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# Report

## Ultra Low Sulphur Fuel Oils (ULSFOs) interactions with shoreline

Fate and behaviour of new generation fuel oils on sediments and bedrock, and effectiveness of shoreline washing agent and flushing.

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# Report

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Fate and behaviour on sediments and bedrock, and effectiveness of methods of action

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## ABSTRACT

The main objective of this project was to obtain a better documentation of the fate and behaviour of Ultra Low Sulphur Fuel Oils (ULSFOs) in contact with shorelines in the event of an acute oil spill from ship traffic, and whether measures as flushing and use of a Shoreline Washing Agent (SWA) can increase the washout efficiency and further collection. Four different ULSFOs were used for this study; MGO 250 °C+, WRG, HDME 50 and ULSFO, both as unemulsified and emulsified. The study was performed at a test temperature of 5 °C.

To study the penetration and remobilization of ULSFOs on shoreline sediment, an experimental column system simulating tidal variation, was used. The fuel oils showed a great variance in penetration depth, the low viscous oils MGO and WRG (< ~1 000 mPa*s) penetrating down to ~ 50 cm at most. For the high wax and viscous oils HDME 50 and ULSFO (5 000 – 60 000 mPa*s), having pour points (12 and 24 °C) above test temperature, almost all the oil was remobilized during the first high tide, incorporating sediments from the substrate surface in the process. To study the washout of fuel oils from bedrock by wave energy, a shoreline simulation system was used. The lowest viscous oil MGO showed > 90 % effectiveness, while for WRG, use of SWA was needed to reach the same degree of effectiveness. The more waxy and viscous oils HDME 50 and ULSFO showed low degree of washout, even with use of SWA. To study the effectiveness of flushing, a flushing robot was used. Flushing pressures of 4, 15, 30 and 45 bar, at temperatures of 5 and 45 °C was applied, depending on the physicochemical properties of the oil. Also here the oils showed a great variance, the low viscous oils showing effectiveness of 80 % already at 5 °C and 15 bar, while for the more challenging oils (HDME 50 unemulsfied and ULSFO unemulsified and emulsified) high temperature flushing in combination with high flushing pressure showed to be an important factor for the effectiveness. The high flushing temperature showed to dominate the effect of SWA.

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# 1 Summary on English and *Norwegian*

As new requirements for the emission of sulphur from exhaust gases from ship traffic came into force, several new fuel products have entered the market, helping to reduce the sulphur content and thus reduce air pollution from ship traffic. This project was initiated to map the new generation Ultra Low Sulphur Fuel Oils – ULSFOs (having < 0.10 % Sulphur content, allowed in SECA areas) penetration and remobilization in and from shoreline sediment, as well as natural and manually washout by wave energy and pressure washing from solid substrates, with and without use of a Shoreline Washing Agent (SWA). Four different ULSFOs were chosen for this study; MGO 250 °C+, WRG, HDME 50 and the specific fuel oil called ULSFO. The fuel oils were both used as unemulsified and emulsified. The emulsified oils represent fuel oils that has been subjected for emulsification at sea for up to two to five days before stranding, depending on the weather conditions and sea state. The study was performed at a test temperature of 5 °C.

To study the penetration and remobilization of ULSFOs on shoreline sediment, an experimental sediment column system, simulating tidal variation, was used. The selected fuel oils showed a great variance in penetration depth, the low viscous oils MGO and WRG (< ~1 000 mPa*s), having low contents of wax and asphaltenes, penetrating down to ~50 cm at most. For the high wax and viscous oils HDME 50 and ULSFO (5 000 – 60 000 mPa*s), having pour points (12 and 24 °C) above the test temperature, almost all the oil was remobilized during the first high tide, incorporating 1-5 % sediments from the substrate surface in the process.

To study the washout of fuel oils from bedrock by wave energy, a shoreline simulation system was used. The washout effectiveness showed also in this study to be dependent on the viscosity and wax content of the oils. The lowest viscous oil MGO showed > 90 % effectiveness, while for WRG, use of SWA was needed to reach the same degree of effectiveness. The more waxy and viscous oils HDME 50 and ULSFO showed low degree of washout (< 25 %), even with use of SWA. Additional flushing may therefore be needed to enhance the washout of these kinds of fuel oils.

To study the effectiveness of high pressure washing for fuel oil removal, a flushing robot was used. A flushing pressure of 4, 15, 30 and 45 bar, at temperatures of 5 and 45 °C was applied, depending on the physicochemical properties of the oil. The low viscous oils showed an effectiveness of > 80 % already at 5 °C and 15 bar, use of SWA showed therefore to be redundant. Emulsified HDME 50 showed a good response by flushing already at 5 °C, 15 bars, while the unemulsified HDME 50, showed to be more challenging, needing high temperature flushing at 30 bar to reach effectiveness > 80 %. The even more challenging oil, ULSFO, needed to be treated at high flushing temperature (45 °C) and high pressure (45 bar) to achieve effectiveness between 60-70 %. The high flushing temperature showed to dominate the effect of SWA.

*Etter at strengere krav relatert til utslipp av svovel fra eksosgasser fra skipstrafikk tredde i kraft, har flere nye drivstofftyper kommet ut på markedet som et bidrag til å redusere svovelinnholdet og dermed redusere luftforurensningen fra skipstrafikken. Dette prosjektet ble initiert for å kartlegge den nye generasjonen Ultra Low Sulphurl Fuel Oils – ULSFO (< 0.10% svovelinnhold, tillatt i SECA områder) penetrasjon og remobilisering i og fra strandsediment, samt naturlig og manuell utvasking ved bølgeenergi, og spyling fra faste substrater, med og uten bruk av strandvaskemiddel. Fire forskjellige ULSFOer ble brukt i denne studien; MGO 250 °C+, WRG, HDME 50 og ULSFO, både som vannfri og som emulgert. De emulgerte oljene representerer oljer som har vært på sjøen opptil to til fem dager før stranding. Studien ble utført ved en testtemperatur på 5 °C.*

*For å studere penetrasjon og remobilisering av ULSFOer i og fra strandsediment, ble det brukt et sedimentkolonnesystem som simulerer tidevannsvariasjon. De valgte drivstofftypene viste stor varians i penetrasjonsdybde. De lavviskøse oljene MGO og WRG (< ~ 1 000 mPa*s), som hadde lavt innhold av voks og asfaltener, penetrerte ned til ~ 50 cm på det meste. For de mer høyviskøse og voksrike oljene HDME 50 og ULSFO (5 000 – 60 000 mPa*s), med stivnepunkt* (12 and 24 °C) *over testtemperatur, ble mesteparten av oljen remobilisert ved første høyvann. Den remobiliserte oljen/emulsjonen inkorporerte 1-5 % sedimenter fra substratoverflaten i prosessen.*

*For å studere utvasking av ULSFOer fra fast substrat ved bølgeenergi, ble et simulert strandsystem brukt. Viskositeten og voksinnholdet i oljene viste seg også her å være av betydning. Den mest lavviskøse oljen MGO viste > 90 % effektivitet, mens for WRG var det nødvendig med bruk av strandvaskemiddel for å oppnå tilsvarende grad av effektivitet. De mer høyviskøse oljene HDME 50 and ULSFO viste liten utvaskingsgrad (< 25 %) ved bølgeenergi, selv ved bruk av strandvaskemiddel. Det vil derfor kunne være nødvendig med manuell spyling for slike drivstofftyper.*

*For å studere effektiviteten av spyling på ULSFOer, ble det brukt en vaskerobot ved spyletrykk på 4, 15, 30 og 45 bar, ved temperaturer på 5 og 45 °C, avhengig av oljens fysiske og kjemiske egenskaper. De lavviskøse oljene viste en effektivitet på > 80 % allerede ved 5 °C og 15 bar, bruk av strandvaskemiddel viste deg derfor å være overflødig. Emulgert HDME 50 viste god respons ved spyling allerede ved 5 °C, 15 bar, mens den uemulgerte HDME 50 viste seg å være mer utfordrende. Spyling ved høy temperatur og 30 bar var for denne nødvendig for å oppnå effektivitet > 80%. Den enda mer utfordrende oljen ULSFO, måtte behandles ved høy spyletemperatur (45 °C) og høyt trykk (45 bar) for å oppnå effektivitet mellom 60-70%. Den høye spyletemperaturen viste seg å dominere effekten av strandvaskemiddel.*

## 2 Introduction and background

There are increasingly strict requirements for what ship traffic is allowed to emit from exhaust gases into the air. Particularly within Sulphur Emission Control Areas (SECA) the requirements for sulphur emissions have been tightened, setting a limit of < 0.10 % Sulphur content in fuel oils (called Ultra Low Sulphur Fuel Oils - ULSFO). This requirement came into force in 2015 and applies to e.g. The Baltic Sea and the North Sea up to 62 degrees latitude. A global limit of 0.5 % sulphur content came into force in 2020 (called Very Low Sulphur Fuel oils - VLSFO). With this, several new products have entered the market, helping to reduce the sulphur content in the exhaust gases and thus reduce air pollution from ship traffic (Marine Fuel Oil Advisory, 2019).

In addition, a ban for both use and carrying of heavy fuel oil in the nature reserves on the east side and in the three large national parks on the west side of Svalbard was introduced in 2007 and 2009. In January 2020, similar regulations were also introduced in the three national parks Sør-Spitsbergen, Forland and Nordvest-Spitsbergen. This was implemented to minimize potential environmental damage in case of an accidental oil spill. A proposal from the Ministry of Climate and Environment to legislate a similar requirement for motor traffic at sea for the entire territorial waters on Svalbard is under consultation and will possibly enter into force from 2022.

In recent years, SINTEF has carried out several projects for the Norwegian Coastal Administration where the weathering properties of the new generation fuels types in an event of an acute discharges at sea have been mapped. This has included physicochemical characterization of weathering properties, dispersibility natural/ dispersant enhanced, ignitability and toxicity testing;

- *Weathering Properties and Toxicity of Marine Fuel Oils* (Hellstrøm, 2017)
- *Characterization of Low Sulfur Fuel Oils (LSFO) – A new generation of marine fuel oils* (Sørheim, et al., 2020)

In the period 2018-2020, studies on bioremediation of the new generation of fuel have also been performed;

- *Biodegradation of spilled fuel oil in Norwegian Marine Environments – A literature Review (Øksenvåg et al., 2018)*
- *Biodegradation of marine fuels in beach sediments at low temperature – A laboratory study* (Nordtug, et al., 2019)
- *Bioremediation of oil on shoreline in Arctic conditions – A laboratory study (Faksness, et.al., 2021)*

Up to now, no studies has been conducted studying the interaction of the new fuel oil types on shoreline sediments and bedrocks, thus a large knowledge gap related to the fate and behaviour of low sulphur fuel oils during stranding and the potential for mitigating measures was identified. This project was initiated to map the ULSFOs penetration and remobilization in and from shoreline sediment, as well as natural washout by wave energy and effectiveness of manual flushing from solid substrates, with and without use of a shoreline washing agent.

# 3 Materials and methods

## 3.1 Fuel types and weathering of the oils

To show the great variance in the fate and behaviour of low sulphur fuel oils on shorelines, four different types of ULSFOs were selected, reflecting a broad spectre within the ISO categorization 8217, see Appendix A. These are; Marine Gas Oil (MGO), Wide Range Gas oil (WRG), Heavy Distillate Marine ECA 50 (Emission Commission Control Area) (HDME 50) and a specific oil called Ultra Low Sulphur Fuel Oil (ULSFO), see Table 3-1. To meet the requirements of new regulations for air pollution, WRGs and to some degree also MGO, can change from year to year. New batches of these fuel types were therefore sent by Kystverket from ExxonMobil in Bergen (Norway) to SINTEF January 2021. HDME 50 and ULSFO have been used in previous studies performed at SINTEF, see Table 3-1. Batches of these oils was therefore already in place at SINTEFS oil storage.

MGO is categorized as a DMA, according to the ISO categorization 8217. MGO-qualities are often used in fishing boats and supply vessels, and for helping engines aboard larger vessels using residual bunker fuel oil as bunker fuel for their main engines. WRG is a heavy distillate and is commonly used by ships along the Norwegian coast and in the northern areas. WRG is further used by larger fishing boats, supply vessels, general cargo ships and Hurtigruta (Norwegian Coastal Express). WRG originate from the ST-1 Swedish refinery and MGO is from the Esso refinery at Slagentangen in Norway.

The new generation of LSFO represent a wide range of properties and do not fit under one specific grade according to the ISO standard. These new fuel types have properties that make in useable in heavy bunker fuel engines, while at the same time having the low sulphur content associated with lighter diesel qualities. Having properties like a hybrid of diesel and heavy fuel oil, these new oils are commonly called Hybrid fuel oils. Presently, several different hybrid fuel oils are available commercially, two of these have been studied in this project; HDME 50 and Shell ULSFO. Both hybrid fuel oils are produced in the Netherlands. The ULSFO is produced by Shell and HDME 50 is produced by ExxonMobil. Hybrid fuel oils are commonly used on larger vessels such as container ships, ro-ro ships and general cargo ships in traffic within SECA areas (Kystverket, 2017). HDME 50 is a heavy distillate cut, less variation in properties is expected for this type of fuel oil compared to fuel oils that are mixed from different cuts, such as the ULSFO. ULSFO contains a residual fraction of heavy compounds that has been mixed into the distillate. Figure 3-1 Show a picture of the four ULSFO oils used in this study.

Figure 3-1 The selected fuel oils for the shoreline studies; MGO, WRG, HDME 50 and ULSFO.

The four ULSFOs used in this project is given in Table 3-1, showing their respective sulphur content, IMO resolution and ISO category 8217. The *IMO resolution MEPC.320(74), 2019 entitled Guidelines for Consistent Implementation of the 0.50 % Sulphur Limit under MARPOL Annex VI*, provides definitions of different marine fuels primarily based on the sulphur content.

**Table 3-1 Fuel types used in this project, their sulphur content, categorisation, and reference to previous projects.**

| Fuel type | SINTEF ID | Sulphur Content | IMO Resolution | ISO category 8217 | Reference to previous projects supported by NCA |
|---|---|---|---|---|---|
| **MGO (Diesel) ESSO, Norway** | 2021-360 | *0.044 (< 500 ppm, 0.05 %) | ULSFO-DM | DMA | - |
| **WRG (MSD) ST-1, Sweden** | 2021-361 | *0.042 (< 500 ppm, 0.05 %) | ULSFO-RM | RMA | - |
| **HDME 50 ExxonMobil, The Netherlands** | 2016-0231 | < 1000 ppm, 0.1 % | ULSFO-RM | RMB | Hellstrøm, 2017<br>Hellstrøm et al., 2017<br>Faksness and Altin, 2017 |
| **ULSFO Shell, The Netherlands** | 2019-11170 | ≤ 1000 ppm, 0.1 % | ULSFO-RM | RMD | Delivered to SINTEF by NCA.<br>Used in NOFO OPV 2018.<br>Sørheim et al., 2020 |

** Data from ExxonMobil, Bergen*

Oil spilled at sea will be subjected for several weathering processes as evaporation (lighter compound evaporates), emulsification (water droplets are incorporated in the oil phase) and photo-oxidation (changing the physical and chemical properties due to sun exposure). These weathering processes will change the physicochemical properties of the oil, being of great importance for the weathered oils fate and behaviour on the shoreline and further effectiveness of remediation processes. The oils were therefore both studies unemulsified and emulsified to simulate as realistic spill scenarios as possible. MGO was also evaporated due to its hight content of light weight components.

### 3.1.1 Evaporation

Evaporation is one of the natural processes that support the removal of spilled oil from the sea surface. The evaporation process starts immediately after the oil is spilled, and the evaporation rate decreases exponentially throughout the duration of the oil spill. The evaporated amount depends on the chemical composition of the oil in addition to the prevailing weather conditions, sea temperature and oil film thickness.

The MGO has a high content (25-30 %) of light weigh components, leaving an evaporated residue of 250 °C+ just after some hours on the sea surface. The MGO was therefore evaporated using the standardized evaporation procedure described in Stiver and Mackay (1984), performing a simple one-step distillation to vapour temperature of 250 °C. In contrast, WRG, HDME 50 and ULSFO have very low contents (< 5 %) of volatiles below 250 °C (see gas-chromatogram in Figure 3-3) and was therefore not evaporated before use in the shoreline studies.

### 3.1.2 Emulsification

The formation of water-in-oil emulsions significantly affects the behaviour and clean-up of oil spilled at sea. As a result of emulsification, the total emulsion volume may increase to as much as six times the original spilled oil volume depending on the properties of the oil. The formation of w/o emulsions also contributes to keeping oil on the sea surface. A w/o emulsion normally has a higher viscosity than the parent crude oil, so the emulsification process will therefore retard/delay evaporation and the natural dispersion process. The minimum criterion for the formation of w/o emulsions is the presence of breaking waves (i.e. a wind speed of >5 m/s). Nonetheless, a slow water uptake can also take place during calmer weather.

Emulsification with 50 % water in oil (wio) was applied on 250 °C+ residue of MGO and unevaporated (i.e., fresh) WRG, HDME 50 and ULSFO, representing fuel oils that has been subjected for emulsification at sea for up to two to five days before stranding, depending on the sea state. The emulsification was performed using the rotating cylinders method as detailed in Hokstad et al. 1993.

Bench-scale laboratory testing using rotating cylinders have previously shown that neither MGO nor its weathered residue (250 °C+) had significant emulsifying properties (Sørheim and Daling, 2015). The lack of emulsifying properties are due to the low content of emulsion stabilizing components, such as asphaltenes and wax. Using the new batch of MGO, 50 % wio were formed, but at rest, the oil started to settle out. Hence the emulsions formed were very unstable and had to be handled with care. The WRG formed 50 % emulsion, HDME 50 43-45 % emulsion, while ULSFO only incorporated 9-20 % seawater. The emulsified fuel oils are shown in Figure 3-2.

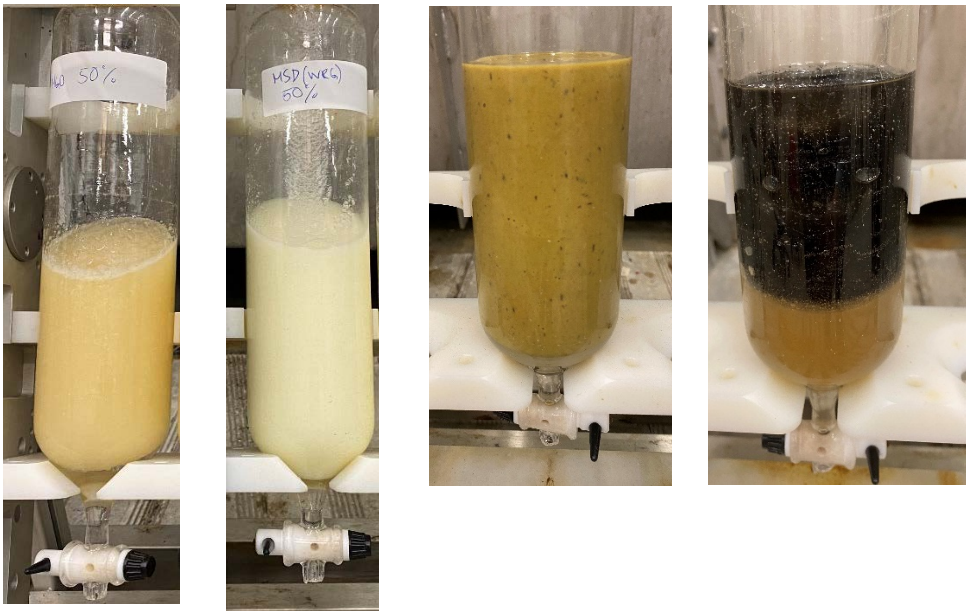


**Figure 3-2 Pictures of the emulsified fuel oils. From left to right: MGO 250 °C+ (50 % wio), WRG (50 % wio), HDME 50 (43-46 % wio) and ULSFO (9-20 % wio). The black patches in the HDME 50 emulsion are likely unemulsified oil.**

### 3.1.3 True boiling point (TBP) curve

The True Boiling Point (TBP), or distillation curve, is obtained by measuring the vapour temperature as a function of the amount of oil distilled. The boiling point of a chemical component depends on its vapour pressure, which is a function of its molecular weight and chemical structure. Hence, the distillation curve is an indicator of the relative amount of different chemical components and shows the relative distribution of volatile and heavier components in the oil.

The TBP curves of WRG 2021, ULSFO and HDME 50 were analysed by use of Simulated Distillation of marine fuel oils (SimDist) in accordance to ASTM D7169 at Intertek, UK. Boiling point values for MGO was retrieved from the Certificate of Quality sheet delivered from ExxonMobil. The distillation curves for the selected oils are shown in Figure 3-3. For comparison, the TBP curve for the 2014 MGO batch, WRG batches from 2014 and 2017, and the TBPs of two traditional heavy fuel oil (IFO 180 and 380) are included in the figure.

As shown in Figure 3-3, the boiling point curves for the two batches of MGO (2021 and 2014) are quite similar. In contrast the WRG show to have changed slightly over the years reflected in a broader range in boiling points for the 2021 batch compared to the 2014 and 2017 batch. HDME 50 consists of components having higher boiling points than WRG and MGO. The boiling points of ULSFO show a quite wide range in components, as it is mix of distillate and a residual fraction of heavier compounds. The traditional HFOs (IFO 180 and IFO 380) have even lower TBPs than the ULSFO, indicating an even higher content of heavy compounds. HFOs have typically an asphaltenic content of 5 - 10 %. Oils containing high amounts of asphaltenes have shown to be quite adhesive to shoreline substrate, as experienced from incidents like Rockness and Full City and as reported in Øksenvåg et al., 2010.

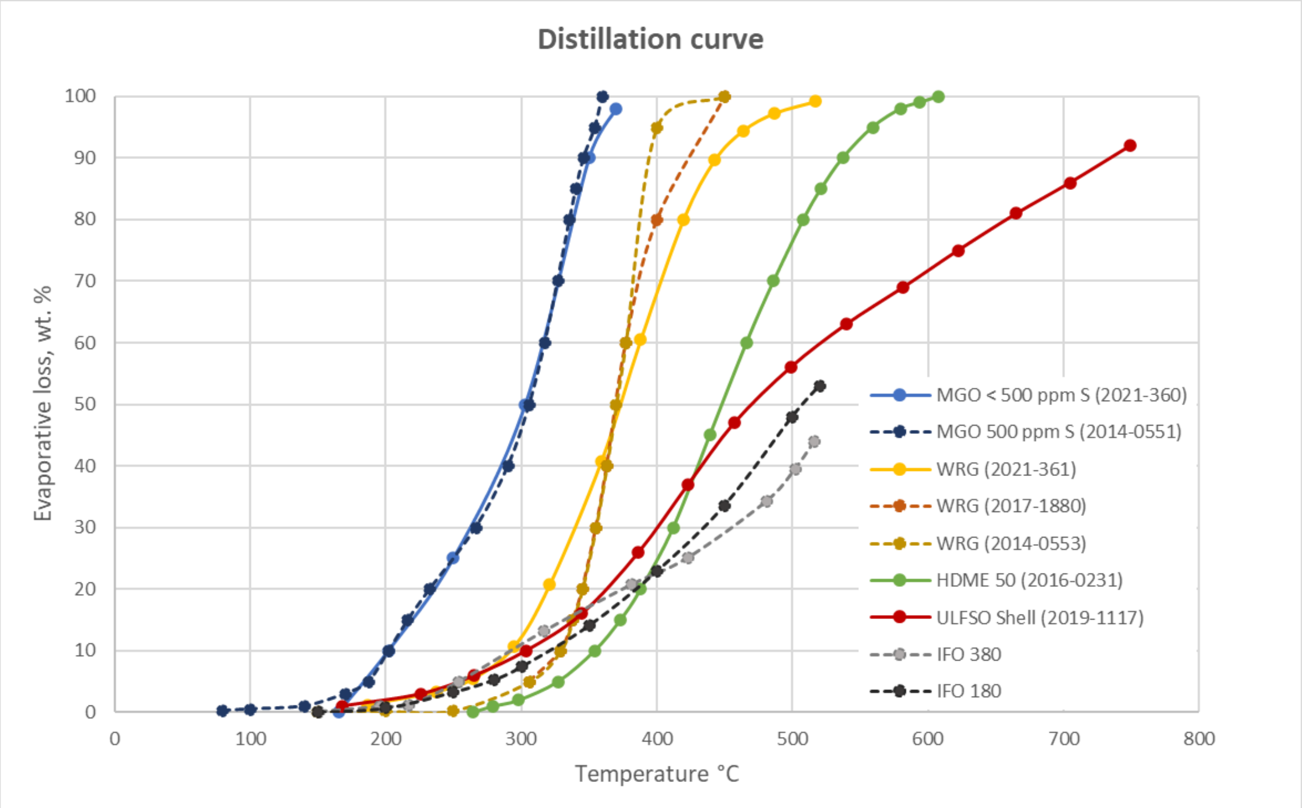
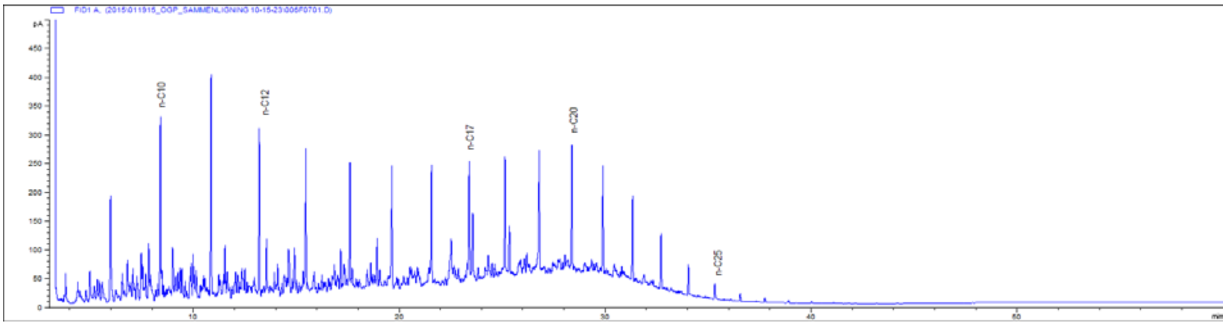


**Figure 3-3 Distillation curve for the selected ULSFOs, previous batches of MGO (2014) and WRG (2014 and 2017) and two traditional fuel oils (IFO 380 and IFO 180), added for comparison.**

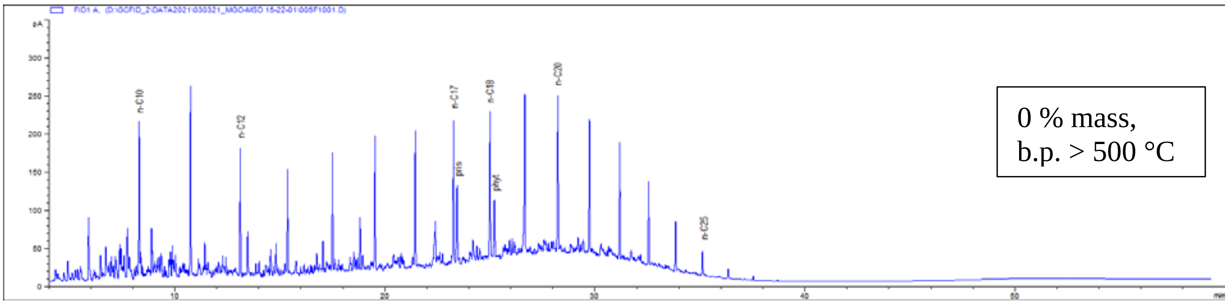
### 3.1.4 Gas Chromatographic analyses (GC-FID)

Gas chromatograms show the n-alkanes (paraffins) as systematic narrow peaks. The first peaks in the chromatogram represent components with the lowest boiling points. Some of the more complex components, such as resins and naphthenes, shown as a broad and poorly defined bump below the sharp peaks, are often described as Unresolved Complex Mixture (UCM). The waxes (n/iso paraffins) are often found from nC20 and above. Heavier compounds such as asphaltenes (> nC40) are not possible to analyse with this technique. The GC-chromatograms of the fresh and 250 °C+ residue of MGO (2021), the fresh oils of WRG (2021), HDME 50 and ULSFO are shown in Figure 3-4. MGO from 2014 and WRG 2014 and 2017 are added for comparison. The oils exhibit different hydrocarbon profiles reflecting variations in the physico-chemical properties. The chromatograms show that the new MGO batch (2021), are similar to the 2014 MGO batch. The new batch of WRG (2021), being a heavy distillate cut, has changed a bit showing less UCM compared to the 2014 and 2017 batch. The HDME 50 is a wide range gas oil made from an even heavier distillation cut than the WRG, reflected in n-alkanes in the range between C15-C35. HDME 50 has a large UCM (Unresolved Complex Mixture) hump indicating a high content of resins and naphthenes. ULSFO, however, contains a residual fraction of heavy compounds that has been mixed into the distillate (the residual fraction is not visible in the chromatograms), reflected in the broad range of components in the chromatogram (reflected in n-alkanes ranging between nC9-nC40).

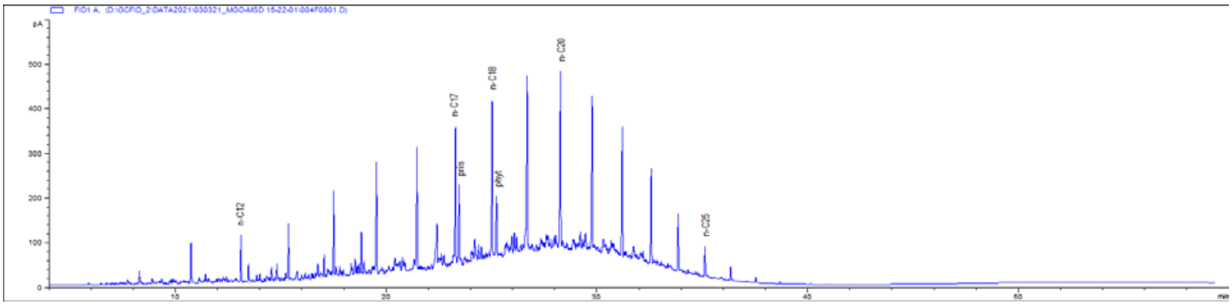
By combining the TBP and the GC-FID analyses, the percent (%) of mass above nC36 (boiling point, b.p.> 500 °C), being none-chromatographable compounds by GC-analysis, was estimated and marked with vertical lines. ULSFO Shell 2019 has a mass of components above 500 °C of 43 %, which are almost in the same level as the traditional IFO 180/380 (52-60 % mass).



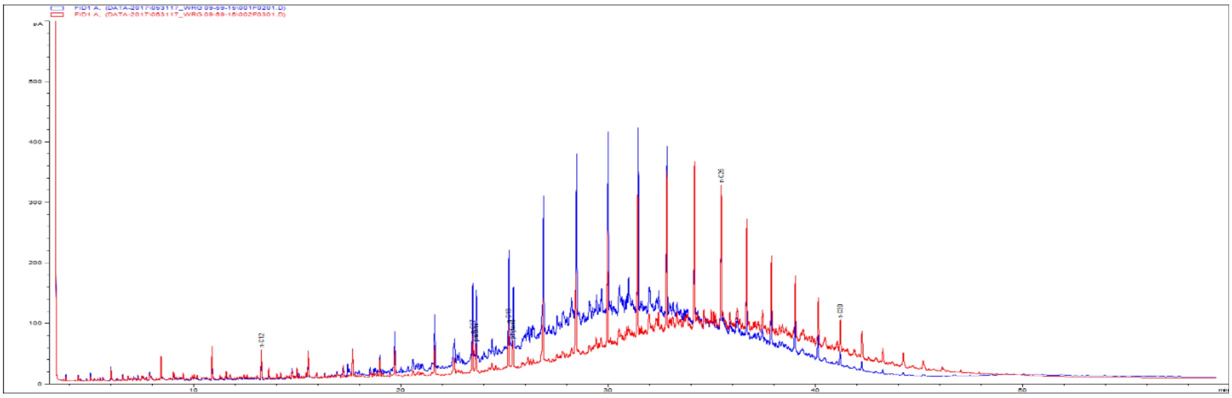
**MGO (2014-0551), 500 ppm Sulphur (Sørheim and Daling, 2015)**



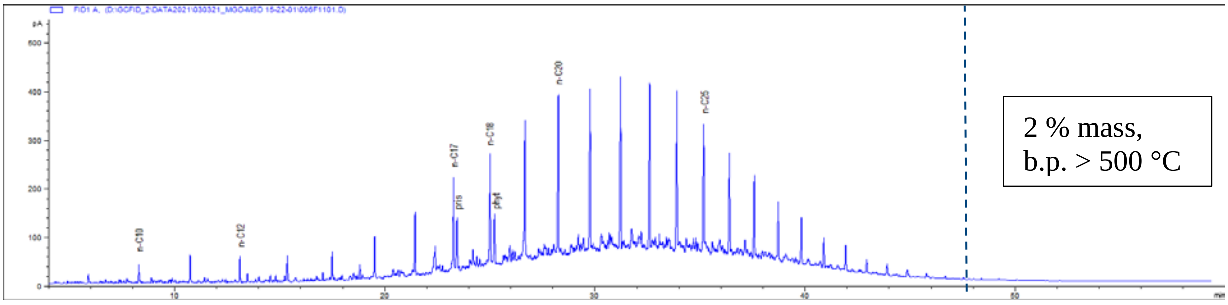
**MGO Fresh (2021-360), 500 ppm Sulphur**



**MGO 250 °C+ (2021-360), 500 ppm Sulphur**

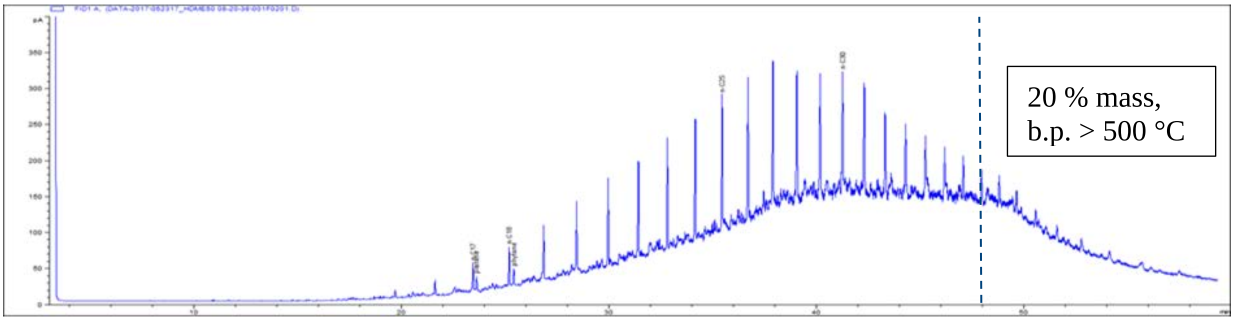


Overlapping gas chromatograms of the 2014 WRG batch (blue) and the 2017 WRG batch (red) (Hellstrøm, 2017).



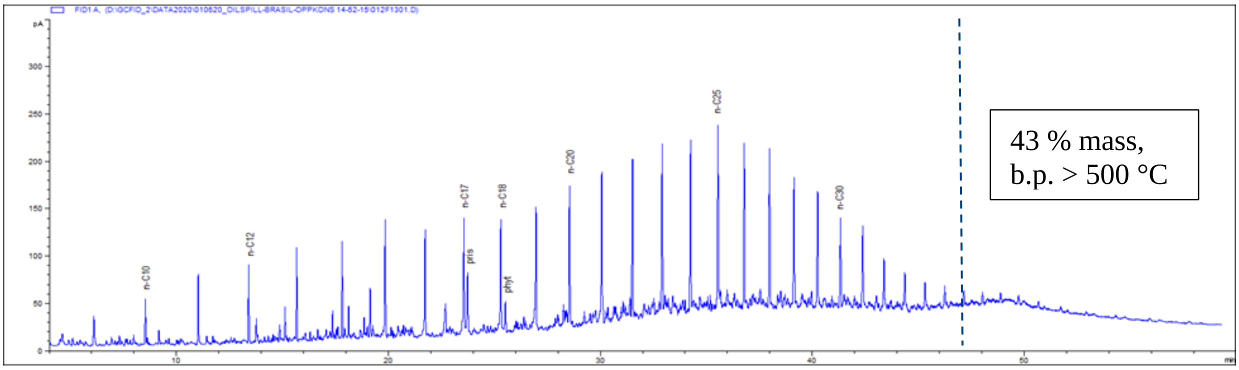
2 % mass,
b.p. > 500 °C

WRG (MSD) (2021-361) Fresh



20 % mass,
b.p. > 500 °C

HDME 50 (2016-0231) Fresh, 20 % mass, b.p. > 500 °C distillate.



43 % mass,
b.p. > 500 °C

ULSFO (2019-11170) Fresh, 43% mass, b.p. > 500 °C (Sørheim et al., 2020).

Figure 3-4 GC-FID chromatograms of MGO fresh and 250 °C+ residue, WRG fresh, HDME 50 fresh and ULSFO fresh. Earlier batches of MGO (2014) and WRG (2014 and 207) are included for comparison. The percent (%) of mass above nC36 (boiling point, b.p.> 500 °C) are marked with vertical lines.

### 3.1.5 Physicochemical properties

To study the oils rheology (viscosity, yield stress and temp sweep) a Physica MCR302 MC1+ rheometer with a RheoCompass software was used. Emulsion viscosity were measured before use to confirm consistency in emulsion properties. Density, pour point and flash point were measured initially for unemulsified oils.

Table 3-2 shows an overview of the physical parameters of the MGO, WRG, HDME 50 and ULSFO used in this project. Since the MGO 2021 batch show more or less the same properties as the previous batch from 2014, reflected in the chromatogram and other physicochemical properties as density and viscosity, data for the 2014 MGO is presented. WRG however, show to have changed a bit over the years. Still, some data for the 2014 WRG batch is presented where data from the 2021 batch do not exist, this to give a feeling of what is expected for the 2021 WRG batch.

Generally, both wax and asphaltenes contribute to stabilize wio emulsion. Asphaltenes have surface active properties that stabilize the water-oil interface, thereby forming a layer that stabilizes the water droplets, whilst the wax contributes to stabilize the asphaltenes near the water-oil interface. The results show a generally low content of asphaltenes in the oils (below 0.14 wt. %). In contrast, the wax content variate greatly between the oils, where HDME 50 and ULSFO have the highest wax content of 9.5 and 20.7 wt. % respectively. This is also reflected in their high pour points (12 and 24 °C), both having pour point above the test temperature of 5 °C. Solidification at low temperatures is therefore a likely scenario. MGO have the lowest flash points (62.5 °C) that reflect a higher content of light compounds, whilst the distillate HDME 50 has the highest flash point (186 °C), due to the lack of components in the range of < C15.

The viscosity of crude oils expresses its resistance to flow and is temperature dependent. For liquids, the viscosity decreases with increasing temperatures. Viscous and waxy crude oils can exhibit non-Newtonian behaviour (viscosity varies with shear rate), especially close to, or below, their pour-point. Water-in-oil emulsions exhibits this non-Newtonian behaviour with shear-thinning. In an oil spill situation, an emulsion may be quite liquid under turbulent conditions at sea, but can become much more viscous, or even semi-solid in calmer water conditions, or on shorelines. Thus, the measurements of the viscosity of w/o-emulsions must be carried out under strictly controlled conditions (defined shear rates and thermal and mechanical history of the sample). At SINTEF a shear rate of 10 s-1 is routinely used for expressing viscosity data on w/o-emulsions. The viscosity of an oil increases with evaporation since the heavier, more viscous components remain in the residue (Mackay and Zagorski, 1982). The difference in viscosity for crude oils is approximately 3 to 2000 mPa·s for fresh crude oils and several hundred/thousand mPa·s for their residues. In comparison water has an “absolute” viscosity of 1 cP and syrup 120 000 cP at 20°C.

The natural weathering processes during an oil spills are dependent on the reaction occurring at the oil/water/air interfaces; water in oil emulsification, oil droplet formation, spreading and biodegradation. InterFacial Tension (IFT) is generally defined as the accumulation of energy and the imbalance force at the interface of two different phases, such as oil and seawater. This changes with time due to leaching of the surfactants at the interface. Asphaltenes, resins, waxes and naphthenic acids are all surface-active components having both hydrophilic and hydrophobic properties. These components will therefore be concentrated at the interface between oil and water forming an interfacial film, resulting in low interfacial tensions. This film will form a physical barrier against coalescence with other oil droplets that would in that case form greater more unstable oil droplets. Oils exposed to sunlight will also generate photo oxidized components which exhibit surface active properties that may reduce the IFT of the oil dramatically. This may generate more stable and viscous emulsions, which may lead to greater oil slick thickness to be stranded on shorelines. Low IFT can also indicate that the oil may have been spiked with surface active chemicals.

**Table 3-2 Physicochemical properties of the MGO, WRG, HDME 50 and ULSFO oil used in this project.**

| Fuel type | Residue | Evaporation (vol. %) | Residue (wt. %) | Density (g/ml) | Flash point (°C) | Pour point (°C) | Viscosity (mPa·s) 5 ˚C (10 $s^{-1}$) | Viscosity (mPa·s) 5 ˚C (100 $s^{-1}$) | ***$\text{IFT}_{in}$ (mN/m) | Asphaltenes "hard" (wt. %) | Wax (wt. %) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **MGO** | Fresh | 0 | 100 | 0.852 | 62.5* | <- 36 | 9 | 9 | 23.7* | 0.02* | 0.81* |
| | 250 °C+ | 27.8 | 73.4 | 0.866 | 113 | <- 36 | 20 | 20 | 22.2 | 0.03 | 1.14 |
| | 250 °C+, 50 % wio<br>*Unstable* | | | - | - | - | 96 - 227 | 27 - 102 | - | - | - |
| **WRG** | Fresh | 0 | 100 | 0.872 | > 100<br>115.5** | - 15 | 102 | 92 | 17.2** | 0.01** | 4.74** |
| | Fresh 50 % wio (49-50 % wio) | - | - | - | - | - | 610 - 759 | 329-366 | - | - | - |
| **HDME 50** | Fresh | 0 | 100 | 0.903 | 186 | 12 | 5 045 | 2 472 | No data | 0.06 | 9.5 |
| | Fresh 50 % wio (43-46 % wio) | - | - | - | - | - | 8 996 - 10 815 | 1 253 - 1 300 | - | - | - |
| **ULSFO** | Fresh | 0 | 100 | 0.917 | 85 | 24 | 42 029 | 9 678 | No data | 0.14 | 20.7 |
| | Fresh 50 % wio (9-20 % wio) | - | - | - | - | - | 57 437 - 58 917 | 7 238 - 6 369 | - | - | - |

- *Not relevant*

**Data for MGO SINTEF ID 2014-0551 (Sørheim and Daling, 2020)*

***Data for WRG SINTEF ID 2014-0553 (Sørheim and Daling, 2020)*

****IFT values at the initial stage of the measurements (IFT_init), measured after 5 min rest.*

## 3.2 Shoreline Cleaning Agent (SCA)

In this study the solvent based Shoreline Washing Agent (SWA) Arrow Delta was used. The choice of this product was based on the availability in Norway, documentation of product and experience from previous studies (Ramstad et al., 2009 and Ramstad et al., 2012). In the laboratory study after the Full City oil spill, Arrow Delta showed good effectiveness (Ramstad et al., 2009). As originally used as a washing agent for cars, it is also relatively affordable and easy to get hold of. 5 l of Arrow Delta was ordered from Aquatiq Chemistry (previously Aco kjemi – incorporated in Aquatiq Chemistry). Arrow Delta passed a toxicity test performed in 2009 using Skeletonema as test organism (Brakstad, 2009). The batch used in this test was dated 2005. According to Aquatiq Chemistry, the agent has not changed chemically over the years. It was therefore considered unnecessary to perform a new toxtest. Arrow Delta is a "cloudy" solution being bright in color, see Figure 3-5.

**Figure 3-5 Picture of the SWA Arrow Delta, used in the shoreline tests.**

Use of Shoreline Cleaning Agents (SCAs) is a very promising cleanup technique for oil contaminated shorelines and a large number and wide range of shoreline cleaning agents is marketed worldwide. Shoreline Cleaning Agents (SCAs) are a common term for products that stimulate the natural processes such as washout, dispersion and biodegradation, so that the recovery of contaminated shorelines is improved. Use of SCA is basically a secondary cleaning technique that is used in the recovery phase, after traditional mechanical and/or manual techniques have been utilized in the acute phase for the bulk or mobile oil. The remaining oil will then be immobilized, strongly weathered and have a thickness of typically less than 1-5 mm. SCA can work through different mechanisms of action and can be classified according to their main working mechanisms, see Table 3-3.

**Table 3-3 Categories of shoreline cleaning agents and their main working mechanisms.**

| **Shoreline cleaning agents (SCA) – (Strandrensemidler - in Norwegian)** | |
|---|---|
| **Shoreline washing agents (SWA)<br>(Strandvaskemidler)<br>* Solvent based<br>* Water based** | Modifies the rheological properties of the oil, so that the oil more easily can be mobilized from the substrate. Washed out oil will accumulate on the sea surface where it can be collected. Primarily used on low energy and sensitive areas. |
| **Shoreline dispersants (SD)<br>(Stranddispergeringsmidler)** | Modifies the surface properties of the oil, so that the oil more easily can be mobilized from the substrate and form stable oil drops in the water, the oil will further be diluted in the water masses. Hence, the oil will not be collected. Primarily used on high energy and less sensitive areas. |
| **Bioremediation products<br>(Bioremedieringsmidler)** | Stimulate microbial activity that accelerates degradation of oil components and recovery of contaminated area and is considered as a polish method on less polluted shorelines. |

The SWAs can be divided into two groups; solvent based and water based. In general, the SWAs modify the rheological properties of the oil, as viscosity and / or surface tension, so that it more easily can be washed out from the substrate. These detergents contain low concentrations of surfactants and does not help to stabilize oil droplets that form. Washed out oil will mainly accumulate on the sea surface where it can be collected by suitable methods such as booms and skimmers, or with use of sorbents. SWA are mainly used on low energy beaches and may require exposure from flushing after application. SWA can also be used in environmentally sensitive areas where it is important to prevent the oil from spreading, and that the oil can be collected. Use of solvent based agents has in previous studies proven to be more efficient than the water based (Carlsen and Ramstad, 2007 and Ramstad et al., 2009). Water based SWA should be used as a 10 % solution to match the guidelines set by the Climate and Pollution Agency (https://www.miljodirektoratet.no/globalassets/publikasjoner/m224/m224.pdf ). The guidelines are based on results derived from the "Ecotoxicity testing of surface cleaning agents used for combating oil spills on shore" – Coastal oil spill JIP report (Hansen et al., 2009).

SDs have some of the same mechanisms of action as SWA but will in addition to a solvent have a higher content of surface active compounds and other types of surfactants. The solvent reduces the viscosity of the oil, making it easier for the surfactants to migrate into the oil. The lipophilic part of the surfactant will orient into the oil phase and the hydrophilic end of the surfactant will orient into the water phase, reducing the interfacial tension between the oil and seawater. This process makes the oil more receptive for wash out and generate the formation of small oil droplets (10-50 µm) under exposure to waves or flushing. SDs should therefore not normally be used in environmentally sensitive areas. In contrast to the SWAs, the SDs stabilizes oil droplets that are formed and keep the droplets remained in the water column, being rapidly dispersed and diluted with time. The dispersed oil will not be able to be collected and should only be used when environmental conditions so require. This applies for example in highly exposed areas with a lot of wave activity / turbulence where the product quickly will be diluted in the water masses, and/or in areas that are difficult to access, making oil collection challenging.

Bioremediation agents stimulate the microbial biological activity that accelerates degradation of oil components and recovery of contaminated area. This can be achieved by different mechanisms of action, but often the products consist of fertilizer with or without presence of microorganisms. Bioremediation agents are primarily used on contaminants in loose substrate and in areas with limited exposure and water flow, as below the substrate surface. Microorganisms help to break down oil components. This happens primarily at the interface between oil and water, as the process is aerobic. In the decomposition process, the microorganisms use oil components as a source of energy. The oil components will then be completely decomposed into carbon dioxide and water, alternatively various intermediates will accumulate in the decomposition process. These processes can be slow, and bioremediation will usually be applied after use of others beach cleaning techniques / strategies.

Figure 3-6 illustrate the working mechanisms for the different SCAs.

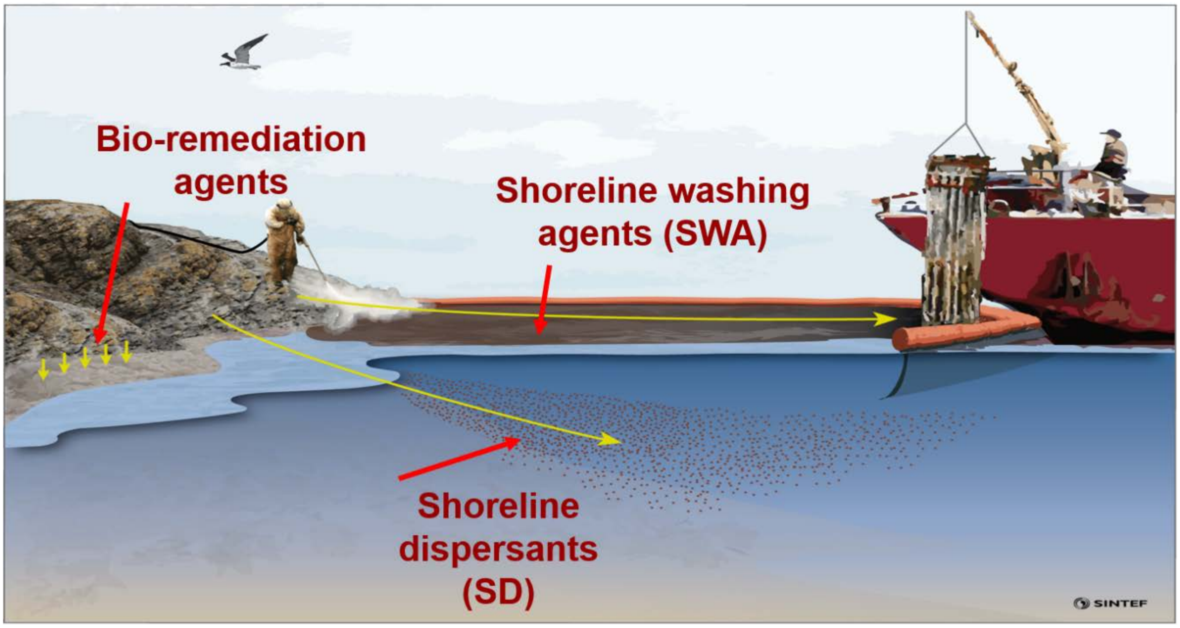


**Figure 3-6 Illustrations of the working mechanisms for the different Shoreline Cleaning Agents.**

## 3.3 Sediment and bedrock

The grain size distribution of the sediments in a shoreline system has shown to be an important parameter for the fate of an oil spill during stranding. Shoreline sediments contain fractions classified over a broad spectre, mainly varying between sand and gravel. The sediment grains have a spherical form due to different weathering processes. It was preferred to use sediment with a limited variation in sediment grains size to get reproducible experimental conditions.

There are several classification scales for sediments and the classification of the fraction may vary. In the United states, the Wentworth classification scale (Wentworth, 1922) are used. An international scale (ISO 14688-1:2002) has also been established giving the basic principles for the identification and classification of soils on the basis of those material and mass characteristics most commonly used for engineering purposes. In this study, a sediment fraction having a grain size variation from 0.063 up to 8 mm was used. This corresponds to sediments ranging from *fine sand* up to *medium gravel* where most of the grains range between 2-6 mm. The sieve analyse from Ramlo Sandtak is given in Appendix B.

According to the Wentworth classification scale, the porosity (ϕ) of sediments of this grain size will be ranging from 4 to -2. The porosity of a porous medium, such as sediment, describes the fraction of void space in a material. That means, if a medium has a large porosity, the medium will have a great amount of small void spaces for containment of liquids. Permeability is a measure of the ability of a medium to transmit fluids. The permeability of sediments is dependent on the size of the pores. Sand will generally have a high porosity due to several small void spaces per cubic meter, but low permeability because the voids are too small for fluid transportation. Gravel has a high permeability due to fewer, but larger void spaces, but lower porosity (Brattli, 1999).

For bedrock, shale tiles having a natural surface (not artificially cut) with a medium surface texture were used in the studies. The shale tiles originate from Alta in Finnmark, Norway. Shale is a sedimentary bedrock and is known for its high content of quarts which make the rock resistant for exposure (https://www.altaskifer.com/). Shale is a quite common bedrock along the Norwegian coast, especially in the north to the middle of Norway. An example of a shale tile and the sediment is shown in Figure 3-7.

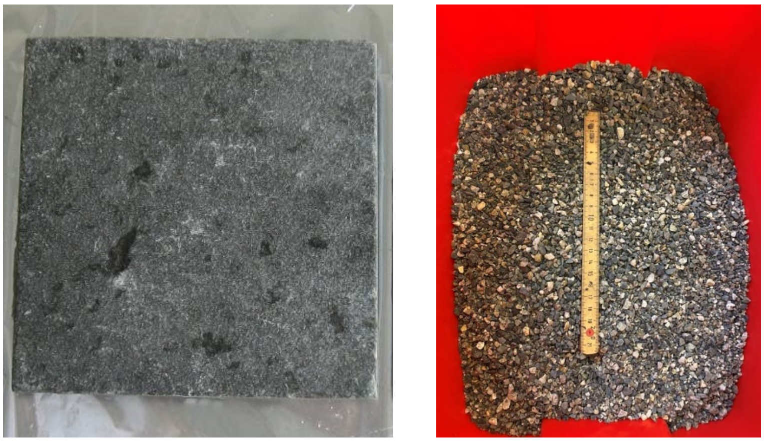


Figure 3-7 Example of a shale tile and sediment (2-6 mm) used in the studies.

## 3.4 The Sediment Column System

To study the fate and behaviour of an oil spill after stranding on shoreline sediment, an experimental column system with a continuous supply of seawater simulating tidal variation, was used. The column system consists of 16 columns which can be filled with desired fraction of sediment. In- and output of seawater is placed at the bottom of the columns for tidal simulation. A computer program, Arduino, is used to simulate the tidal variation by controlling the number, duration and hight of the tidal periods. The tidal fluctuation can be monitored in real-time online using a Raspberry Pi program and the app ThingView. The water fluctuation takes form as a sinus curve, which is similar to natural tidal cycles. Figure 3-8 shows the setup of the column system with columns, pressure sensors for regulation of water level, valves, in- and outlets from the water reservoir and monitor.

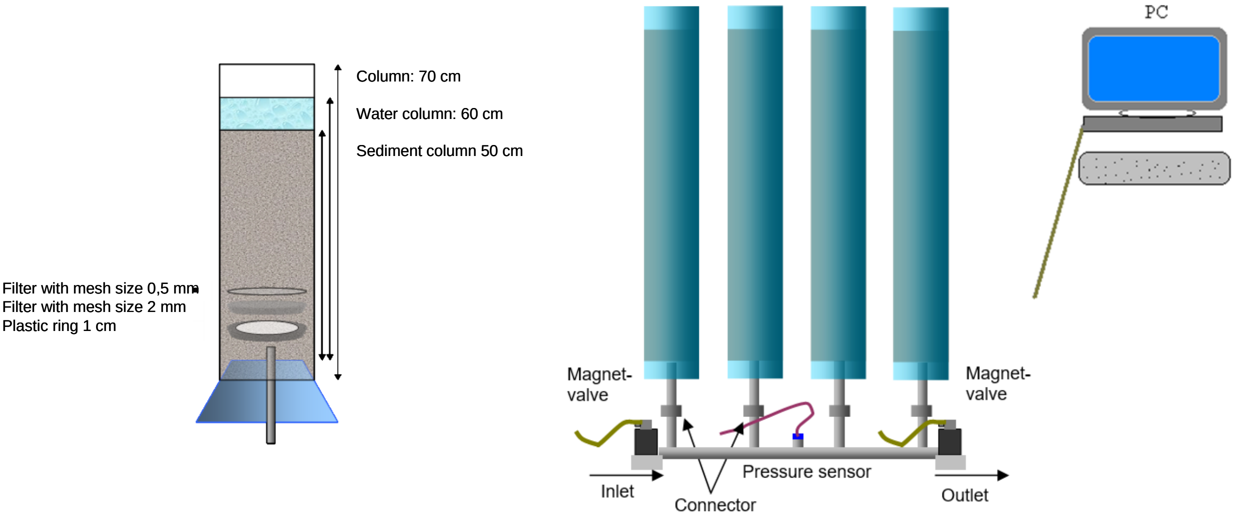


Figure 3-8 Design and setup of the Sediment Column System.

The columns have a length of 70 cm and an inner diameter of 10 cm. The columns are made of plexiglass for observation of oil behaviour. The columns are filled with sediments, reaching a sediment hight of 50 cm from the bottom. A vertical flux of simulated tidal water varies between 10 and 60 cm from the bottom, which means that the sediment column never will be totally drained for seawater and the water column will reach 10 cm above the sediment surface. To prevent sediment clogging the pipes, two filters with different mesh size are placed in the bottom of each column.

### 3.4.1 Experimental procedure using the Sediment Column System

To reduce the presence of fines in the sediments, the sediment was flushed with water before being introduced to the columns. The tidal simulation was then started to remove the last remains of fines before experimental start up.

An oil/emulsion layer of approximately 10 mm (78,5 g) was applied to the water surface at high tide, simulating an oil spill during the acute phase. A tidal period of 8 cycles with a tide cycle of 3 hours was used, the experimental period will therefore have a duration of 22,5 h, this based on results from previous studies (Carlsen, 2006 and Øksenvåg et al., 2009). Observation and photo documentation of the penetration of oil/emulsion was mainly performed at the first two and the last low tide. The resurfacing of emulsion was mainly documented during the second and third high tides, when the refloating of oil/emulsion was at its greatest. The resurfaced emulsion was collected by pads and quantified gravimetrically. The timing for application and documentation during the experimental period is given in Figure 3-9.

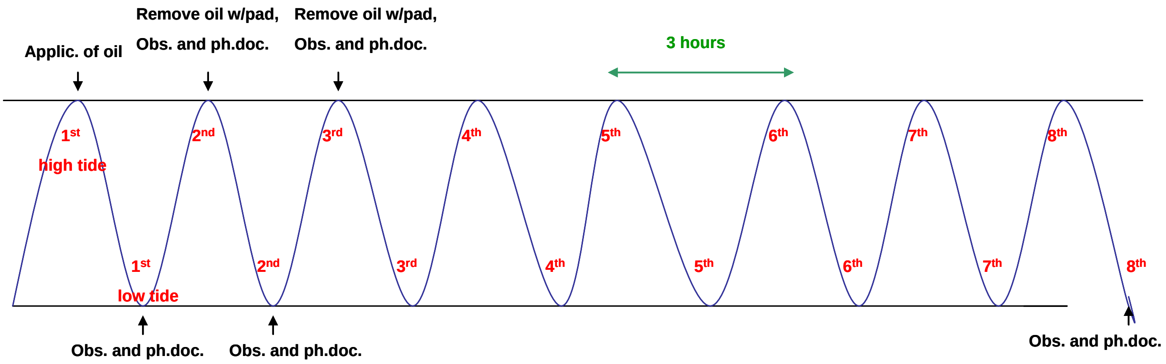


Figure 3-9 Operational overview during one experiment using the Sediment Column System.

The relative retention of oil in the sediment was calculated by subtracting the resurfaced oil from the applied oil loading during the tidal cycles. After finalisation, a hydraulic jack was used to do sediment sampling, see Figure 3-10. To find the concentration of oil in the sediment samples, the samples were extracted in dichloromethane (DCM) and analysed using a Hitachi U-2000 spectrophotometer, or by use of GC for the oils being too bright in colour to be analysed by the spectrophotometer (MGO and WRG).

Figure 3-10 The hydraulic jack used for sediment sampling.

The MGO and WRG was white to yellow in colour, see Figure 3-2, making them hard to observe through the plexiglass columns, blending with the sediment. UV lamps was therefore used to discriminate between sediment and oil. UV radiation produces luminescence which make the oil in a dark room light up. This radiation is therefore also called black light. Figure 3-11 shows how the UV-Light was set up in the Sediment Column Studies.

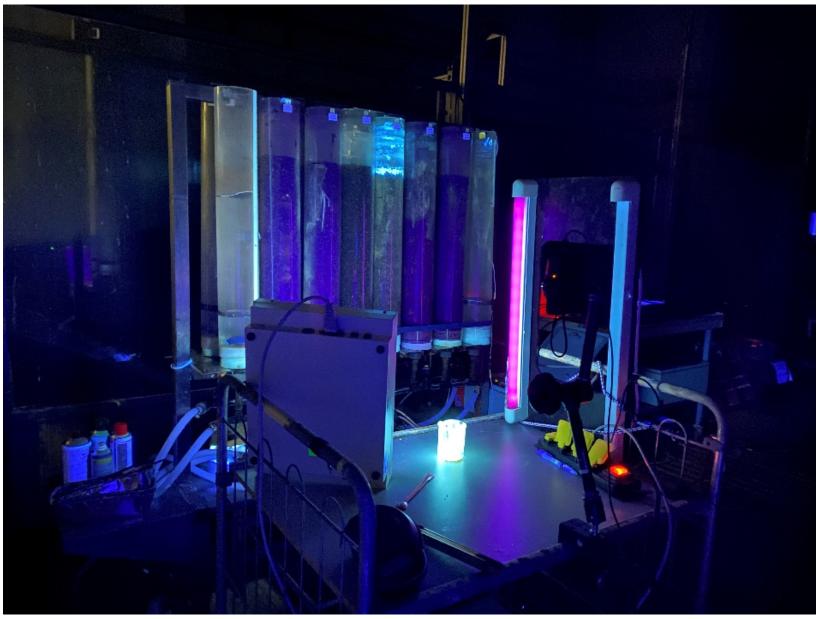


**Figure 3-11 Set up of UV-lights in the sediment column studies.**

The SINTEF operational procedure "*Operation of the column system and* sample analysis" *(Dok.nr 8016-09-005)* was used as a basis in this study, to ensure reproducibility of the experimental setup compared to previous studies, as well as for studies to come.

## 3.5 The Shoreline Simulation System

The Shoreline Simulation System are used to study the "natural" washout of fuel oils from bedrock by waves. The system was constructed in Norway and established at SINTEF SeaLab in 2006. A similar system was then already in use at Cedre in France. The Shoreline Simulation System contains 12 reservoirs installed on an oscillating table. The reservoirs are filled with seawater, before introducing bedrock tiles (or sediments) in the system, see Figure 3-12. The system is placed in a temperature-controlled room to ensure the required test temperature.

**Figure 3-12 The Shoreline Simulation System and the water reservoirs containing the tiles.**

The simulation systems generate wave energy by tilting the oscillating table from one side to another with a standard angel and frequency, as shown in Figure 3-13. For this purpose, a compressed air jack along with a control unit programmed for a uniform movement is used.

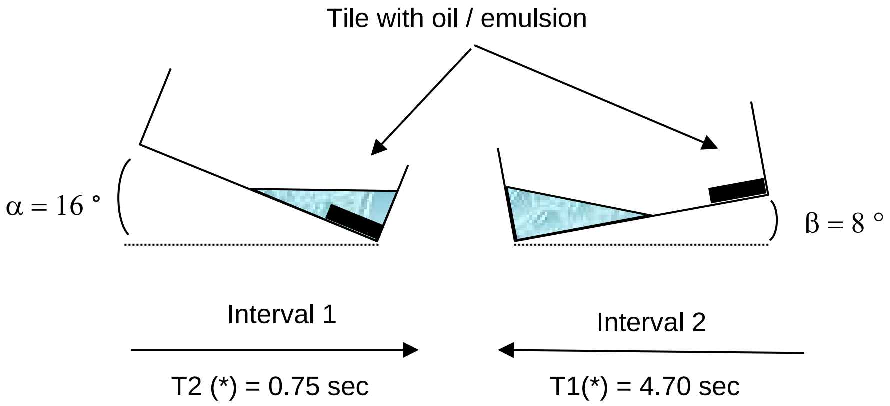


**Figure 3-13 The mechanisms of the oscillating table – Shoreline Simulation System.**

The exposure degree is regulated by adjusting the amount of water applied to the individual reservoirs. 1 and 2 litres of seawater represent "high" energy levels in the Shoreline Simulation System, and 4 litres represents a "low" energy level. The energy levels in the different scenarios are simulated using a Computational Fluid Dynamics (CFD) model Flow-3D and is further described in Øksenvåg et al., 2009 (Coastal Oil Spill JIP – SINTEF report number F9031).

### 3.5.1 Experimental procedure using The Shoreline Simulation System

Before introducing the tiles to the Shoreline Simulation System, the reservoirs were filled with seawater and temperate to the study temperature of 5 °C. In this study 2 litres of seawater were used for simulating "high" level of exposure. The edges of the tiles were masked with tape to avoid quantification of oil/emulsion covering the edges and tempered to 5 °C before use. As a standard, 22.5 g +/-0.5 g of weathered oil was applied to the bedrock tiles measuring 15x15 cm, representing an oil/emulsion film thickness of 1 mm. The MGO and WRG fuel types had quite low viscosities, causing a runoff of excess oil. To reduce the risk of runoff, only 1/5 of the standard oil/emulsion loading was applied (4.5 g), representing an oil/emulsion film thickness of 0.2 mm. The tiles were then placed horizontally for 1 day to let the oil/emulsion settle and cover the tile evenly. The SWA Arrow Delta was applied using an Agent to Oil Ratio (AOR) ratio of 1:5, using a pipette. SWA applied to the weathered MGO and WRG was reduced accordingly, still representing an AOR of 1:5. The agent was then allowed to soak for 20 min before introducing them to the reservoirs. The oil covered tiles were exposed for 30 min, before being retrieved from the Shoreline Simulation System.

After exposure, the samples were blow dried with a small air pressurised pistol to remove seawater covering the oil surface, see Figure 3-14. The tiles were then placed horizontally at test temperature for 1 day to dry off the last remains of seawater before quantifying the remaining oil/emulsion on the tiles gravimetrically. The tape on the edges were removed before quantification. The tiles were photo documented before and after exposure. MGO and WRG was hard to observe by the naked eye due to its white to yellow colour, see Figure 3-2. UV-Light was therefore used for observations and documentation. UV radiation produces luminescence which make the oil in a dark room light up.

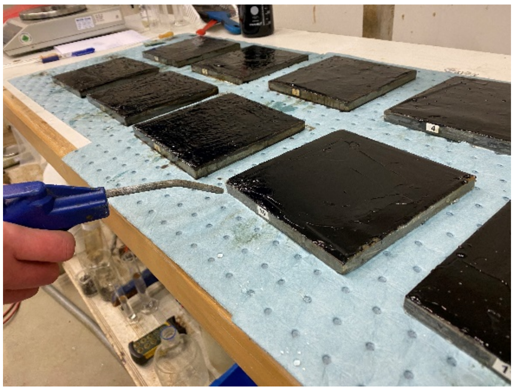


**Figure 3-14 Blow drying oil surface after simulating natural wash out in the Simulated Shoreline System.**

As a part of the Coastal Oil Spill JIP (2006-2013), a standardized SINTEF test protocol for the Effectiveness testing of SCAs on oil/emulsions simulating natural washout were developed; *Effektivitetstesting av strandrensemidler – Simulerte Strand Systemer (Dok nr. 8016-09-009)*. This protocol was used as a basis in this study, to ensure reproducibility of the experimental setup compared to previous studies, as well as for studies to come.

## 3.6 The Flushing Robot

The Flushing Robot was established at SINTEF SeaLab in 2006 and has since then been used to study the effectiveness of different shoreline cleaning agents on oil contaminated bedrock, using flushing as a countermeasure. The Flushing Robot was constructed at Cedre, a copy of this is placed at SINTEF Sealab in Trondheim. The machine frame is built of stainless steel and the internal volume is approx. 316 litres. The machine consists of a small trolley that is made to receive the washing nozzle. The trolley is driven according to a defined and reproducible path (spray width, speed and distance) to ensure equal washing operation for all subsequent tests, so that comparable studies can be performed.

Oil contaminated bedrock tiles are placed in a steel rack and exposed for fresh water flushing ranging from 4 bars (unpressurised water) up to 45 bars using a high-pressure washer. Specific nozzles are used with respect to desired opening diameter, angle and spreading orientation. As a standard, a nozzle with number 25065, giving a spray angle of 25 ° and an opening of 1.5 mm is used, see nozzle specifications in Appendix C, showing the flow rate capacity (litres per minute). The distance from the nozzle to the tile is 30 cm. The Flushing Robot has the ability to perform both a vertical and a horizontal cycle at five different cycle selections. The robot is programmed using Zélio soft SR2 B201 BD Schneider. The stepwise distance can be adjusted using the time cycle selection button or by using the software Zelio soft V.2.4. In the studies performed by SINTEF, the vertical cycles have been used, applying the 60-80 % time cycle. The shale tiles are exposed for flushing only for a few seconds, following the movement set in the robot program. A picture of the Flushing Robot is shown in Figure 3-15.

**Figure 3-15 Pictures showing the Flushing Robot, the steel rack holding the tiles and the nozzle.**

### 3.6.1 Experimental procedure for The Flushing Robot

The edges of the tiles were masked with tape to avoid quantification of oil/emulsion covering the edges and tempered to the study temperature of 5 °C before use. As a standard, 10 g +/-0,25 g of weathered oil is applied to the bedrock tiles measuring 10x10 cm, representing an oil/emulsion film thickness of 1 mm. The MGO and WRG fuel types had quite low viscosities, causing a runoff of excess oil. To reduce the risk of runoff, only 1/5 of the standard oil/emulsion loading was applied (2 g), representing an oil/emulsion film thickness of 0,2 mm. The tiles were then stored horizontally in a temperature-controlled room at test temperature of 5 °C for 1 day to let the oil/emulsion settle and cover the tile evenly.

The shoreline cleaning agent Arrow Delta was applied using a pipette, at an Agent to Oil (AoR) ratio of 1:5. SCA applied to the weathered MGO and WRG was reduced accordingly, still representing an agent to oil ration of 1:5. The agent was then allowed to soak for 20 min before the tiles were mounted on the steel rack for flushing treatment. A flushing pressure of 4, 15, 30 and 45 bar, serving approximately 3, 5, 8, 10 litres per minute (see Appendix C), at temperatures of 5 and 45 ° C was applied, depending on the physical properties of the oil.

After exposure, the samples were blow dried with a small air pressurised pistol to remove seawater covering the oil surface, see Figure 3-14. The tiles were then placed horizontally at test temperature for 1 day to dry off the last remains of seawater, before quantifying the remaining oil/emulsion on the tiles gravimetrically. The tape on the edges were removed before quantification. The tiles were photo documented before and after exposure. Two of the oil types used in this study (MGO and WRG) was challenging to observe by the naked eye due to its white to yellow colour, see Figure 3-2. UV-Light was therefore used for observations and documentation. UV radiation produces luminescence which make the oil in a dark room light up.

As a part of the Coastal Oil Spill JIP (2006-2013), a standardized SINTEF test protocol for the Effectiveness testing of SCAs on oil/emulsions simulating natural washout were developed; *Effektivitetstesting av strandrensemidler – Vaskerobot (VR) (Dok nr. 8016-09-010)*. This protocol was used as a basis in this study, to ensure reproducibility of the experimental setup compared to previous studies, as well as for studies to come.

# 4 Results and discussions - The ULSFO fuel types interaction with sediment shorelines and bedrock, and effectiveness of actions

## 4.1 Fuel oil penetration in sediments, remobilization of excess oil/emulsion and incorporation of sediments in remobilized oil

Penetration of unweathered and weathered fuels oils in sediments during 8 tidal cycles was studied using the Sediment Column System. The penetration depth and oil concentration as a function of sediment depth was analysed. Remobilized oil/emulsion and sediments incorporated in the refloated oil/emulsion was observed and quantified. Pictures to illustrate the sediment columns containing the different oils are shown in Figure 4-1.

As Figure 4-2 show, the penetration depth was greatest for the low viscous oil, MGO 250 °C+ and MGO 250 °C+ emulsified (50 % wio), the emulsified oil penetrating less than the unemulsified oil. The MGO 250 °C+ emulsion was very unstable and separated at rest into two phases; oil and seawater. The unemulsified and emulsified MGO 250 °C+ are therefore considered to have more or less the same properties. Still, the oil loading will be less for the emulsified oil, as the emulsion contain less oil than the unemulsified. The reduced penetration will therefore primarily be due to the reduced oil content in emulsions, containing half the amount of oil in 50 % wio emulsions. Most of the penetration occurred during the first tidal cycle, but the results show penetration to continue with time, reaching down to almost 50 cm depth for the unemulsified MGO 250 °C+ residue after 8 tidal cycles.

The same trend was observed for the unweathered and weathered WRG (50 % wio), the unweathered penetrating down to almost 30 cm, while the weathered WRG only penetrated down to about 20 cm depth. In addition to the oil loading factor, the weathered WRG have a higher viscosity than the unweathered (760 versus 100 mPa*s), which also will contribute to a reduction in penetration depth. Previous studies have shown that both a reduction in oil loading and an increase in viscosity will lead to a reduced penetration depth (Øksenvåg et al., 2009). The oil penetrated the sediment successively, having the greatest penetration during the first tidal cycle.

HDME 50 and ULSFO have a very high pour point (12 and 24 °C), which lead to a semi solid material at test temperature of 5 °C. In addition, the oil/emulsions were quite viscous having viscosities ranging from 5 000 to ~ 60 000 mPas*s at 10 s-1. Therefore, neither unemulsified HDME 50 or unemulsified and emulsified ULSFO penetrated the sediment. The oil/emulsion refloated and was removed manually after the first high tide. For HDME 50, parts of the emulsion remained in the upper two cm of the sediment column, while the rest of the emulsion was remobilized at the next high tide, see Figure 4-1.

Pictures taken of the respective oils/emulsions during the tidal periods is shown in Appendix D.

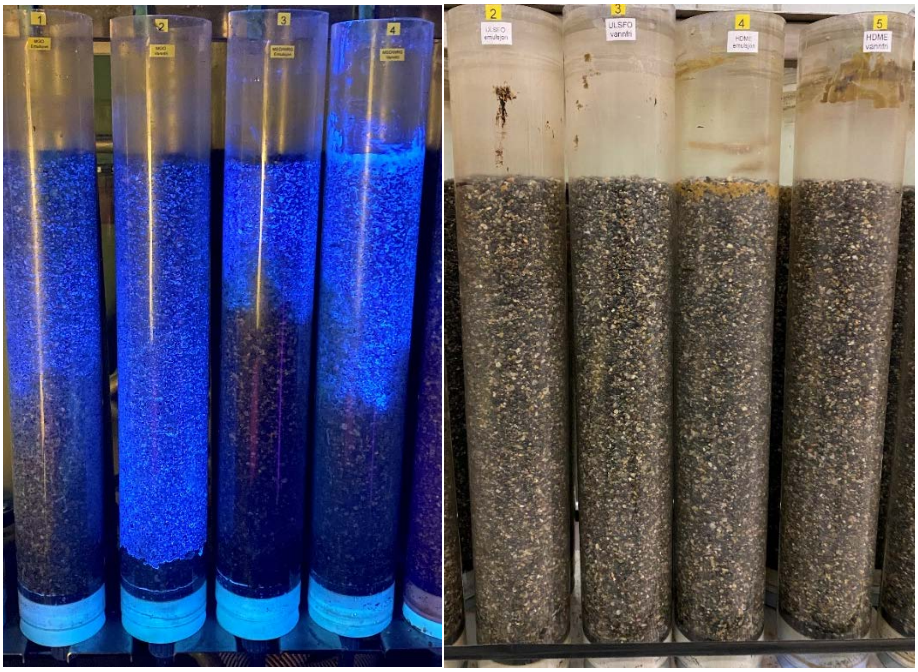


**Figure 4-1 Pictures of the sediment columns holding the different fuel oils after 8 tidal cycles. The oils are in the following order from left to right: MGO 250 °C+ emulsified, MGO 250 °C+, WRG emulsified, WRG, ULSFO emulsified, ULSFO, HDME 50 emulsified and HDME 50.**

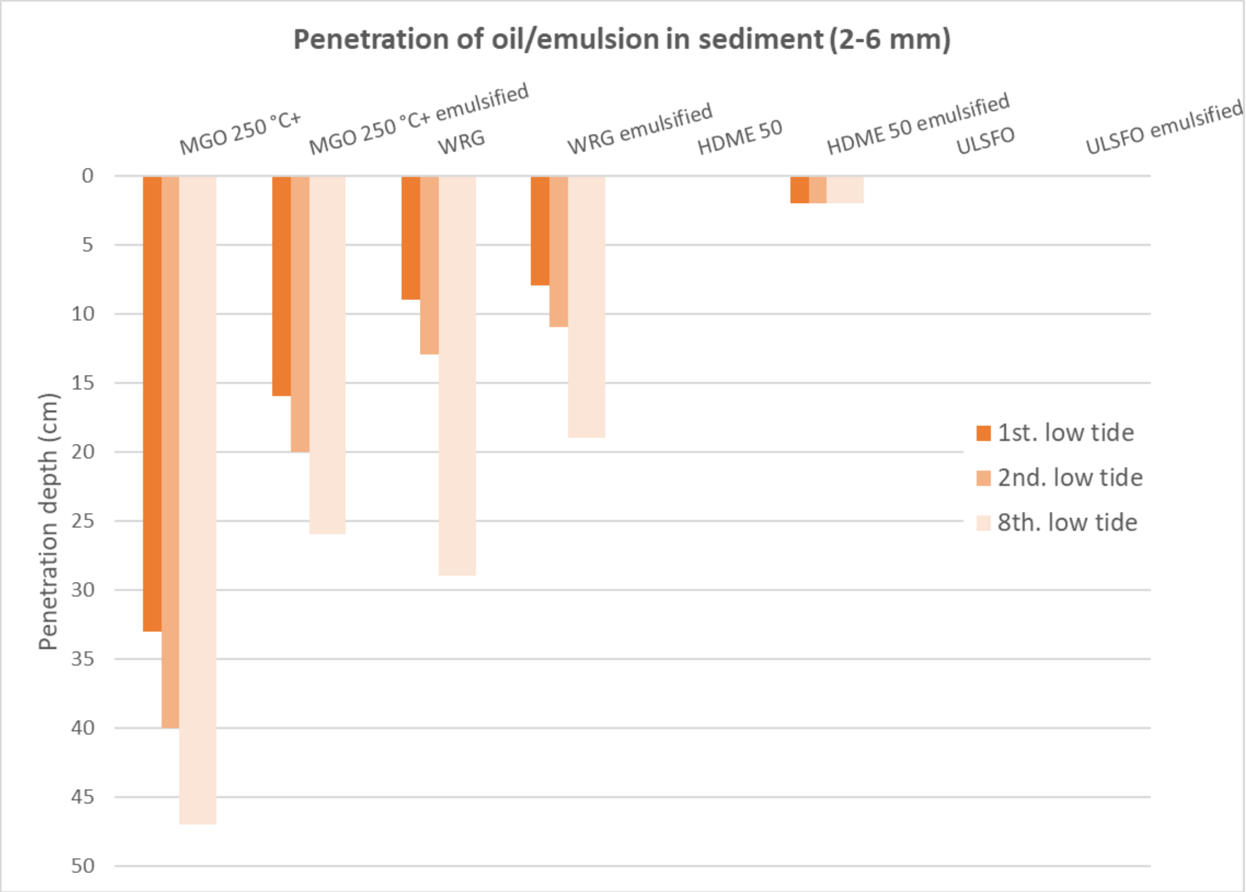


**Figure 4-2 Penetration depth in sediment (2-6 mm grain size) for unemulsified and emulsified MGO 250 °C+, WRG, HDME 50 and ULSFO, performed at 5 °C.**

The distribution between oil/emulsion retained in the sediment and remobilized in the water phase is given in Figure 4-3. As the figure show, less than 15 % of the unemulsified and emulsified MGO 250 °C+ and WRG was remobilized during the 8 tidal periods. In contrast, HDME 50, ULSFO and ULSFO emulsified did not retain at all, everything being refloated during the first hight tide. For HDME 50 emulsified, ~30 % of the emulsion adhered to the sediment surface, being retained and distributed in the upper two centimetres of the sediment, see Figure 4-6.

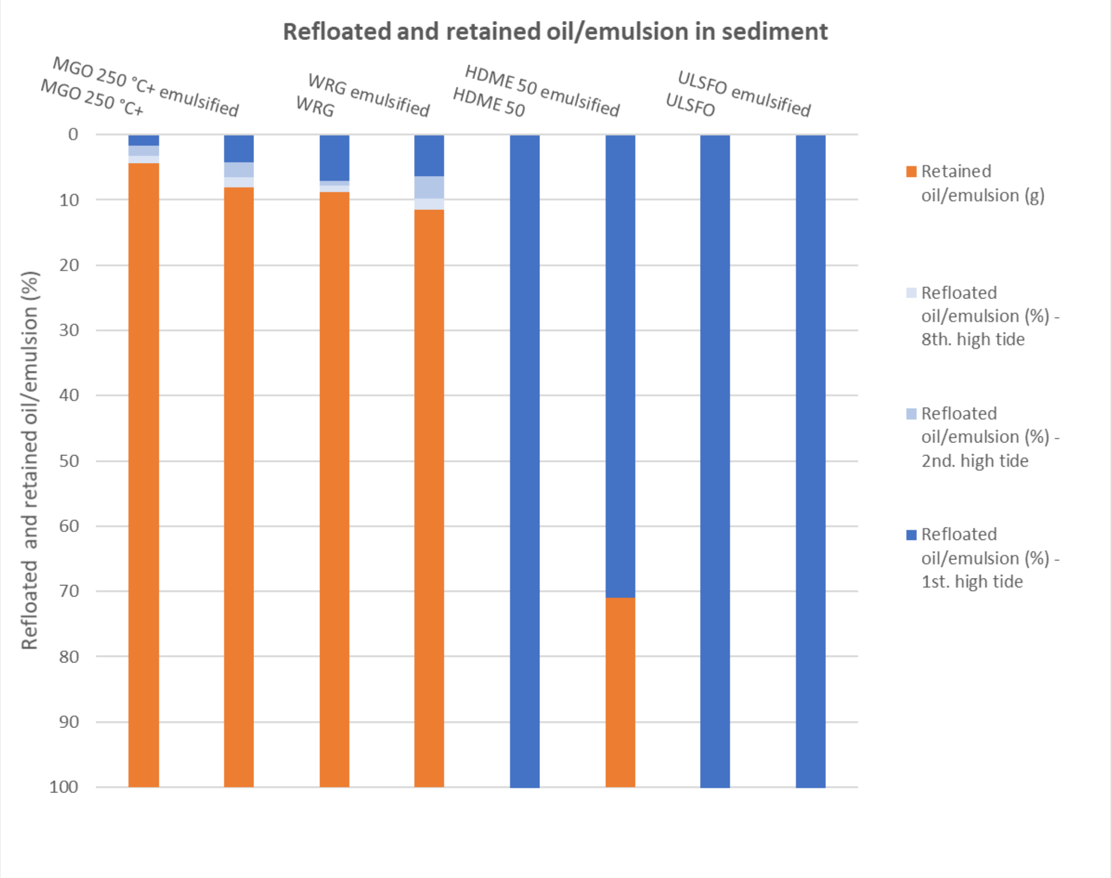


**Figure 4-3 Refloated and retained fuel oil/emulsion in sediment given in percent, using grain size 2-6 mm, performed at 5 °C.**

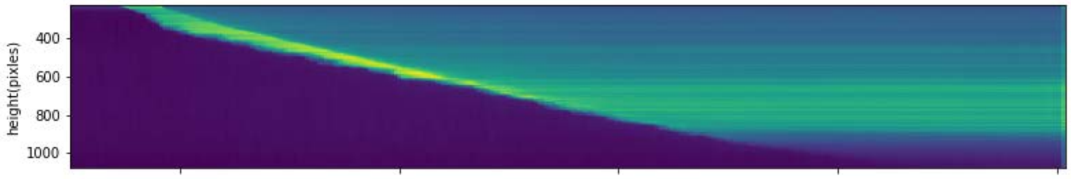
As the fuel oils refloated during the first high tide, HDME 50 emulsion, ULSFO and ULSFO emulsion adhered and incorporated sediment grains from the sediment surface, see Figure 4-4. The amount of oil, as well as the sediments incorporated was quantified for the respective oils, given in Table 4-1. The amount of sediment varied between the parallels.

Figure 4-4 Sediment grains incorporated in HDME 50 emulsion when refloating at high tide.

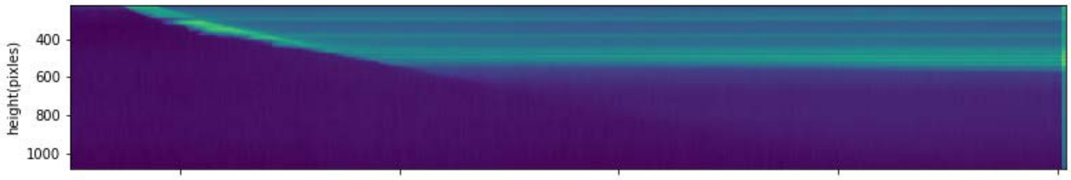
Table 4-1 Overview of oil/emulsion refloated and amount of sediment incorporated.

| | Oil / emulsion refloated | | Incorporated sediment | |
|---|---|---|---|---|
| | (g) | (%) | (g) | (%) |
| **HDME 50 emulsion** | 52-58 | 67-80 | 2-3 | 1-5 |
| **ULSFO** | 78.5 | 100 | 0.2-0.5 | 1 |
| **ULSFO emulsion** | 78.5 | 100 | 2-3 | 3-4 |

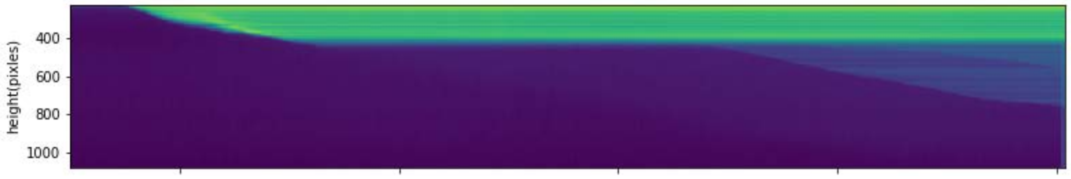
During the first fall tide of the penetration studies, the time laps function on iPhone was used to take picture of the oils/emulsions penetration as a function of time, using UV light, see Figure 4-5. These images were converted to hight in pixels (y-axis). The x-axis is given as number of pictures, representing time. The intensity of the green/yellow colour indicates the relative concentration of the oil/emulsion in the sediment. The dark blue colour indicates no oil. This was only performed for the two oils MGO and WRG, being white to yellow in colour, making it a challenge to observe with the naked eye. The indications from these images corresponded well with the concentration studies performed after the experimental period was finished, see Figure 4-6.



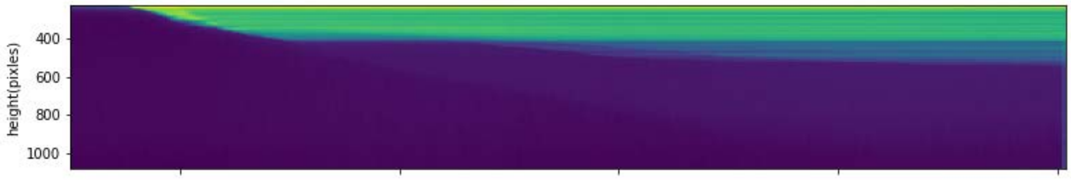
MGO 250 °C+



MGO 250 °C+ emulsified



WRG



WRG emulsified

**Figure 4-5 Penetration of MGO 250 °C+ and WRG oil and emulsions in sediment, illustrated by time laps pictures from initial high tide to first low tide, with use of UV- light. The pictures are presented as height in pixels (y-axis) and number of images (x-axis).**

As shown in Figure 4-6, MGO 250 °C+ unemulsified and emulsified show to be quite evenly distributed in the sediment down to 20 cm depth. The unemulsified oil (having a greater oil loading than emulsified), was observed to penetrate down to about 50 cm. The rest of the oil is therefore assumed to be concentrated in the last 30 cm of the sediment column, from 20-50 cm depth. The oil concentration may even be higher in the 20-50 cm fraction, considering the results from the time laps pictures in Figure 4-5. The WRG fuel oil and emulsion show a decreasing trend in concentration as a function of penetration depth. The remaining WRG oil is therefore assumed to be precent in the next 10 cm of sediments, 20-30 cm depth. Oil concentration analysis confirmed that the HDME 50 emulsion was retained in the upper 2 cm, as observed visually.

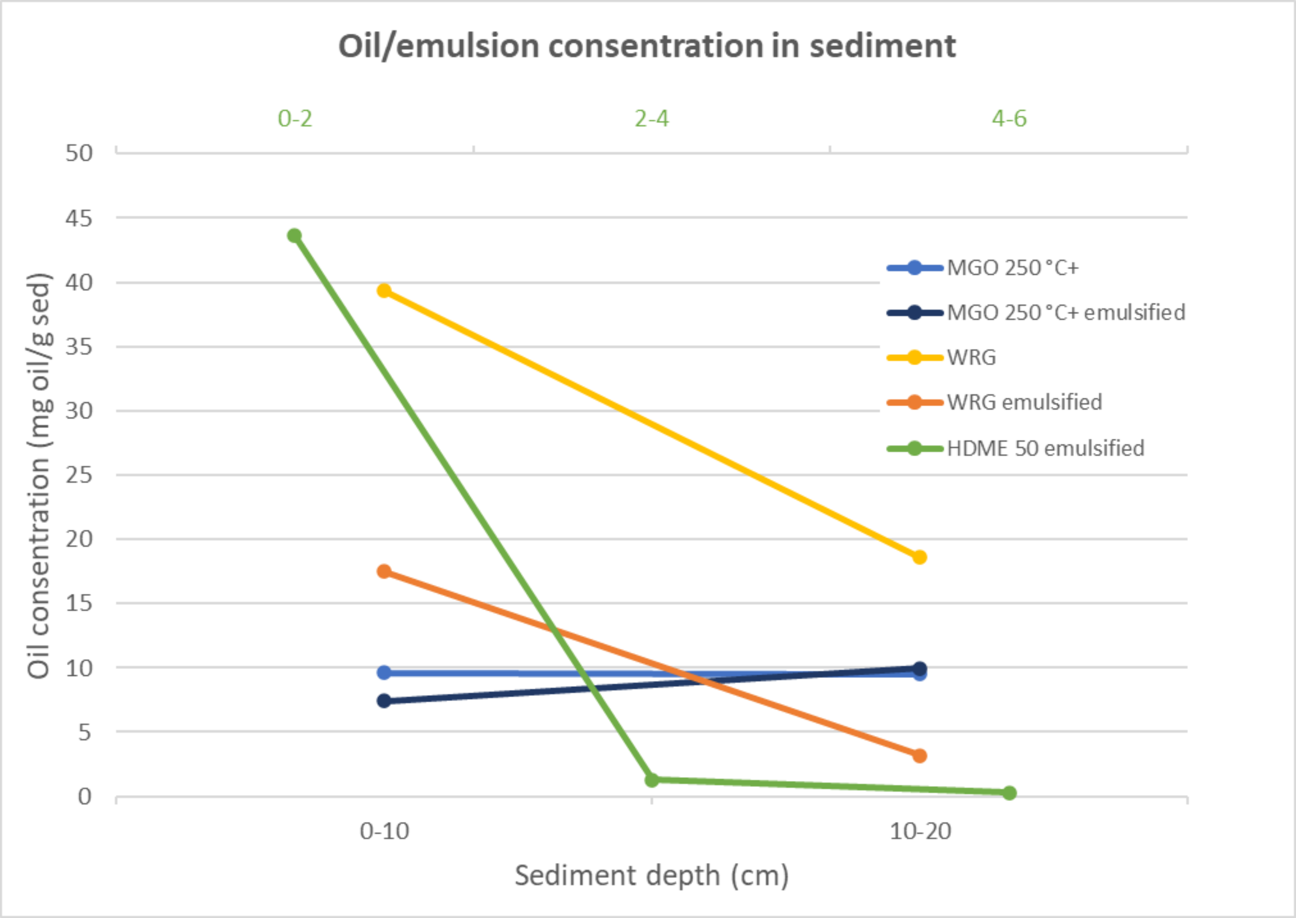


**Figure 4-6 Oil/emulsion concentration in the sediment analysed by use of GC and spectrophotometer. Note that HDME 50 have a separate x-axis divided in 2 cm fractions.**

The penetration studies are performed under low energy conditions, only simulating tidal cycles. In a natural environment, wave energy will affect how the oil is forced down into the sediment and further remobilized from the sediment system. In addition, wave energy can cause the oil/emulsion to roll up on the beach, incorporating both fines and sediment grains which may affect the further faith of the oil. Taking this into consideration, these results present only indications of how the fate and behaviour of the oil will be in case of an oil spill reaching the shoreline.

***Essential findings:***

***For the low viscous oils MGO 250 °C+ and WRG (< ~ 1000 mPa*s at 10 s-1), the penetration showed to be between 20-50 cm, the emulsified oils penetrating less than the unemulsified oils. The reduced penetration is primarily due to the reduced oil content in emulsions, but also caused by an increase in viscosity. Most of the penetration occurred during the first tidal cycle, the penetration rate decreasing with time. For these oils, < 15 % of the oil/emulsion was remobilized from the sediment. The concentration profile of the oil/emulsion in the sediment showed to be dependent on the viscosity, the very low viscous fuel oil MGO (< ~ 300 mPa*s) being evenly distributed, or potentially increasing further down in the sediment column. WRG showed decreasing concentration profiles, having viscosity ranging from 100-760 mPa*s.***

***For HDME 50 and ULSFO having pour point above the test temperature of 5 °C and viscosities in the range of 5 000 – 60 000 mPa*s, the oil/emulsion did not penetrate the sediment at all and was remobilized during the next high tide. These high wax oils (> 9 wt. %) showed to adhere sediment grains in the process.***

## 4.2 Washout of fuel oil from bedrock by wave energy – with and without use of SWA

Washout of fuel oil/emulsion from bedrock by wave energy was simulated using the Simulated Shoreline System. The effectiveness of the washout was studied with and without using the SWA Arrow Delta at an agent to oil ratio of 1:5. The effectiveness is given in percent and represents the amount of oil/emulsion washed out during exposure, compared to the initial loading applied to the tile surface.

The results, presented in Figure 4-7, show a very good washout effectiveness (> 90 %) for the unemulsified and emulsified MGO 250 °C+ (50 % wio emulsion). Use of SWA showed therefore to be redundant. The MGO 250 °C+ emulsion was very unstable and separated quickly into two phases, oil and seawater. The unemulsified and emulsified MGO 250 °C+ are therefore considered to have more or less the same properties. Still, the oil loading will be less for the emulsified oil, as the emulsion contain less oil than the unemulsified.

For the WRG fuel oil, the washout results show moderate effectiveness (~ 60 %) for both the unemulsified and the emulsified oil. Use of SWA increased the effectiveness by 20-30 %, showing best effect on weathered WRG, reaching a washout effectiveness of 95 %.

For both unemulsified and emulsified HDME 50 and ULSFO, very little oil/emulsion was washed out during wave exposure, leaving almost all the oil/emulsion left on the tiles. The effect by using SWA was limited, showing best results for the weathered HDME 50, gaining an effectiveness of 25 %. Washout by wave energy proved therefore to be insufficient for high wax oils (> 9 wt. %) having viscosities in the range of 5 000 – 60 000 mPa*s.

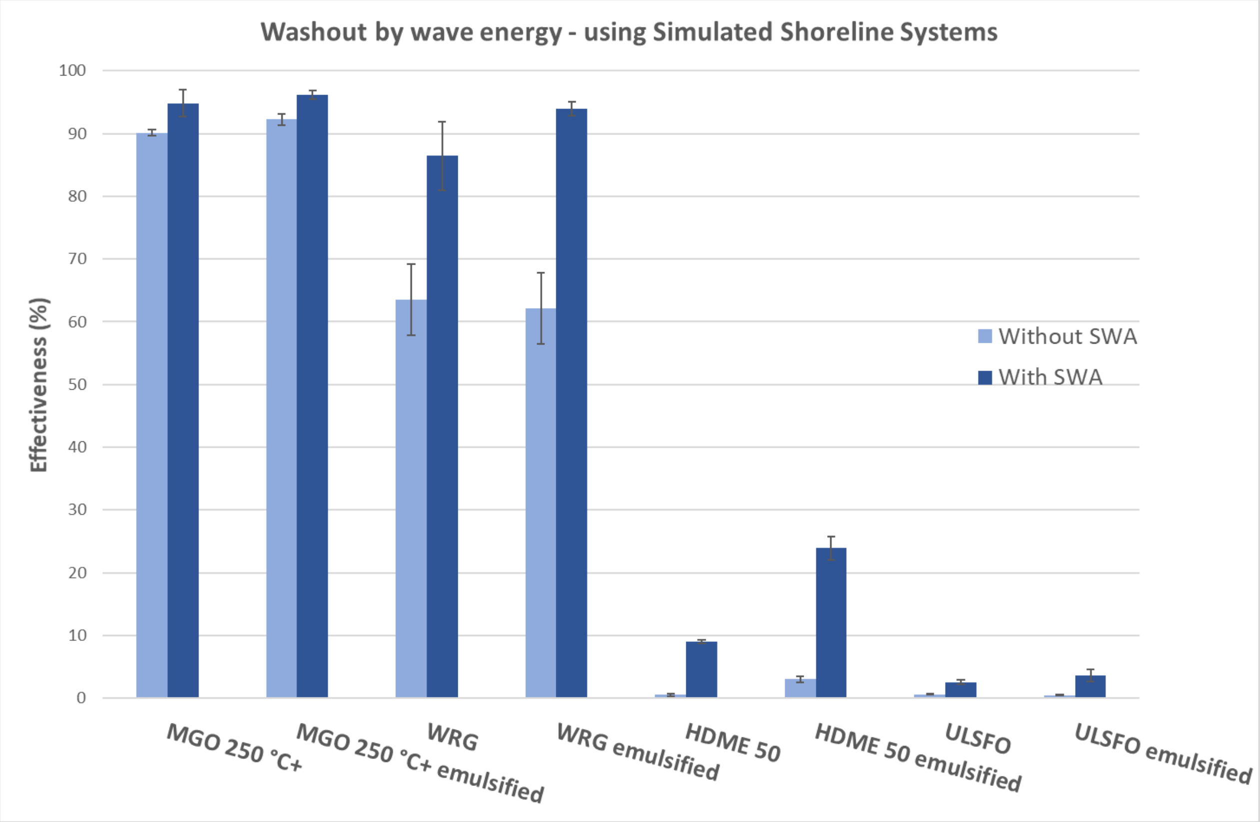


**Figure 4-7 Effectiveness of washout by wave energy, with and without use of SWA for unemulsified and emulsified MGO 250 °C+, WRG, HDME 50 and ULSFO, performed at 5 °C.**

Example images of tiles with weathered MGO 250 °C+ and weathered and unweathered WRG before, during, and after washout using the Simulated Shoreline System is shown in Appendix E. As illustrated, the fuel oil was not easy to see with the naked eye. By using UV light, the oil became visible.

***<u>Essential findings</u>:***
***The low viscous oil MGO (< 300 mPa*s) was very receptible for washout by wave energy, showing very good effectiveness (> 90 %), even without use of SWA. For WRG having viscosities from 100 to ~ 1 000 mPa*s, washout by wave energy show moderate effectiveness (60 %), increasing with use of SWA reaching effectiveness in the range of 85 – 95 %.***

***In contrast, washout by wave energy has proven to be insufficient for an effective removal of high wax (>~ 9 wt. %) fuel oils, having viscosities in the range of 5 000 – 60 000 mPa*s. Use of SWA on these oils proved to have limited effect.***

## 4.3 Effectiveness of high pressure washing for fuel oil removal – with and without SWA

To study the effectiveness of high pressure washing for fuel oil removal, the Flushing Robot was used. A flushing pressure of 4, 15, 30 and 45 bar at temperatures of 5 and 45 ° C was applied, depending on the physicochemical properties of the oil. The effectiveness of flushing was studied with and without using the SWA Arrow Delta at an agent to oil ratio of 1:5. The effectiveness is given in percent and represents the oil/emulsion loading removed after flushing, compared to the initial loading applied to the tile surface. Example pictures taken of the respective oils/emulsions before and after flushing exposure are shown in Appendix F.

## MGO 250 °C+

MGO 250 °C+ show high effectiveness (> 90 %) already at the lowest exposure degrees, using 5 °C flushing water and 4 bars flushing pressure, see Figure 4-8. Use of SWA, increased flushing pressure and washing temperatures showed therefore to be redundant.

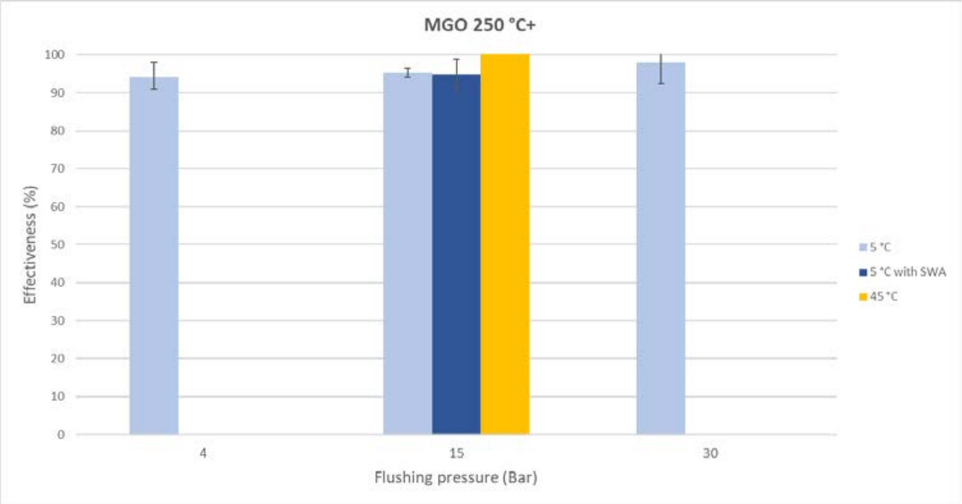


**Figure 4-8 Effectiveness of different flushing pressures, at low and high flushing temperatures, with and without use of SWA on MGO 250 °C+ (viscosity: 20 mPa*s at 10s-1), performed at 5 °C.**

## WRG and WRG emulsified

WRG show good effectiveness (> 80 %) already at the lowest exposure degrees, using 5 °C flushing water and 4 bars flushing pressure, see Figure 4-9. Due to minimal difference in viscosity between the unemulsified and emulsified WRG, the emulsified WRG was tested using a limited test regime, showing effectiveness between 80-100 % at 15 bar, even without use of SWA and high temperate flushing water, see Figure 4-10.

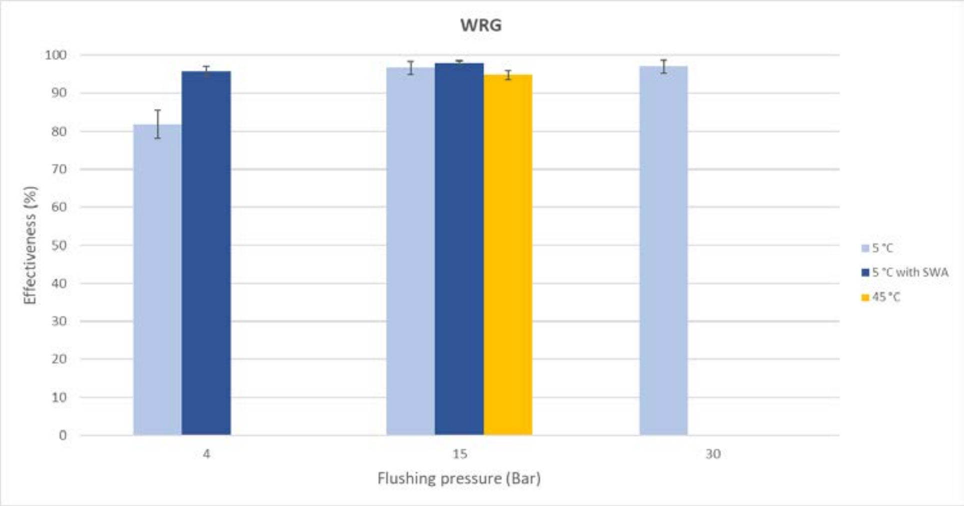


**Figure 4-9 Effectiveness of different flushing pressures, at low and high flushing temperatures, with and without use of SWA on WRG (viscosity: 102 mPa*s at 10s$^{-1}$), performed at 5 °C.**

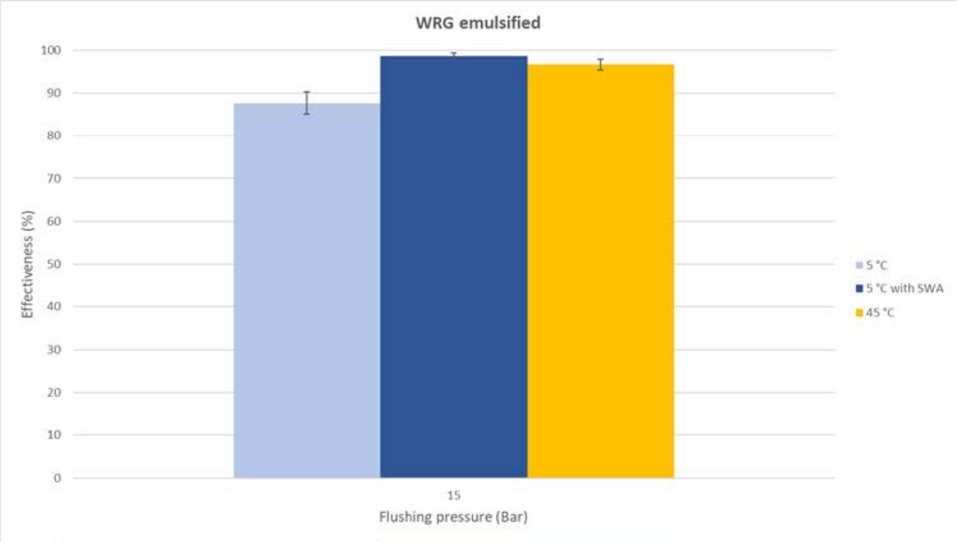


**Figure 4-10 Effectiveness of flushing at 15 bar, at low and high temperatures, with and without use of SWA on WRG emulsified (50 % wio, viscosity: ~ 685 mPa*s at 10s$^{-1}$), performed at 5 °C.**

## HDME 50 and HDME 50 emulsified

For unemulsified HDME 50, flushing using cold water (5 °C) showed low effectiveness, despite an increase in flushing pressure, see Figure 4-11. Use of SWA showed only a limited positive effect, increasing the effectiveness of the flushing from about 0-10 to about 15-25 %. By increasing the flushing temperature to 45 °C, the flushing effectiveness was enhanced considerable, successively increasing with an increase in flushing pressure, reaching an effectiveness > 80 % at 30 bar. The high flushing temperature showed to be quite dominating, showing little effect by use of SWA.

The emulsified HDME, having an increased viscosity compared to the unweathered, show effectiveness results of 90 % already at 15 bars, using low flushing temperatures (5 °C), see Figure 4-12. As Table 3-2 shows, the wax content of HDME 50 is quite high (9.5 wt. %). The increased response to flushing is therefore probably due to the reduced oil amount, as HDME 50 achieves an oil in water emulsion of ~ 45 % at 5 °C. The wax content, known to enhance the adherence to bedrock, will then also be reduced, making it more receptible for washout. For the lowest flushing pressure (4 bar), use of SWA showed little effect, increasing the flushing effectiveness from 40 to 55% at a flushing temperature of 5 °C, and from about 50 % to 70 % at a flushing temperature of 45 °C. At higher flushing pressures (15, 30 and 45 bar), the effectiveness of the flushing was so hight (> 90 %), that the effect by using SWA was limited.

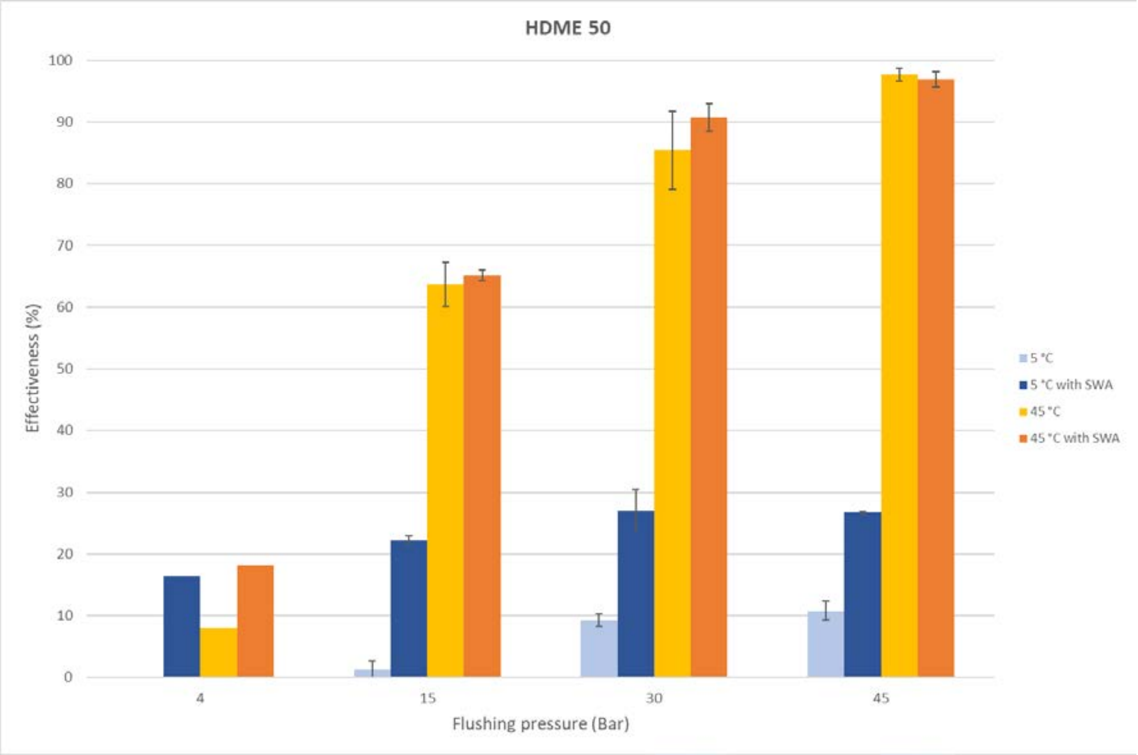


**Figure 4-11 Effectiveness of different flushing pressures, at low and high flushing temperatures, with and without use of SWA on HDME 50 (viscosity: 5 045 mPa*s at 10s$^{-1}$), performed at 5 °C.**

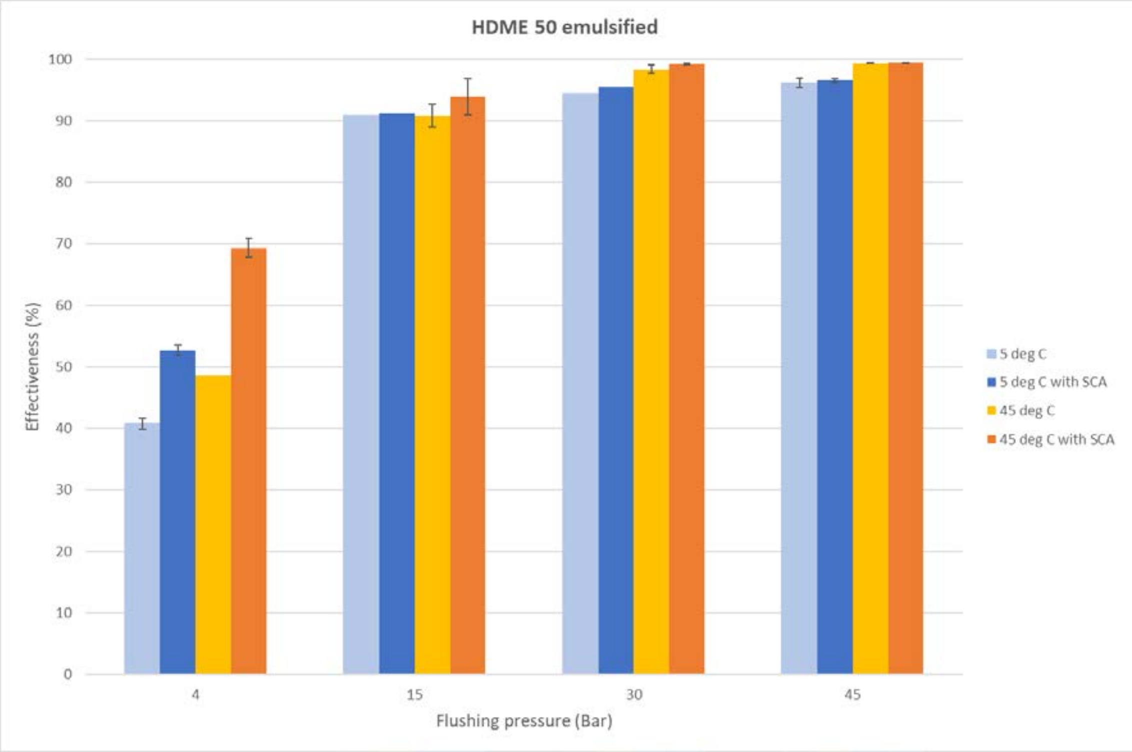


**Figure 4-12 Effectiveness of different flushing pressures, at low and high temperatures, with and without use of SWA on HDME 50 emulsified (46 % wio, viscosity: ~ 9 600 mPa*s at 10s$^{-1}$), performed at 5 °C.**

## ULSFO and ULSFO emulsified

For both unemulsified and emulsified ULSFO, having pour point above the test temperature of 5 °C and viscosities of ~ 50 000, flushing using cold water (5 °C) showed limited effectiveness, despite an increase in flushing pressure (for the unemulsified oil), see Figure 4-13 and Figure 4-14. Use of SWA increased the effectiveness from about 0 to 20 %, still showing low effectiveness results. Increasing the flushing temperature to 45 °C caused a considerable increase in flushing effectiveness, from about 5 % to 65 % at 45 bars. The high flushing temperature showed to be quite dominating, showing little effect by applying SWA. The emulsified ULSFO, achieving a water content of 10 % at 5 °C and increasing in viscosity from ~ 42 000 to ~ 58 000 mPa*s, show a slight increased washout effectiveness compared to the unweathered. This can, as for HDME 50, be explained by the decreased oil amount in emulsions, reducing the wax content per area and hence the emulsions adherence to the bedrock.

As a supplementary study, pre-heating was used to stimulate the effect by using SWA. The oil was tried pre-heated using hot water prior application of SWA and later flushing following the procedure. By pre-heating the oil, the viscosity will be lowered and the SWA may have the opportunity to migrate into the oil/emulsion sufficiently. Even by applying pre-treatment of the oil, the SWA showed little effect, only increasing the effectiveness with about 10 %. Pre-heating the oil for 5 min, caused the oil to run off the tile, reaching an effectiveness of about 100 % even before use of SWA. The different methods used in this process is shown in Figure 4-13 and Figure 4-14.

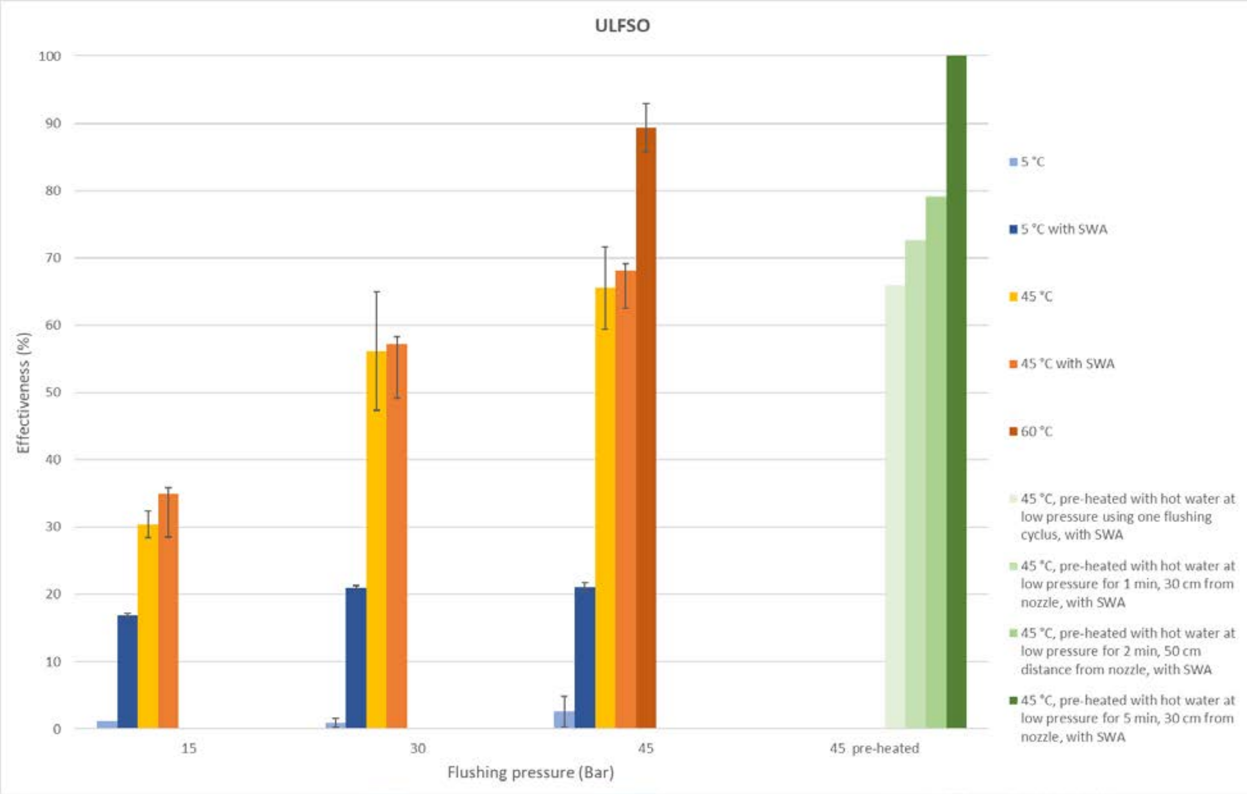


**Figure 4-13 Effectiveness of different flushing pressures, at low and high temperatures, with and without use of SWA on ULSFO (viscosity: 42 029 mPa*s at 10s$^{-1}$), performed at 5 °C.**

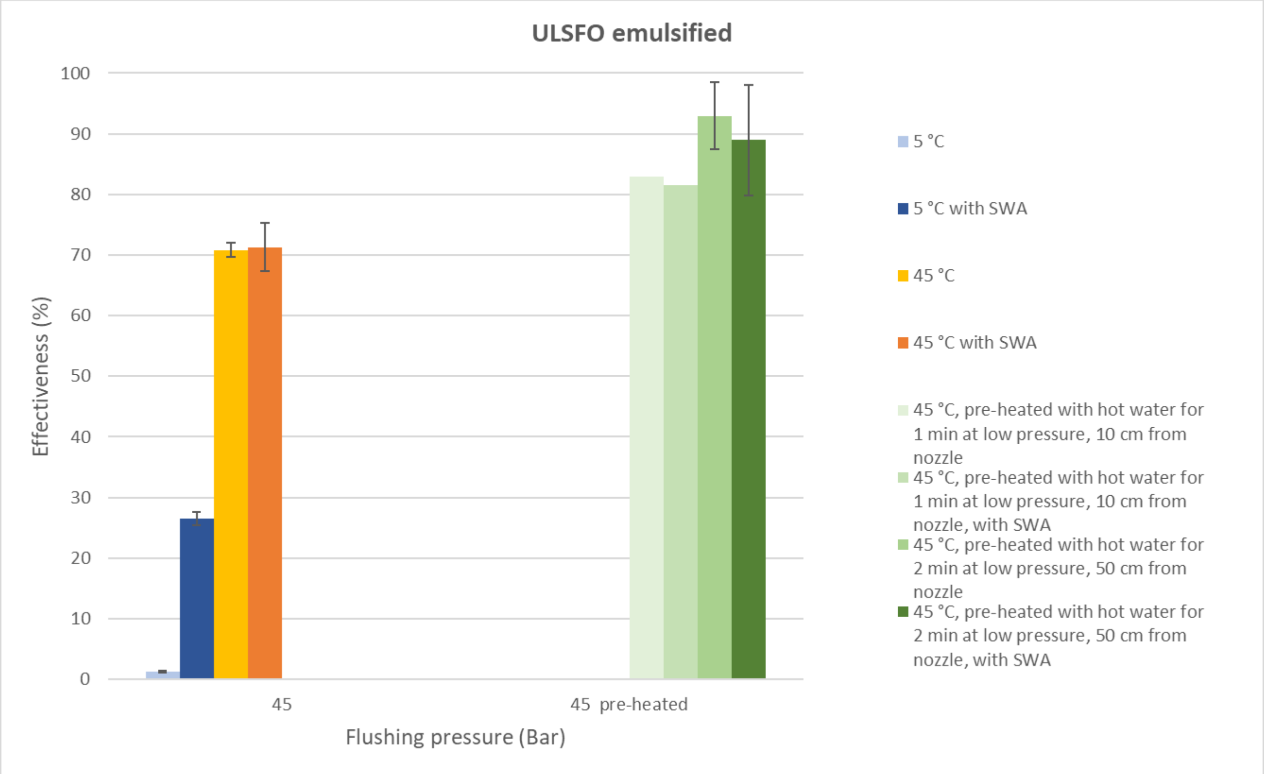


**Figure 4-14 Effectiveness of flushing at 45 bar, at low and high temperatures, with and without use of SWA on ULSFO emulsified (10 % wio, viscosity: ~ 58 200 mPa*s at 10s$^{-1}$), performed at 5 °C.**

***<u>Essential findings</u>:***

***The low viscous fuel oils MGO and WRG (< 1 000 mPa*s at 10s-1), having low contents of wax and asphaltenes, are very receptible for flushing. These fuel oils have the potential to achieve > 80 % flushing effectiveness, even at low flushing temperatures (5 °C) and pressure (15 bar). Use of SWA showed to be redundant.***

***For unemulsified HDME 50, having pour point above ambient temperature and viscosities about 5 000, high temperature flushing (> 45 ° C) was needed to get an efficient washout, as an increase in flushing pressure alone showed to have limited effect. Use of SWA proved to enhance the washout effectiveness by 15-20 % at a flushing temperature of 5 °C. For emulsified HDME 50, the flushing process showed to be more efficient (despite having a higher viscosity), as the oil loading is less compared to unemulsified oil, reaching very good effectiveness (> 90 %) already at low flushing temperatures and pressures. The use of SWA showed then be redundant.***

***For both unemulsified and emulsified ULSFO fuel oil, having pour point above ambient temperature and viscosities about 40 000 - 60 000 mPa*s, high temperature flushing (> 45 ° C) at high flushing pressures (45 bar) was needed to get an efficient washout, as an increase in flushing pressure alone showed limited effect. At high flushing temperatures (> 45 ° C), the temperature showed to dominate the effect of SWA.***

## 5 Conclusions and recommendations for further documentation of other VLSFO

Penetration and remobilization studies in shoreline sediments, using the Sediment Column System, show that the penetration of low viscous oils (< ~ 1 000 mPa*s at 10 $s^{-1}$), having low contents of asphaltenes and waxes (as for MGO 250 °C+ and WRG), will be between 20-50 cm, the emulsified oils penetrating less than the unemulsified oils. The reduced penetration is primarily due to the reduced oil content in emulsions. In addition to the oil loading factor, the emulsified WRG had a higher viscosity than the unemulsified (760 versus 100 mPa*s), which also will contribute to a reduction in penetration depth. Even though most of the penetration show to occur during the first tidal cycle, the penetration continues with time. For these oils, < 15 % of the oil/emulsion was remobilized from the sediment. The lowest viscous oil MGO (having viscosities between 20 and 230 mPa*s) was evenly distributed in the upper 20 cm of the sediment column, the oil concentration potentially even increasing further down in the sediment column. WRG (having viscosities from 100 to 760 mPa*s), showed decreasing concentration profiles from the top and down. In contrast, the high wax and viscous oils HDME 50 and ULSFO, having pour points (12 and 24 °) above the test temperature of 5 °C (having viscosities in the range of 5 000 – 60 000 mPa*s), did not penetrate the sediment at all and was remobilized during the next high tide.

The high wax oils HDME 50 and ULSFO, showed to adhere and incorporate sediment grains from the sediment surface, containing 1-5 % sediment. One can assume that the sediment load would be greater for oils on wave exposed shorelines, where sediment relocation would take place. This would affect the further fate, as remobilization and sedimentation of the oils. SINTEF would based on this expectations, recommend to perform tests to study the different oils sediment uptake from a sediment shoreline and perform sedimentation tests to find the sediment load needed for a sedimentation process to take place. This would give important knowledge on the fate and behaviour of ULSFOs in a coastal oil spill situation and could potentially be used in model tools to predict the fate of such oil spills.

The washout of fuel oils from bedrock, by simulated wave energy using the Simulated Shoreline System, showed very good washout effectiveness (> 90 %) for the very low viscous oil MGO (< 230 mPa*s). Use of SWA for this category of oils will therefore be redundant. For WRG (having viscosities ranging from 100 to 760 mPa*s at 10 $s^{-1}$as emulsified), the washout showed moderate effectiveness (60-80 %), increasing with use of SWA reaching effectiveness in the range of 85 – 95 %. In contrast, washout by wave energy has proven to be insufficient for an effective removal of high wax and viscous fuel oils, as HDME 50 and ULSFO, showing washout effectiveness levels of < 25 %, even with use of SWA. The purpose for use of SWA is to reduce the viscosities of the oils, making the oil/emulsion more receptive for washout. Use of SWA will therefore have greatest potential on oils with viscosities > 1 000 mPa*s. Still, use of SWA on this category of oils, have proven to have limited effect. This might be due to the oils high wax content, reflected in high pour point, making it semi solid and hence less penetrable, causing a reduction in the mixing of oil and SWA.

Flushing, with the intention of fuel oil removal from bedrock, using the Flushing Robot, show that the low viscous fuel oils MGO and WRG (< 1 000 mPa*s), having low contents of wax and asphaltenes, are very receptible for flushing. This category of fuel oils has the potential to achieve > 80 % flushing effectiveness, even at low flushing temperatures (5 °C) and pressure (15 bar). Use of SWA will therefore be redundant. For fuel oils having higher viscosities (~ 5 000 – 10 000 mPa*s), as HDME 50, the wax content of the oil will be important, as oils having high wax content has a greater ability to adhere to the substrate. For this category of oils, having high wax content, an increase in flushing temperature may be needed (> 45 °C), as an increase in flushing pressure may not be enough to achieve satisfactory remediation. Use of SWA has proven to enhance the washout effectiveness by 15-20 % at a flushing temperature of 5 °C. The water content of the oil will also be important, as this will reduce the oil amount per area, adhering less to the surface, reaching greater flushing effectiveness at lower flushing temperatures and pressures. The use of

SWA may then be unnecessary. For ULSFO, having a high wax contents and viscosities ranging from 40 000 to 60 000 mPa*s at 10 $s^{-1}$ (depending on the water content), high temperature flushing (> 45 ° C) in combination with high flushing pressure will be needed to get an efficient washout, as increasing the flushing pressure alone have shown limited effect. High flushing temperature have shown to dominate the effect of SWA.

**Recommendation**

The fuel oil studied in this project is categorised as ULSFOs as they all have a sulphur content of < 0.1 %. As the majority of the oils used by ships along the Norwegian Coast are in the VLSFO category (having sulphur content of < 0.5 %), a similar study looking at the VLSFOs fate and behaviour in contact with the shoreline, and whether measures as flushing and use of shoreline cleaning agents can increase the washout efficiency, would be valuable. This in order to get a more complete picture of the great span in properties of the new generation of low sulphur fuel oils (ULSFO and VLSFO), that influence the mitigation process when stranding.

To study the effect of photooxidation would in this context be valuable, as photooxidation is known to increase the oils viscosity and effect the stability of emulsions created at sea.

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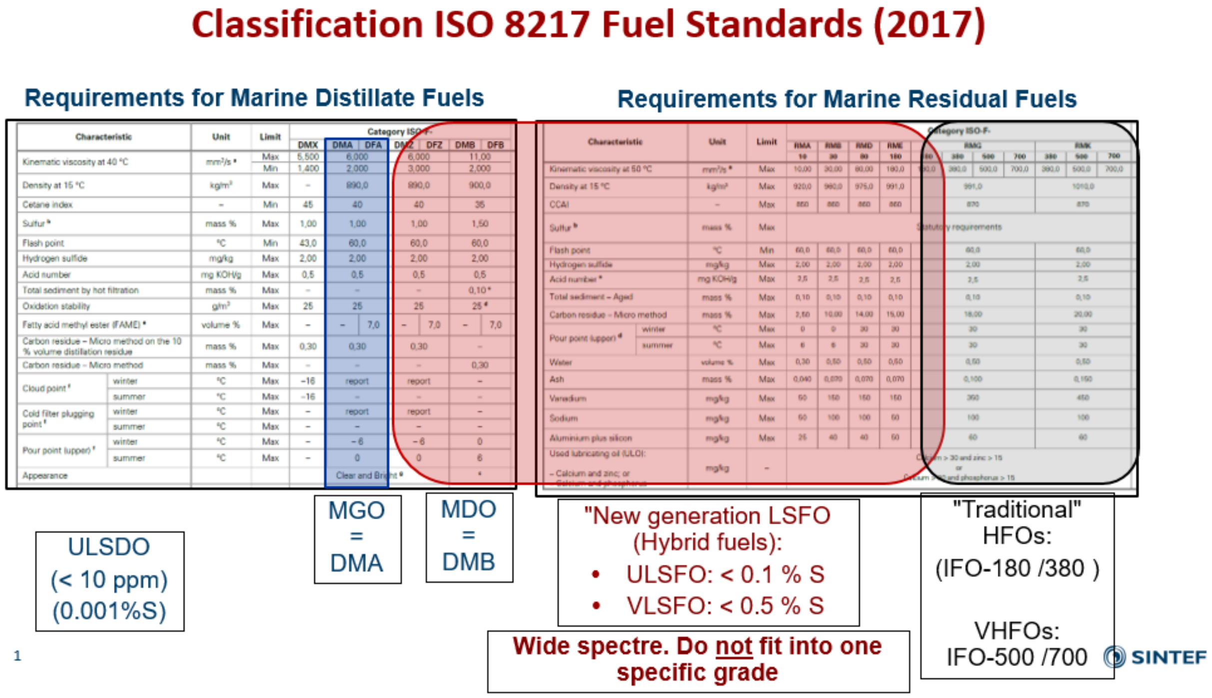
Øksenvåg, J.H.C., Daling P., Ramstad, S. and Bakken, O.M., 2010: *C13.10 and C16.10-30 – Development of test protocols for dispersibility and effectiveness testing of shoreline cleaning agents (SCAs) and effectiveness results for 9 selected SCAs - Revised version 1, Coastal Oil Spills JIP. Report No. 23* (SINTEF F12806) - Restricted.

Øksenvåg, J.H.C., Daling P., Ramstad S. and Bakken, O.M., 2010: *C16.40 and 50 – Window of opportunity for shoreline cleaning agents (SCAs) on various weathered oils on shale tiles - Revised version 1, Coastal Oil Spills JIP. Report No. 24*. (SINTEF F13691) - Restricted.

Øksenvåg, J.H.C., McFarlin, K., Netzer, R., Brakstad, O.G., Hansen, B.H. and Størseth, T., 2018: *Biodegradation of Spilled Fuel Oil in Norwegian Marine Environments – A literature Review.* (OC2017 A-218) – Unrestricted.

# Appendix

## A ISO category for Fuel Standards 2017



Classification ISO 8217 Fuel Standards (2017)

Requirements for Marine Distillate Fuels

| Characteristic | | Unit | Limit | DMX | DMA | DFA | DMZ | DFZ | DMB | DFB |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Category ISO-F- | | | | | | |
| Kinematic viscosity at 40 °C | | mm$^2$/s [a] | Max | 5,500 | 6,000 | | 6,000 | | 11,00 | |
| | | | Min | 1,400 | 2,000 | | 3,000 | | 2,000 | |
| Density at 15 °C | | kg/m$^3$ | Max | – | 890,0 | | 890,0 | | 900,0 | |
| Cetane index | | – | Min | 45 | 40 | | 40 | | 35 | |
| Sulfur [b] | | mass % | Max | 1,00 | 1,00 | | 1,00 | | 1,50 | |
| Flash point | | °C | Min | 43,0 | 60,0 | | 60,0 | | 60,0 | |
| Hydrogen sulfide | | mg/kg | Max | 2,00 | 2,00 | | 2,00 | | 2,00 | |
| Acid number | | mg KOH/g | Max | 0,5 | 0,5 | | 0,5 | | 0,5 | |
| Total sediment by hot filtration | | mass % | Max | – | – | | – | | 0,10 [c] | |
| Oxidation stability | | g/m$^3$ | Max | 25 | 25 | | 25 | | 25 [d] | |
| Fatty acid methyl ester (FAME) [e] | | volume % | Max | – | – | 7,0 | – | 7,0 | – | 7,0 |
| Carbon residue – Micro method on the 10 % volume distillation residue | | mass % | Max | 0,30 | 0,30 | | 0,30 | | – | |
| Carbon residue – Micro method | | mass % | Max | – | – | | – | | 0,30 | |
| Cloud point [f] | winter | °C | Max | −16 | report | | report | | – | |
| | summer | °C | Max | −16 | – | | – | | – | |
| Cold filter plugging point [f] | winter | °C | Max | – | report | | report | | – | |
| | summer | °C | Max | – | – | | – | | – | |
| Pour point (upper) [f] | winter | °C | Max | – | −6 | | −6 | | 0 | |
| | summer | °C | Max | – | 0 | | 0 | | 6 | |
| Appearance | | | | | Clear and Bright [g] | | | | [c] | |

Requirements for Marine Residual Fuels

| Characteristic | | Unit | Limit | RMA 10 | RMB 30 | RMD 80 | RME 180 | RMG 180 | RMG 380 | RMG 500 | RMG 700 | RMK 380 | RMK 500 | RMK 700 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Category ISO-F- | | | | | | | | | | |
| Kinematic viscosity at 50 °C | | mm$^2$/s [a] | Max | 10,00 | 30,00 | 80,00 | 180,0 | 180,0 | 380,0 | 500,0 | 700,0 | 380,0 | 500,0 | 700,0 |
| Density at 15 °C | | kg/m$^3$ | Max | 920,0 | 960,0 | 975,0 | 991,0 | 991,0 | | | | 1010,0 | | |
| CCAI | | – | Max | 850 | 860 | 860 | 860 | 870 | | | | 870 | | |
| Sulfur [b] | | mass % | Max | Statutory requirements | | | | | | | | | | |
| Flash point | | °C | Min | 60,0 | 60,0 | 60,0 | 60,0 | 60,0 | | | | 60,0 | | |
| Hydrogen sulfide | | mg/kg | Max | 2,00 | 2,00 | 2,00 | 2,00 | 2,00 | | | | 2,00 | | |
| Acid number [c] | | mg KOH/g | Max | 2,5 | 2,5 | 2,5 | 2,5 | 2,5 | | | | 2,5 | | |
| Total sediment – Aged | | mass % | Max | 0,10 | 0,10 | 0,10 | 0,10 | 0,10 | | | | 0,10 | | |
| Carbon residue – Micro method | | mass % | Max | 2,50 | 10,00 | 14,00 | 15,00 | 18,00 | | | | 20,00 | | |
| Pour point (upper) [d] | winter | °C | Max | 0 | 0 | 30 | 30 | 30 | | | | 30 | | |
| | summer | °C | Max | 6 | 6 | 30 | 30 | 30 | | | | 30 | | |
| Water | | volume % | Max | 0,30 | 0,50 | 0,50 | 0,50 | 0,50 | | | | 0,50 | | |
| Ash | | mass % | Max | 0,040 | 0,070 | 0,070 | 0,070 | 0,100 | | | | 0,150 | | |
| Vanadium | | mg/kg | Max | 50 | 150 | 150 | 150 | 350 | | | | 450 | | |
| Sodium | | mg/kg | Max | 50 | 100 | 100 | 50 | 100 | | | | 100 | | |
| Aluminium plus silicon | | mg/kg | Max | 25 | 40 | 40 | 50 | 60 | | | | 60 | | |
| Used lubricating oil (ULO):<br>– Calcium and zinc; or<br>– Calcium and phosphorus | | mg/kg | – | Calcium > 30 and zinc > 15<br>or<br>Calcium > 30 and phosphorus > 15 | | | | | | | | | | |

MGO
=
DMA

MDO
=
DMB

ULSDO
(< 10 ppm)
(0.001%S)

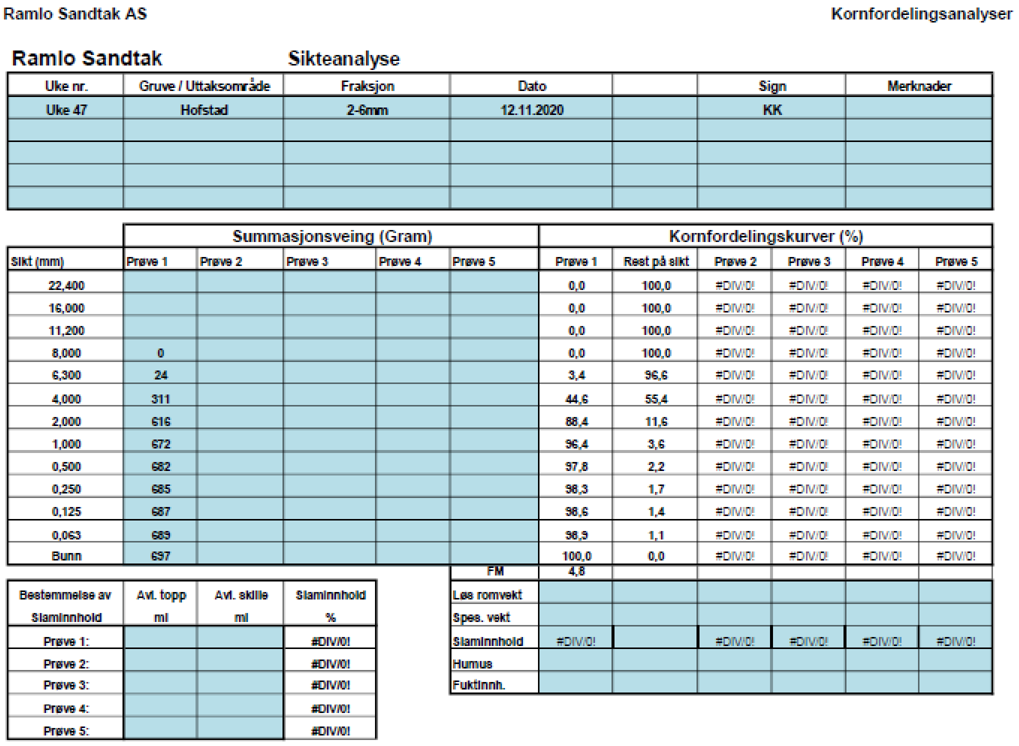
"New generation LSFO
(Hybrid fuels):
- ULSFO: < 0.1 % S
- VLSFO: < 0.5 % S

**Wide spectre. Do <u>not</u> fit into one specific grade**

"Traditional"
HFOs:
(IFO-180 /380 )

VHFOs:
IFO-500 /700

# B The sieve analyse from Ramlo Sandtak



Ramlo Sandtak AS

Kornfordelingsanalyser

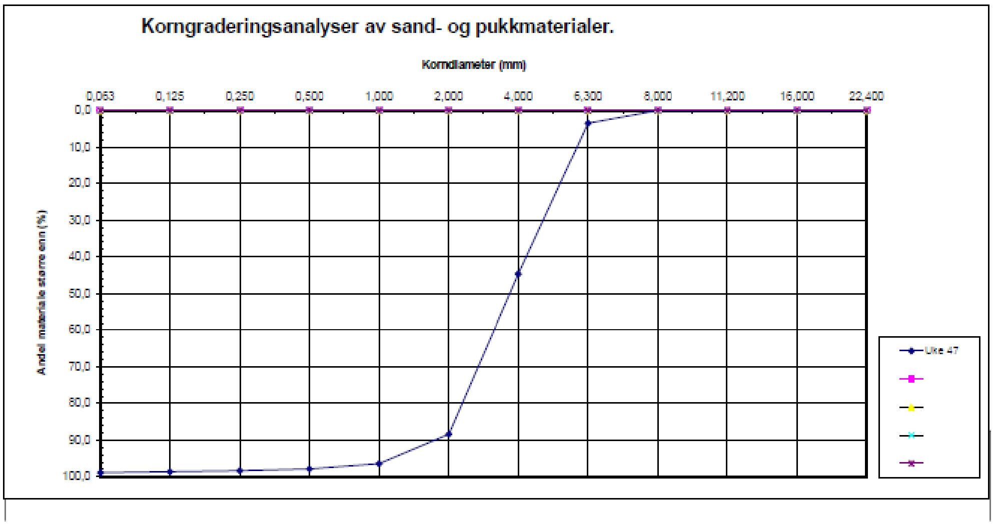
**Ramlo Sandtak** **Sikteanalyse**

| Uke nr. | Gruve / Uttaksområde | Fraksjon | Dato | | Sign | Merknader |
|---|---|---|---|---|---|---|
| Uke 47 | Hofstad | 2-6mm | 12.11.2020 | | KK | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

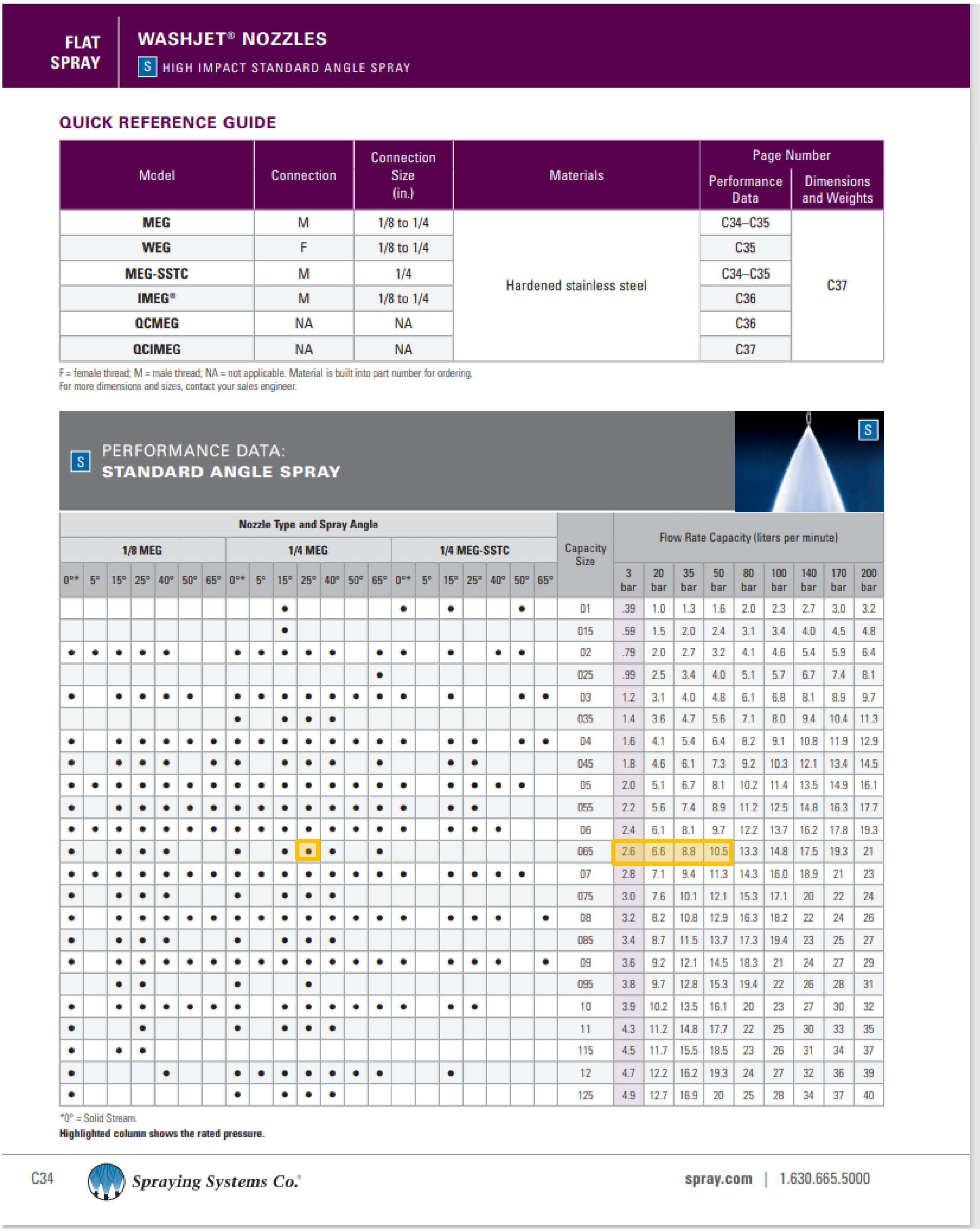
| | Summasjonsveing (Gram) | | | | | Kornfordelingskurver (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sikt (mm) | Prøve 1 | Prøve 2 | Prøve 3 | Prøve 4 | Prøve 5 | Prøve 1 | Rest på sikt | Prøve 2 | Prøve 3 | Prøve 4 | Prøve 5 |
| 22,400 | | | | | | 0,0 | 100,0 | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| 16,000 | | | | | | 0,0 | 100,0 | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| 11,200 | | | | | | 0,0 | 100,0 | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| 8,000 | 0 | | | | | 0,0 | 100,0 | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| 6,300 | 24 | | | | | 3,4 | 96,6 | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| 4,000 | 311 | | | | | 44,6 | 55,4 | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| 2,000 | 616 | | | | | 88,4 | 11,6 | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| 1,000 | 672 | | | | | 96,4 | 3,6 | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| 0,500 | 682 | | | | | 97,8 | 2,2 | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| 0,250 | 685 | | | | | 98,3 | 1,7 | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| 0,125 | 687 | | | | | 98,6 | 1,4 | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| 0,063 | 689 | | | | | 98,9 | 1,1 | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| Bunn | 697 | | | | | 100,0 | 0,0 | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| | | | | | FM | 4,8 | | | | | |

| Bestemmelse av Slaminnhold | Avl. topp ml | Avl. skille ml | Slaminnhold % |
|---|---|---|---|
| Prøve 1: | | | #DIV/0! |
| Prøve 2: | | | #DIV/0! |
| Prøve 3: | | | #DIV/0! |
| Prøve 4: | | | #DIV/0! |
| Prøve 5: | | | #DIV/0! |

| | | | | | | |
|---|---|---|---|---|---|---|
| Løs romvekt | | | | | | |
| Spes. vekt | | | | | | |
| Slaminnhold | #DIV/0! | | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! |
| Humus | | | | | | |
| Fuktinnh. | | | | | | |



# C Nozzle specifications



**FLAT SPRAY**

## WASHJET® NOZZLES

S HIGH IMPACT STANDARD ANGLE SPRAY

### QUICK REFERENCE GUIDE

| Model | Connection | Connection Size (in.) | Materials | Page Number | |
|---|---|---|---|---|---|
| | | | | Performance Data | Dimensions and Weights |
| **MEG** | M | 1/8 to 1/4 | Hardened stainless steel | C34–C35 | C37 |
| **WEG** | F | 1/8 to 1/4 | | C35 | |
| **MEG-SSTC** | M | 1/4 | | C34–C35 | |
| **IMEG®** | M | 1/8 to 1/4 | | C36 | |
| **QCMEG** | NA | NA | | C36 | |
| **QCIMEG** | NA | NA | | C37 | |

F = female thread; M = male thread; NA = not applicable. Material is built into part number for ordering.
For more dimensions and sizes, contact your sales engineer.

S PERFORMANCE DATA:
**STANDARD ANGLE SPRAY**

| Nozzle Type and Spray Angle | | | | | | | | | | | | | | | | | | | | | Capacity Size | Flow Rate Capacity (liters per minute) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1/8 MEG | | | | | | | 1/4 MEG | | | | | | | 1/4 MEG-SSTC | | | | | | | | | | | | | | | | |
| 0°* | 5° | 15° | 25° | 40° | 50° | 65° | 0°* | 5° | 15° | 25° | 40° | 50° | 65° | 0°* | 5° | 15° | 25° | 40° | 50° | 65° | | 3 bar | 20 bar | 35 bar | 50 bar | 80 bar | 100 bar | 140 bar | 170 bar | 200 bar |
| | | | | | | | | | ● | | | | | ● | | ● | | | ● | | 01 | .39 | 1.0 | 1.3 | 1.6 | 2.0 | 2.3 | 2.7 | 3.0 | 3.2 |
| | | | | | | | | | ● | | | | | | | | | | | | 015 | .59 | 1.5 | 2.0 | 2.4 | 3.1 | 3.4 | 4.0 | 4.5 | 4.8 |
| ● | ● | ● | ● | ● | | | ● | ● | ● | ● | ● | | ● | ● | | ● | | ● | ● | | 02 | .79 | 2.0 | 2.7 | 3.2 | 4.1 | 4.6 | 5.4 | 5.9 | 6.4 |
| | | | | | | | | | | | | | ● | | | | | | | | 025 | .99 | 2.5 | 3.4 | 4.0 | 5.1 | 5.7 | 6.7 | 7.4 | 8.1 |
| ● | | ● | ● | ● | ● | | ● | ● | ● | ● | ● | ● | ● | ● | | ● | | | ● | ● | 03 | 1.2 | 3.1 | 4.0 | 4.8 | 6.1 | 6.8 | 8.1 | 8.9 | 9.7 |
| | | | | | | | ● | | ● | ● | ● | | | | | | | | | | 035 | 1.4 | 3.6 | 4.7 | 5.6 | 7.1 | 8.0 | 9.4 | 10.4 | 11.3 |
| ● | | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | | ● | ● | 04 | 1.6 | 4.1 | 5.4 | 6.4 | 8.2 | 9.1 | 10.8 | 11.9 | 12.9 |
| ● | | ● | ● | ● | | ● | ● | | ● | ● | ● | | ● | | | ● | ● | | | | 045 | 1.8 | 4.6 | 6.1 | 7.3 | 9.2 | 10.3 | 12.1 | 13.4 | 14.5 |
| ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | | 05 | 2.0 | 5.1 | 6.7 | 8.1 | 10.2 | 11.4 | 13.5 | 14.9 | 16.1 |
| ● | | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | | | | 055 | 2.2 | 5.6 | 7.4 | 8.9 | 11.2 | 12.5 | 14.8 | 16.3 | 17.7 |
| ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | | | 06 | 2.4 | 6.1 | 8.1 | 9.7 | 12.2 | 13.7 | 16.2 | 17.8 | 19.3 |
| ● | | ● | ● | ● | | | ● | | ● | ● | ● | | ● | | | | | | | | 065 | 2.6 | 6.6 | 8.8 | 10.5 | 13.3 | 14.8 | 17.5 | 19.3 | 21 |
| ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | | 07 | 2.8 | 7.1 | 9.4 | 11.3 | 14.3 | 16.0 | 18.9 | 21 | 23 |
| ● | | ● | ● | ● | | | ● | | ● | ● | ● | | | | | | | | | | 075 | 3.0 | 7.6 | 10.1 | 12.1 | 15.3 | 17.1 | 20 | 22 | 24 |
| ● | | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | | ● | 08 | 3.2 | 8.2 | 10.8 | 12.9 | 16.3 | 18.2 | 22 | 24 | 26 |
| ● | | ● | ● | ● | | | ● | | ● | ● | ● | | | | | | | | | | 085 | 3.4 | 8.7 | 11.5 | 13.7 | 17.3 | 19.4 | 23 | 25 | 27 |
| ● | | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | ● | | ● | 09 | 3.6 | 9.2 | 12.1 | 14.5 | 18.3 | 21 | 24 | 27 | 29 |
| | | ● | ● | | | | ● | | | ● | | | | | | | | | | | 095 | 3.8 | 9.7 | 12.8 | 15.3 | 19.4 | 22 | 26 | 28 | 31 |
| ● | | ● | ● | ● | ● | ● | ● | | ● | ● | ● | ● | ● | ● | | ● | ● | | | | 10 | 3.9 | 10.2 | 13.5 | 16.1 | 20 | 23 | 27 | 30 | 32 |
| ● | | | ● | | | | ● | | ● | ● | ● | | | | | | | | | | 11 | 4.3 | 11.2 | 14.8 | 17.7 | 22 | 25 | 30 | 33 | 35 |
| ● | | ● | ● | | | | | | | | | | | | | | | | | | 115 | 4.5 | 11.7 | 15.5 | 18.5 | 23 | 26 | 31 | 34 | 37 |
| ● | | | | ● | | | ● | ● | ● | ● | ● | ● | ● | | | ● | | | | | 12 | 4.7 | 12.2 | 16.2 | 19.3 | 24 | 27 | 32 | 36 | 39 |
| ● | | | | | | | ● | | ● | ● | ● | | | | | | | | | | 125 | 4.9 | 12.7 | 16.9 | 20 | 25 | 28 | 34 | 37 | 40 |

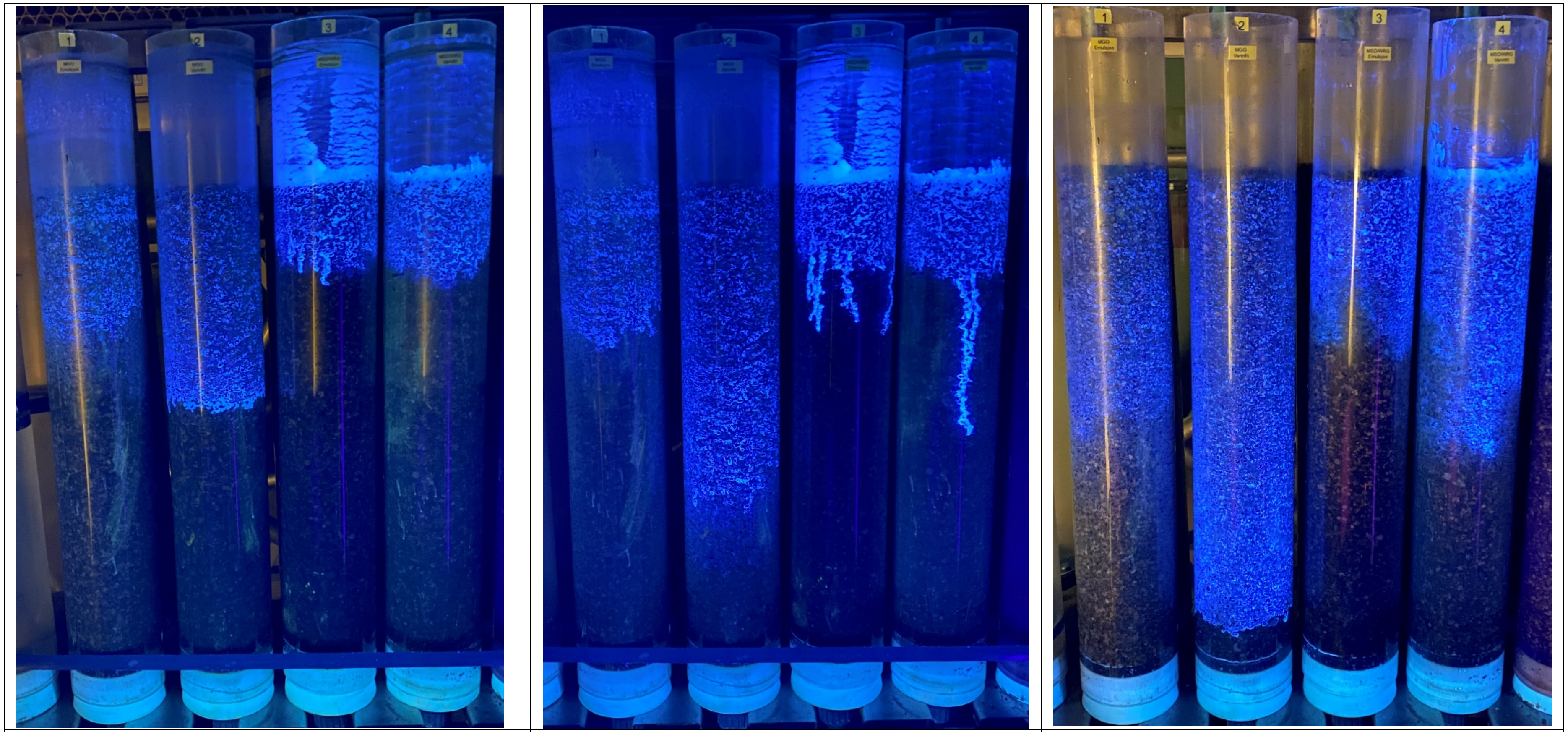
*0° = Solid Stream.

**Highlighted column shows the rated pressure.**

C34 Spraying Systems Co.® spray.com | 1.630.665.5000

https://www.spray.com/-/media/dam/industrial/usa/sales-material/catalog/cat75hyd_metric_flat-spray_c.pdf

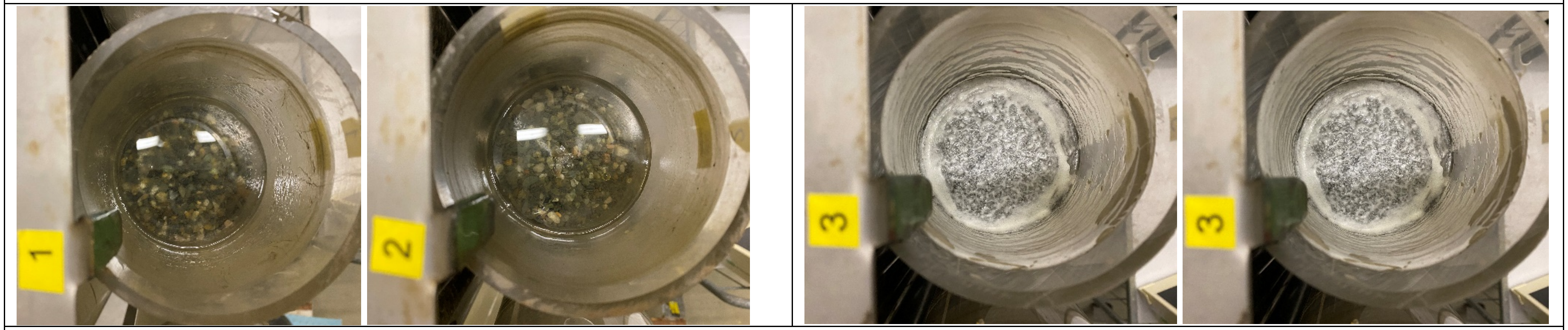
# D Photo documentation from penetration studies using the Sediment Column System.



1st low tide | 2nd low tide | 8th low tide

Figure D-1 Pictures showing the penetration during the tidal cycles in sediments (2-6 mm grain size) using UV-light. The oils are shown in the following order: MGO 250 °C+ emulsified, MGO 250 °C+, WRG emulsified, WRG.

1st low tide

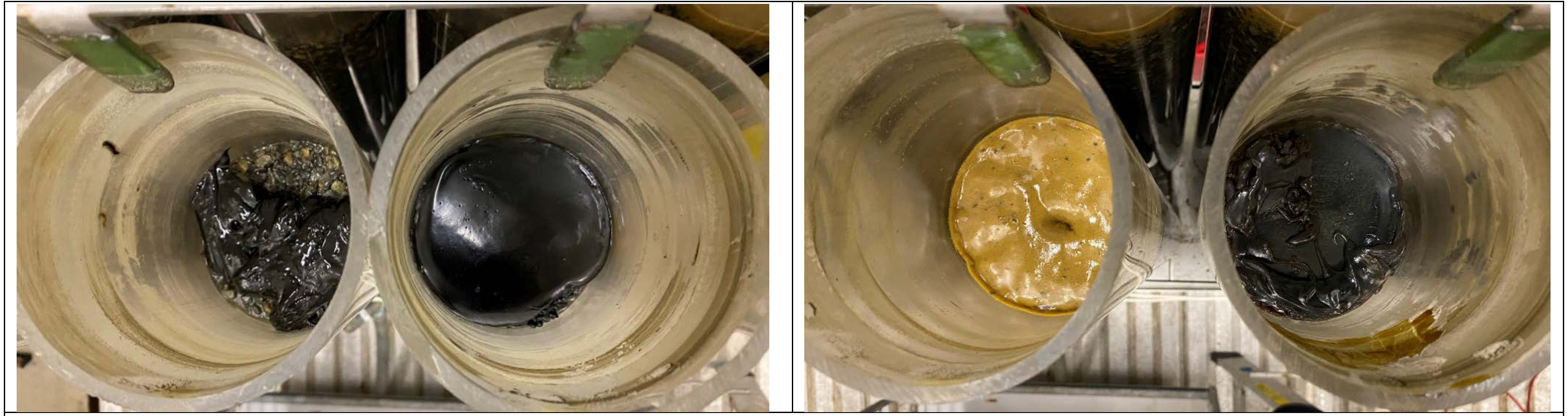


1st high tide

**Figure D-2 Pictures of the sediment surface at the 1st low tide and the 1st high tide. The oils are shown in the following order: MGO 250 °C+ emulsified, MGO 250 °C+, WRG emulsified, WRG.**

1st low tide | 2nd low tide | 8th low tide

**Figure D-3 Pictures showing the penetration during the tidal cycles in sediments (2-6 mm grain size). The oils are shown in the following order: ULSFO emulsified, ULSFO, HDME 50 emulsified and HDME 50.**

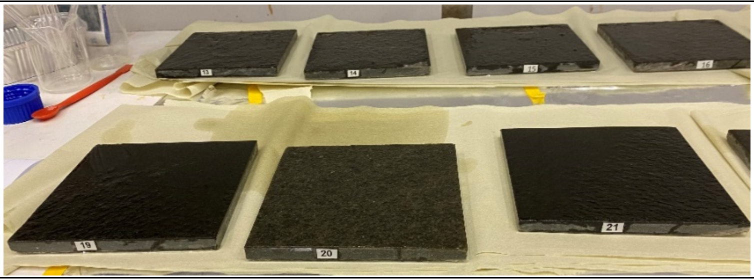
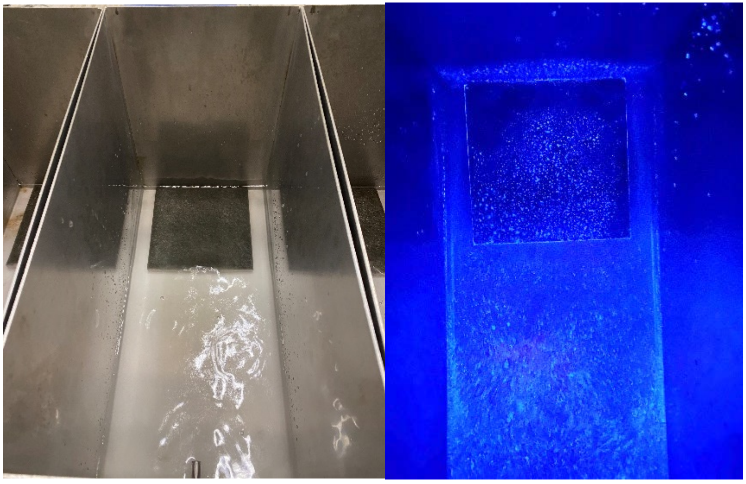


1st low tide

1st high tide

Figure D-4 Pictures of the sediment surface at the 1st low tide and the 1st high tide. The oils are shown in the following order: ULSFO emulsified, ULSFO, HDME 50 emulsified, HDME 50.

# E Photo documentation from washout studies using the Simulated Shoreline System

| | |
|---|---|
|  | **Tiles with emulsion (upper tiles) and oil (lower tiles) before exposure** |
|  | **Tiles with emulsion (upper tiles) and oil (lower tiles) before exposure – with UV-light** |
|  | **Tiles with emulsion during washout using SWA – without and with UV-light** |

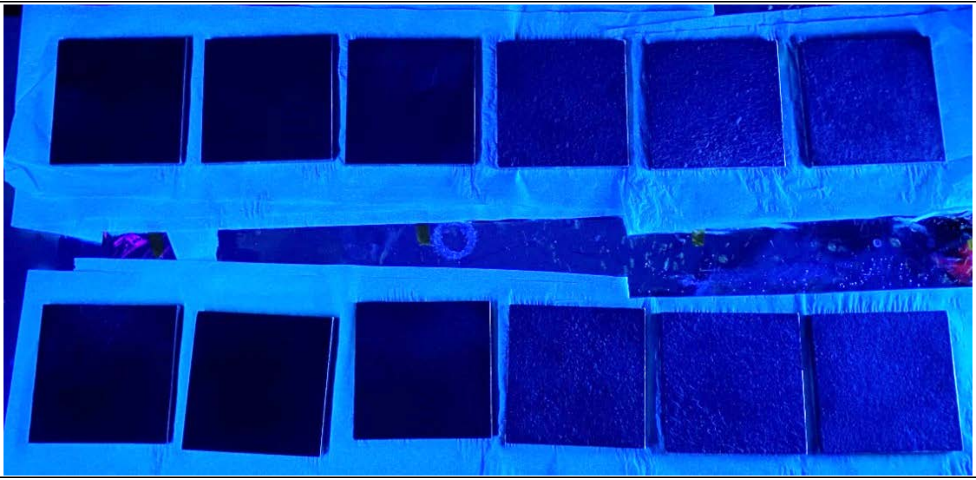
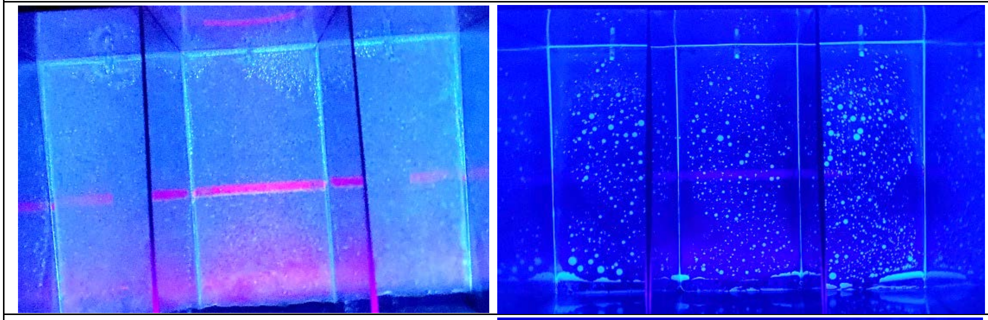
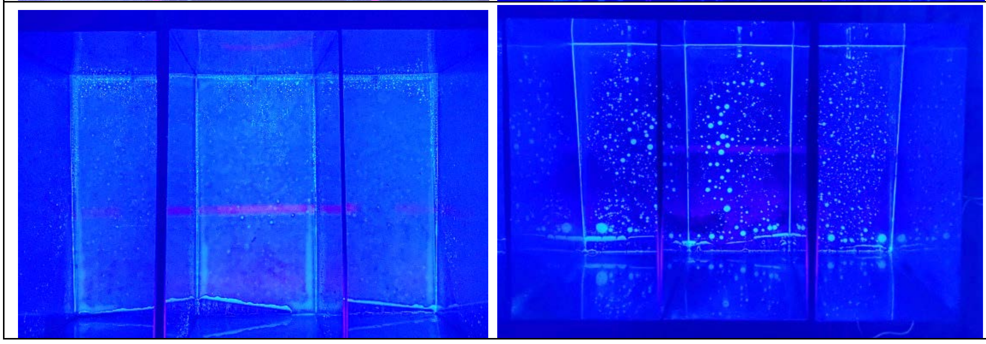
| | |
|---|---|
|  | **Tiles with oil/emulsion after washout.**<br>**In the upper row: Emulsified oil with SWA (three tiles to the left) and without use of SWA (three tiles to the right)**<br>**In the lower row: Unemulsified oil with SWA (three tiles to the left) and without SWA (three tiles to the right)** |
|  | **Emulsion left in resovares after washout with (left) and without using SWA (right)** |
|  | **Oil left in resovares after washout with (left) and without using SWA (right)** |

**Figure E-1 Example images of tiles with weathered MGO 250 °C+ (50 % wio emulsion) before, during, and after washout using the Simulated Shoreline System. The oil/emulsion is visible having a brighter colour than its surroundings due to the reflection of fluorescence using UV-lights. The pink stripe is a side effect by using UV-light.**

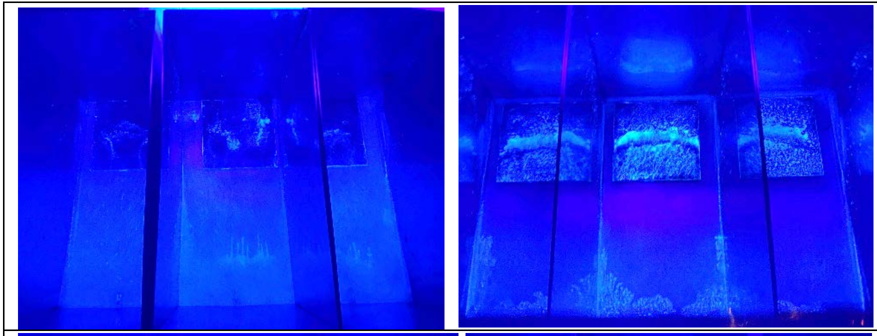
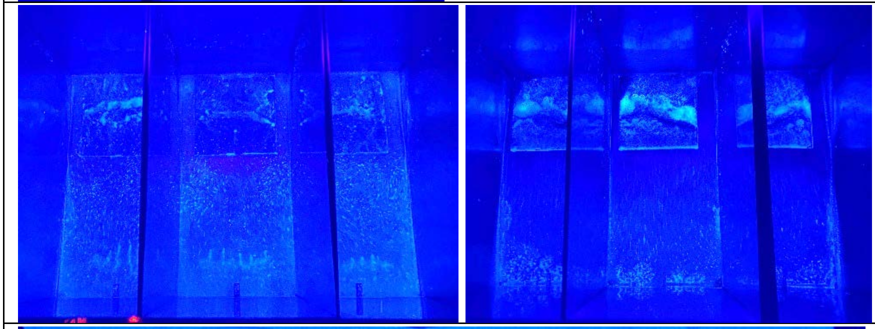
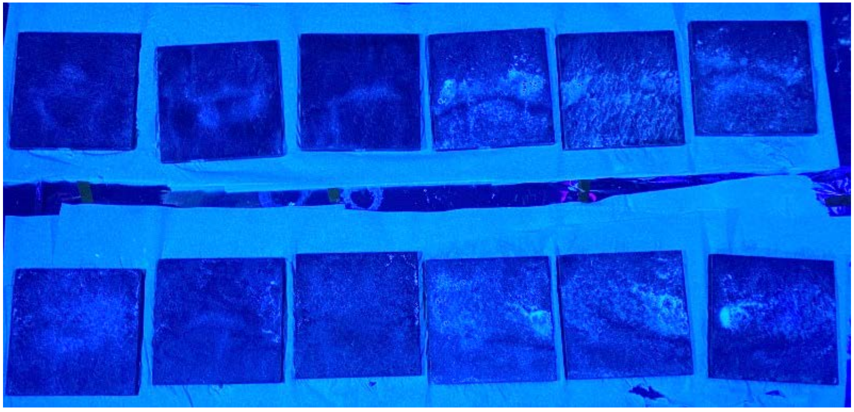
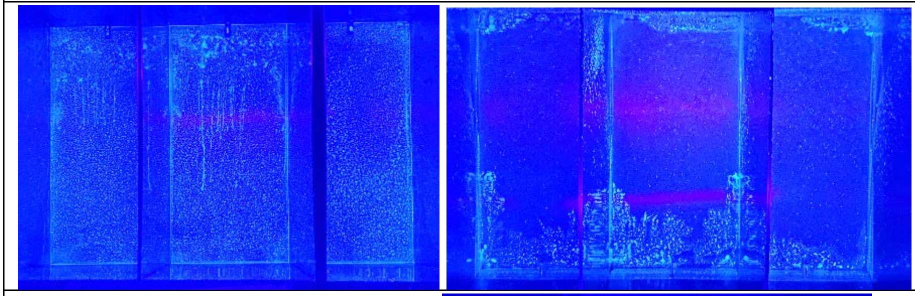
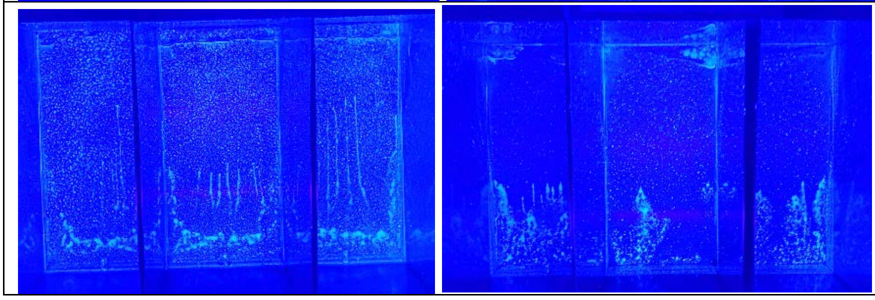
| | |
|---|---|
|  | **Tiles with emulsion during washout, with (left) and without (right) using SWA** |
|  | **Tiles with oil during washout, with (left) and without (right) use of SWA** |
|  | **Tiles with oil/emulsion after washout.**<br>**In the upper row: Emulsified oil with SWA (three tiles to the left) and without use of SWA (three tiles to the right).**<br>**In the lower row: Unemulsified oil with SWA (three tiles to the left) and without SWA (three tiles to the right).** |
|  | **Emulsion left in resovares after washout with (left) and without (right) using SWA** |
|  | **Oil left in resovares after washout with (left) and without (right) using SWA** |

**Figure E-2 Example images of tiles with weathered WRG (50 % wio emulsion) before, during, and after washout using the Simulated Shoreline System. The oil/emulsion is visible having a brighter colour than its surroundings due to the reflection of fluorescence using UV-lights. The pink stripe is a side effect by using UV-light.**

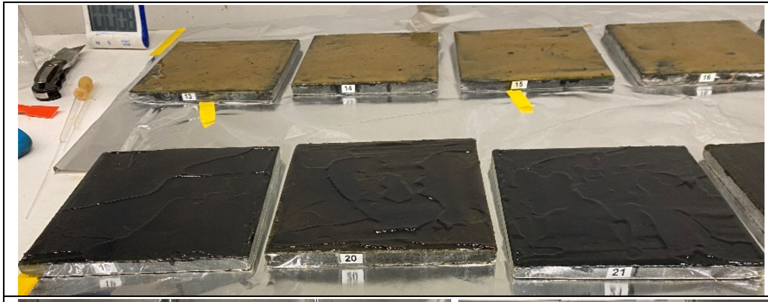
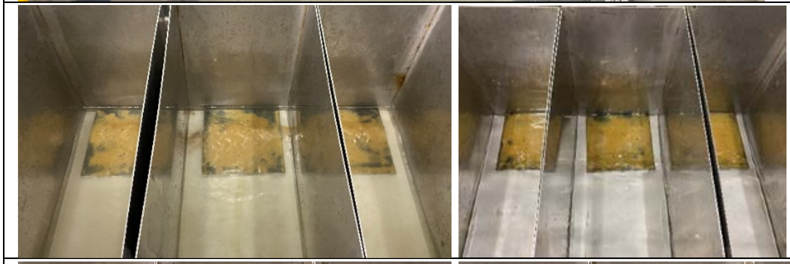
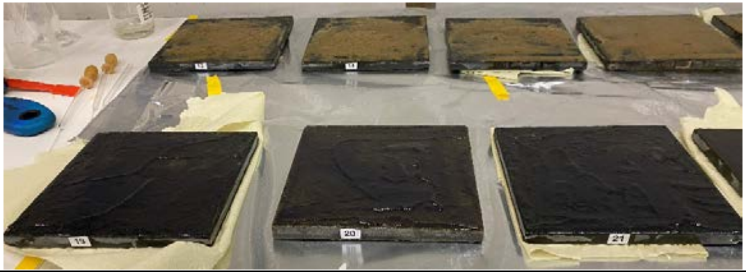
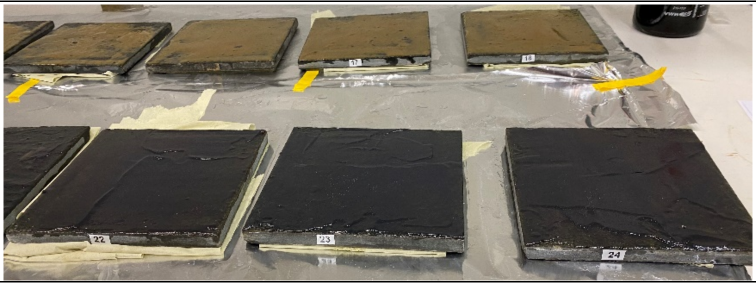
| | |
|---|---|
|  | **Tiles with emulsion (upper tiles) and oil (lower tiles) before exposure** |
|  | **Tiles with weathered oil during washout, with (left) and without (right) use of SWA** |
|  | **Tiles with unweathered oil during washout, with (left) and without (right) use of SWA** |
|  | **Tiles with emulsion (upper tiles) and oil (lower tiles) after washout – with use of SWA** |
|  | **Tiles with emulsion (upper tiles) and oil (lower tiles) after washout** |

**Figure E-3 Example images of tiles with unweathered and weathered HDME 50 (43 % wio emulsion) before, during, and after washout using the Simulated Shoreline System.**

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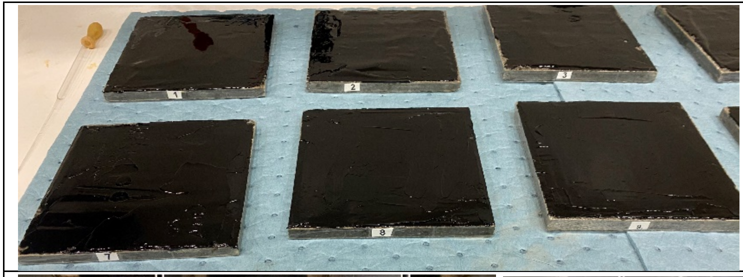
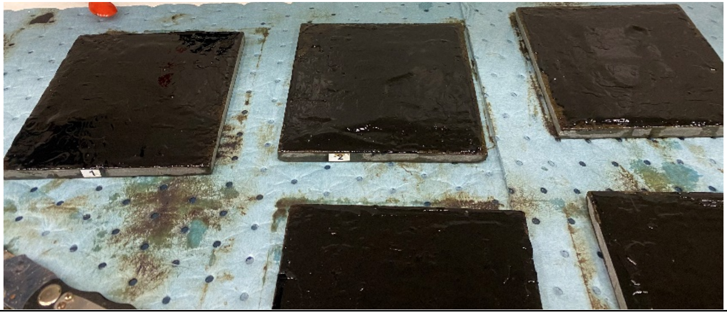
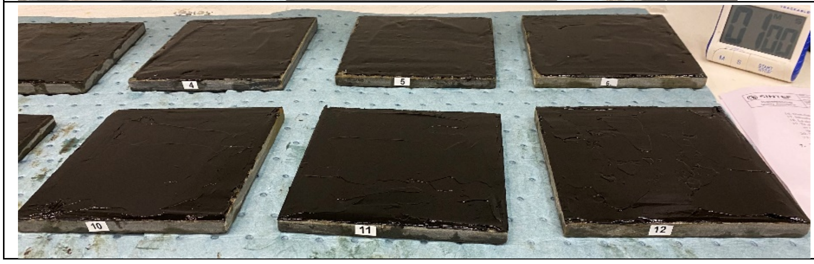
|---|---|
|  | **Tiles with emulsion (upper tiles) and oil (lower tiles) before exposure** |
|  | **Tiles with weathered oil during washout, with (left) and without (right) use of SWA** |
|  | **Tiles with unweathered oil during washout, with (left) and without (right) use of SWA** |
|  | **Tiles with emulsion (upper tiles) and oil (lower tiles) after washout – with use of SWA** |
|  | **Tiles with emulsion (upper tiles) and oil (lower tiles) after washout** |

**Figure E-4 Example images of tiles with unweathered and weathered ULSFO (9 % wio emulsion) before, during, and after washout using the Simulated Shoreline System.**

# F Photo documentation from flushing using the Flushing Robot

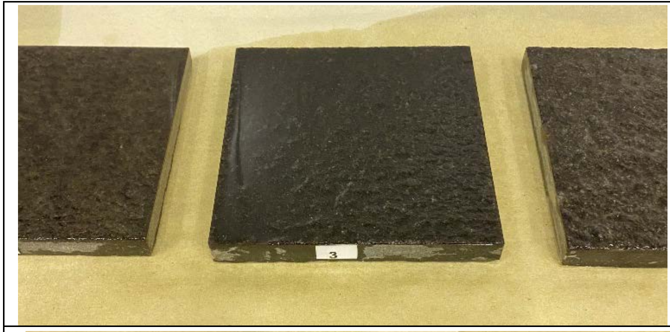
| | |
|---|---|
|  | **Tiles with fuel oil before exposure** |
|  | **Tiles with fuel oil after exposure – 5 °C, 15 bar** |

**Figure F-1 Example images of tiles with MGO 250 °C+ before and after flushing using the Flushing Robot.**

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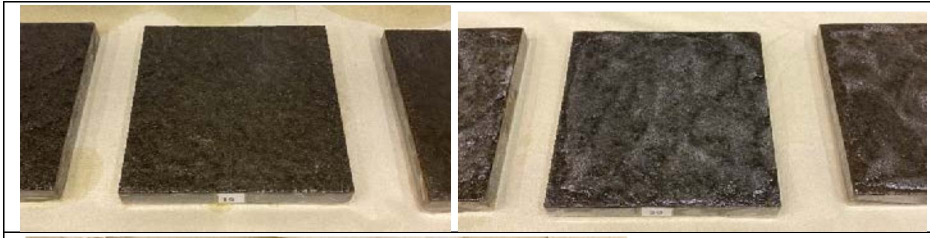
|---|---|
|  | **Tiles with unweathered (left picture) and weathered (right picture) fuel oil before exposure** |
|  | **Tiles with unweathered fuel oil after exposure – 5 °C, 15 bar** |
|  | **Tiles with weathered fuel oil after exposure – 5 °C, 15 bar** |

**Figure F-2 Example images of tiles with unweathered and weathered WRG (50 % wio emulsion), before and after flushing, using the Flushing Robot.**

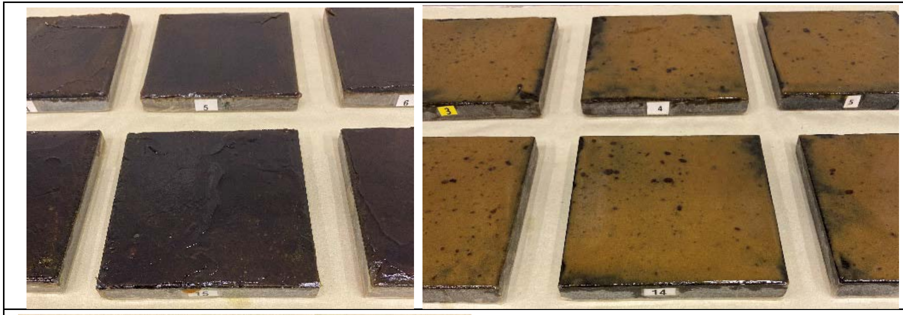
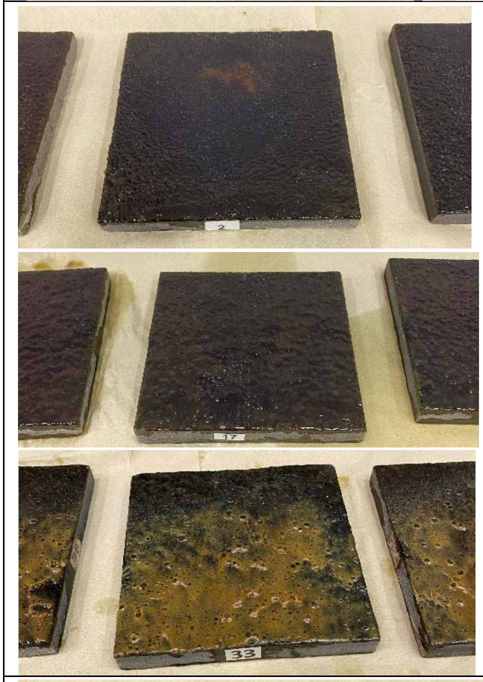
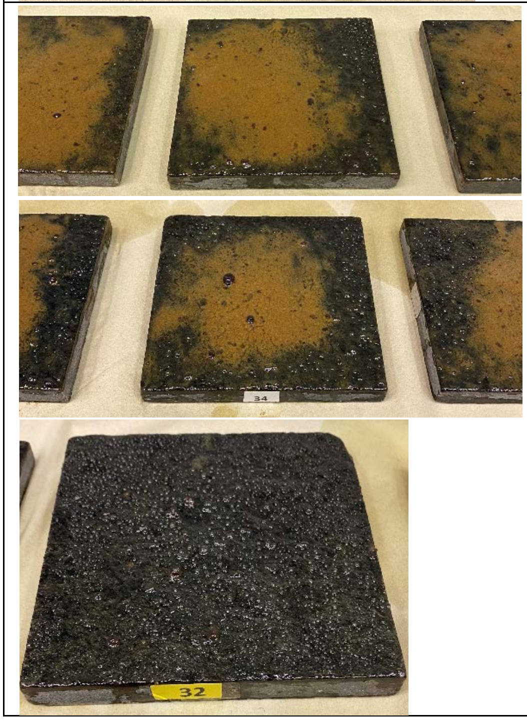
| | |
|---|---|
|  | **Tiles with unweathered (left picture) and weathered (right picture) fuel oil before exposure** |
|  | **Tiles with unweathered fuel oil after exposure, given in the following order:**<br>**5 °C, 15 bar**<br>**5 °C, 15 bar, with SCA**<br>**45 °C, 15 bar** |
|  | **Tiles with weathered fuel oil after exposure, given in the following order:**<br>**5 °C, 4 bar**<br>**5 °C, 4 bar, with SCA**<br>**5 °C, 15 bar** |

**Figure F-3 Example images of tiles with unweathered and weathered HDME 50 (46 % wio emulsion), before and after flushing, using the Flushing Robot.**

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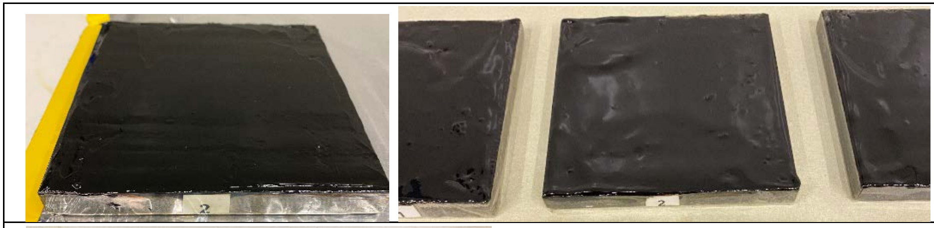
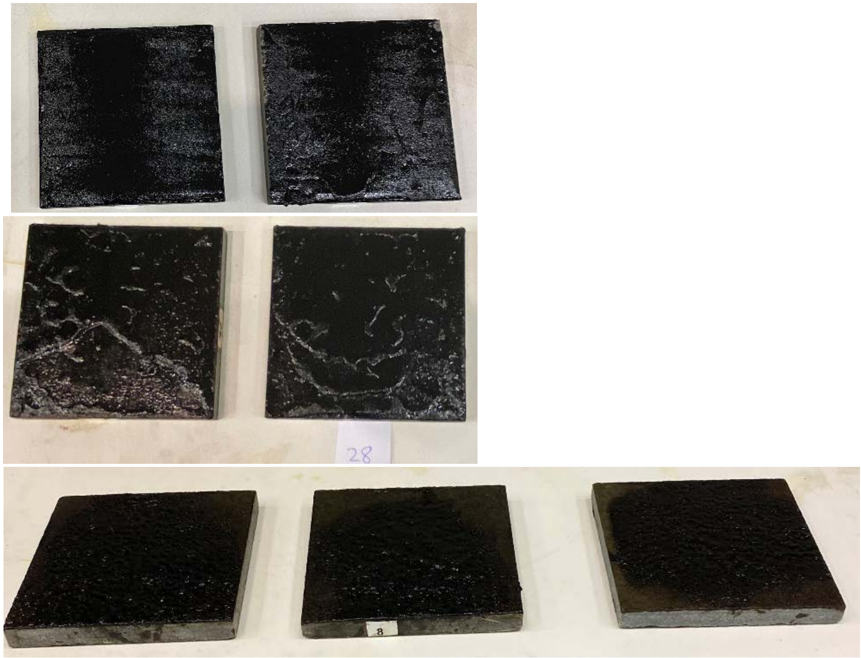
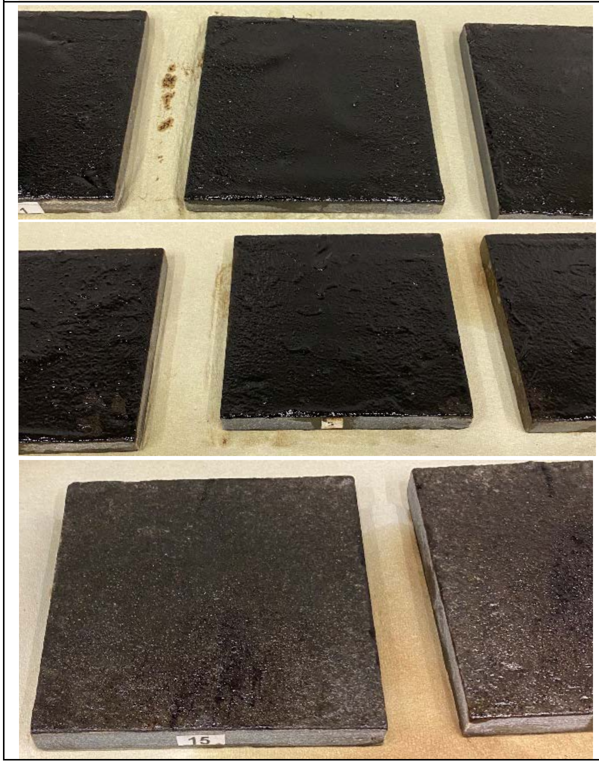
|---|---|
|  | **Tiles with unweathered (left picture) and weathered (right picture) fuel oil before exposure** |
|  | **Tiles with unweathered fuel oil after exposure, given in the following order:**<br>**5 °C, 45 bar**<br>**5 °C, 45 bar, with SCA**<br>**45 °C, 45 bar** |
|  | **Tiles with weathered fuel oil after exposure, given in the following order:**<br>**5 °C, 45 bar**<br>**5 °C, 45 bar, with SCA**<br>**45 °C, 45 bar** |

**Figure F-4 Example images of tiles with unweathered and weathered ULSFO (10 % wio emulsion), before and after flushing, using the Flushing Robot.**