicated that for hard polymers and metals \( \theta \propto \text{Ca}^{0.2} \) \((r = 0.87)\), while for the elastomers \( \theta \propto \text{Ca}^{0.18} \) \((r = 0.82)\). Thus, a weaker relationship was observed between \( \theta \) and \( \text{Ca} \), possibly due to surface impurities despite the efforts to clean the surfaces before the tests.

Because of the sensitivity of contact angle measurements to the surface roughness of the test materials, data for hard polymers and metals were analyzed separately from the data for elastomers. The relation between the cosine of advancing angle and the recovered oil mass by elastomers, normalized by the test surface area is shown in Fig. 4. Every line on this figure represents values of contact angles for the 4 test elastomers and test oil at a given temperature. Every point represents a contact angle value for each elastomer. For these materials, the amount of recovered oil increases as the cosine of the contact angle approaches unity, indicating complete wetting. These experiments indicated that Hypalon and Neoprene have the largest oil recovery potential, while Epichlorohydrin had the lowest oil recovery potential among the oleophilic elastomers tested.

Fig. 4 also demonstrates the effect of oil properties on the recovery efficiency of various materials. More viscous IFO-120 formed a thicker film on the test surface yielding a higher recovered mass compared to other oils and the recovery was a stronger function of the type of material. HydroCal had a much weaker correlation between the material type and the amount of recovered oil than other oils. Relative to other oils, the viscosity of Pt. McIntyre oil did not change significantly between 15 and 25 °C, resulting in very similar behavior at the two temperatures. For the three oils tested, the contact angle measured at 25 °C was smaller than at 15 °C due to decreased viscosity and increased spreading rates at the higher temperature.
It was observed that for the least viscous oil tested (Pt. McIntyre), the amount of recovered mass was unusually high for the materials characterized by small contact angles. This was due to the ability of this light oil to penetrate deep into the surface texture of rough oleophilic elastomers and be retained there after withdrawal. Due to their higher viscosities, IFO-120 and HydroCal did not penetrate into the surface texture of the elastomers and had much smaller effective contact area with the surface. The effective contact area between liquids with low viscosity and rough surfaces can vary significantly between tests, affecting the value of the estimated contact angle and making a comparison between materials more difficult. In the case of rough materials and low viscosity test liquids, local roughness may have a greater effect on the contact angle than the chemical properties of the material. Therefore, rough materials should not be used for contact angle measurements with liquids of low viscosities. Thus, other light oils (weathered Pt. McIntyre, fresh and weathered Cook’s Inlet) were not tested with elastomers.

The relation between contact angle hysteresis and recovered mass for five plastics and metals is presented in Fig. 5. The total mass recovered by a test surface was normalized by the sample area in contact with oil to account for minor difference in sample sizes. Every line in this figure represents values of contact angle hysteresis for the 5 test surfaces and test oil at a given temperature. Every point represents a hysteresis value for each individual type of hard polymer or metal.

For hard polymers and metals (Fig. 5), the high affinity of oil for a surface, as indicated by a small contact angle, does not directly translate into an ability of the material to retain oil after it has been withdrawn from the oil. For smooth polymers and metals, larger advancing angles corresponded to the materials that recovered the largest amount of oil after the advancing and receding steps. The contact angle hysteresis was used to describe the recovery potential of hard plastics and metals. The recovery potential of these materials increases with increasing hysteresis. The contact angle hysteresis has been used by a number of researchers to characterize the wetting processes between a solid and a liquid [26–31].

In general, polypropylene and aluminum were found to retain more oil in a water-free environment. While polyethylene had the highest affinity to the tested oils indicated by small contact angles, it recovered the lowest amount of oil in most cases. This result may change in the presence of water.

Fig. 5 shows that the amount of recovered oil is strongly affected by oil properties. More dense and viscous oils (IFO and HydroCal) form a thicker film on the test surface leading to higher recovered mass. Less viscous oils form thinner films which yield a lower recovered mass. As oil weathers and becomes more viscous, it forms thicker films and the total recovered mass increases. A temperature increase causes a decrease in the contact angle hysteresis and oil viscosity, resulting in a formation of thinner oil films and a decrease in the amount of oil recovered.

The observed variability in the contact angle measurements were most likely caused by the imperfections in the surfaces of the industrially manufactured polymers, variations in roughness and errors in the measurement of sample weight. The variation in weight measurements were about 1–13% (reaching 20% for oleophobic materials such as Teflon and antistatic polyurethane), while variations in contact angle measurements were less than 3%.

Overall, oleophilic elastomers recovered higher amounts of oil because of their surface texture than hard polymers and metals. Fig. 6 represents the amount of oil recovered by polypropylene, low density polyethylene, Hypalon and Neoprene plotted against oil viscosity. In all cases, the two elastomers recovered higher amounts of oil than the hard polymers. This is due to the fact that these two elastomers have a high affinity for oil combined with higher surface roughness, which allows them to retain higher amounts of oil. These elastomers were especially effective in retaining oils with low viscosity. While Hypalon seemed to be slightly more efficient for oils with low viscosity, Neoprene was more efficient on viscous oils. Although similar to polypropylene, low density polyethylene recovered the least amount of oil in most cases.

Fig. 6 also shows the importance of oil viscosity on the amount of recovered oil. The amount of recovered oil increased with increasing viscosity for polyethylene and polypropylene, for all tested oils. Recovery by elastomers seemed to be unaffected by the increase in oil viscosity until it reached 170 mPa s.
At higher viscosities, an increase of recovered mass with increasing viscosity was observed.

4. Conclusions

In this work we studied the affinity of various oils to a number of hard polymers, metals and elastomers as well as the ability of these materials to retain an oil film after withdrawal from the test liquid. It was found that for hard polymers and metals a high affinity of a material to oil, indicated by a smaller advancing contact angle, does not necessarily translate into an increased amount of oil retained. Contact angle hysteresis can be used to describe the ability of these materials to retain oil. For elastomers, the advancing contact angle was a good indicator of their oil retention potential. Better spreading of oil on the elastomers allows oil to penetrate into the rough elastomeric texture and be retained there by surface features after withdrawal. This study found that oleophilic elastomers such as Neoprene and Hypalon have a high potential for oil spill recovery due to their high oleophilicity and their ability to retain oil at the surface after withdrawal from the liquid. A full scale oil recovery study is required to determine the relation between the recovery efficiency and wetting properties of materials in the presence of water.

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