Statistical Analysis of Washing Efficiency for Solid Particle Soil

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Abstract: In a previous study, statistical method using two distributions was applied to analyze detergency of oily soil. The method uses statistical distributions of detergent power and adhesive force of soil. In this paper, this method was applied to an analysis of detergency of solid particles. Soiled cotton cloth was prepared with red iron oxide dispersion liquid in Terg-O-Tometer. Four-time consecutive washings tests were conducted with dodecyl sulfonic acid sodium salt (SDS) and alcohol ethoxylate (AE) aqueous solutions in Terg-O-Tometer. Change of removal efficiencies due to repetitive washing was utilized to seek the two distributions. Predicted removal efficiencies calculated from computer simulation corresponded to experimental values. Different adhered states of soil, prepared by varying soiling conditions, were expressed as Removal Resistance. As soiling mechanical power increased, Removal Resistance shifted toward higher adhesive force of soil and an amount of soil had also increased. Iron oxide concentration only had an affect on an amount of soil. The results showed that the method using two statistical distributions can be applied to the detergency of solid particle.

Key words: removal efficiency, resistance of soil toward washing, detergent power, iron oxide, statistical distribution

1 INTRODUCTION

In a previous paper¹, detergency of oily soil was analyzed by a concept based on statistical distribution. The concept uses two statistical distributions: adhesive force of soil and detergent power. Removal efficiency was linked to a relation between two distributions. Results showed that predicted removal efficiencies calculated from two distributions corresponds to experimental removal efficiencies.

Detergency of oily soil was affected by emulsification, solubilization, rolling-up, mechanical power, etc. Removal mechanisms of solid particle is different from oily soil, since detergency of solid particle is mostly affected by mechanical power of washing, surface electric potential, and dispersion of particles. In this paper, the statistical method was applied to the analysis of detergency of solid particles.

Adhesion state of solid particles is affected by: substrate and property of solid particles, solid particle concentration and mechanical power in soiling procedure², solubility parameter of dispersion solvent³, and coexistence of surfactant⁴. In related researches, Incubator²,³,⁵,⁶,⁹, Launder-O-Meter⁴,⁷, Terg-O-Tometer⁸, tumbler type soiling machine⁹, etc., were used as soiling apparatus. These apparatus also have an affect on adhesion state of soil. In this paper, soiling sample was prepared in Terg-O-Tometer with varying mechanical power and solid particle concentration. The difference of adhesion state of soil, due to iron oxide concentration of soiling bath and mechanical power of soiling, were expressed as distribution of resistance of soil against washing.

2 THEORY

We have assumed that soil removal is determined from detergent power and resistance of soil against washing. These two factors were expressed as statistical distributions. Paradigm is shown in Fig. 1. With an assumption of a distribution of resistance of soil against washing following

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normal distribution, probability density function \( f(x) \) was set as Removal Resistance. Graphically, resistance of soil against washing is taken in a horizontal axis, and density is taken in a vertical axis. In the previous paper\(^1\), adhesive force of soil was taken in a horizontal axis. In this paper, however, resistance of soil against washing was taken in a horizontal axis, because soil removability is also affected by an interaction between soil and substrate. The distribution of detergent power was expressed by cumulative distribution function \( F(x) \) which is set as Removal Load. Resistance of soil is taken in a horizontal axis, and probability is taken in a vertical axis. Removal Resistance and Removal Load are statistically independent, and relative position and shape of these two distributions are the factors determining removal portion of soil.

Probability density function is calculated from equation [1], and cumulative distribution function is calculated from the area of probability density function.

\[
 f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \quad [1]
\]

\( f(x) \): probability density function, \( x \): probability variable, \( \pi \): circular constant, \( \sigma \): standard deviation

An amount of soil removed in a certain resistance interval is represented by the product of cumulative density value of \( \Phi(x) \) and interval area of \( f(x) \). Total amount of soil removed is represented by equation [2].

\[
 \int_{-\infty}^{\infty} \Phi(x) f(x) \, dx \quad [2]
\]

Change of removal efficiency due to repetitive washing can be calculated from repetitive application of Removal Load to Removal Resistance.

3 EXPERIMENTAL

3.1 Soiling of fabric clothes

Red iron oxide (Toda Pigment Corp., 100ED) was used to soil 5 x 5 cm cotton clothes. 20 clothes were soiled in 1L of iron oxide / distilled water dispersion liquid using Terg-O-Tometer. Dispersion liquid was prepared by ultrasonic treatment of 28 MHz for 20 min. Soiling time was 3 min. and temperature was 30°C. Five kinds of soiled cloth were prepared by a controlled amount of iron oxide and agitation speed of Terg-O-Tometer.

3.2 Washing condition

Dodecyl sulfonic acid sodium salt (SDS) and polyoxyethylene lauryl ether (C12, 23 ethylene oxide, AE) were used to prepare 0.3% surfactant aqueous solution for washing. Two sets of five cotton clothes were used for each washing conditions. Washings were carried out in a Terg-O-Tometer for 5 min. at a washing temperature of 30°C. After washing test, soiled clothes were rinsed three times with 1L of distilled water without mechanical power.

Two kinds of washing experiments were conducted; (i) four-time consecutive washing test for determination of Removal Load or Removal Resistance, (ii) two-time consecutive washing test by two distinct washing condition for comparison with washing simulation results by computer.

(i) Identical soiled clothes, prepared by soiling condition of iron oxide 0.4 g/L and agitation speed 100 rpm, were washed four times using fresh solution per wash. Two surfactants and three agitation speeds (60, 100, 140 rpm) were used. Removal efficiencies of four-time washing test were used for calculation of Removal Load. Another consecutive washing tests were conducted with four different soiled clothes (soiling conditions: 0.2 g/L 100 rpm, 0.6 g/L 100 rpm, 0.4 g/L 80 rpm, and 0.4 g/L 160 rpm). Washing conditions were: SDS solution 120 rpm agitation speed and AE solution 120 rpm agitation speed. These removal efficiencies were used for calculation of Removal Resistance, and also for comparison with the simulation results.

(ii) Predicted removal efficiencies of repetitive washing can be obtained by the application of Removal Load to Removal Resistance repetitively. For the comparison of experimental removal efficiency and predicted removal efficiency, two-time consecutive washing tests with two distinct washing conditions were conducted. Identical soiled clothes, prepared by a soiling condition of iron oxide 0.4 g/L and agitation speed 100 rpm, were first washed with SDS solution and 80 rpm agitation speed, then washed again with SDS solution of 160 rpm agitation speed. Similarly soiled clothes were washed with AE solution of 80 rpm agitation speed, then washed with AE solution of 160 rpm agitation speed. In both washing tests, washing condition with lower agitation speed were applied initially.

3.3 Detergency evaluation using surface reflection

There have been various investigations on determination
Statistical Analysis of Washing Efficiency for Solid Particle Soil

of solid particles by a reflectance measurement using Kubelka-Munk equation\(^{7,10-12}\). Confirmation experiment was carried out to apply the reflectance measurement method to detergency evaluation assessment for iron oxide. The actual amount of adhered soil particle was calculated from chemical determination. Iron oxide adhered on cotton clothes was dissolved and heated in dilute hydrochloric acid for approximately 20 min. Fe\(^{3+}\) was reduced to Fe\(^{2+}\) by hydroxylammonium chloride (Guaranteed Reagent, Junsei Chemical Co., Ltd.), formed a complex with \(\alpha\)-phenanthroline hydrochloride (Guaranteed Reagent, Junsei Chemical Co., Ltd.), and the absorbance (wave length at 510 nm) of the complex’s solution was measured by spectrophotometer. Surface reflectance was measured by color difference meter (Nihon Densyoku Kougyou, ND101-DP), and K/S value was calculated from Equation [3].

\[
\text{K/S} = \frac{(1-R)^2}{2*R} \quad [3]
\]

Soiled clothes, prepared by soiling condition of iron oxide 0.4 g/L and agitation speed 100 rpm, were used as a sample. Three sets of five soiled clothes were washed with different washing conditions. Another set of soiled clothes was used as an unwashed sample. The applied three washing conditions were; SDS 0.3% 160 rpm, SDS 0.3% 120 rpm, and AE 0.3% 120 rpm. Washing was conducted in a Terg-O-Tometer for 5 min. K/S values calculated from surface reflection and amount of soil obtained from absorbency are shown in Fig. 2.

A quantity of adhered soil obtained by surface reflection and absorptiometry had a high correlation. Thus, it was confirmed that the method using surface reflection and K/S value could also be used for determination of a quantity of adhered iron oxide particles adhered after washing.

An amount of adhered iron oxide on each cloth (soiling condition: iron oxide 0.4 g/L, agitation speed 100 rpm) was 8.9 mg. Since 20 clothes were soiled in 1L of 0.4 g iron oxide dispersion liquid, approximately 0.178 g (45%) out of 0.4 g iron oxide have adhered to substrate within 3 min. with Terg-O-Tometer at 30°C.

3.4 Removal load and removal resistance calculation by computer simulation

Removal Load and Removal Resistance each has two parameters concerning average (\(\mu_{RL}, \mu_{RR}\)) and standard deviation (\(\sigma_{RL}, \sigma_{RR}\)). In calculations of Removal Load parameters, first, Removal Resistance was set as standard normal distribution (\(\mu_{RR} = 0, \sigma_{RR} = 1\)), then optimum parameters were calculated from least square method between experimentally obtained removal efficiencies and simulated removal efficiencies. On the other hand, in calculation of Removal Resistance parameters, Removal Load which is already known, was used for a calculation of simulated removal efficiency, then least square method was conducted again. Removal Resistance was sought by parameters of distribution average, standard deviation, and area of distribution.

An area of soil removal was partitioned into 0.001 width trapezoids, and was calculated. Calculations were carried out to a standardized resistance range of \(-5.0\) to \(5.0\), which contains over 99.99% of Removal Resistance’s area. Variable range of parameters was set to sufficient values (\(\mu_{RL} = -6.0\) to \(2.0\), \(\sigma_{RL} = 0.1\) to \(30.0\), based on a preceding research) to match experimental values. The parameters of Removal Load and Removal Resistance were varied at an interval of 0.1.

4 RESULTS AND DISCUSSION

4.1 Calculation of removal load expressing detergency

The four-time washing test results of six washing conditions for the soiled clothes, prepared by the same soiling condition of 0.4 g iron oxide/L and agitation speed 100 rpm, are shown in Fig. 3. In all washing conditions, removal efficiency increased along with number of washings. Washings using SDS or with higher mechanical power showed higher removal efficiencies.

Parameters of Removal Load, expressing detergency were calculated by least squared method. However, for the Removal Load expressing SDS 120 rpm and SDS 160 rpm, there was a range which showed higher removal ratio for SDS 120 rpm than SDS 160 rpm. Therefore with an assumption of Removal Load having same gradient for each detergent, \(\sigma_{RL}\) was arranged to same value (average of distribution) for each detergent. Results showed that Removal Load with higher agitation speed showed higher \(\mu_{RL}\) parameter. Removal Load for SDS showed higher \(\mu_{RL}\) and lower \(\sigma_{RL}\) than AE. Three Removal Load expressing the detergency for SDS 80 rpm, SDS 120 rpm, and SDS 160 rpm, are shown in Fig. 4. Since \(\sigma_{RL}\) were arranged to a
same value for each detergent, three Removal Load had a same gradient.

However, $\mu_{RL}$ which indicates average distribution of Removal Load, shifted toward right (i.e. higher resistance) as mechanical power increased. Thus condition with higher mechanical power tends to remove soil with higher resistance against washing.

4.2 Comparison of experimental and predicted value of two-time repetitive washing simulation

Two-time repetitive washing simulation with two types of Removal Load was carried out, and predicted removal efficiencies were calculated. Predicted removal efficiencies were compared with experimental values, to examine whether predicted removal efficiency curve is adequate or not to indicate detergency curve. Two kinds of washing simulations, (i) and (ii), were conducted in a condition of initial wash: 80 rpm agitation speed, and second wash: 160 rpm.

![Fig. 3](image3.png) **Fig. 3** Removal Efficiencies of Four-Time Repetitive Washing.

![Fig. 4](image4.png) **Fig. 4** Removal Load for SDS 80 rpm, SDS 120 rpm and SDS 160 rpm.

![Fig. 5](image5.png) **Fig. 5** Comparison between Experimental Value and Predicted Value of Two-Time Repetitive Washing in Two Distinct Washing Conditions (SDS 80 rpm → SDS 160 rpm, and Two Experimental Values of Two-Time Repetitive Washings in Same Washing Conditions Respectively.

![Fig. 6](image6.png) **Fig. 6** Comparison between Experimental Value and Predicted Value of Two-Time Repetitive Washing in Two Distinct Washing Conditions (AE 80 rpm → AE 160 rpm), and Two Experimental Values of Two-Time Repetitive Washings in Same Washing Conditions Respectively.
rpm agitation speed. In both washing simulations, the conditions with a higher detergent power was used in a second-time washing in order to increase the removal efficiency in repetitive washing. As a surfactant, SDS was used for (i), and AE was used for (ii). Results are shown in Fig. 5 (i), and Fig. 6 (ii). In both Figures, two solid lines represent experimental and predicted values of a combination of two distinct washing conditions, and two dotted lines both represent the experimental values for two-time repetitive washing conducted in same washing conditions respectively. The predicted values were nearly equal to the experimental values.

4.3 Calculation of removal resistance expressing different soil states

Detergent power could be expressed using Removal Load (section 3.2). However the Removal Load expresses relative position and shape of the soil state used in experiment. Therefore, if adhered state of soil was different, this Removal Load cannot be applied, thus we attempt to express adhered state of soil as Removal Resistance to evaluate and compare washing tests with different state of soil.

In the previous section, soiled cloth with soiling condition of iron oxide 0.4 g/L and agitation speed 100 rpm was used to calculate Removal Load. In this section, this soiled cloth was set as standard soil state, and Removal Resistance were calculated from repetitive washings of soiled clothes prepared by four types of soiling conditions (0.4 g/L 60 rpm, 0.4 g/L 140 rpm, 0.2 g/L 100 rpm, and 0.6 g/L 100 rpm).

![Fig. 7](image1.png)  
**Fig. 7** Removal Resistance of Soiling Conditions: 0.2 g/L 100 rpm, 0.4 g/L 100 rpm, and 0.6g/L 100 rpm.

![Fig. 8](image2.png)  
**Fig. 8** Removal Resistance of Soiling Conditions: 0.4 g/L 60 rpm, 0.4 g/L 100 rpm, and 0.4 g/L 140 rpm.

Fig. 9 Comparison between Experimental Value and Predicted Value of Four-Time Repetitive Washing with Two Distinct Soiled Clothes (soiling condition: 0.2 g/L 100 rpm and 0.6 g/L 100 rpm).

![Fig. 10](image3.png)  
**Fig. 10** Comparison between Experimental Value and Predicted Value of Four-Time Repetitive Washing with Two Distinct Soiled Clothes (soiling condition: 0.4 g/L 60 rpm and 0.4 g/L 140 rpm).
rpm. Washings were carried out with SDS and agitation speed 120 rpm. Removal Resistances of soiled clothes prepared by varying iron oxide concentration of soiling bath are shown in Fig. 7, and Removal Resistances of soiled clothes prepared by varying soiling mechanical power are shown in Fig. 8.

Removal Resistance curve shifted toward higher resistance of soil as soiling mechanical power increased, and an amount of soil has also increased. On the other hand, iron oxide concentration of soiling bath only had an effect on an amount of soil.

4.4 Washing simulation using removal resistance

In section 3.3, adhesion states of soil on soiled cloth were expressed using Removal Resistance. To examine the validity of this expressing method, predicted removal efficiencies calculated from a combination of Removal Load and Removal Resistance were compared with experimentally obtained removal efficiencies. Washings were carried out using AE and agitation speed of 120 rpm. Experimental and predictive value using Removal Resistance with varying iron oxide concentrations are shown in Fig. 9, and with varying mechanical power are shown in Fig. 10.

The maximum difference was approximately 4% at iron oxide concentration of 0.4 g/L and mechanical power 140 rpm. The difference suggests that the shape of Removal Resistance may not follow normal distribution in the soil ing with 140 rpm agitation speed. Nevertheless, in both Fig. 9 and Fig. 10, the rest of the predicted values were nearly equal to the experimentally obtained values. The result confirmed that our theory can be applied to detergency of solid particles.

5 CONCLUSIONS

Results showed that it is possible to express detergency of various washing conditions as Removal Load. In two-time repetitive washing, predictive removal efficiencies calculated from various combination of Removal Loads corresponded to experimentally obtained value.

Adhesive force distributions of soiled clothes prepared by various soiling conditions were calculated as Removal Resistance. Mechanical power of soiling had an influence of both amount of adherent soil and adhesive force. On the other hand, iron oxide concentration only had an influence on amount of adherent soil.

In a detergency simulation of soiled clothes with various soiling conditions, predictive value mostly corresponded to experimentally obtained value.

References