Method to Diagnose Lubricating Oils by Analysis of UV-VIS-NIR Reflectance and Transmittance Spectrum and Colorimetry

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The degradation of lubricating oil, which is used in various machines and devices, can be broadly classified into two types: the one which is caused by solid particles and the other by oxidation. For the present study, we collected lubricating oils and hydraulic oils at random from operational machines and filtered the oils through membrane filters. Using UV-VIS-NIR(Ultra Violet-Visible-Near InfraRed) spectrophotometer, we diagnosed these oils by reflectance from the contaminants caught in the membrane filter and by transmittance through the oils. In addition, we used the colorimetric technique. We calculated the average reflectance for a given visible wavelength and examine the relationship between the average reflectance and the transmittance at 496 nm, and found a difference in the degradation path for the oils. For degradation due to solid particles, the membrane filter became gray or black, and the average reflectance changed significantly whereas the transmittance only changed slightly. On the other hand, for degradation by oxidation products, the membrane filters were brown, and both the average reflectance and transmittance changed significantly. Finally, we confirmed the usefulness of this method applying to the hydraulic oils used for press machines.

Key Words **:** Spectrophotometer, Colorimetric analysis, Hydraulic oil, Contaminant, RGB, Membrane patch, Maintenance

1. Introduction

Lubricating and hydraulic oils used for various types of machines and equipment degrade with use, and about 70% of hydraulic problems are attributable to contaminants in oils[1]. Therefore, a proper diagnosis of the causes of oil degradation is important to prevent the machine-malfunction problems that are associated with oil deterioration. Lubrication management based on good diagnostic technology would thus be able to prevent equipment malfunction, thereby increasing productivity. In a previous publication, we reported the colorimetric technique to diagnose oil condition, which is based on analyzing the color of contaminants[2]. In the present study, we develop a combined technology of colorimetry, reflectance spectrophotometry of oil contaminants, and transmission spectrophotometry of the oil.

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2. Experimental

To filter the lubricating oils, we used a membrane filter with a pore size of 0.8 μm and a diameter of 25 mm that was clamped between the filter support of a vacuum flask and the filter funnel (see Fig. 1). By reducing the pressure, a 10 ml sample of oil was forced through the filter and into the flask, following which the membrane patch was dried. To obtain color information we scanned the contaminant-impregnated membrane patch using a

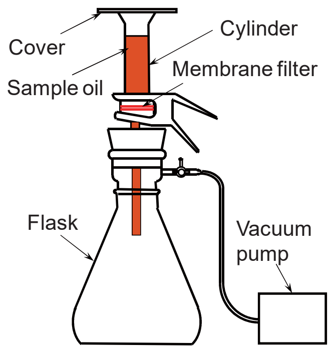

Fig.1 Filtering equipment.

general-purpose image scanner and recorded the images as 256-level red-green-blue (RGB) images.

With the help of image-editing software, the RGB values from the images were adopted as intermediate values from a histogram.

Using a spectrometer, we measured the reflectance of the membrane patches and the transmittance of the oils. Table 1 gives the specifications of the spectrometer and the measurement conditions. The reflectance was obtained by comparison with a new membrane filter and the transmittance was obtained by comparison with an empty quartz cell.

The lubricating oils and hydraulic oils analyzed in this study were collected at random from operational machines. The number of oils collected and their types are shown in Table 2. In the experimental results, we focused on the hydraulic oil.

Table 1 Specifications of spectrometer and test condition.

Monochromator		Prism-grating type Double monochromator
Detector		Photomultiplier (UV-VIS)/ Cooling type PbS (NIR)
		ø60 mm integrating sphere: Inner face coated with $BaSO_4$
Light source	UV	Deuterium lamp
	VIS・NIR	50W tungsten Halogen lamp
Pphotometry method		Double beam direct ratio method
Wave length		190～2600nm
Sampling interval		0.5nm

Table 2 Summary of analyzed oil samples.

Oil	Number of Samples	Oil	Number of Samples
Processing oils	19	Antirusting oils	3
Test oils	24	Pump oils	15
Hydraulic oils	190	Others	23
Lubricating oils	7		
		Total	281

3. Results and discussion

3.1 Color of membrane patches

Figure 2 shows some examples of used membrane patches. Each membrane patch was scanned with the image scanner, and exhibited various colors such as black, gray, brown, yellow, and white. For hydraulic oils, the RGB levels of the membrane patches were in the order R > G > B for 179 samples, G > R > B for 6 samples, and R = G > B for 5 samples.

For the latter two sets, the difference between the R and G values is less than 2. In other words, the majority of hydraulic-oil contaminants are reddish in color. Similar results were obtained from the other oil samples.

The R value was the largest of the three colors for most of the membrane patches. For membrane patches in which the RGB values do not follow the R > G > B ordering, each color exceeds the value of 230, indicating that there is little coloration. Figure 3 shows a three-dimensional distribution of the colors. The diagonal line extends from black to white and includes gray between these two extremes. The off-diagonal colors are in the direction of red and yellow. The oil-contaminant colors occupy the brown area from the diagonal toward red and yellow. Therefore, all colors are in the pyramid with four apexes of black, white, red and yellow.

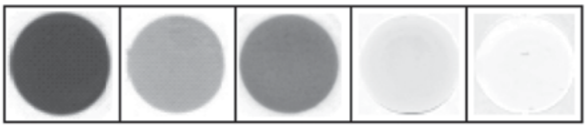

Fig.2 Some examples of the membrane patches.

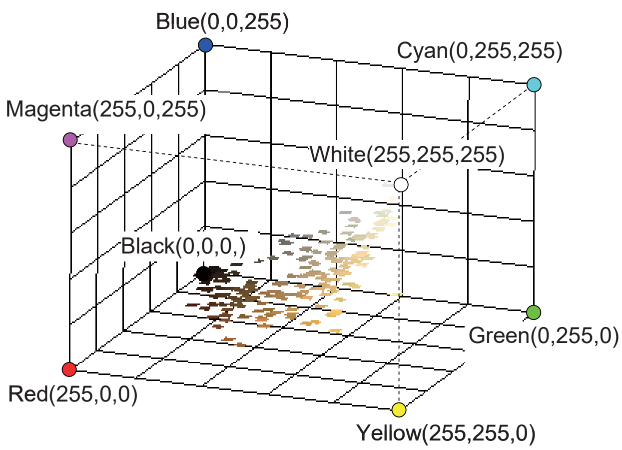

Fig.3 Color distribution of analyzed membrane patches.

3.2 Spectroscopic analysis

Figure 4 shows the reflectance of several membrane patches. In the near-infrared region (λ > 780 nm), the reflectance spectrum has dips near 1200, 1415, 1720, 1910, and 2307 nm, although each sample oil has a distinct reflectance. In the visible regime (380 < λ < 780 nm), the reflectance decreases with decreasing wavelength. In the ultraviolet range (λ < 380 nm), the reflectance exhibits its smallest value near 300 nm.

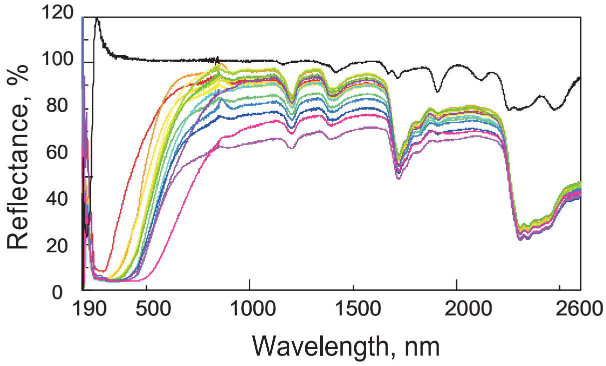

Fig.4 Spectrum curve of membrane patches.

To quantitatively evaluate the color data, we calculated the average reflectance of visible light, as shown in Fig. 5 and compared it with transmittance at 496 nm, which is related to ASTM color[3].

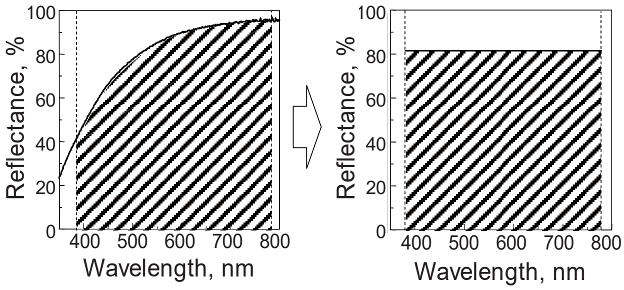

Fig.5 Calculation method for average reflectance.

Figure 6 shows the results of the analyses of the hydraulic oils used for 100- ~ 600-tons press machines. The operating conditions are given in Table 3. In all cases, the membrane patches were brown, as shown in Fig. 7. These oils were used for 1000 ~ 8000 hours, and the quantities of the oils ranged from 1500 to 1800 liters. The oils were purified by an electrostatic dust cleaner (EDC). For the 100-tons press machine, transmittance varies with operation time, whereas for the 600-tons press machines, transmittance variation is less and the variation in average reflectance is significant. The corresponding values for the oils used in the 300-tons press machine were distributed between the values for those used in the 100- and 600-tons press machines.

When the average reflectance is below 80%, the membrane patch is colored. It appears that the progress of oil degradation is indicated by the deepening of the brown color. This coloration is caused by the appearance of substances that are insoluble in oil. Most color disappears when these contaminants are dissolved in toluene and re-filtered. In other words, brown substances

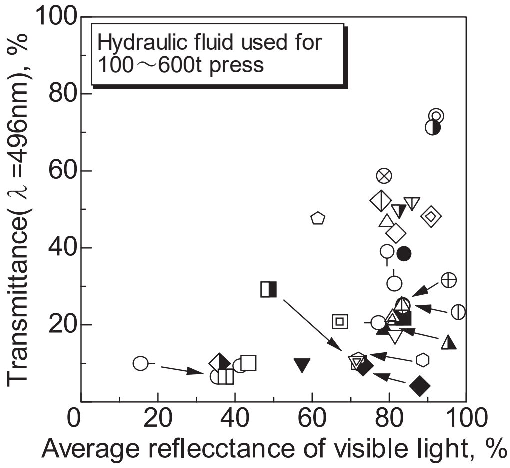

Fig.6 Relationship between average reflectance and transmittance at 496 nm.

Table 3 Operating conditions of lubricating oil used in Fig.6.

Load, t	Symbol	Time, hours
100	■	1102
	◎	2171
	▽	3869
	◐	4142
	⊕	5950
	△	6049
	⚲	7900
300	▽	1094
	⊡	1876
	▲	2651
	⦶	3994
	⚲	6834
	■	-
	◇	-
	◈	-
	▼	-
	◇	-
	⬠	-

Load, t	Symbol	Time, hours
400	△	1903
	⊗	2023
	-○	4155
	◭	8300
600	⬡	1924
	◫	1928
	▼	1976
	◆	2022
	△	2022
	○-	2022
	◆	2217
	◨	2249
	○	4079
	□	4079
	▽	4205

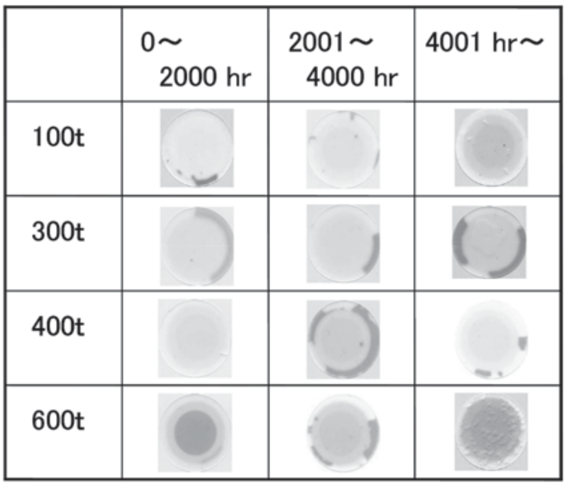

Fig.7 Typical samples of the membrane patch images in Fig.6.

are oxidation products that are soluble in toluene. Heating hydraulic oils is considered to significantly influence its oxidation[4]~[6].

The oils for the 1000-tons press machines are the same brand as those for the 100- to 600-tons press machines and the oils were not purified by the EDC. Figure 8 shows the results of the analyses of the hydraulic oils used for 1000-tons press machines. Each membrane patch used to filter the oils is gray in color, as shown in Fig. 9. Compared with Fig. 6, the change in reflectance is significant, but that in transmittance is less. In contrast to contaminants such as oil-oxidation products, which are molecular sized and numerous, contaminants such as wear debris are large in size and few in number. Therefore, only a weak diffuse reflection is observed, and transmittance is high. However, the size of wear debris causes a reduction in the average reflectance because most of the large contaminants are caught by the membrane filter.

Membrane patches washed with toluene to dissolve the oxidation products were observed with a scanning electron microscope (SEM) to investigate the color difference of the contaminant with insoluble material and

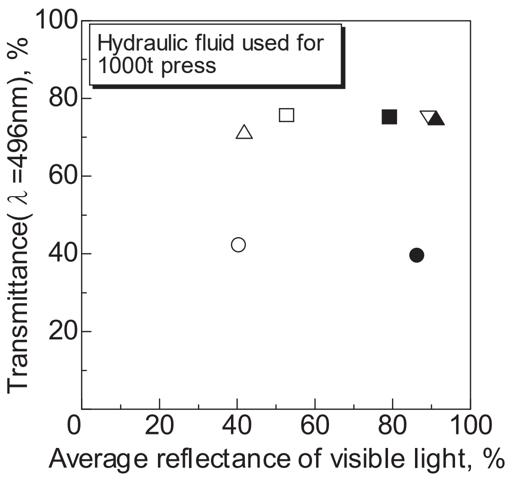

Fig.8 Relationship between average reflectance and transmittance at 496 nm.

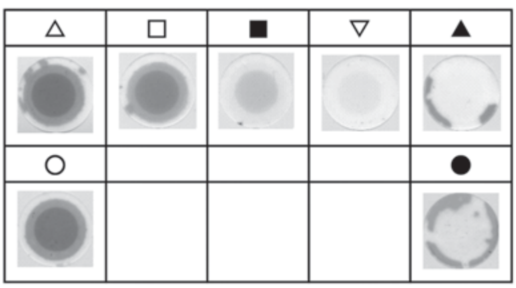

Fig.9 Membrane patch images of Fig.8.

the transmittance. Figure 10 shows an SEM photograph of a membrane patch used for the 100-tons press machines with an oil purifier, while Fig. 11 shows an SEM photograph of a membrane patch used for the 1000-tons press machine with no oil purifier. This latter membrane patch contains a lot of contaminants, mainly composed of Zn, which are cylindrical or spherical in shape and have an average size of 10 μm. Because of the operating conditions, most contaminants are believed to be metallic wear debris generated from the bearings.

These results indicate that the degree of oxidation can be estimated by transmittance and the degree of degradation and the contaminant properties can be estimated by the color and the average reflectance of membrane patches.

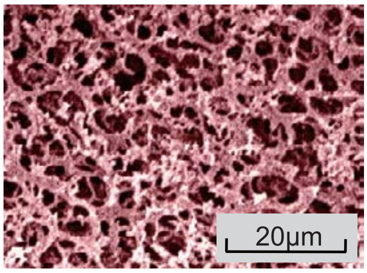

Fig.10 SEM photograph of the membrane patch of the 100-tons press machine with an oil purifier.

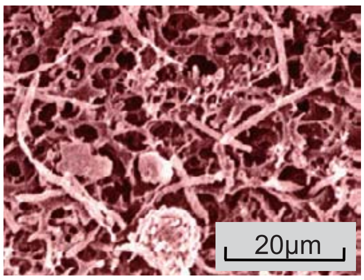

Fig.11 SEM photograph of the membrane patch of the 1000-tons press machine without an oil purifier.

4. Conclusions

The color of oil contaminants ranges throughout the area in Fig.3 from the diagonal line toward red and yellow, (i.e., brown). Therefore, all colors in the pyramid have four tops: black, white, red, and yellow.

The difference in the relationship between the average reflectance and the transmittance was related to the color of the membrane patches. If the membrane patch turns brown, the change in transmittance is large compared with the average reflectance. If the membrane patch turns gray and the color is displaced along the diagonal line toward white or black, the change in the average reflectance is large compared with the transmittance.

A reduced transmittance and an average reflectance are caused by an increase of the amount of oxidation products and of the number of solid particles, such as the wear debris.

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