A STUDY OF PENETRATION OF OIL INTO SORBENTS

by

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ABSTRACT

This study was initiated to absorb petroleum spills in sea waters. For this purpose, polyurethane and polypropylene were used as sorbents, and SAE 20W-20 motor oil and SAE 90W gear oil were used as oils. To observe the penetration of oils into sorbents, four groups of experiments were carried out : the horizontal penetration of oils into dry polyurethanes, the horizontal displacement of water from polyurethanes(pre-wetted with water) by oil, the vertical penetration of oils into dry polypropylenes, and the vertical retention of oils by polyurethanes(pre-wetted with oil).

Sorbents are characterized by their porosities, thicknesses, and fiber diameters. Such properties of the sorbents used were obtained from the literature. The important properties of an oil are the density, the viscosity and the surface tension coefficient. The values for the density and the viscosity of oils used were supplied by Mobil Oil Company in Istanbul. The surface tension coefficients of these oils also were measured in Boğaziçi University Labs. The sorbent/oil contact angle, which is another important parameter, was taken as zero by assuming that the sorbents were completely wetted with oil.

A linear model, developed in literature for the horizontal penetration of oils into sorbents, was used in this study, and the experimental results obtained in this study did not agree with this model. Here, the distance penetrated by oil into sorbents was observed to be directly proportional to the square root of time.

In addition, the horizontal displacement of water from sorbents by oil was also studied here. The polyurethane samples(pre-wetted with water) did not absorb oil, that is, water prevented the penetration of oil into sorbent. Therefore, the displacement of water from sorbents by oil could not be achieved. This indicates that the sorbents can absorb oil from the surface of sea waters, if they are prevented from being wetted.

The vertical penetration rate model, taken from the literature, is nonlinear. The vertical retention model, which was developed in this study, is also nonlinear. The experimental and the theoretical results showed that both the vertical penetration rate and the vertical retention were nonlinear. In the vertical penetration rate experiments, the rate at which oil climbed up the sorbent was measured. In the vertical retention experiments, the rate at which oil drained from the sorbent was measured. The evaluations were based on these measurements.

YAĞIN SORBANTLARA NÜFÛZUNUN İNCELENMESİ

ÖZET

Bu çalışma denizlerdeki petrol ürünlerinin döküntülerini temizlemek için başlatılmıştır. Bu amaçla sorbent olarak poliüretan ve polipropilen, yağ olarak da SAE 20W-20 motor yağı ve SAE 90W dişli makina yağı kullanılmıştır. Burada, yağın nüfûz edişini gözlemek üzere 4 grup deney yapılmıştır: Kuru poliüretanlarda yağın yatay nüfûzu, önceden su ile ıslatılmış poliüretanlardan suyun yağ ile atılması, kuru polipropilenlerde yağın dikey nüfûzu, ve önceden yağ ile ıslatılmış poliüretanlarda yağın dikey şekilde bekletilmesi.

Sorbantlar porozite, kalınlık ve lif çapları ile belirlenir. Kullanılan sorbantlara ait bu özellikler kaynaklardan alınmıştır. Yağın önemli özellikleri yoğunluk, viskozite ve yüzey gerilim katsayısıdır. Kullanılan yağların yoğunluk ve viskozite değerleri İstanbul'daki Mobil Petrol Şirketi'nden temin edilmiştir. Bu yağların yüzey gerilim katsayıları ise Boğaziçi Üniversitesi Laboratuvarları'nda ölçülmüştür. Diğer bir önemli parametre olan sorbant/yağ temas açısı, sorbantların yağ ile tam ıslandığı kabul edilerek, sıfır olarak alınmıştır.

Yağların sorbantlara yatay nüfuz edişini belirlemek üzere, kaynaklarda geliştirilen doğrusal model bu çalışma-

da da kullanılmış ve bu çalışmada elde edilen deneysel sonuçların bu model ile uyumlu olmadığı görülmüştür. Burada, yağın sorbanta nüfûz ettiği mesafenin zamanın kare kökü ile doğru orantılı olduğu da gözlenmiştir.

Ayrıca, burada suyun sorbantlardan yağ ile yatay olarak atılması üzerinde de çalışıldı. Önceden su ile ıslatılmış poliüretan numuneleri yağı emmediler, başka bir deyimle, su yağın nüfûz etmesini engelledi. Bu yüzden, sorbantlarda suyun yağ ile yer değiştirmesi başarılamadı. Islanmaları önlendiği takdirde sorbantların deniz suları üstündeki yağları toplayabilecekleri söylenebilir.

Kaynaklarda geliştirilmiş olan dikey nüfûz hızı modeli doğrusal değildir. Bu çalışmada geliştirilmiş olan dikey tutma modeli de doğrusal değildir. Deneysel ve teorik sonuçlar hem dikey nüfûz hızı, hem de dikey tutmanın doğrusal olmadığını göstermiştir. Dikey nüfûz hızı deneylerinde yağın sorbanta tırmanma hızı ölçülmüştür. Dikey tutma deneylerinde ise yağın sorbanttan akma hızı ölçülmüştür. Değerlendirmeler bu ölçümlere göre yapılmıştır.

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NOMENCLATURE

d_f : average fiber diameter(cm),

F_1 : surface tension force responsible for oil penetration(dynes/cm^2),

F_2 : exterior surface tension force that resists to oil penetration(dynes/cm^2),

F_3 : shear force which is the major resistance to oil penetration(dynes/cm^2),

F_4 : gravitational force which opposes oil penetration when flow is non-horizontal(dynes/cm^2),

g : gravitational acceleration(=980 cm/sec^2),

$h_{eq.}$: equilibrium height-of-rise of oil into sorbent (cm),

h_{final} : final height of oil into sorbent in vertical retention(cm),

k : permeability constant, Carman-Kozeny equation coefficient, dimensionless(=5 for polypropylene and polyurethane),

K_1, K_2, K_3 : parameters in eq.(4),

k_1, k_2, k_3, k_4, k_5 : parameters in eqs.(6) and (25),

L : distance penetrated by oil into sorbent(cm),

L_0 : initial height of oil into sorbent in vertical retention(cm),

L_0-L : distance drained by oil into sorbent in vertical retention(cm),

m : mass of oil penetrating into sorbent per unit cross-sectional area normal to flow(g),

S : wetted surface area per unit volume of sorbent (cm^{-1}),

t : penetration time, or retention time(sec, min),

t_s : sorbent thickness(cm),

V : superficial liquid velocity in the open cross-sectional area(cm/sec),

V' : observed velocity of the oil front(cm/sec),

w : sorbent width(cm),

ϕ : angle of inclination of sorbent with vertical (deg.),

θ : sorbent/oil contact angle(deg.),

β : angle between fibers and moving liquid front (deg.),

μ : liquid viscosity(poise),

ρ : liquid density(g/cm^3),

γ : surface tension coefficient of liquid(dyn/cm),

ΔP : pressure difference($dynes/cm^2$),

CHAPTER 1

INTRODUCTION

Due to various accidents, petroleum and its products are spilt into the water bodies, especially the seas, causing major environmental problems. The removal of the petroleum products from the seas is very crucial for the survival of the biota in the water, and for the cleaning of the environment as well as for the recovery of the petroleum products for use. The effective techniques for the cleaning of oil spills should not be expensive for applications in practice.

The mechanical collecting equipments, the scrapping equipments, sinking agents, emulsifiers or dispersants, surfactants, and sorbents are the significant techniques used for removing oil spills from waters. Sinking agents can worsen the situation. Chemical methods are not immediately effective. Surfactants can be used to direct the spread of the slicks. Dispersants can break up the oil to a point where microorganisms can digest it. However, spilt oil is not recoverable when these methods are used alone.

Sorbents, which absorb or adsorp oil, can provide a quick and effective way of removing oil from waters. Sorbents should be oleophilic, hydrophobic, absorbtive or adsorptive, inexpensive, and should have a very large oil retention capacity. A sorbent should be able to float in every condition and no oil should leak after the sorbent is cleaned from oil by compression. The principal advantage of the floating sorbents is that they show little or no toxicity towards marine life since they are removed totally from the marine environment.

The synthetic polymeric materials, especially polyurethane and polypropylene, are the most efficient sorbents. The synthetic sorbents can be used by spreading over an oil covered body of water, or in devices such as continuous belts, rotating discs, booms, skimmers, etc. An important advantage of the oil collecting systems with synthetic sorbents is that the oil can be recovered by compressing the sorbent by scrappers or wheels. Polyurethanes with their foamy structures are widely used as sponges, and have very low densities, high elasticities, large oil retention capacities, and high oil-sorption rates. The foams consist of the polyurethane fibers, and resemble a three dimensional fish network structure. Polypropylenes are also made of the synthetic fibers, and have advantages similar to polyurethanes; however their structures resemble that of woven textile. Since the synthetic sorbents are light-weight materials and compressible, they can be reused. Furthermore, they are inexpensive and can be transported easily.

The oil is penetrated into sorbent horizontally and vertically. The horizontal and vertical penetration of oils into polypropylenes and polyurethanes were studied before by Walline(1974) and Lay(1980). Since the sorbents would be reused and pre-wetted with water and oil in practice, the experiments by sorbents pre-wetted with water and oil should be carried out. Also the oil should be retained until the sorbent was taken out of the sea water with oil and the oil was recovered from sorbent.

In this study, the horizontal and vertical penetration rate experiments will be repeated to verify the studies of Lay(1980) and Walline(1974) for the same polyurethanes and polypropylenes, and for the oils with different properties. Considering the fact that sorbents used in practice are wetted with water, the studies of Lay and Walline will be extended by additional horizontal penetration rate experiments using polyurethane sorbents pre-wetted with water. Furthermore, the vertical retention experiments of oils in polyurethanes will be carried out to find the rate at which oil drained from the sorbent.

CHAPTER 2

REVIEW OF PREVIOUS WORK ON PENETRATION OF OILS INTO SORBENTS

A review of the literature on penetration of oils into sorbents indicates such sorbent properties as porosity, fiber diameter, thickness, capacity, floatability, reusability, and such oil properties as density, viscosity, and surface tension coefficient to be important. In addition, sorbent/oil contact angle and oil-sorption rate of the sorbent are found to be significant. The previous work on penetration of oil into sorbents may be summarized as follows :

Washburn(1921) used Poiseuille's law to develop an expression for the rate of a liquid into an horizontal capillary. The resulting expression was given as:

$$L = \sqrt{\frac{\gamma \, r \, \mathrm{Cos}\theta}{2\mu}} \; t^{1/2}$$

where r= the radius of the capillary,

L= the depth of penetration of liquid,

γ= the surface tension coefficient of liquid,

μ= the absolute viscosity of liquid,

t= the penetration time,

θ= the sorbent/liquid contact angle.

To obtain a useful relationship, Carman used the Carman-Kozeny equation(Walline 1974 ; Lay 1980) which is given by :

$$V = \frac{\varepsilon^3}{k\,\mu\,S^2}\,\frac{(-\Delta P)}{L} \qquad (2)$$

where V= the superficial liquid velocity in the open cross-sectional area,

k= the permeability constant(=5 for polypropylene and polyurethane),

ε= the porosity, or void fraction of porous material ; it is the area available for flow per unit cross-sectional area,

S= the wetted surface area per unit volume of porous material,

ΔP= the pressure difference.

This equation provides a basis for relating rate of flow to the force gradient, and contains pore size as parameter.

Walline(1974) developed models to predict the oil-sorption rate into polypropylene sorbents for the horizontal and vertical penetration cases. These models were based on penetration induced by surface tension with resistances due to gravity and shear forces. The polypropylene structure, which consists of randomly oriented fibers, effects the liquid penetration as following :

"Desired Surface Force=(Sinβ) x Total Surface Force"

where surface force is the driving force and β is the angle between the fiber and the moving oil front because of orientation.

In the horizontal case, Walline's model results in the following expression for the distance penetrated by oil into a sorbent strip (L) with time (t) :

$$L = \sqrt{\frac{d_f \varepsilon}{(1-\varepsilon)} \frac{\gamma \cos\theta}{\pi k \mu}}\, t^{1/2} \qquad (3)$$

where d_f is the average fiber diameter of the sorbent. Walline measured sorbent properties and oil-sorption capacities using different types of polypropylenes (see Appendix II). He also measured oil properties and oil-sorption rates. He verified that the distance penetrated by oil into sorbent was directly proportional to the square root of time. He observed that the horizontal rate expements were in agreement, especially for polypropylenes of Typar^R 3400 and 3401.

In the vertical case, Walline's model results in the following expression for the distance penetrated by oil into a sorbent strip (L) with time (t) :

$$t = K_3 \left[\frac{K_1}{K_2^2} \ln\left(\frac{K_1}{K_1 - K_2 L}\right) - \frac{L}{K_2} \right] \qquad (4)$$

where $K_1 = \frac{2\gamma\, S \cos\theta}{\pi}$, $K_3 = \frac{k\, \mu\, S^2}{\varepsilon^2}$

$K_2 = \rho\, g\, \varepsilon \cos\phi$ $S = \frac{4(1-\varepsilon)}{d_f}$

g= the gravitational acceleration,
ϕ= the angle of inclination of flow,
ρ= the oil density.

Available non-horizontal rate data were not taken in Walline's study, so the eq.(4) could not be verified experimentally. However, when Walline compared the horizontal and non-horizontal models, he found that these results were in close agreement.

Lay(1980) developed models for penetration of oils into polyurethane foams for the horizontal and vertical cases. These models are based on Walline's models(1974). In the horizontal case, Lay's model results in the following expression for L with t :

$$L = \sqrt{\frac{\varepsilon^2 d_f^2 \gamma}{4(1-\varepsilon)^2 k\mu}\left[\frac{4(1-\varepsilon)}{\pi \, d_f}\operatorname{Cos}\theta - \frac{(t_s+w)}{t_s w}\right]}\; t^{1/2} \qquad (5)$$

where t_s and w are the sorbent thickness and width. Lay measured sorbent properties and oil-sorption capacities using different types of polyurethanes(see Appendix II). She also measured oil properties and oil-sorption rates. She verified that the distance penetrated by oil into sorbent was directly proportional to the square root of time as in Walline's study(1974). She found that the model was in agreement with the experiments.

In the vertical case, Lay's model results in the following expression for L and t :

$$t = k_4\left[\frac{k_1-k_2}{k_3^2}\ln\left(\frac{k_1-k_2}{k_1-k_2-k_3L}\right) - \frac{L}{k_3}\right] \qquad (6)$$

where $$k_1 = \frac{8(1-\varepsilon)\,\gamma\,\mathrm{Cos}\theta}{\pi\ d_f}\ , \qquad k_3 = \rho\ g\ \varepsilon\ \mathrm{Cos}\phi\ ,$$

$$k_2 = \frac{2\,\gamma\ (t_s + w)}{t_s w}\ , \qquad k_4 = \frac{16k\ \mu\ (1-\varepsilon)^2}{\varepsilon^2\ d_f^2}.$$

She could not obtain succesfull results in this case, since the maximum height climbed by oil into sorbent was only 2-3 cm.

Comparison of Lay's expressions with Walline's expressions shows that there is a correction term due to the addition of the exterior surface tension force which resists the oil penetration into a sorbent. In the studies of Walline(1974) and Lay(1980), deviations from predictions are due to errors in calculating porosity from fiber and pore diameter measurements, and from slight inclinations of the sorbent strips when measuring horizontal penetration rates of oils into sorbents.

According to West(1980), when porosity and fiber diameter of a sorbent are increased, the oil penetration rate into a sorbent increases ; however, the oil retention capacity of the sorbent decreases. To increase both the oil penetration rate and the oil retention capacity of the sorbent, it is suggested that the fiber diameter should be reduced and porosity increased.

Walline(1974) and Lay(1980) recommended the following additional investigations :

1. According to Walline, the experiments for the pe-

netration of oil into sorbents should be conducted with materials which provides a wider range for such sorbent properties as fiber diameter and porosity.

2. According to Lay, new vertical penetration experiments should be done to verify the non-horizontal rate expression. The model should be incorporated both the horizontal and non-horizontal rate expressions to predict the oil penetration rates into sorbents of various sizes and in slick of varying thicknesses. Then this model could be used to specify the optimal sorbent material for a given oil spill application.

In the light of work done previously, the following will be studied in this work :

a. The horizontal and vertical penetration rate experiments for polyurethanes and polypropylenes will be done and they will be evaluated by using Lay's models.

b. The experiments for the displacement of water by oil (horizontally) will be carried out and the results will be modelled.

c. The experiments for the vertical retention of oils will be carried out and the results will be modelled.

CHAPTER 3

GENERAL EQUATION OF MOTION OF OIL IN A SORBENT

In this chapter, a model is developed for predicting the penetration rate of oil into the porous sorbent and solved for several cases. The development of the model is based on the models of Walline(1974) and Lay(1980) and includes the following assumptions :

1. Surface tension is the driving force for the movement of oil into the sorbent.

2. The resistance to oil motion includes viscous shear with no slip at the sorbent/oil boundary, gravity, and a surface tension force at the air/oil interface.

3. The oil completely fills the available voids.

4. Fibers have the same diameter.

For penetration of oil into a sorbent, oil contacts the rectangular sorbent strip at one end and moves into a constant cross-sectional area that is perpendicular to the direction of penetration. A force balance on the oil which flows into the sorbent requires :

Mass x Acceleration = Total forces

$$\frac{d(mV')}{dt} = \Sigma F$$

where V'= the actual average velocity of the oil moving into the sorbent, which is the observed velocity of the oil front, m= the mass of oil penetrating into sorbent per unit cross-sectional area that is perpendicular to flow

F= the sum of the forces mentioned in assumptions 1 and 2 above.

Since

$$V' = \frac{dL}{dt} \quad , \quad m = \rho L \varepsilon \tag{8}$$

The equation of motion of oil into a sorbent becomes :

$$m \frac{dV'}{dt} + V' \frac{dm}{dt} = \rho L \varepsilon \frac{d^2L}{dt^2} + \rho \varepsilon \left(\frac{dL}{dt}\right)^2 = \Sigma F \tag{9}$$

There are four forces affecting this motion : surface tension on the fibers, surface tension on the exterior surface, shear force, and gravitational force.

The surface tension force on the fibers, F_1', which is responsible for penetration of oil into sorbent, is given by :

$$F_1' = N \pi d_f \gamma \cos\theta \tag{10}$$

where N is the number of fibers per unit cross-sectional area, that is the total sorbent volume divided by the volume per fiber and can be expressed as :

$$N = \frac{(1-\varepsilon)\ L}{(\pi d_f^2/4)\ L} = \frac{4(1-\varepsilon)}{\pi d_f^2} \tag{11}$$

Combining eqs.(10) and (11) gives :

$$F_1' = \frac{4(1-\varepsilon)\gamma}{d_f} \cos\theta \tag{12}$$

Since the fibers are randomly oriented, the desired surface tension force includes only the surface normal to flow direction. F_1 is the surface tension force normal to the direction of penetration, and is given by :

$$F_1 = (\mathrm{Sin}\beta)_{avg.} F_1' \tag{13}$$

Since the fibers are randomly oriented, the average value of Sinβ is given by :

$$(\mathrm{Sin}\beta)_{avg.} = \frac{\int_0^{\frac{\pi}{2}} \mathrm{Sin}\beta \, d\beta}{\int_0^{\frac{\pi}{2}} d\beta} = \frac{2}{\pi} \tag{14}$$

Thus, the surface tension force becomes :

$$F_1 = \frac{2}{\pi} \frac{4(1-\varepsilon)\,\gamma}{d_f} \mathrm{Cos}\theta \tag{15}$$

The exterior surface tension force, F_2', that resists oil penetration into sorbents due to the creation of an air/oil interface at the outer perimeter of the sorbent, is defined by :

$$F_2' = \gamma\, 2(t_s + w) \tag{16}$$

where γ= the air/oil interfacial surface tension coefficient, which is equal to the surface tension coefficient of oil,

$2(t_s+w)$= the outer perimeter of the sorbent.

The resisting force per unit cross-sectional area for flow, F_2, becomes :

$$F_2 = \frac{2(t_s+w)\,\gamma}{t_s w} \qquad (17)$$

Shear force, F_3, is the major resistance to flow and is defined by :

Shear force= f(liquid viscosity ; velocity) (18)

Here, the liquid viscosity and the velocity gradient are not constant, and the velocity gradient is represented by Carman-Kozeny equation given by eq.(2). The oil velocity V in this equation can be related to oil velocity V' by :

$$V = \varepsilon V' = \varepsilon \frac{dL}{dt} \qquad (19)$$

The wetted surface area per unit volume, S, is defined as (See Appendix V) :

$$S = \frac{4(1-\varepsilon)}{d_f} \qquad (20)$$

There is no pressure difference in the present system. Shear and pressure forces are the only forces to be considered in the Carman-Kozeny equation. Therefore, the pressure difference can be replaced by the total shear force per unit cross-sectional area normal to flow, F_3, and eqs.(2), (19), and (20) can be combined to give :

$$V = \varepsilon \frac{dL}{dt} = \frac{\varepsilon^3 d_f^2}{16k\,\mu(1-\varepsilon)^2} \frac{F_3}{L} \qquad (21)$$

Solving for F_3 gives :

$$F_3 = \frac{16k\,\mu\,(1-\varepsilon)^2}{\varepsilon^2\, d_f^2} L \frac{dL}{dt} \qquad (22)$$

The gravitational force, F_4, per unit cross-sectional area normal to flow, which opposes oil flow when flow is non-horizontal, is :

$$F_4 = \rho \varepsilon L g \cos\phi \qquad (23)$$

Therefore, the complete equation of oil motion into sorbent becomes :

$$\rho \varepsilon L \frac{d^2L}{dt^2} + \rho \varepsilon \left(\frac{dL}{dt}\right)^2 = \frac{2}{\pi} \frac{4(1-\varepsilon)\gamma}{d_f} \cos\theta - \frac{2\gamma(t_s+w)}{t_s w} - \rho \varepsilon L g \cos\phi - \frac{16 k \mu (1-\varepsilon)^2}{\varepsilon^2 d_f^2} L \frac{dL}{dt} \qquad (24)$$

In this equation, the only variables are L and t. The other parameters are constant for a given system. For a given sorbent and oil, this nonlinear differential equation can be represented by the following equation :

$$k_5 \left[L \frac{d^2L}{dt^2} + \left(\frac{dL}{dt}\right)^2 \right] = k_1 - k_2 - k_3 L - k_4 L \frac{dL}{dt} \qquad (25)$$

where k_1, k_2, k_3, and k_4 are defined similarly as in eq. (6) and k_5 is defined as :

$$k_5 = \rho \varepsilon$$

When the acceleration terms are negligible, eq.(25) reduces to :

$$k_1 - k_2 - k_3 L - k_4 L \frac{dL}{dt} = 0 \qquad (26)$$

The acceleration terms were found to be negligible by Walline(1974) and Lay(1980) .

For complete oil wetting, the sorbent/oil contact angle may be taken as zero ($\theta=0$). Then :

$$\cos\theta=1, \quad \text{and} \quad k_1=\frac{8(1-\varepsilon)\gamma}{\pi\, d_f}$$

3.1. The Horizontal Flow Equation and Its Solution

In this case, there is no gravity term, and $k_3=0$, since $\phi=90$. Therefore, eq.(26) reduces to :

$$k_1-k_2-k_4 L\,\frac{dL}{dt}=0 \tag{27}$$

The solution of this equation for t yields :

$$t=\frac{k_4}{k_1-k_2}\left(\frac{L^2}{2}+C\right)$$

For the initial condition L=0 at t=0, C=0. The solution of the flow equation then becomes :

$$t=\frac{k_4}{k_1-k_2}\,\frac{L^2}{2} \tag{28}$$

or

$$L=\left[\frac{2(k_1-k_2)}{k_4}\right]^{1/2} t^{1/2}=(\text{slope})\ t^{1/2} \tag{28a}$$

The distance penetrated by oil into sorbent is directly proportional to the square root of time and has a linear form. It is obtained from eq.(5) by taking $\cos\theta=1$:

$$L=\sqrt{\frac{\varepsilon^2\, d_f^2\ \gamma}{4(1-\varepsilon)^2 k\mu}\left[\frac{4(1-\varepsilon)}{\pi\, d_f}-\frac{(t_s+w)}{t_s\ w}\right]}\ t^{1/2} \tag{5a}$$

In this equation, the term with the square root sign is the slope of L vs. t curves and contains the properties both the sorbent and teh oil. Here, the sorbent properties may be combined to define a sorbent parameter:

$$\sqrt{\frac{\varepsilon^2 d_f^2}{4(1-\varepsilon)^2}\left[\frac{4(1-\varepsilon)}{\pi d_f}-\frac{(t_s+w)}{t_s w}\right]}$$

Similarly the effect of oil properties may be shown by an oil parameter:

$$\sqrt{\frac{\gamma}{\mu}}$$

As apparent from eq.(5a), the oil penetration is directly proportional to porosity and fiber diameter.

3.2. The Vertical Flow Equation and Its Solution

In this case, $k_3=\rho g\varepsilon$, since $\phi=0(\cos\phi=1)$. Then , by using eq.(25) one obtains:

$$t=k_4\left[\frac{k_1-k_2-k_3L}{k_3^2}-\frac{k_1-k_2}{k_3^2}\ln(k_1-k_2-k_3L)\right]+C$$

Imposing the initial condition L=0 at t=0, the solution becomes :

$$t=k_4\left[\frac{k_1-k_2}{k_3^2}\ln\left(\frac{k_1-k_2}{k_1-k_2-k_3L}\right)-\frac{L}{k_3}\right] \qquad (29)$$

As seen, the time required for the oil to climb a vertical distance L is nonlinear with this distance.

The maximum distance the oil will rise vertically against gravity when a sorbent strip is partially immersed in an oil reservoir, will be considered first. Since motion ceases at the maximum height, acceleration and shear terms will be zero. Letting $h_{eq.}$ be the height reached by the oil after a long time interval, eq.(26) becomes :

$$k_1-k_2=k_3h_{eq.} \quad \text{or} \quad h_{eq.}=\frac{k_1-k_2}{k_3} \tag{30}$$

where $h_{eq.}$ is the equilibrium height-of-rise. At this level, the oil stops rising since the gravitational force becomes equal to the surface tension force.

3.3. The Vertical Retention Equation and Its Solution

In this case, again $\text{Cos}\phi=1$, and $k_3=\rho g\varepsilon$. And there is no contact between the sorbent and the oil in the reservoir, therefore, the exterior surface tension term is negligible($k_2=0$). Thus eq.(26) reduces to:

$$k_1-k_3L-k_4L\frac{dL}{dt}=0 \tag{31}$$

The solution of this equation yields:

$$t=k_4\left[\frac{k_1-k_3L}{k_3^2}-\frac{k_1}{k_3^2}\ln(k_1-k_3L)\right]+C$$

Using initial condition $L=L_0$ at $t=0$(where L_0 is the initial and maximum distance of oil into sorbent), the following result is obtained :

$$t = k_4 \left[\frac{L_0 - L}{k_3} + \frac{k_1}{k_3^2} \ln\left(\frac{k_1 - k_3 L_0}{k_1 - k_3 L}\right) \right] \qquad (32)$$

This retention time is the time required for the oil to drain a distance of (L_0-L) from the sorbent. As seen, the time is nonlinear with the distance of (L_0-L).

The final height of oil in the sorbent is :

$$k_1 - k_3 h_{final} = 0 \quad \text{or} \quad h_{final} = \frac{k_1}{k_3} \qquad (33)$$

At this level, since the gravitational force becomes equal to the surface tension force which resists the oil dripping from the sorbent, the oil stops draining.

CHAPTER 4

EXPERIMENTAL PROCEDURE

4.1. Material Used

In this study, polyurethane and polypropylene samples were used as sorbents while SAE 20W-20 motor oil and SAE 90W gear oil were used as the test oils.

Polyurethanes used in this study are the same as those used by Lay(1980). Polyurethanes, with their foamy structures, are widely used as sponges, and have very low densities, large oil capacities, high elasticities, and high oil-sorption rates. The foams consist of polyurethane fibers, and resemble a three dimensional fish network structure, as shown in Figure 1. Polyurethane foams are reusable. The foams have circular cross-sections, and the fibers are cylindrical. The sorbent properties were measured by Lay(1980). The data obtained is given in Table 20 in Appendix II, have been used in this study. The polyurethane sorbents are manufactured by Scott Paper Company in U.S.A. To obtain a large sorbent/oil contact surface, thin rectangular sheets of the sorbents were used.

Polypropylenes used in this study are the same as those used by Walline(1974). Polypropylenes are made of synthetic fibers, and resemble the woven textile structure shown in Figure 2. The important properties which were

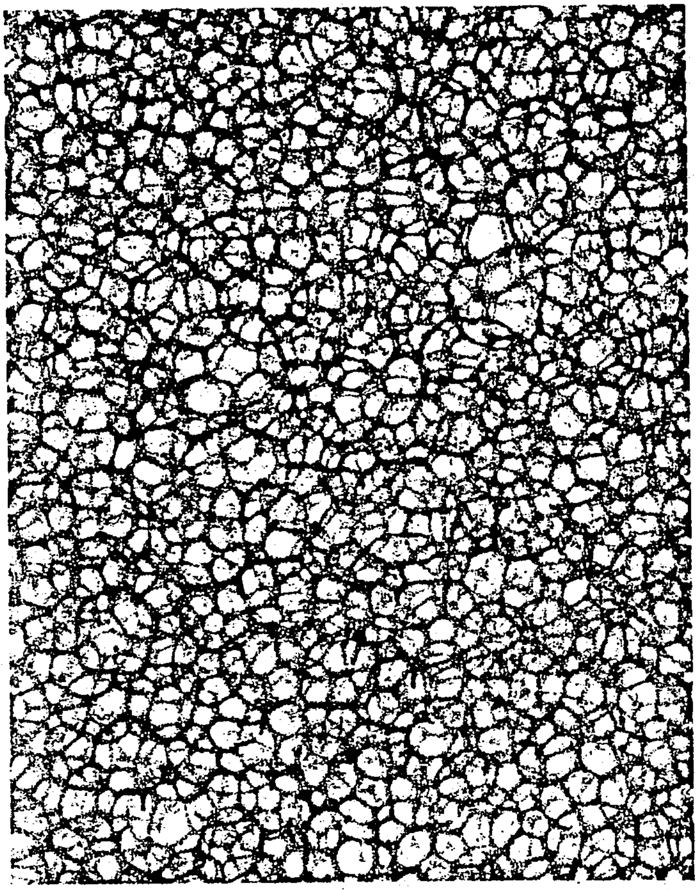


Figure 1. Polyurethane Structure

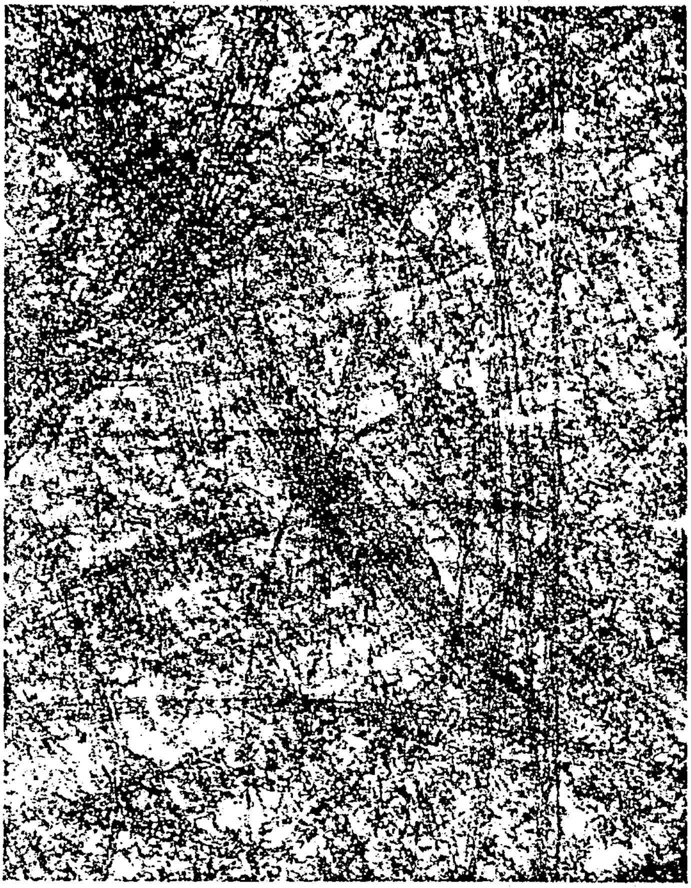


Figure 2. Polypropylene Structure

used are given in Table 20 in Appendix II, as measured by Walline(1974). The polypropylene samples, called Typar^R, are manufactured by Du Pont Company in U.S.A., and are grey in color due to the addition of carbon black. Here again, thin rectangular sheets of the sorbents were used.

The oils used in this study belong to Mobil Oil Company in Istanbul. Data for density and viscosity were taken from this company, and are given in Table 21, and Figures 15 and 16 in Appendix III. The required viscosity conversions are also given in Appendix III. Surface tension coefficients of the oils used were measured at Boğaziçi University, and the data are presented in Table 22 in Appendix III. The experimental procedure for measurement of surface tension coefficients of oils is explained in Appendix III.

4.2. The Horizontal Penetration Rate Experiments

The purpose of these experiments is to verify the study of Lay(1980) for the oils with different properties. The experimental setup used for the horizontal penetration of oils into dry polyurethane sorbents floating on water is shown in Figure 3. This setup contains a rectangular liquid reservoir made of tin and has two sections, which are seperated by a thin metal wall with a rectangular cavity in the middle to put the sorbant into. In the

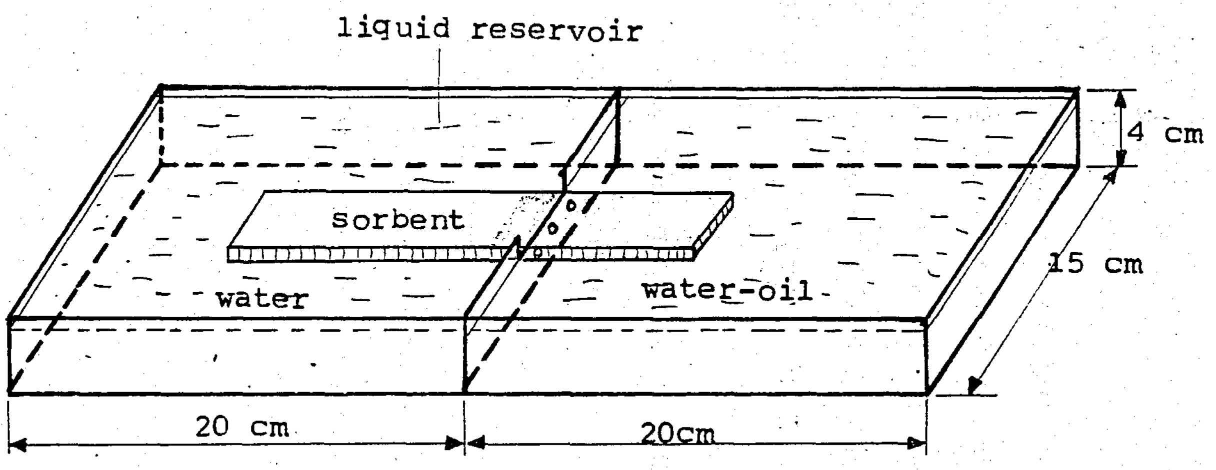


Figure 3. The Setup for the Horizontal Penetration Rate Experiments.

left section there is only water, while there are water and oil in the right section. Thus, the right end of the sorbent was placed on oil, and this part quickly absorbed oil. The left end of the sorbent was placed on water however,this part, because of the oleophilic and hydrophobic characters of the polyurethane sorbents, did not absorb water. Then, the movement of oil into dry polyurethanes was observed at certain times. The experimental and theoretical results for this case are summarized in Tables 4-9 in Appendix I.

4.3. Experiments for the Horizontal Displacement of Water by Oil

The purpose of these experiments was to simulate the conditions of oil spills in sea waters and remove oil by the polyurethane sorbents pre-wetted with water. This set of experiments was conducted for observation of the penetration of oil into the sorbents pre-wetted with water. Here again, the setup in Figure 3 was used. About 15 cm of the sorbent was wetted with water, and about 6 cm of the sorbent was immersed into the right section of the reservoir which contains water and oil. Then the movement of oil into the sorbent was observed periodically.

4.4. The Vertical Penetration Rate Experiments

The purpose of these experiments was to verify the study of Walline(1974) for the oils with different properties. This set of experiments was conducted for observation of the vertical penetration of oils into dry polypropylene sorbents. In these experiments, the setup in Figure 4 was used. This setup contains two parts: an oil reservoir, and one hanger consisting of a ruler and the sorbent sample. In these experiments, the height climbed by oil into the sorbent was measured. For this purpose, the second part was immersed into the oil reservoir at a certain level, such as $h=1$ cm at $t=0$. Then the rise of oil in the sorbent was observed at certain times. The experimental and the theoretical results are summarized in Tables 10-13 in Appendix I.

4.5. The Vertical Retention Experiments

The purpose of these experiments was to recover the oils from the sorbents wetted with oil. The setup shown in Figure 5 was used to study the draining of oils from polyurethane sorbents wetted with oil. The setup consists of two parts: a reservoir to collect the oil drained from the sorbent, and one hanger with a ruler and the sorbent

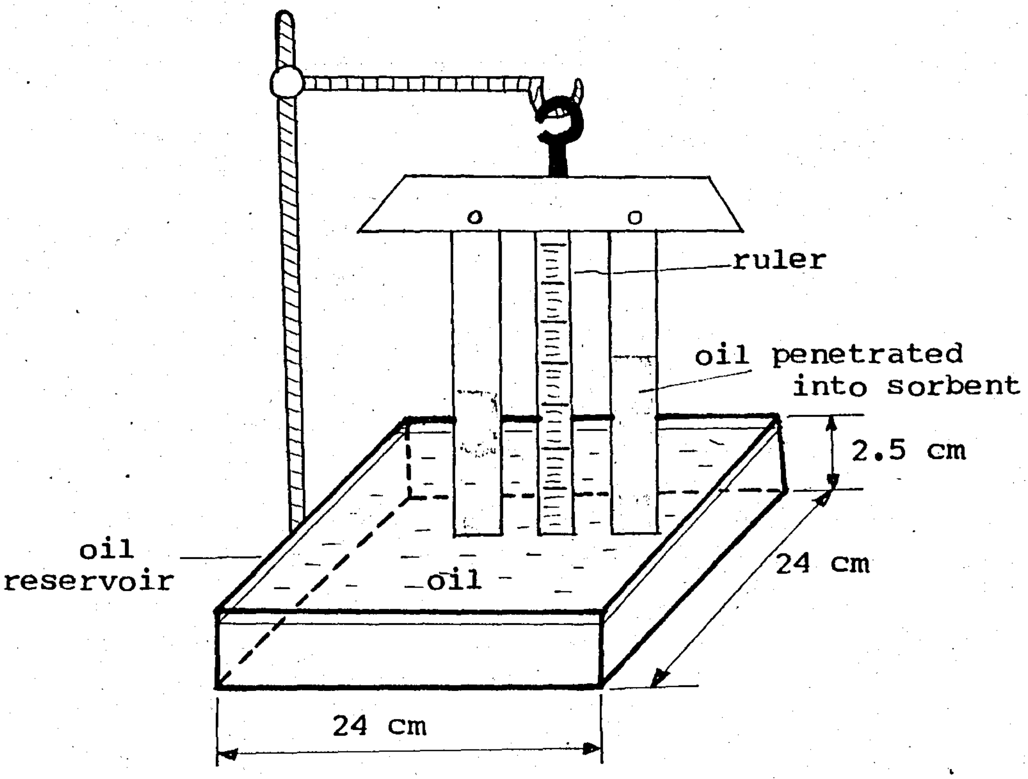


Figure 4. The Setup for the Vertical Penetration Rate Experiments.

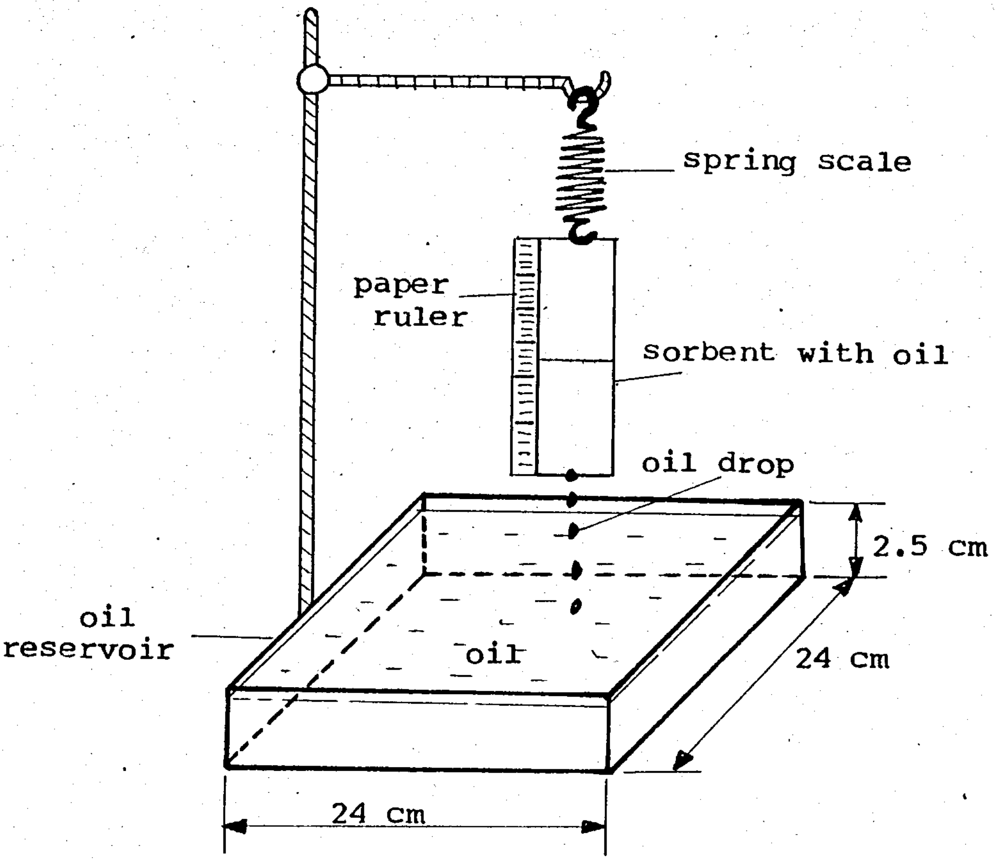


Figure 5. The Setup for the Vertical Retention Experiments.

sample. Here the sorbent samples were completely wetted with oil before, then suspended and left to drip. Thus, the drop in oil height in the sorbent against time was observed. The experimental and theoretical results for this case are summarized in Tables 14-19 in Appendix I.

CHAPTER 5

RESULTS AND DISCUSSION

5.1. The Horizontal Penetration Rate Experiments

In these experiments the oil motion into dry polyurethane sorbents was observed up to a critical distance, after which the sorbent absorbed water. Then, the weight of the sorbent increased and the sorbent sank into water. Dry black and orange sorbents could not be used, they absorbed water quickly; therefore, they could not float on water and sank, thus the black and orange sorbents were soaked with oil in advance.

The experimental and the theoretical results were plotted as in Figures 6-8. The model is linear as explained in Chapter 3. Therefore, the linear curves of the distance penetrated by oil vs. the square root of time were obtained for both the experimental and the theoretical results. A sample calculation for the generation of the theoretical curves is shown in Table 23 in Appendix IV. The effect of sorbent properties are shown in Figures 6 and 7, for SAE 20W-20 motor oil and SAE 90W gear oil, respectively. As seen in both of these figures, the oil penetration rate increases as porosity and fiber diameter increase. Figure 8 shows the effect of oil properties : SAE 90W gear oil has a lower oil penetration rate than SAE 20W-20

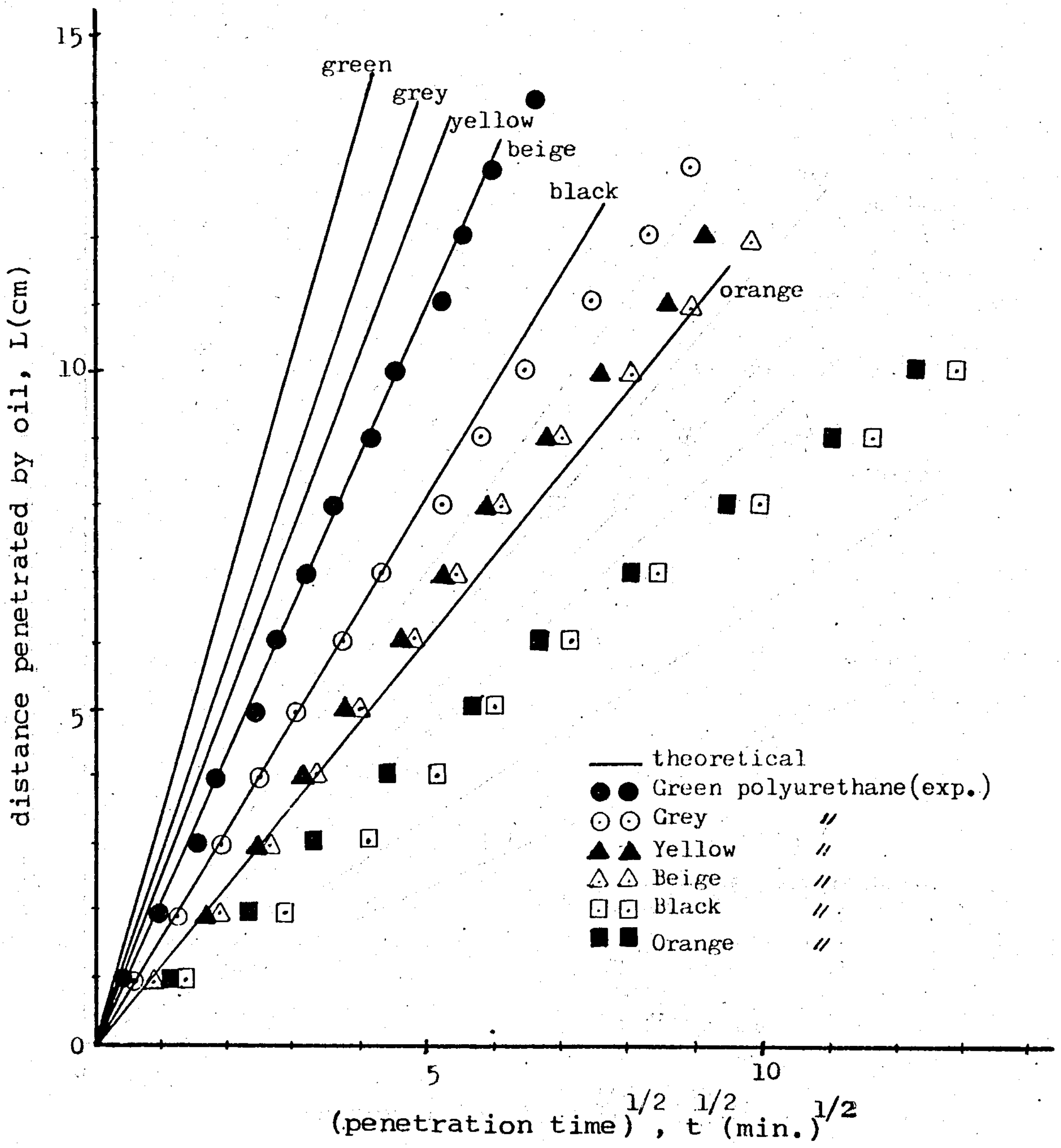


Figure 6. Effect of Polyurethane Sorbent Properties on Horizontal Penetration of SAE 20W-20 Motor Oil.

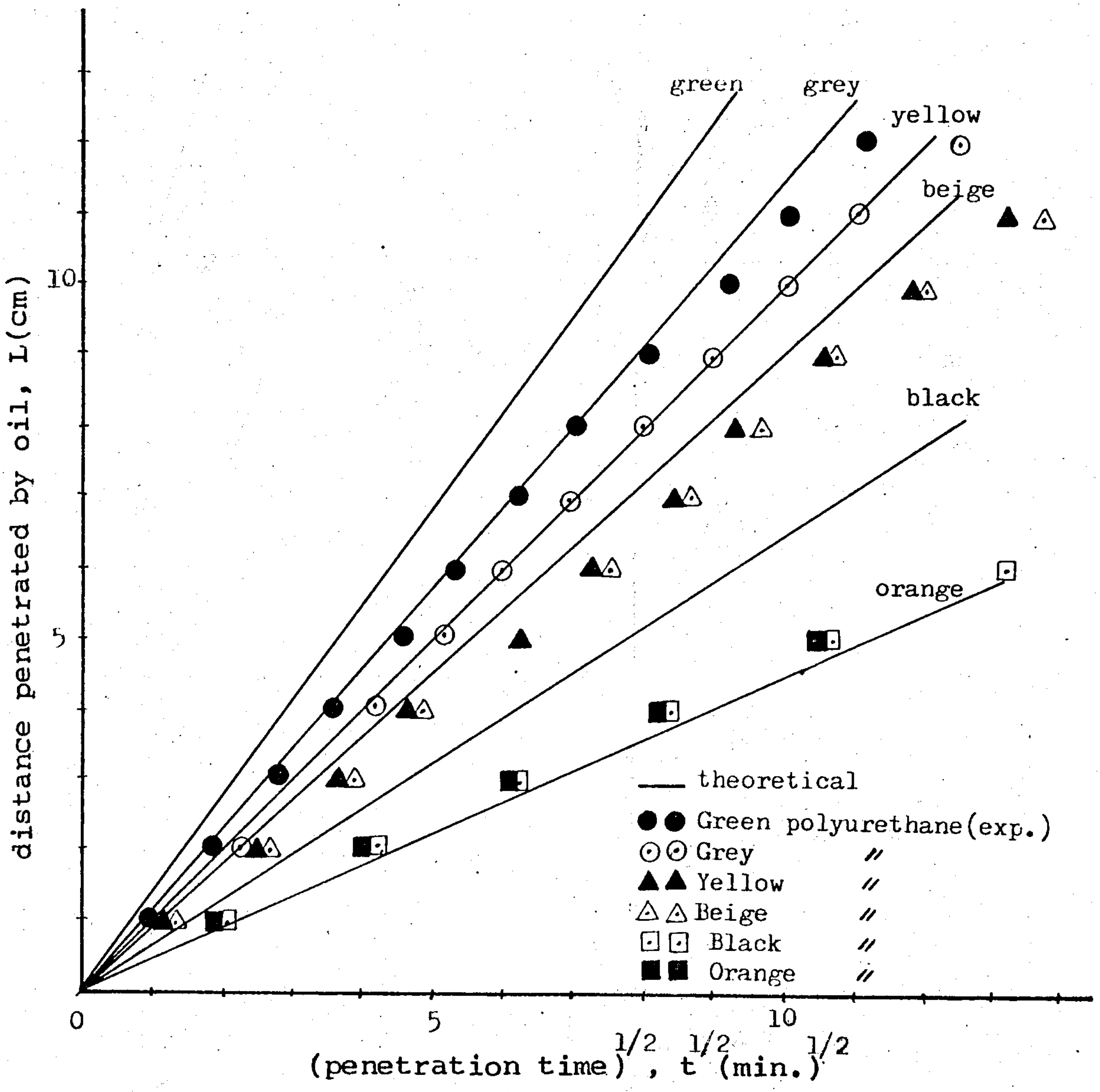
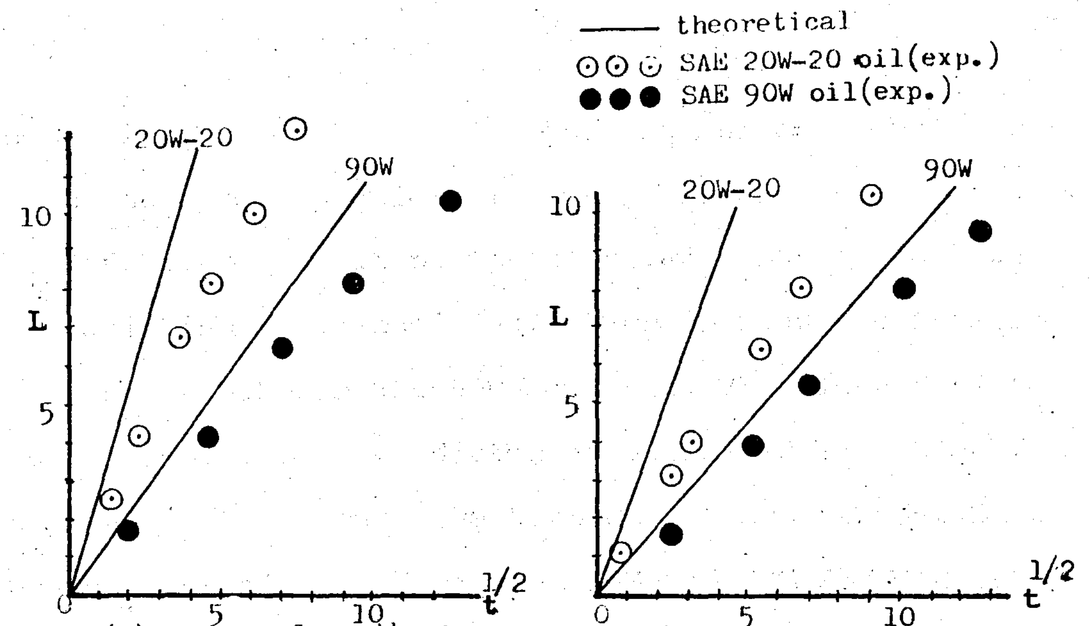
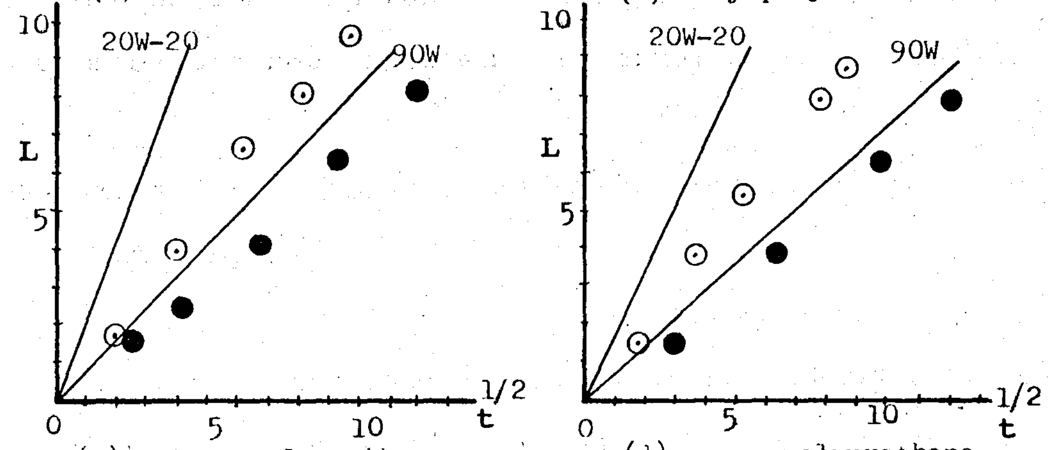


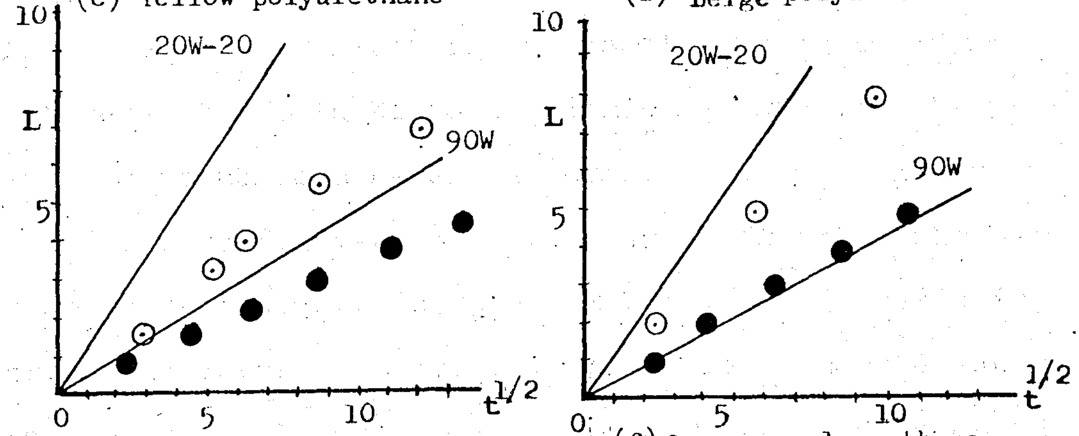
Figure 7. Effect of Polyurethane Sorbent Properties on Horizontal Penetration of SAE 90W Gear Oil.



(a) Green polyurethane (b) Grey polyurethane



(c) Yellow polyurethane (d) Beige polyurethane



(e) Black polyurethane (f) Orange polyurethane

Figure 8. Effect of Oil Properties on Horizontal Penetration of Oils into Sorbents, L: distance penetrated by oil(cm), $t^{1/2}$: (penetration time)$^{1/2}$ (min.)$^{1/2}$.

motor oil. Since the density and the surface tension coefficients are approximately equal for both these oils, the difference in oil penetration rates must be due to the variation of viscosities, which increases by nearly a factor of 5.5 for SAE 90W gear oil. The slope deviations from model were predicted as explained in Table 26 in Appendix IV. These are between 26% and 54% for SAE 20W-20 motor oil, and between 12% and 30% for SAE 90W gear oil as shown in Table 1. Thus, it was decided that this model did not represent the experiments well.

5.2. Experiments for the Horizontal Displacement of Water by Oil

In these experiments, the sorbents wetted with water were used, but no oil penetration into sorbents could be observed. Therefore, no model was developed for this case. The reluctance of oil in penetrating the prewetted sorbents can be explained as follows : the surface tension coefficient of water is greater than the oil's as shown in Table 22 in Appendix III, and the resisting force is greater than the driving force. Thus the water prevents the oil penetration into sorbent, and so an additional force is required to push the water out. Besides, acceleration may not be negligible in this case.

TABLE 1

COMPARISON OF THE SLOPES OF THE HORIZONTAL PENETRATION RATE CURVES

Oil	Polyurethane sorbent	Experimental slope ($cm/min^{1/2}$)	Theoretical slope ($cm/min^{1/2}$)	Slope deviation (%)
SAE 20W-20 motor oil	Green	2.00	3.40	41
	Grey	1.50	2.60	42
	Yellow	1.25	2.40	48
	Beige	1.28	2.14	40
	Black	0.77	1.66	54
	Orange	0.87	1.17	26
SAE 90W gear oil	Green	1.08	1.33	19
	Grey	1.00	1.14	12
	Yellow	0.83	1.00	17
	Beige	0.77	0.90	14
	Black	0.47	0.67	30
	Orange	0.50	0.44	14

5.3. The Vertical Penetration Rate Experiments

In these experiments, the rise of oil into dry polypropylene sorbents could be observed up to a critical height, where the gravitational force became equal to the surface tension force, and the advance of the oil front stopped. These experiments required long time periods varying from 6 to 10 days.

The experimental and the theoretical results for the distance penetrated by oil were plotted against time as in Figures 9-11. The model is nonlinear as explained in Chapter 3. A sample calculation for the generation of the theoretical curves is shown in Table 24 in Appendix IV. The effect of sorbent properties are shown in Figures 9 and 10, for SAE 20W-20 motor oil and for SAE 90W gear oil. The effect of oil properties is shown in Figure 11. As seen in Figures 9-11, the vertical penetration rate of oil into sorbents decreases as porosity and fiber diameter of the sorbent, and viscosity of the oil increase. However, as seen in these figures again, there is a quite a bit of difference between the experimental the theoretical results indicating that the model used here do not represent the experimental results well. According to the Figures 9-11, the polypropylene Typar^{R} 3401 is the best sorbent for this work. Furthermore, the experimental and the theoretical values of the equi-

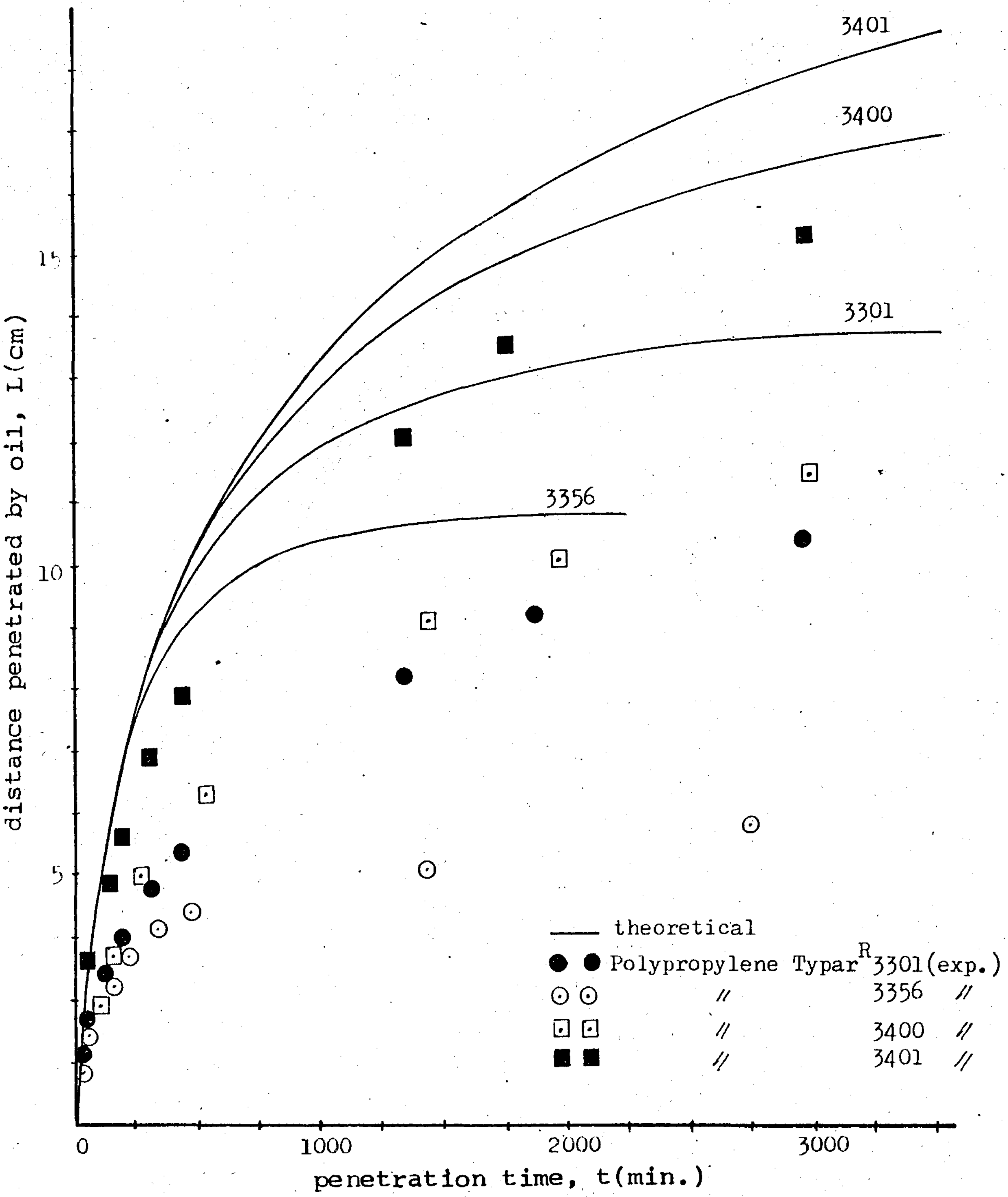


Figure 9. Effect of Polypropylene Sorbent Properties on Vertical Penetration of SAE 20W-20 Motor Oil.

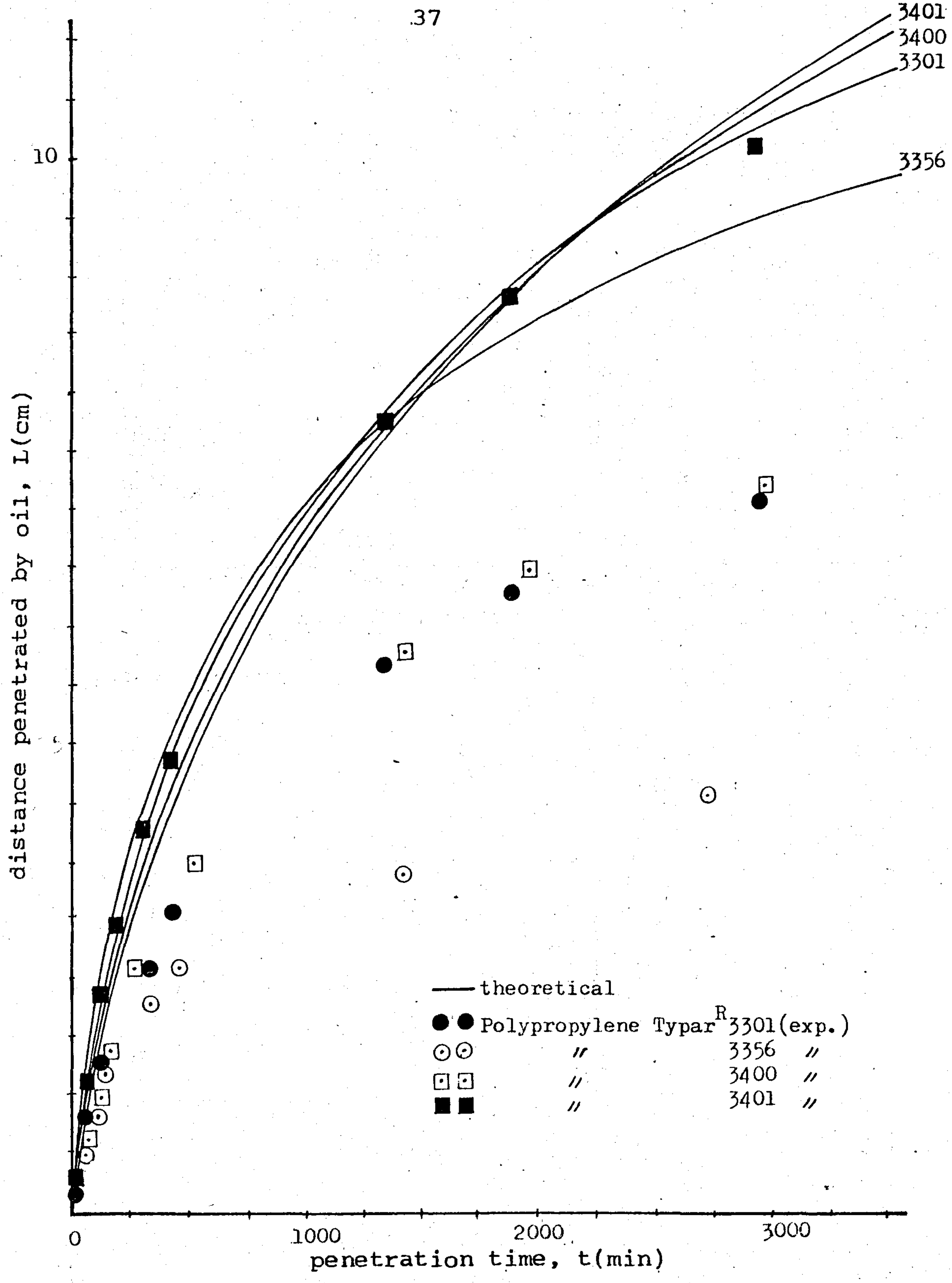
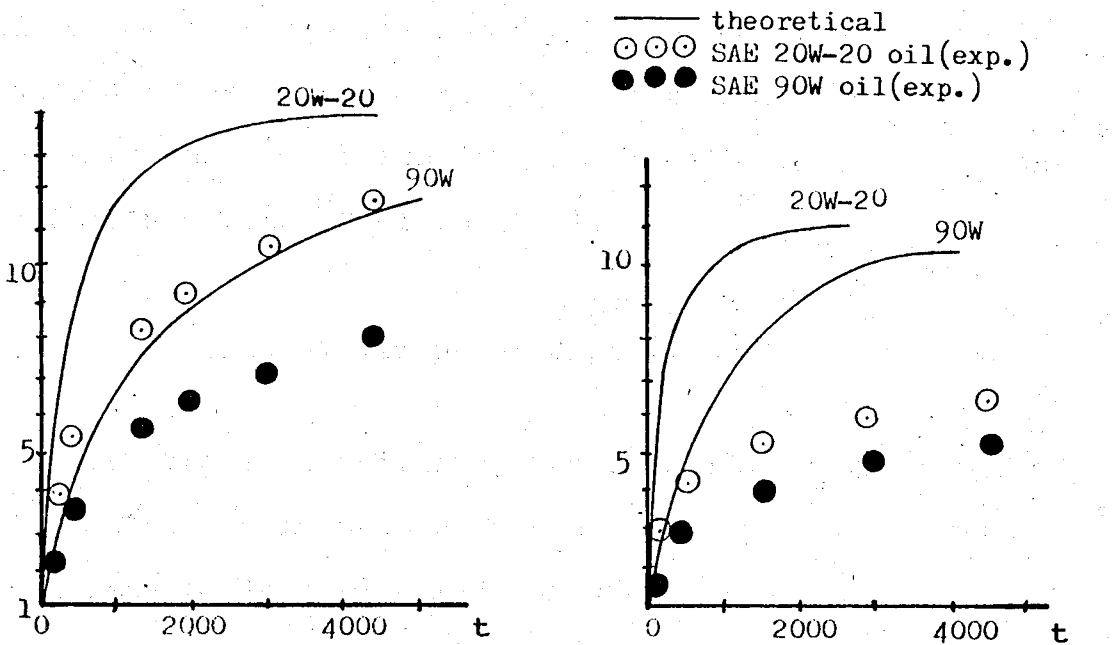
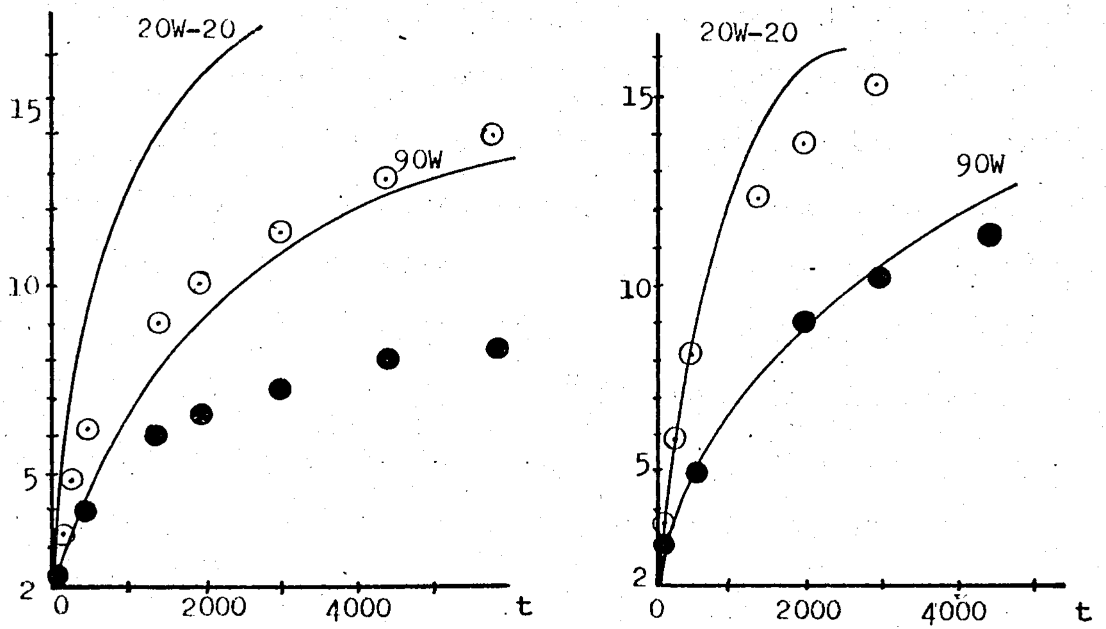


Figure 10. Effect of Polypropylene Sorbent Properties on Vertical Penetration of SAE 90W Gear Oil.



(a) Polypropylene Typar^{R}3301 (b) Polypropylene Typar^{R}3356



(c) Polypropylene Typar^{R}3400 (d) Polypropylene Typar^{R}3401

Figure 11. Effect of Oil Properties on Vertical Penetration Of Oils into Sorbents, L:distance penetrated by oil(cm), t:penetration time(min.).

librium height-of-rise for the oil samples are shown in Table 2. These values are higher for SAE 20W-20 motor oil which has a lower viscosity and agree better for the polypropylene Typar^{R}3301 and 3401.

5.4. The Vertical Retention Experiments

In these experiments, the dripping(or draining) of oil from the polyurethane sorbents could be observed up to a final(critical) height as shown in Table 3.

The experimental and the theoretical results on the distance drained by oil were plotted against the retention time as shown in Figures 12-14. The model is nonlinear as explained in Chapter 3. A sample calculation for the generation of the theoretical curves is shown in Table 25 in Appendix IV. The effect of sorbent properties for SAE 20W-20 motor oil and SAE 90W gear oil are shown in Figures 12 and 13, respectively. The effect of oil properties is shown in Figure 14. The oil draining rate increases as porosity and fiber diameter of the sorbent increase, and viscosity of the oil decreases, according to the Figures 12-14. The agreement between the model and the experimental results for green, grey and beige polyurethane samples with SAE 20W-20 motor oil, and for green and yellow polyurethane samples with SAE 90W gear oil is acceptable.

TABLE 2

COMPARISON OF THE EQUILIBRIUM HEIGHT-OF-RISE VALUES OF OILS INTO POLYPROPYLENES

Oil	Polypropylene sorbent	Experimental $h_{eq.}$ (cm)	Theoretical $h_{eq.}$ (cm)
SAE 20W-20 motor oil	Typar^R 3301	13.5	13.80
	" 3356	6.5	10.80
	" 3400	16.6	17.70
	" 3401	20.4	20.79
SAE 90W gear oil	Typar^R 3301	10.8	14.00
	" 3356	5.5	10.98
	" 3400	9.8	17.97
	" 3401	14.4	21.10

TABLE 3

COMPARISON OF THE FINAL HEIGHTS OF OILS INTO POLYURETHANES

Oil	Polyurethane sorbent	Experimental h_{final} (cm)	Theoretical h_{final} (cm)
SAE 20W-20 motor oil	Green	0.8	0.72
	Grey	1.8	1.31
	Yellow	4.3	1.95
	Beige	4.4	2.62
	Black	4.9	4.21
	Orange	4.5	7.44
SAE 90W gear oil	Green	0.8	0.72
	Grey	2.2	1.33
	Yellow	4.2	1.97
	Beige	4.1	2.66
	Black	5.1	4.26
	Orange	4.8	7.55

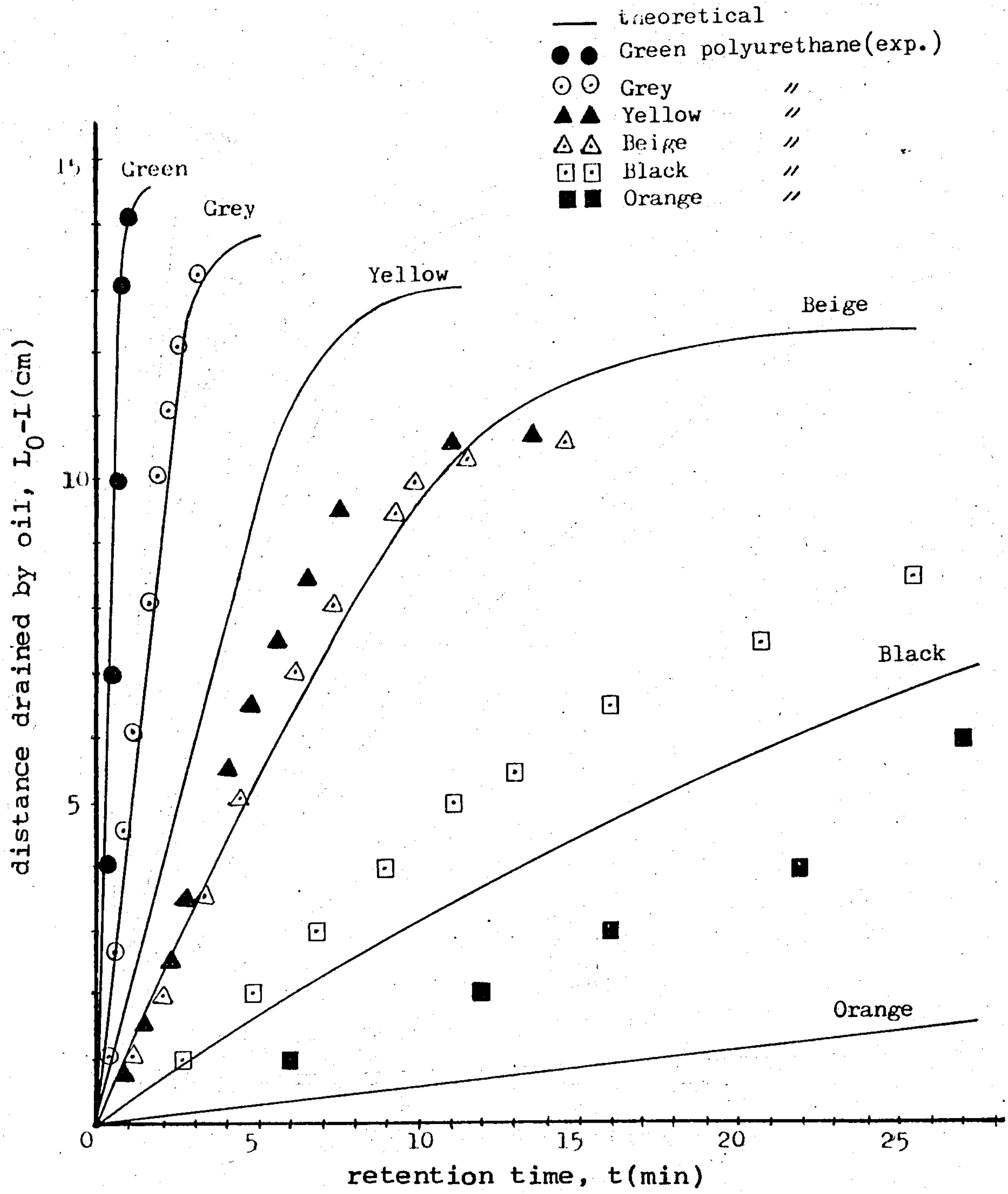


Figure 12. Effect of Polyurethane Sorbent Properties on Vertical Retention of SAE 20W-20 Motor Oil.

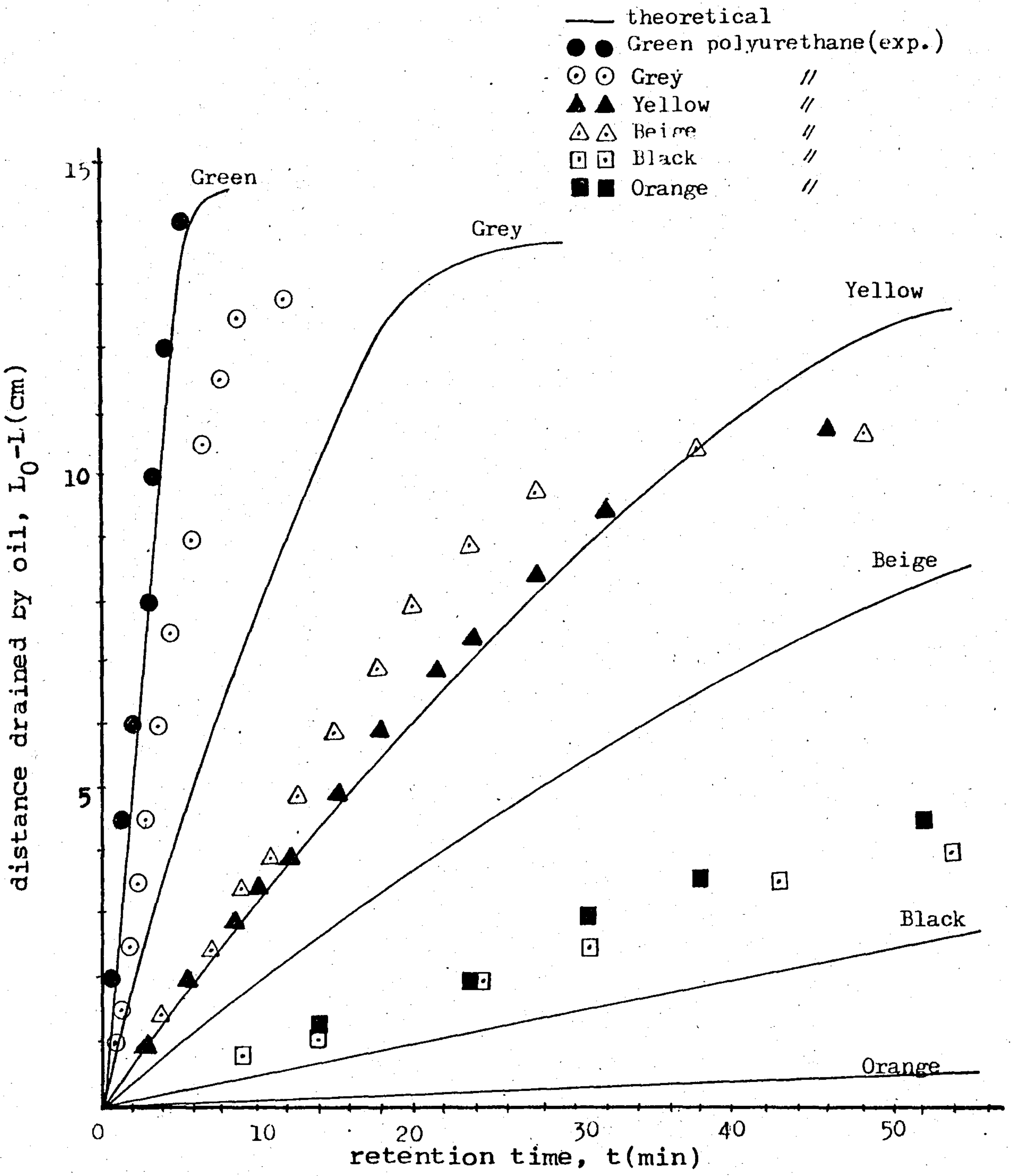
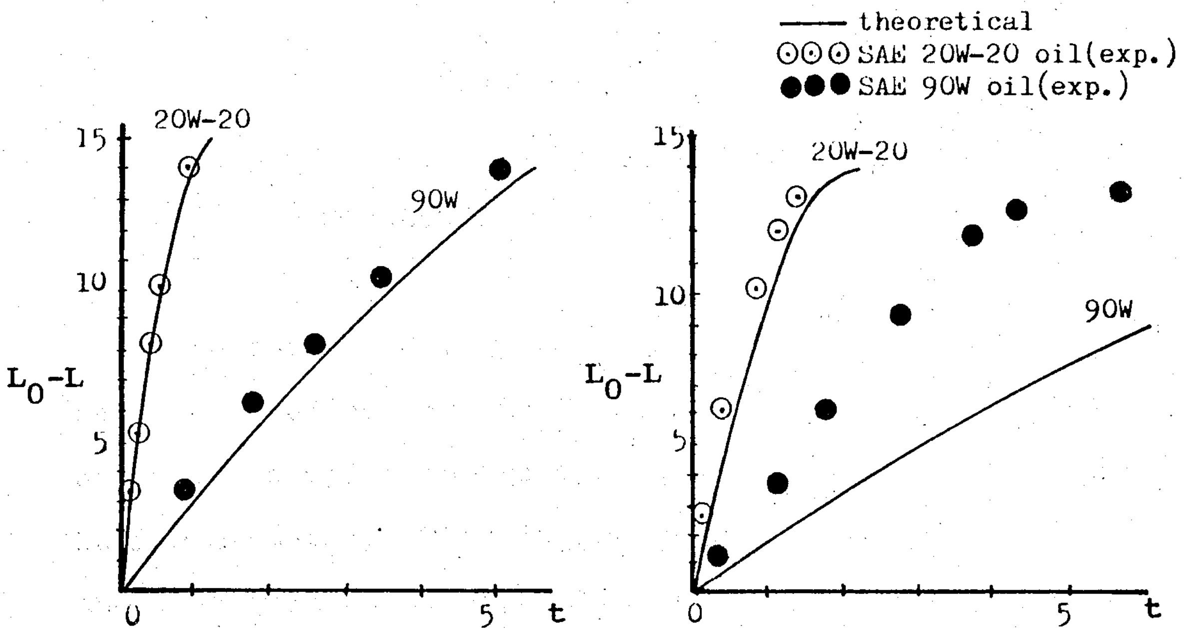
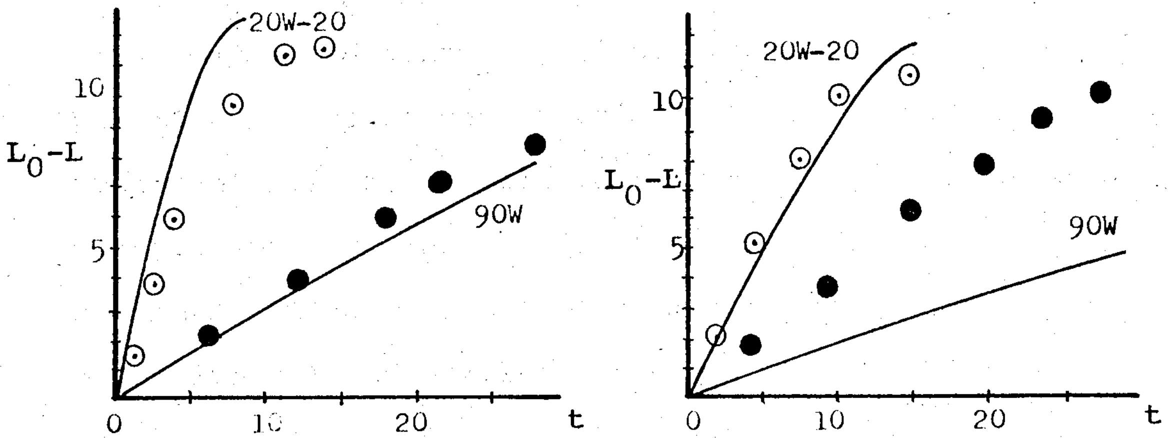


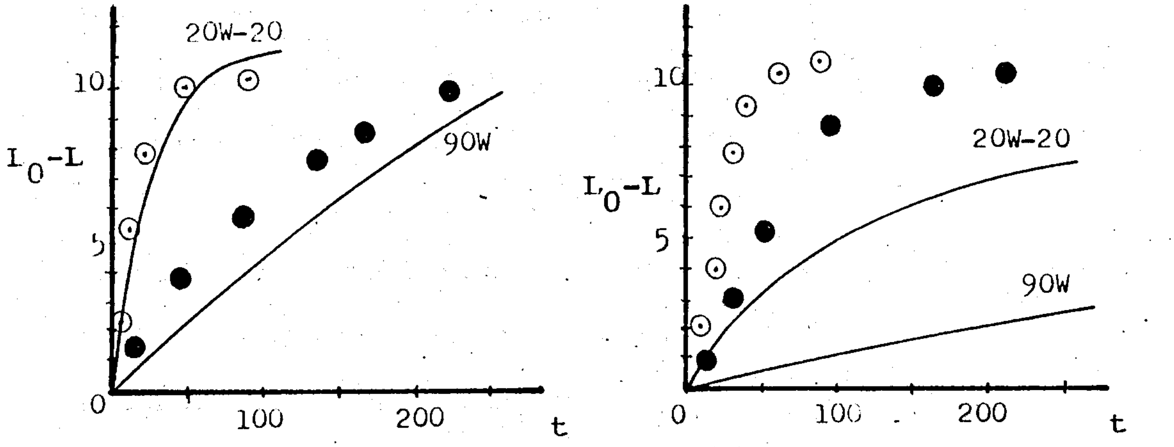
Figure 13. Effect of Polyurethane Sorbent Properties on Vertical Retention of SAE 90W Gear Oil.



(a) Green polyurethane (b) Grey polyurethane



(c) Yellow polyurethane (d) Beige polyurethane



(e) Black polyurethane (f) Orange polyurethane

Figure 14. Effect of Oil Properties on Vertical Retention of Oils into Sorbents, L_0-L: distance drained by oil(cm), t: retention time(min).

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

In this study, penetration of oil into sorbents has been studied for the purpose of recovering petroleum products spilt in the sea, thus eliminating the pollution of waters. This is important in practice for economic as well as water quality reasons. Here, polyurethanes and polypropylenes, and motor oil and gear oil were used as sorbents and oils, respectively. Four types of experiments were carried out: horizontal penetration of oil, horizontal displacement of water by oil, vertical penetration of oil, and vertical retention of sorbents filled with oil. The models used for the cases of horizontal and vertical penetration of oils were taken from Walline(1974) and Lay(1980). The model for the fourth case was developed on the basis of the works of Walline and Lay. Since water prevented the penetration of oil into sorbent, unsuccessful results were obtained in the experiments for the displacement of water by oil, therefore, no mathematical model was developed for the second case. However, mathematical used for each of horizontal penetration of oil, vertical penetration of oil, vertical retention of sorbents completely wetted with oil did not predict the experimental results well.

These conclusions can be drawn from this study:

1. The porosity, thickness, and fiber diameter of a sorbent, the viscosity and surface tension coefficient of an oil, and the sorbent/oil contact angle are the significant parameters in the expression developed for the penetration of oils into sorbents.

2. According to the horizontal penetration rate experiments and model, the distance penetrated by oil into a sorbent is linearly proportional to the square root of time. And the horizontal penetration rate of oil into a sorbent is directly proportional to porosity and fiber diameter of sorbent, and inversely proportional to the viscosity of oil in general.

3. The vertical penetration rate and the vertical retention models are nonlinear. The experimental and the theoretical curves of the distance penetrated by oil vs. the time also verified this behaviour. The vertical penetration rate decreases as porosity, fiber diameter and viscosity increase; and the oil draining rate on vertical retention of the sorbents filled with oil increases with porosity and fiber diameter, and decreases with viscosity, according to the experimental and theortical curves.

4. In the experiments here, the liquid was stagnant. However in practice, the liquid(sea water) is not stagnant and wets the sorbent continuously. Since water

prevents the penetration of oil into sorbent, the application of this study is difficult in practice.

For further work, the following are recommended:

1. All models used for theoretical calculations should be evaluated again.

2. The physical properties of sorbents, especially porosity, should be checked.

3. The non-horizontal penetration rate model should be verified experimentally for different angles of inclination of flow using various sorbents and oils.

4. The horizontal displacement of water by oil using various other sorbents, not tried here, should be carried out and modelled.

6. The experiments should be conducted in as much a stagnant sea-water environment as possible.

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APPENDIX I

SUMMARY OF EXPERIMENTAL AND THEORETICAL RESULTS

The experimental procedures for the horizontal penetration rate, the vertical penetration rate, and the vertical retention experiments were explained in Chapter 4, and the corresponding theoretical models were explained in Chapter 3. The experimental and the theoretical results can be located in the following tables :

a. the horizontal penetration rate results in Tables 4-9,

b. the vertical penetration rate results in Tables 10-13,

c. the vertical retention results in Tables 14-19.

The theoretical results with sample calculations are given in Appendix IV. The symbols used for column headings in these tables have the following meanings :

L: the distance penetrated by oil into sorbent,

L_0: the initial and the maximum distance of oil in the sorbent on vertical retention,

L_0-L: the distance drained by oil into sorbent on vertical retention,

t: the penetration time, or the draining time.

TABLE 4

HORIZONTAL PENETRATION RATE RESULTS FOR GREEN POLYURETHANE AND TWO TYPES OF OILS

Sample dimensions : 31.6 x 4.0 x 0.330(cm)

Oil	Experimental			Theoretical		
	L(cm)	t(min)	$t^{1/2}$	L(cm)	t(min)	$t^{1/2}$
SAE 20W-20 motor oil at 21°C.	1	0.25	0.50	1	0.08	0.29
	2	0.83	0.91	2	0.34	0.58
	3	2.25	1.50	3	0.76	0.87
	4	3.17	1.78	4	1.35	1.16
	5	5.75	2.40	5	2.11	1.45
	6	6.92	2.63	6	3.04	1.74
	7	9.66	3.11	7	4.13	2.03
	8	12.25	3.50	8	5.40	2.32
	9	17	4.12	9	6.83	2.61
	10	20	4.47	10	8.43	2.90
	11	27	5.20	11	10.21	3.19
	12	31	5.57	12	12.15	3.49
	13	36	6.00	13	14.25	3.78
	14	45	6.70	14	16.53	4.07
	15	53	7.28	15	18.98	4.36
SAE 90W gear oil at 21°C.	1	0.75	0.87	1	0.54	0.73
	2	3.50	1.87	2	2.15	1.47
	3	8.00	2.83	3	4.83	2.20
	4	12.50	3.54	4	8.59	2.93
	5	21	4.58	5	13.42	3.66
	6	28	5.29	6	19.33	4.40
	7	39	6.25	7	26.31	5.13
	8	49	7.00	8	34.36	5.86
	9	65	8.06	9	43.49	6.60
	10	85	9.22	10	53.70	7.33
	11	102	10.10	11	64.97	8.06
	12	126	11.22	12	77.32	8.79
	13	155	12.45	13	90.74	9.53

(Always L=0 at t=0)

TABLE 5

HORIZONTAL PENETRATION RATE RESULTS FOR GREY POLYURETHANE AND TWO TYPES OF OILS

Sample dimensions : 30.6 x 4.0 x 0.341(cm)

Oil	Experimental			Theoretical		
	L(cm)	t(min)	$t^{1/2}$	L(cm)	t(min)	$t^{1/2}$
SAE 20W-20 motor oil at 21°C.	1	0.42	0.65	1	0.12	0.35
	2	1.50	1.22	2	0.48	0.69
	3	3.42	1.85	3	1.08	1.04
	4	5.75	2.40	4	1.91	1.38
	5	8.83	2.97	5	2.99	1.73
	6	14	3.74	6	4.31	2.08
	7	18	4.24	7	5.86	2.42
	8	27	5.20	8	7.66	2.77
	9	33	5.74	9	9.69	3.11
	10	42	6.48	10	11.96	3.46
	11	55	7.42	11	14.47	3.80
	12	69	8.31	12	17.22	4.15
	13	80	8.94	13	20.22	4.50
SAE 90W gear oil at 21°C.	1	1.42	1.19	1	0.76	0.87
	2	5.00	2.24	2	3.05	1.75
	3	10.50	3.24	3	6.86	2.62
	4	17	4.12	4	12.19	3.49
	5	27	5.20	5	19.05	4.36
	6	35	5.92	6	27.42	5.24
	7	47	6.92	7	37.33	6.11
	8	63	7.94	8	48.76	6.98
	9	80	8.94	9	61.71	7.86
	10	100	10.00	10	76.18	8.73
	11	123	11.10	11	92.18	9.60
	12	157	12.53	12	109.70	10.47
	13	182	13.49	13	128.74	11.35

TABLE 6
HORIZONTAL PENETRATION RATE RESULTS FOR YELLOW POLYURATHANE AND TWO TYPES OF OILS

Sample dimensions : 30.6 x 4.0 x 0.317(cm)

Oil	Experimental			Theoretical		
	L(cm)	t(min)	$t^{1/2}$	L(cm)	t(min)	$t^{1/2}$
SAE 20W-20 motor oil at 22°C.	1	1.08	1.04	1	0.15	0.39
	2	3.42	1.85	2	0.60	0.77
	3	6.17	2.48	3	1.35	1.16
	4	9.83	3.14	4	2.40	1.55
	5	16	4.00	5	3.74	1.93
	6	21	4.58	6	5.39	2.32
	7	28	5.29	7	7.33	2.71
	8	36	6.00	8	9.58	3.10
	9	48	6.93	9	12.12	3.48
	10	64	8.00	10	14.97	3.87
	11	78	8.83	11	18.11	4.25
	12	96	9.80	12	21.55	4.64
SAE 90W gear oil at 21°C.	1	1.58	1.26	1	1.00	1.00
	2	6	2.45	2	4.03	2.00
	3	14	3.74	3	9.07	3.01
	4	23	4.74	4	16.12	4.02
	5	39	6.24	5	25.19	5.o2
	6	56	7.48	6	36.27	6.02
	7	71	8.43	7	49,37	7.03
	8	86	9.27	8	64.48	8.o3
	9	113	10.63	9	81.61	9.03
	10	141	11.83	10	100.75	1o.04
	11	173	13.15	11	121.91	11.04.

TABLE 7

HORIZONTAL PENETRATION RATE RESULTS FOR BEIGE POLYURETHANE AND TWO TYPES OF OILS

Sample dimensions : 30.6 x 4.0 x 0.325(cm)

Oil	Experimental			Theoretical		
	L(cm)	t(min)	$t^{1/2}$	L(cm)	t(min)	$t^{1/2}$
SAE 20W-20 motor oil at 21°C.	1	0.83	0.91	1	0.21	0.46
	2	2.75	1.66	2	0.83	0.91
	3	5.92	2.43	3	1.87	1.37
	4	9.58	3.10	4	3.32	1.82
	5	13.50	3.67	5	5.19	2.28
	6	22	4.70	6	7.48	2.74
	7	27	5.20	7	10.18	3.19
	8	35	5.92	8	13.30	3.65
	9	45	6.71	9	16.83	4.10
	10	56	7.48	10	20.78	4.56
	11	72	8.49	11	25.14	5.01
	12	83	9.11	12	29.92	5.47
	13	103	10.15	13	35.11	5.93
SAE 90W gear oil at 22°C.	1	1.66	1.29	1	1.23	1.11
	2	6.92	2.63	2	4.90	2.21
	3	14.50	3.81	3	11.03	3.32
	4	22	4.69	4	19.61	4.43
	5	39	6.25	5	30.65	5.54
	6	53	7.28	6	44.13	6.64
	7	75	8.66	7	60.07	7.75
	8	93	9.64	8	78.46	8.86
	9	116	10.77	9	99.30	9.96
	10	144	12.00	10	122.59	11.07
	11	188	13.71	11	148.34	12.18
	12	216	14.70	12	176.53	13.29

TABLE 8

HORIZONTAL PENETRATION RATE RESULTS FOR BLACK POLYURETHANE AND TWO TYPES OF OILS

Sample dimensions : 31.6 x 3.8 x 0.335(cm)

	Experimental			Theoretical		
Oil	L(cm)	t(min)	$t^{1/2}$	L(cm)	t(min)	$t^{1/2}$
SAE 20W-20 motor oil at 21°C.	1	1.92	1.39	1	0.38	0.61
	2	8.17	2.86	2	1.50	1.22
	3	17	4.12	3	3.38	1.84
	4	26	5.10	4	6.00	2.45
	5	36	6.00	5	9.38	3.06
	6	51	7.14	6	13.50	3.67
	7	71	8.43	7	18.68	4.29
	8	99	9.95	8	24.00	4.90
	9	134	11.58	9	30.39	5.51
	10	166	12.88	10	37.52	6.12
SAE 90W gear oil at 21°C.	1	4.25	2.06	1	2.39	1.55
	2	18	4.25	2	9.56	3.09
	3	38	6.16	3	21.50	4.64
	4	68	8.24	4	38.22	6.18
	5	114	10.68	5	59.73	7.73
	6	174	13.19	6	86.00	9.27

TABLE 9

HORIZONTAL PENETRATION RATE RESULTS FOR ORANGE POLYURETHANE AND TWO TYPES OF OILS

Sample dimensions : 30.6 x 3.8 x 0.300(cm)

Oil	Experimental			Theoretical		
	L(cm)	t(min)	$t^{1/2}$	L(cm)	t(min)	$t^{1/2}$
SAE 20W-20 motor oil at 22°C.	1	1.42	1.19	1	0.68	0.83
	2	5.33	2.31	2	2.72	1.65
	3	10.92	3.30	3	6.13	2.48
	4	19	4.36	4	10.90	3.30
	5	32	5.66	5	17.03	4.13
	6	44	6.63	6	24.52	4.95
	7	66	8.12	7	33.37	5.78
	8	90	9.49	8	43.59	6.60
	9	122	11.05	9	55.17	7.43
	10	152	12.33	10	68.11	8.25
	11	192	13.86	11	82.41	9.08
SAE 90W gear oil at 20° C.	1	3.92	1.98	1	5.06	2.25
	2	16	4.00	2	20.22	4.50
	3	37	6.08	3	45.50	6.75
	4	69	8.31	4	80.89	8.99
	5	110	10.49	5	126.39	11.24

TABLE 10

VERTICAL PENETRATION RATE RESULTS FOR POLYPROPYLENE TYPAR^R 3301 AND TWO TYPES OF OILS

Sample dimensions : 31.6 x 4.8 x 0.026(cm)

Oil	Experimental		Theoretical	
	L(cm)	t(min)	L(cm)	t(min)
SAE 20W-20 motor oil at 26.5°C.	0.7	5	1	2.4
	1.5	15	2	10.1
	2.2	38	4	45.5
	2.7	68	6	117.6
	3.4	128	8	248.5
	4.0	188	10	488.2
	4.8	308	12	1004
	5.4	428	13	1624
	8.2	1328	13.5	2378
	9.2	1868	13.8	4178
	10.4	2948		
	11.7	4418		
	13.1	7328		
	13.5	8768		
SAE 90W gear oil at 26.5°C.	0.5	5	1	13.6
	1.0	15	2	57.3
	1.4	33	4	257.3
	1.8	63	6	663.7
	2.3	123	8	1396
	2.6	183	10	2719
	3.1	303	10.8	3553
	3.6	423	12	5472
	5.7	1323	13	8258
	6.3	1868	14	23816
	7.1	2943		
	7.9	4413		
	9.3	7323		
	9.8	8763		
	10.5	11643		
	10.8	14523		

TABLE 11

VERTICAL PENETRATION RATE RESULTS FOR POLYPROPYLENE TYPAR^R 3356 AND TWO TYPES OF OILS

Sample dimensions : 31.6 x 4.9 x 0.032 (cm)

Oil	Experimental		Theoretical	
	L(cm)	t(min)	L(cm)	t(min)
SAE 20W-20 motor oil at 26°C.	0.9	5	1	2.0
	1.4	20	2	8.3
	1.9	40	3	20.2
	2.4	70	4	39.1
	2.8	100	5	67.2
	3.3	160	6	108.1
	3.7	220	6.5	135.0
	4.1	340	8	257.4
	4.4	460	9	404.1
	5.1	1425	10	702.8
	5.8	2865	10.5	1080
	6.2	4485	10.8	2153
	6.5	7245		
SAE 90W gear oil at 26°C.	0.5	6	1	11.5
	0.9	21	2	49.0
	1.2	36	3	119.0
	1.5	66	4	229.9
	1.8	96	5	394.5
	2.2	156	5.5	502.7
	2.4	216	7	977
	2.8	336	8	1490
	3.1	456	9	2311
	3.9	1421	10	3890
	4.6	2861	10.5	5604
	5.1	4481	10.9	9972
	5.4	7241		
	5.5	8621		

TABLE 12

VERTICAL PENETRATION RATE RESULTS FOR POLYPROPYLENE TYPAR^R 3400 AND TWO TYPES OF OILS

Sample dimensions : 32.0 x 4.8 x 0.034(cm)

Oil	Experimental		Theoretical	
	L(cm)	t(min)	L(cm)	t(min)
SAE 20W-20 motor oil at 25.5°C.	0.7	5	1	2.9
	1.1	15	2	11.9
	1.8	35	4	51.8
	2.5	65	6	128.8
	3.0	95	8	256.0
	3.7	155	10	459.5
	4.9	275	12	781.2
	6.3	515	14	1328
	9,1	1415	16	2465
	10.1	1955	16.6	3150
	11.4	2975	17	3878
	12.8	4415	17.5	5916
	14.1	5855	17.7	10930
	15.0	7295		
	15.9	10085		
	16.4	11525		
	16.6	12965		
SAE 90W gear oil at 25.5°C.	0.6	5	1	16.2
	0.9	15	2	67.4
	1.2	35	4	294.1
	1.6	65	6	729.4
	2.0	96	8	1450
	2.2	155	9.9	2515
	3.1	275	12	4373
	4.0	515	14	7360
	5.8	1415	15	9720
	6.5	1955	16	13292
	7.2	2975	17	19853
	8.0	4415	17.9	45392
	8.5	5855		
	8.9	7295		
	9.5	10085		
	9.8	11525		

TABLE 13

VERTICAL PENETRATION RATE RESULTS FOR POLYPROPYLENE TYPAR^R 3401 AND TWO TYPES OF OILS

Sample dimensions : 31.6 x 4.9 x 0.031(cm)

Oil	Experimental		Theoretical	
	L(cm)	t(min)	L(cm)	t(min)
SAE 20W-20 motor oil at 26.5°C.	1.0	5	1	3.1
	2.1	18	2	13.0
	2.9	38	4	55.9
	3.6	68	6	136.4
	4.8	128	8	265.3
	5.6	188	10	459.3
	6.9	308	12	745.1
	7.9	428	14	1170
	12.0	1328	16	1834
	13.5	1868	18	3000
	15.3	2948	20	6057
	17.1	4418	20.4	8613
	19.3	7328	20.7	11609
	20.0	8768		
	20.4	11648		
SAE 90W gear oil at 26.5°C.	0.7	5	1	17.8
	1.3	15	2	73.8
	1.7	33	4	316.9
	2.2	63	6	771.8
	2.9	123	8	1499
	3.5	183	10	2588
	4.3	303	12	4184
	4.9	423	14	6541
	7.8	1323	14.4	7299
	8.8	1863	16	10168
	10.1	2943	18	16358
	11.1	4413	20	30794
	12.6	7323	21.1	115581
	13.3	8763		
	14.1	11463		
	14.4	12903		

TABLE 14

VERTICAL RETENTION RESULTS FOR GREEN POLYURETHANE AND TWO TYPES OF OILS

Sample dimensions : 31.0 x 3.7 x 0.330(cm)

Oil	Experimental		Theoretical	
	L_0^1-L(cm)	t(min)	L_0-L(cm)	t(min)
SAE 20W-20 motor oil at 26.5°C.	2	0.08	2	0.10
	3	0.12	3	0.16
	4	0.18	4	0.22
	5	0.23	5	0.27
	7	0.33	7	0.38
	8	0.42	8	0.44
	10	0.60	10	0.55
	12	0.66	12	0.68
	13	0.75	13	0.75
	14	0.83	14	0.85
	14.2	0.92	14.2	0.90
			14.28	0.96
SAE 90W gear oil at 25°C.	1	0.33	1	0.34
	2	0.58	2	0.69
	3	0.92	3	1.03
	4.5	1.33	5	1.73
	6	1.83	6	2.08
	8	2.50	8	2.80
	10	3.33	10	3.54
	12	4.00	12	4.34
	13	4.42	13	4.84
	14	4.92	14	5.47
	14.2	5.17	14.2	5.80
			14.28	6.43

$^{1}L_0$=15cm.

TABLE 15

VERTICAL RETENTION RESULTS FOR GREY POLYURETHANE AND TWO TYPES OF OILS

Sample dimensions : 31.0 x 3.7 x 0.341(cm)

Oil	Experimental		Theoretical	
	L_0^1-L(cm)	t(min)	L_0-L(cm)	t(min)
SAE 20W-20 motor oil at 26°C.	1	0.25	1	0.20
	2.5	0.50	2	0.41
	4.5	0.75	4	0.82
	6	1.00	6	1.24
	8	1.42	8	1.69
	10	1.75	10	2.16
	11	2.00	11	2.42
	12	2.33	12	2.71
	13	2.82	13	3.11
	13.2	3.00	13.2	3.23
			13.69	4.56
SAE 90W gear oil at 25°C.	1	0.83	1	1.27
	1.5	1.17	2	2.55
	2.5	1.83	3	3.83
	3.5	2.33	4	5.14
	4.5	2.92	5	6.45
	6	3.58	6	7.80
	7.5	4.50	8	10.56
	9	5.75	9	12.00
	10.5	6.50	10	13.53
	11.5	7.50	11	15.17
	12.5	8.75	12	17.03
	12.8	11.50	12.8	18.95
			13.67	28.43

[1] L_0=15cm.

TABLE 16
VERTICAL RETENTION RESULTS FOR YELLOW POLYURETHANE AND TWO TYPES OF OILS

Sample dimensions : 31.0 x 3.7 x 0.317(cm)

	Experimental		Theoretical	
Oil	L_0^1-L(cm)	t(min)	L_0-L(cm)	t(min)
SAE 20W-20 motor oil at 26°C.	0.7	0.75	1	0.46
	1.5	1.42	2	0.92
	2.5	2.25	3	1.38
	3.5	2.75	4	1.86
	4.5	3.50	5	2.34
	5.5	4.00	6	2.84
	6.5	4.75	7	3.35
	7.5	5.50	8	3.88
	8.5	6.50	9	4.45
	9.5	7.50	10	5.06
	10.6	11.00	10.6	5.46
	10.7	13.50	12	6.66
			13.05	11.00
SAE 90W gear oil at 24°C.	1	3.00	1	3.20
	2	5.50	2	6.43
	2.5	7.00	3	9.71
	3	8.50	4	13.04
	3.5	10.00	5	16.44
	4	12.00	6	19.93
	5	15.25	7	23.53
	6	17.83	8	27.27
	7	21.33	9	31.24
	7.5	23.66	10	35.56
	8.5	27.50	10.5	37.91
	9.5	32.00	10.8	39.44
	10.5	37.83	12	46.97
	10.8	46.00	13.03	69.50

[1] L_0=15cm.

TABLE 17

VERTICAL RETENTION RESULTS FOR BEIGE POLYURETHANE AND TWO TYPES OF OILS

Sample dimensions : 31.0 x 3.7 x 0.325(cm)

	Experimental		Theoretical	
Oil	L_0^1-L(cm)	t(min)	L_0-L(cm)	t(min)
SAE 20W-20 motor oil at 26°C.	1	1.00	1	0.89
	2	2.17	2	1.80
	3.5	3.25	4	3.67
	5	4.42	5	4.64
	7	6.17	7	6.71
	8	7.33	8	7.83
	9.5	9.25	9	9.06
	10	9.92	10	10.46
	10.4	11.50	10.6	11.46
	10.6	14.50	11.5	13.46
			12.38	25.52
SAE 90W gear oil at 25°C.	0.7	2.00	1	5.60
	1.5	4.00	2	11.29
	2.5	6.75	3	17.09
	3.5	9.08	4	23.04
	4	10.75	5	29.16
	5	12.25	6	35.50
	6	14.75	7	42.16
	7	17.25	8	49.24
	8	19.25	9	57.00
	9	23.50	10	65.88
	9.8	27.17	10.7	73.39
	10.7	48.42	10.9	75.88
	10.9	65.88	12.34	157.49

[1] L_0=15cm.

TABLE 18

VERTICAL RETENTION RESULTS FOR BLACK POLYURETHANE AND TWO TYPES OF OILS

Sample dimensions : 31.0 x 3.7 x 0.335(cm)

	Experimental		Theoretical	
Oil	L_0^1-L(cm)	t(min)	L_0-L(cm)	t(min)
SAE 20W-20 motor oil at 25°C.	1	2.66	1	3.29
	2	4.92	2	6.68
	3	6.83	3	10.20
	4	9.00	4	13.89
	5	11.17	5	17.79
	5.5	13.00	6	22.00
	6.5	16.00	7	26.62
	7.5	20.75	8	31.96
	8.5	25.50	9	38.65
	9.5	35.58	10	49.00
	10	48.00	10.1	50.64
	10.1	88.00	10.79	102.81
SAE 90W gear oil at 25°C.	0.8	9	1	19.50
	1.2	14	2	39.64
	2	24	3	60.55
	2.5	31	4	82.45
	3.5	43	5	105.66
	4	54	6	130.69
	4.5	69	7	158.40
	5.5	86	8	190.49
	6.5	113	9	231.00
	7.5	135	9.9	286.51
	8.5	165	10.74	566.80
	9.5	193		
	9.9	223		

$^1L_0$=15cm.

TABLE 19

VERTICAL RETENTION RESULTS FOR ORANGE POLYURETHANE AND TWO TYPES OF OILS

Sample dimensions : 31.0 x 3.7 x 0.300(cm)

Oil	Experimental		Theoretical	
	L_0^1-L(cm)	t(min)	L_0-L(cm)	t(min)
SAE 20W-20 motor oil at 26°C.	1	6	1	15.8
	2	12	2	32.9
	3	16	3	51.9
	4	22	4	73.7
	6	27	5	100.1
	7.5	32	6	140.8
	9	40	7	202.0
	10.3	62	7.56	512.4
	10.5	90		
SAE 90W gear oil at 26°C.	1	14	1	94.3
	2	24	2	196.6
	3	31	3	310.7
	4	38	4	442.4
	5	52	5	604.0
	6.5	74	6	827.6
	8.5	94	7	1271
	9.5	122	7.45	1617
	10	165		
	10.2	212		

[1] L_0=15cm.

APPENDIX II

SORBENT PROPERTIES

TABLE 20

SORBENT PROPERTIES[1,2]

Sorbent	Porosity (ε)	Fiber diameter d_f(cm)	Thickness t_s(cm)	Oil capasity[3] 20W-20	Oil capasity[3] 90W
Polyurethane					
Green[4]	0.92	0.0131	0.330	0.41	0.71
Grey[4]	0.90	0.0090	0.341	0.83	0.98
Yellow[5]	0.93	0.0041	0.317	1.07	1.12
Beige[5]	0.91	0.0040	0.325	1.14	1.14
Black	0.78	0.0071	0.335	0.91	0.92
Orange	0.70	0.0061	0.300	0.80	0.80
Polypropylene					
Typar^R 3301	0.57	0.0041	0.026	0.54	—
〃 3356	0.58	0.0050	0.032	—	—
〃 3400	0.53	0.0042	0.034	—	—
〃 3401	0.51	0.0039	0.031	—	—

The permeability constant for polyurethane and polypropylene : k=5.

[1] Polyurethane sorbent properties were measured by Walline(1974) in University of Colorado in U.S.A.

[2] Polypropylene sorbent properties were measured by Lay (1980) in University of Colorado in U.S.A.

[3] Sorbent's oil capacity= $\frac{\text{Oil volume}}{\text{Void volume}}$x100%.

[4] In green and grey samples, there was oil loss due to dripping, therefore these reported capacities are lower than 1.0.

[5] In yellow and beige samples, since the oil clung to the outside of the sorbent, the reported capacities are higher than 1.0.

APPENDIX III

OIL PROPERTY DATA, MEASUREMENTS, AND CALCULATIONS

TABLE 21

DENSITIES OF OILS USED[1,2]

Oils	Density at 20°C ρ(g/cm)
SAE 20W-20 (motor oil)	0.884
SAE 90W (gear oil)	0.900

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[1] The data was obtained from Mobil Oil Company in Istanbul.

[2] The oil densities were assumed to be constant at all temperatures.

VISCOSITY CONVERSIONS

Dynamic Viscosity=Density x Kinematic Viscosity

$$\underset{\left(\frac{g}{cm\ sec}\right)}{\overset{(\text{Poise})}{\parallel}} = \underset{\left(\frac{g}{cm^3}\right)}{\overset{(g/cc)}{\parallel}} \times \underset{\left(\frac{cm^2}{sec}\right)}{\overset{(\text{Stoke})}{\parallel}}$$

For SAE 90W gear oil at 25°C (Figure 16) :

Kinematic viscosity=500 cs=5 stokes

Density =0.900 g/cm^3

Dynamic viscosity=(5).(0.900)=4.5 Poise

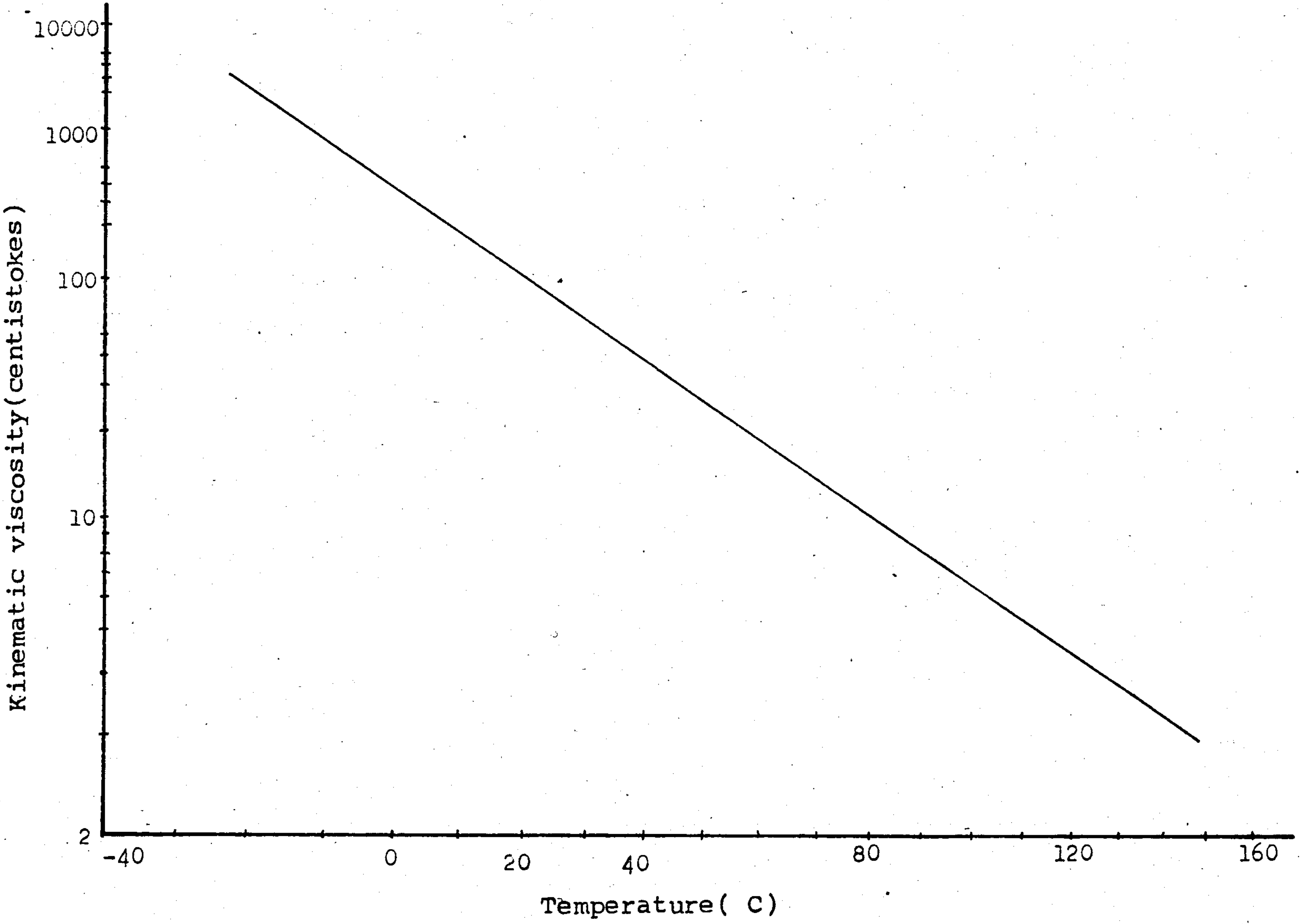

Figure 15. Viscosity-Temperature Chart for SAE 20W-20 Motor Oil.

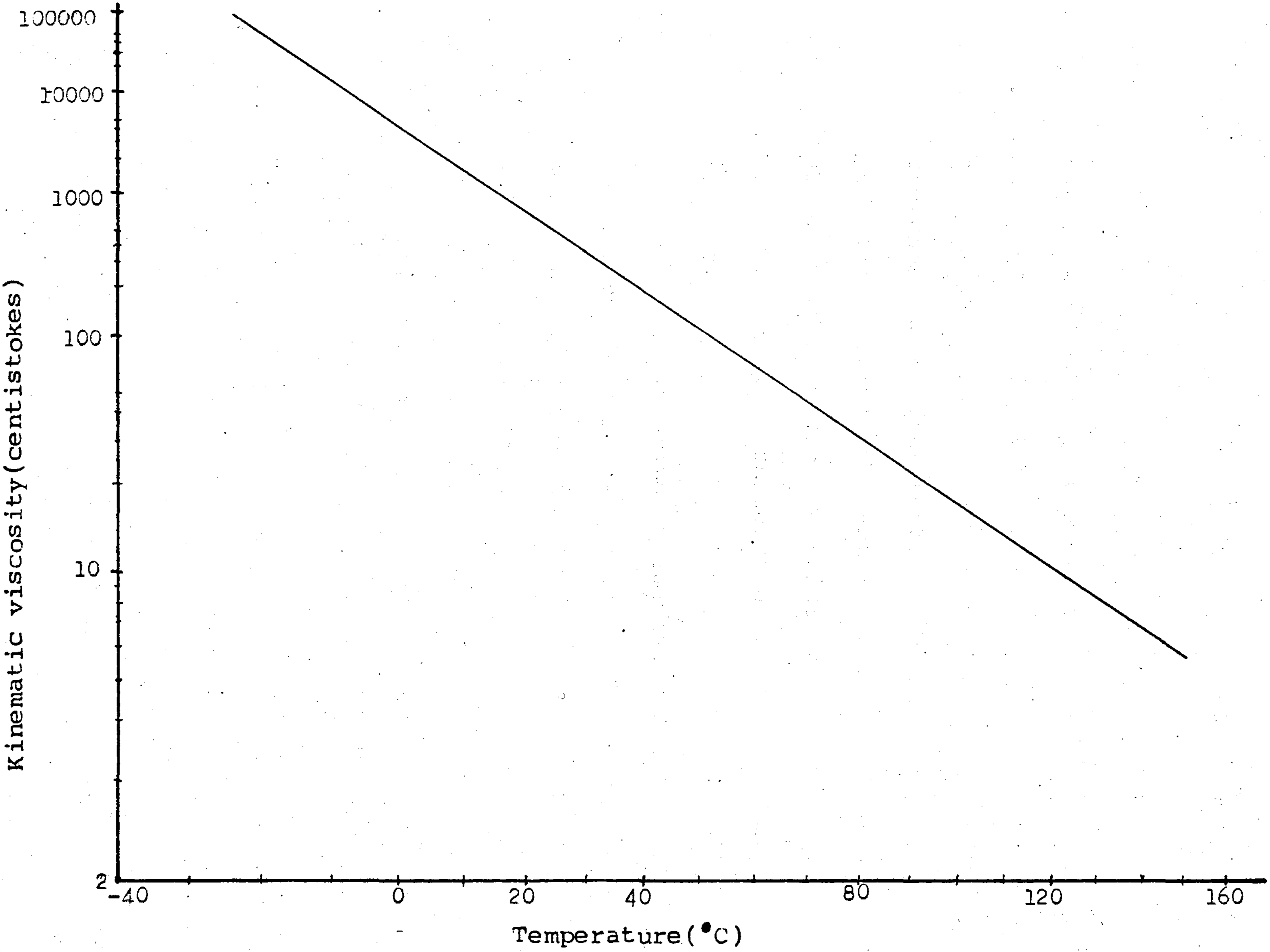

Figure 16. Viscosity-Temperature Chart for SAE 90W Gear Oil.

SURFACE TENSION COEFFICIENT MEASUREMENTS

The surface tension coefficients of oils used and water were measured in Chemistry Department Lab. of Boğaziçi University(Table 22). For this purpose, a surface tensiometer apparatus was used(Figure 17). This apparatus consists of four parts : a liquid reservoir, a wire-ring system, a mirror, and a scale which shows the values of surface tension coefficients in dynes/cm.

The working procedure of this apparatus is as follows :

1. The wire-ring is immersed into the oil in a beaker. Then the zero-balance of the wire-ring is adjusted in the mirror by turning switch 1.

2. The dial of this apparatus is turned on by switch 2 until the oil sphere of the wire-ring breaks out. Then the value of surface tension coefficient is read in dynes/cm from the scale of the apparatus.

TABLE 22

SURFACE TENSION COEFFICIENTS OF OILS USED AND WATER

Fluids	Surface tension coefficient γ(dynes/cm) at 22°C[1] Measurements	Average
Water/Air	65.8 65.4 65.5 65.7	65.6
SAE 20W-20 (motor oil) / Air	36.0 36.1 35.9 36.0	36.0
SAE 90W (gear oil) / Air	37.3 37.1 37.2 37.2	37.2
Water / SAE 20W-20 (motor oil)	32.8 33.0 33.2 33.1	33.0
Water / SAE 90W (gear oil)	29.9 29.8 29.7 29.8	29.8

[1] Surface tension coefficients were assumed to be constant with respect to temperature changes.

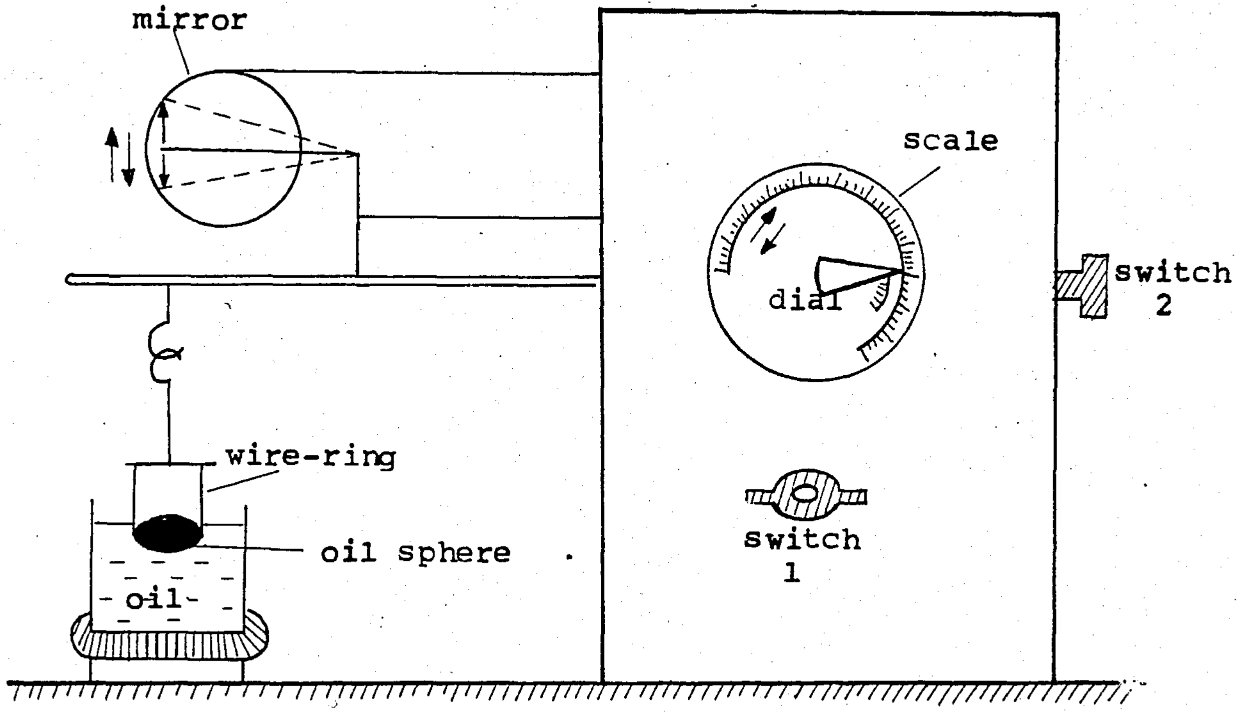

Figure 17. Surface Tensiometer Apparatus.

APPENDIX IV

SAMPLE CALCULATIONS

TABLE 23

A SAMPLE CALCULATION USING THE THEORETICAL HORIZONTAL PENETRATION RATE MODEL

Example: Yellow polyurethane and SAE 20W-20 motor oil (see Figures 6 and 8).

Parameters	Values of parameters used in the calculation Values	Tables used
k	5	20
ε	0.93	20
d_f	0.0041 cm.	20
t_s	0.317 cm.	20
w	3.7 cm.	6
T	22°C	6
ρ	0.884 g/cm^3.	21
μ	95cs=0.84 poise.	Figure 15.
γ	36 dynes/cm.	29

	parameters calculated
$k_1 = \dfrac{8(1-\varepsilon)\gamma}{\pi d_f}$	1566.0 dynes/cm^2.
$k_2 = \dfrac{2\gamma(t_s+w)}{t_s w}$	246.6 dynes/cm^2.
$k_4 = \dfrac{16k\mu(1-\varepsilon)^2}{\varepsilon^2\, d_f^2}$	22648 dynes-sec/cm^4.
$t = \frac{1}{2}L^2\left(\dfrac{k_4}{k_1+k_2}\right)$	858.3 sec.=14.3 min. at L=10 cm.
$t^{1/2}$	3.78(min)$^{1/2}$.

TABLE 24

A SAMPLE CALCULATION USING THE THEORETICAL VERTICAL PENETRATION RATE MODEL

Example: Polypropylene Typar^R 3301 and SAE 20W-20 motor oil(see Figures 9and 11).

Values of parameters used in the calculation

Parameters	Values	Tables used
k	5	20
ε	0.57	20
d_f	0.0041 cm.	20
t_s	0.026 cm.	20
w	4.9 cm.	10
T	26.5°C	10
ρ	0.884 g/cm^3.	21
μ	78cs=0.69 poise.	Figure 15.
γ	36 dynes/cm.	22

	parameters calculated
$k_1 = \dfrac{8(1-\varepsilon)\gamma}{\pi\, d_f}$	9619.4 dynes/cm^2.
$k_2 = \dfrac{2\gamma(t_s+w)}{t_s w}$	2783.9 dynes/cm^2.
$k_3 = \rho g \varepsilon$	493.8 dynes/cm^3.
$k_4 = \dfrac{16k\mu(1-\varepsilon)^2}{\varepsilon^2\, d_f^2}$	1868782 dynes-sec/cm^4.
$h_{eq.} = \dfrac{k_1-k_2}{k_3}$	13.8 cm.
$t = k_4\left[\dfrac{k_1-k_2}{k_3^2}\ln\left(\dfrac{k_1-k_2}{k_1-k_2-k_3 L}\right) - \dfrac{L}{k_3}\right]$	29292 sec=488.2 min. at L=10 cm.

TABLE 25

A SAMPLE CALCULATION USING THE THEORETICAL VERTICAL RETENTION MODEL

Example: Green polyurethane and SAE 90W gear oil (see Figures 13 and 14).

Values of parameters used in the calculation

Parameters	Values	Tables used
k	5	20
ε	0.92	20
d_f	0.0131 cm.	20
t_s	0.330cm.	20
w	3.7 cm.	14
T	25°C.	14
ρ	0.900 g/cm^3.	21
μ	500cs=4.5 poise.	Figure 16
γ	37.2 dynes/cm.	22

	parameters calculated
$k_1 = \frac{8(1-\varepsilon)\gamma}{\pi\, d_f}$	578.8 dynes/cm^2.
$k_3 = \rho g \varepsilon$	811.4 dynes/cm^3.
$k_4 = \frac{16k\mu(1-\varepsilon)^2}{\varepsilon^2\, d_f^2}$	15862 dynes-sec/cm^4.
$h_{final} = \frac{k_1}{k_3}$	0.72 cm.
$t = k_4\left[\frac{L_0 - L}{k_3} + \frac{k_1}{k_3^2}\ln\left(\frac{k_1 - k_3 L_0}{k_1 - k_3 L}\right)\right]$	103.8 sec=1.73 min. at L=10 cm. (here L_0=15 cm.)

TABLE 26

A SAMPLE CALCULATION FOR THE SLOPE DEVIATIONS

Example: Beige Polyurethane and SAE 20W-20 motor Oil (see Figures 6 and 8).

Parameters	Values
Theoretical slope	2.14
Experimental slope	1.28
Slope deviation %[1]	40 %

[1] Slope deviation % = $\frac{\text{Theoretical slope-Experimental slope}}{\text{Theoretical slope}}\%$

APPENDIX V

DERIVATION OF THE EXPRESSION OF WETTED SURFACE AREA

It was assumed that the fibers which make up the material have a large length(L) to diameter(d_f) ratio.

Let S= the wetted surface area per unit volume of the porous material.

$$S = \frac{\text{total fiber area}}{\text{total fiber volume}}(1-\epsilon)$$

$$S = \frac{N(\pi d_f L - 2\pi d_f^2/4)}{N(\pi d_f^2/4)L}(1-\epsilon)$$

$$S = \frac{4-2d_f/L}{d_f}(1-\epsilon)$$

For $d_f \ll L$, d_f/L term will be very small, therefore :

$$S = \frac{4(1-\epsilon)}{d_f}$$

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[1] Walline,1974.