5. Problem •6: Wet cleaning

5.2. Solution of Korea

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The Problem:

A wet rag is hard to drag when it is spread out and pulled across the floor. What does the resistive force depends on?

A wet rag spread out on the floor is hard to drag. This paper will first examine the main source of the frictional force which are lubrication and hydroplaning and prove this theory by conducting various experiments. Moreover, we will discuss the factors on which the resistive force required to drag the wet rag depends: namely, the amount of water per unit area, force exerted vertically on the rag, surface tension of liquid, contact area, and surface texture of the rag. The relationship between the frictional force and each variable will be supported by specific theoretical backgrounds and experiments.

Keywords
wet rag, lubrication, cohesion, adhesion

I. Introduction

A wet rag is hard to drag when it is spread out and pulled across the floor. The force one should exert in order to pull the wet rag is greater than that required for dragging the dry rag. The resistive force for dragging rag depends primarily on the amount of water put on the rag. However, since some of the water is absorbed while some are not, it is important to investigate the effective amount of water which is ultimately influential to determine the resistive force. Moreover, although the wet rag is harder to drag than dry one, the resistive force decreases as the amount of water increases when sufficient water is put on. The resistive force also depends on other diverse variables: pressure, surface tension of liquid, contact area, and surface texture.

This paper will first discuss the relationship between the resistive force and the amount of water, and then analyze the physical reasons for the phenomenon. Furthermore, we will focus on other important factors which can influence the resistive force required for dragging the rag.

II. Theory

1. Cohesion and Adhesion

Cohesion is an attraction force between the molecules of the same substance; adhesion is an attraction force between molecules of unlike substances. In general, solids are highly cohesive but only slightly adhesive. Liquid materials, however, are highly adhesive but only slightly cohesive. We can easily observe these characteristics when we put our finger into the water and take it out. Then, a thin water film coats our finger, which indicates that water, as a representative liquid, has greater attractive force with the molecules of finger than with other water molecules. However, solid objects are not easily mixed or attached with each other because they have strong cohesion force among themselves. [3]

2. *Lubrication*

Friction can be divided into two big categories: dry friction and wet friction. Dry friction is friction between two bodies in absence of contaminations of the contact surfaces; wet friction is friction between two contaminated surfaces, especially by liquid. Wet friction can also be classified into several categories by the amount of water between two contact surfaces. The first regime is boundary lubrication in which some breakdowns of boundary film, where solid-solid contact occurs, are detected because of insufficient water. Generally, thickness of water film for the boundary friction is about 1~3nm. This thickness is close to the sum of diameters of ten water molecules (1Åm). The liquid has tendency to move together by a group of shortly connected molecules which is the reason for liquid's relatively low cohesion force. Therefore, when the boundary lubrication occurs, the intermolecular force which mainly causes the resistive force is not the cohesion between liquid molecules, but the adhesion between a water molecule and a rag molecule or a ground molecule. This adhesion force is relatively strong because of the characteristic of liquids.

When the water film becomes thicker as more water is put on, the breakdowns of film disappears and the full-film(>0.26 •m) is constructed. The resistive force for full-film lubrication is primarily created by the cohesion force between groups of water molecules. Since the cohesion force between liquid molecules is relatively weak, the full-film lubrication has less friction than the boundary friction. [1]

3. *Hydroplaning*

Hydroplaning is a term generally used for a car running with high velocity in a rainy day. With sufficiently high velocity and enough depth of water on the ground, the car is slightly lifted on the water film which ultimately makes the frictional force between the tire and the ground very small. Similarly, the hydroplaning effect will occur when the wet rag is moving with sufficient velocity. The equation for the lift force (L) is the following: [2], [3]

$$L = \frac{1}{2}\rho v^2 A C_L$$

L : lift force (N)

ρ : density of the liquid(kg/m^3)

v : velocity (m/s)

A : contact area(m^2)

C_L : lift coefficient

This equation will be used to decide whether the velocity of the wet rag is sufficient for generating hydroplaning effect when the other variables are granted. Also, the lift force(L) for the wet rag will be numerically calculated from the equation and compared to the experimental value.

III. Experiment

Figure 1 shows a simplified diagram for the experimental setup. The wet rag is connected to the force sensor which is attached to the mechanical cart by the string. As the power is applied to the cart by the power supply(not shown), the cart starts moving toward the right side; then, the wet rag also moves toward the same direction and the resistive force will be recorded by the force sensor. The acceleration of this system is restricted to $0 \pm 0.1\ m/s^2$ by abandoning the data when the acceleration, measured by the motion sensor, is out of this range. The reason for restricting the acceleration is because the recorded force is directly regarded as the resistive force. Since a certain amount of force is used for accelerating the wet rag when the system is accelerating, the recorded force could be divided into two categories:

the force used for accelerating and that for overcoming the resistive force. Thus, by restricting the acceleration to $0\, m/s^2$, the recorded force can directly be the resistive force.

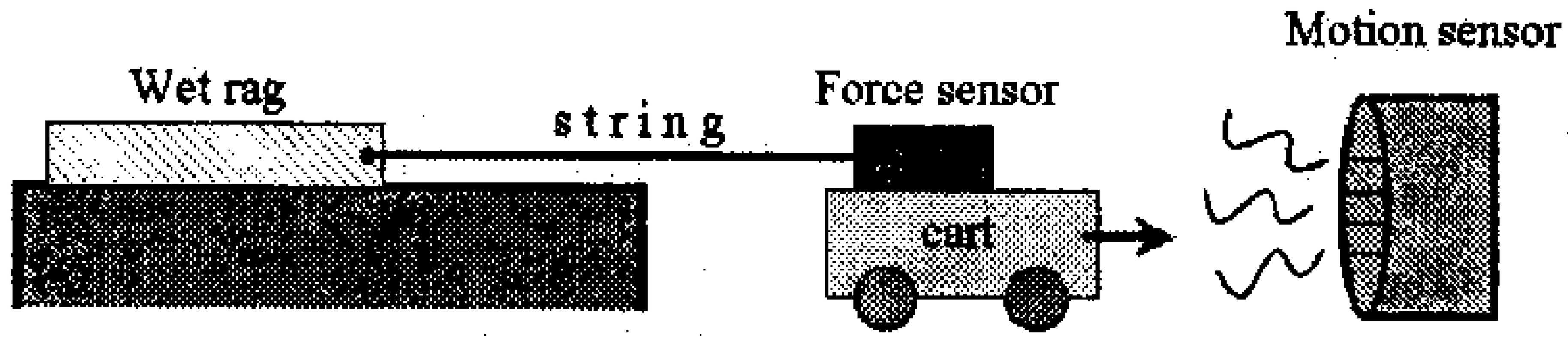

Figure 1 Simple Diagram of experimental

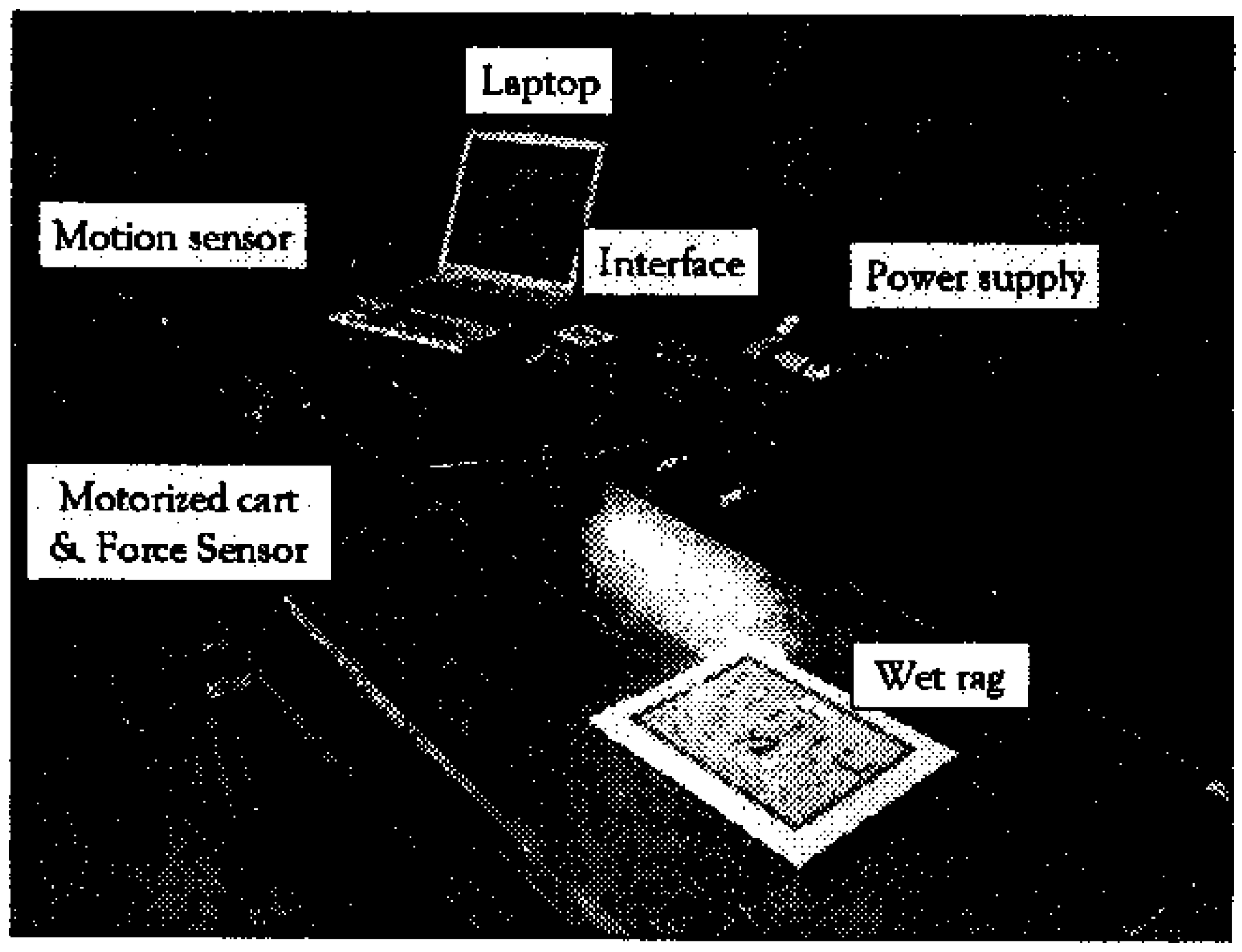

Figure 3 shows general graphs for acceleration and for the force. The first vertical line is the point when the system starts moving and the second one is the point when the system stops moving. The acceleration graph implies that the acceleration during the movement was relatively constant and all measured points between the two vertical bars are in the range $0 \pm 0.1\, m/s^2$. The lower force graph implies that the mean force $\overline{F} = \frac{1}{T_0 - t}\int_{T_0}^{t} F dt$ is constant if the t is in the range $T_0 < t < T_f$ in which T_0 is starting time and T_f is stopping time. Therefore, it is reasonable to take the mean value of force while the system is moving.

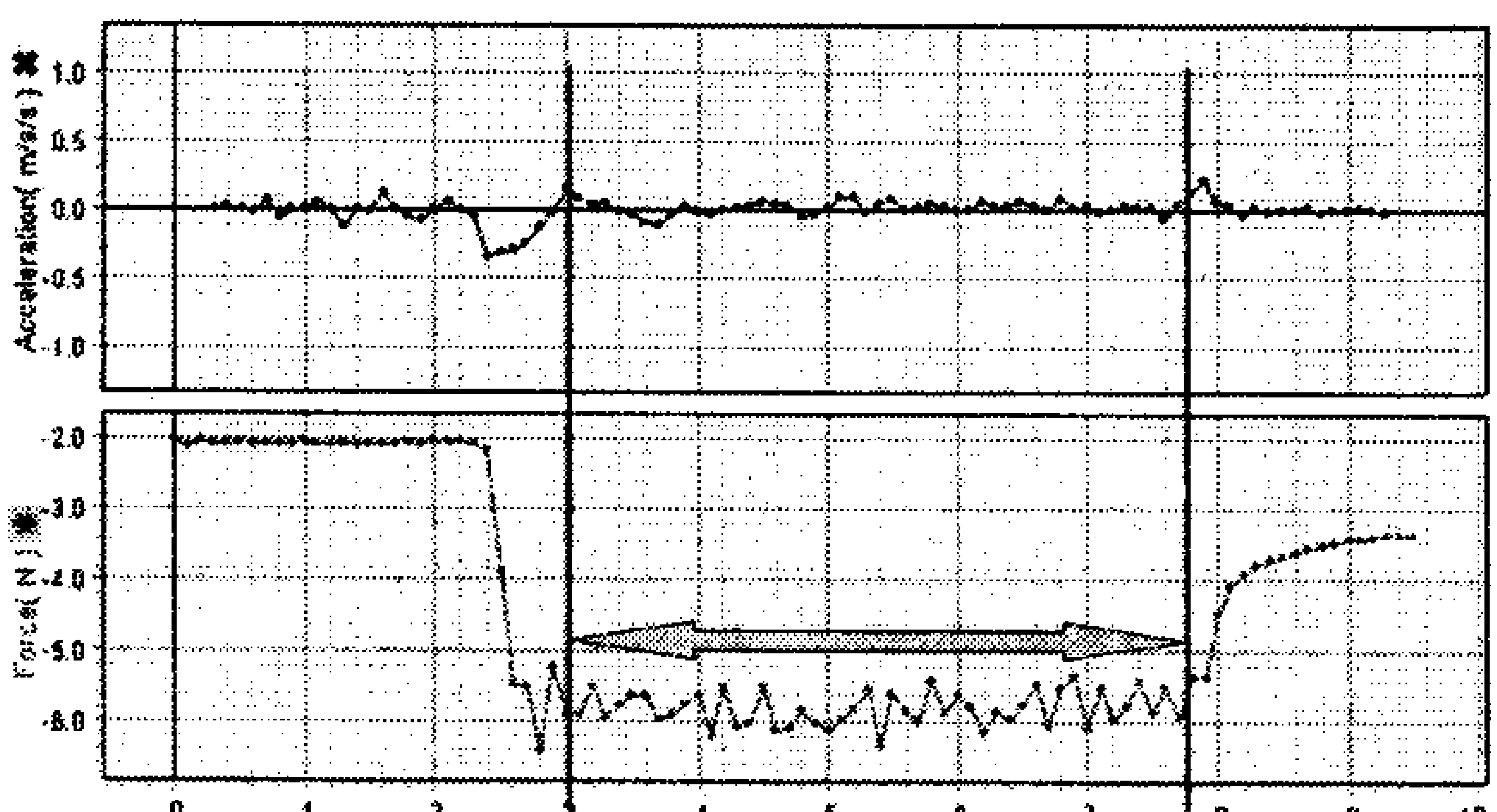

Figure 3 General graphs for acceleration(upper) and

First of all, the amount of water per unit area was altered from $0\,g/cm^2$ to $0.18\,g/cm^2$ with the interval of 5g. For each case, we measured the resistive force and found out the tendency of the result. Moreover, pressure on the rag, surface tension of the liquid, contact area, and the surface texture of the rag are also changed. We focus on investigate the relationship between the resistive force and these variables.

The maximum amount of water the rag can absorb was also experimentally measured. First, we put the wet rag on a bunch of filtering paper as shown in the Figure 4. After a few minutes, we measured the increase in mass of the filtering paper which is the water not absorbed.

Figure 4. Experimental setup for measuring maximum absorption

IV. Result and Discussion

1. Water per Unit Area

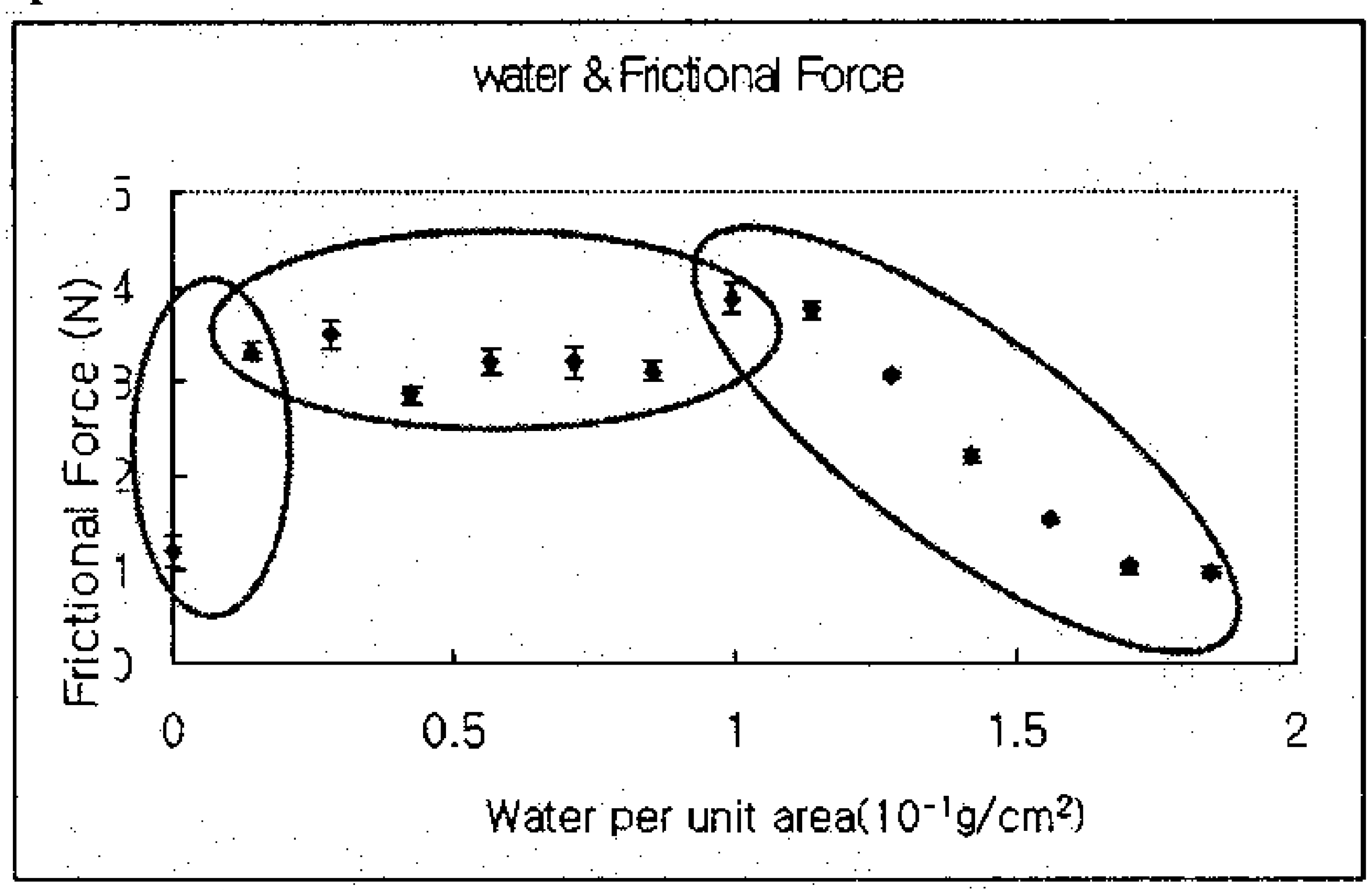

Figure5. Relationship between amount of water and frictional force

Figure 5 shows the change in the resistive force when the amount of the water per unit area alters. The tendency of the graph can be divided into three portions. The first apparent tendency we can notice from the graph is the sudden jump denoted as the red circle in the left side. The sudden jump occurs as the dry rag changes into the wet rag($0.014g/cm^2$), and thus wet friction, instead of dry friction, starts to be applied. The second tendency signified by the circle in the middle shows an irregular pattern without any certain increasing or decreasing tendency. Although the amount of water increases, the resistive force does not show any clear pattern. This phenomenon could be explained by the absorption of water. That is, although we measured the amount of total water, what constructs water film and influences the frictional force is the water which is not absorbed and lies in between the rag and the ground. Therefore, until the maximum amount of water the rag can absorb is reached, the increase in the total water does not always leads to the increase in the amount of water between the rag and ground.

The peak of the graph is when the amount of water per unit area is $0.1\,g/cm^2$. Through the experiment to measure the rag's absorbing ability, we got the results as shown in Figure 6. There is a sudden jump at $0.1\,g/cm^2$ which implies that this is the maximum amount of water a unit area of rag can contain. Therefore, after this point, the more water put on the rag is not absorbed but lies between the rag and the ground and forms the water film. In the Figure 5, the decreasing tendency denoted by the oval at the right hand is caused by the thickening water film as more total water increases. The full-film lubrication occurs in this portion because of sufficient amount of not-absorbed water.

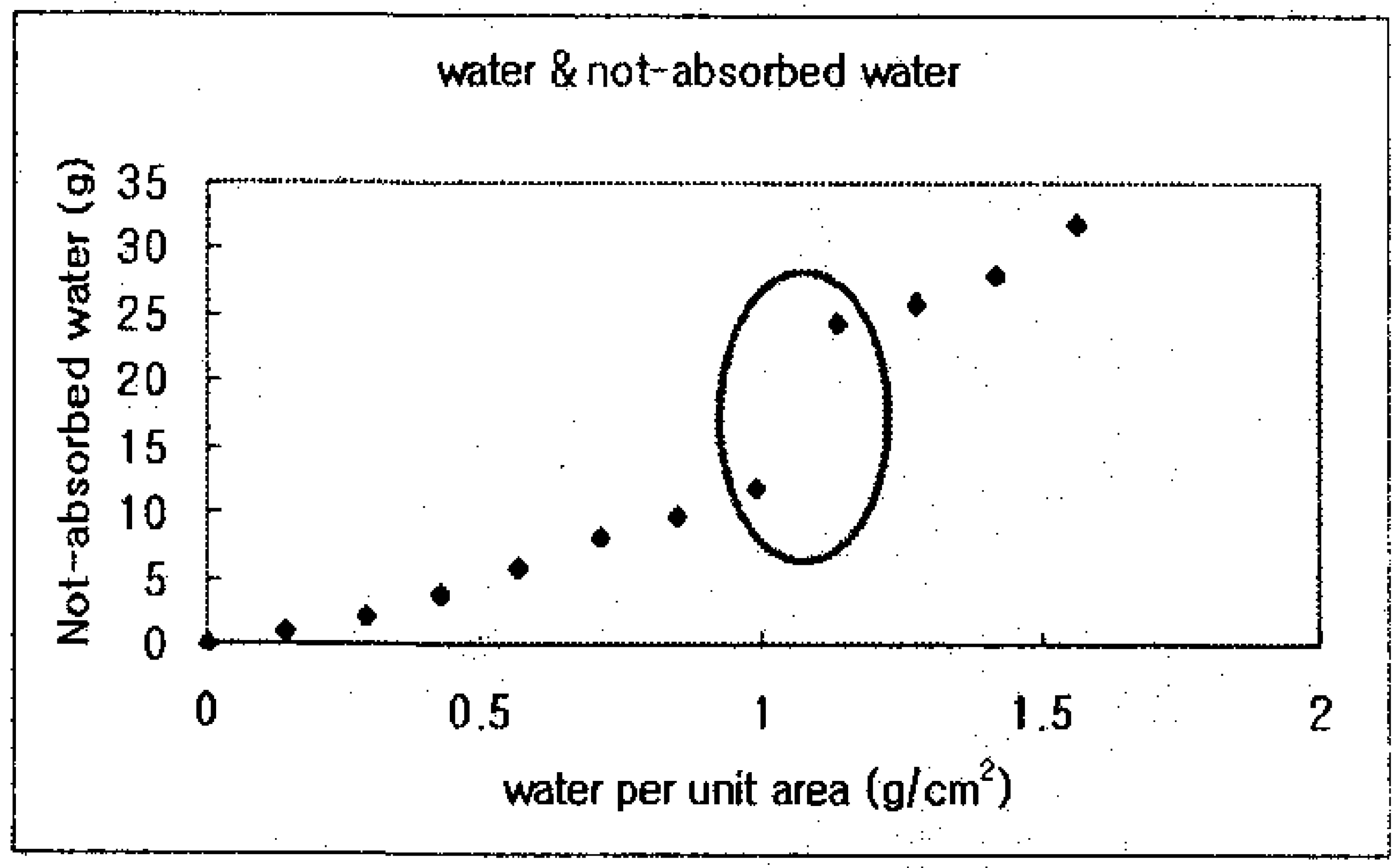

Figure 6 Relationship between amount of water per unit area and not-absorbed water

In order to prove the generation of hydroplaning as well as the full-film lubrication, we should certify that the velocity of the wet rag is sufficient for creating hydroplaning effect. The following equation is the one to calculate sufficient velocity for generating hydroplaning:

$$v = \sqrt{\left(\frac{F}{A}\right)\frac{2}{C_L \rho}}$$

For a car, in general, $p_{car} = \frac{F}{A} = 2.0\times10^5 N/m^2$ and $v_{car} = 19m/s$. For the wet rag, in the experiment, $p_{rag} = 27.84N/m^2$ and $v_{rag} = 0.2m/s$ which are experimentally measured values. Since $p_{rag} = p_{car} \div 7200$ and $v_{rag} = v_{car} \div \sqrt{7200}$, the velocity of the wet rag used in the experiment is apparently sufficient velocity to cause hydroplaning. [4]

2. *Pressure*

By increasing the mass of burden on the rag, we could increase the pressure exerted vertically on the rag with the constant total water 40g. Figure 7 suggests us that the increase of pressure decreases the kinetic friction coefficient. (Kinetic friction coefficient is used for the y-axis instead fictional force in order to make the effect of mass negligible. The greater pressure squeeze the wet rag and thus let some absorbed water to come out and form the water film. Therefore, with sufficient water to have full-film lubrication, the higher pressure causes smaller kinetic friction coefficient.

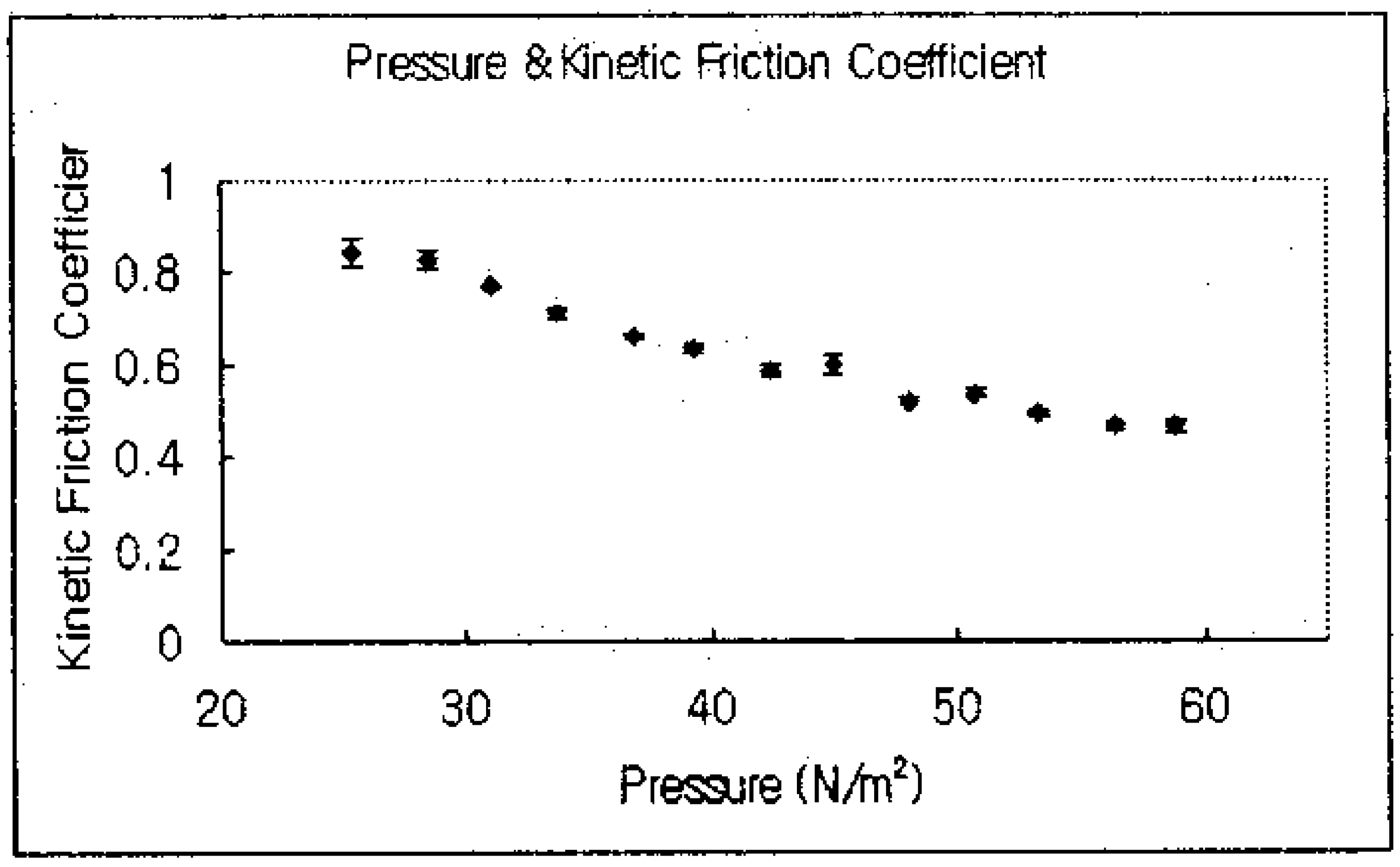

Figure7. Relationship between pressure and kinetic friction coefficient

3. Surface Tension of Liquid

Since the resistive force is fundamentally generated from the intermolecular forces such as cohesion and adhesion, the surface tension, or intermolecular force, is also crucial factor in determining the frictional force. The surface tension of liquid is altered by changing the concentration of detergent solution. According to the Figure 8, as the concentration increase, the friction decreases; that is, the surface tension and friction are positively related.

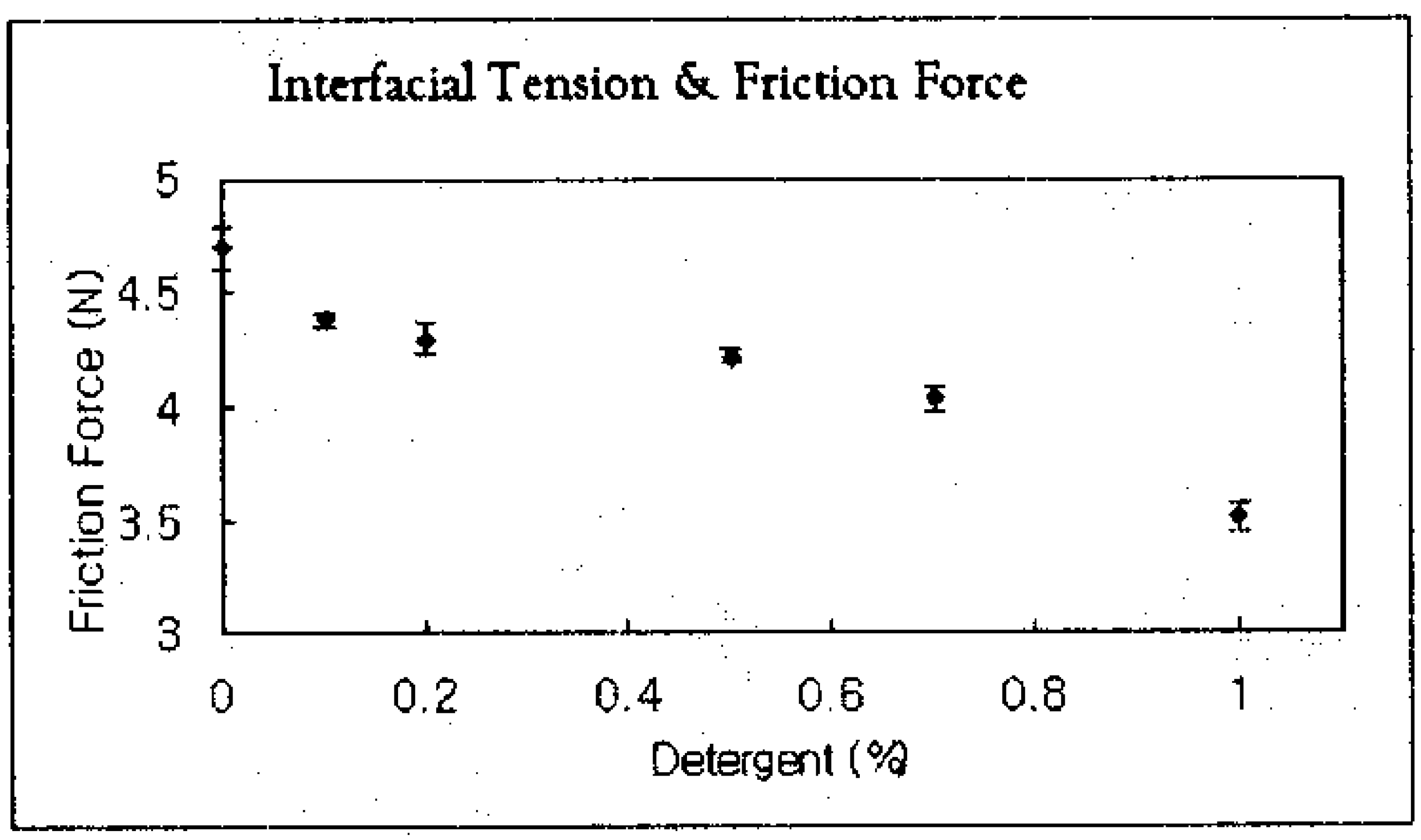

Figure8. Relationship between amount of detergent and friction force

4. Contact Area

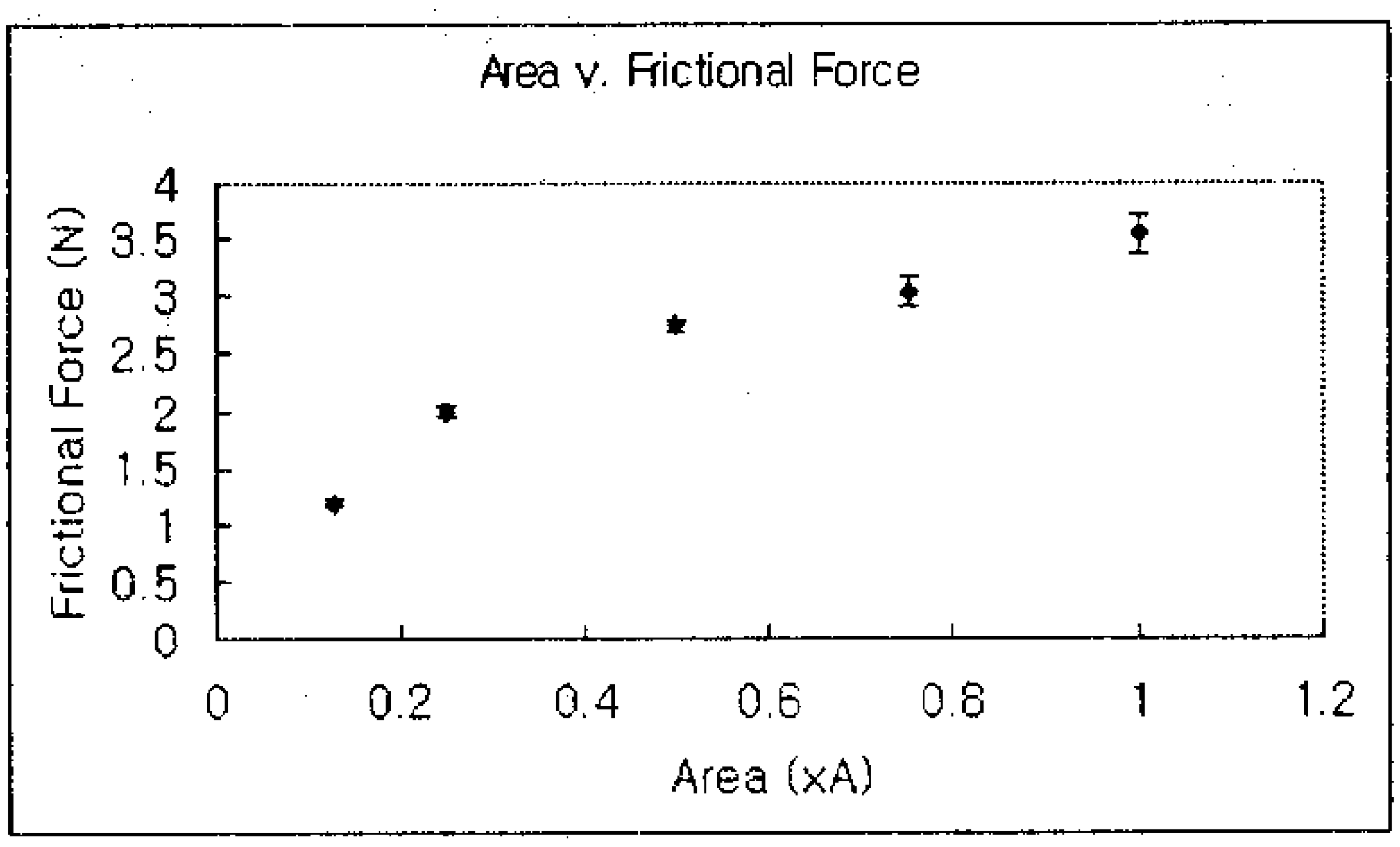

Figure9. Relationship between contact area and frictional force

For the constant amount of total water (25g), the contact area was varied. The standard area of the rag was denoted as A, we did the experiments for A, 3/4A, 1/2A, 1/4A, and 1/8A. Figure 9 tells us that the increase of area also increases frictional force. The reasonable account for this tendency is that as the more molecules are in contact, the sum of intermolecular force will naturally increase as well.

5. *Surface Texture*

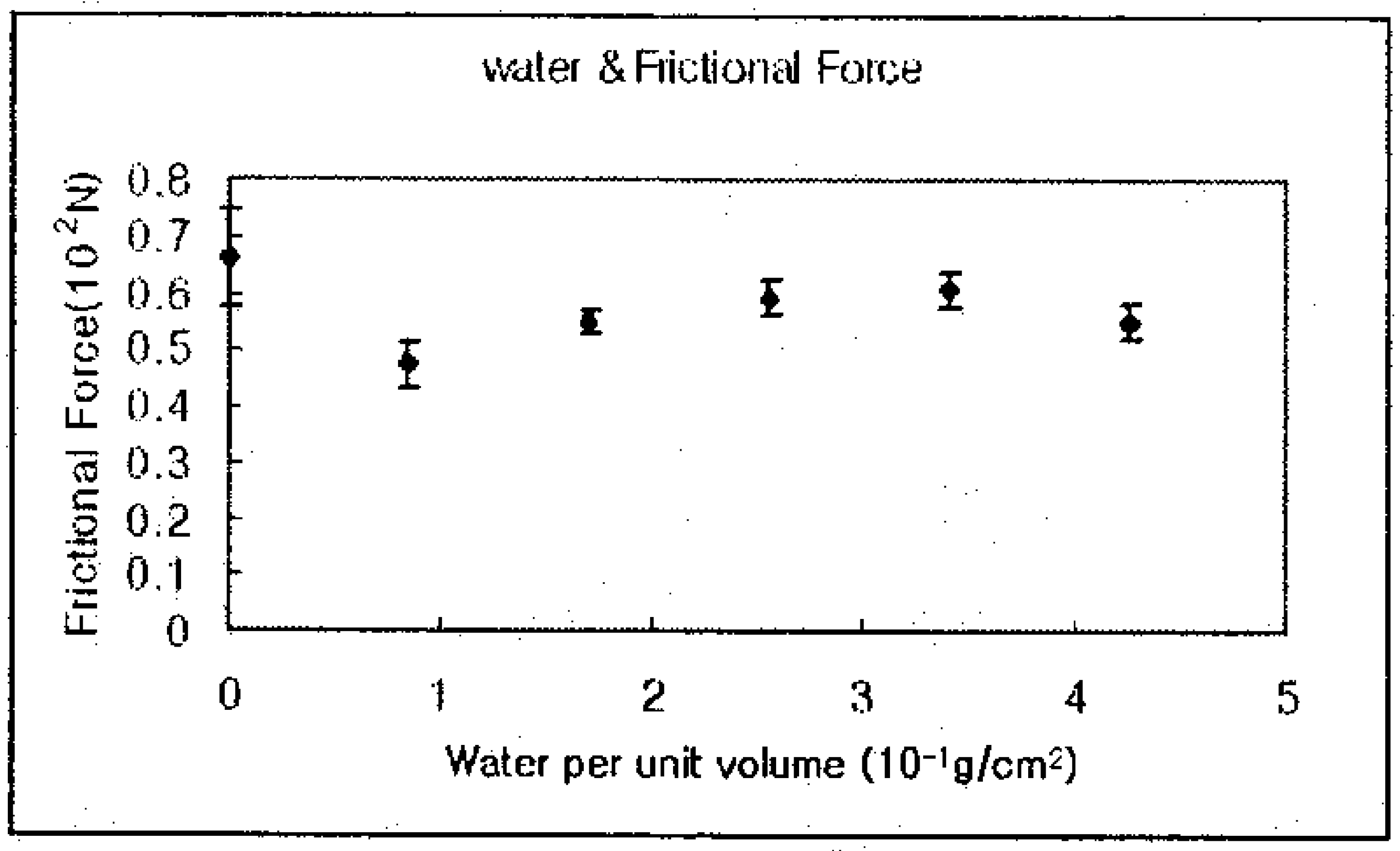

Figure10. Relationship between water per unit volume and frictional force for different surface texture

Another experiment was conducted with rougher rag with lower absorbing ability. Contrary to the Figure 5, Figure 10 shows sudden decrease of frictional force when the dry friction changes into the wet friction. It implies that the maximum absorption is in between the first two points in the graph which could be accounted by low absorbing ability. Moreover, we could not detect any clear tendency generated by lubrication or hydroplaning since roughness hindered the creation of water film. Rough rag contains a number of broad paths for trapped water to escape delaying the buildup of water film as shown in Figure 11.

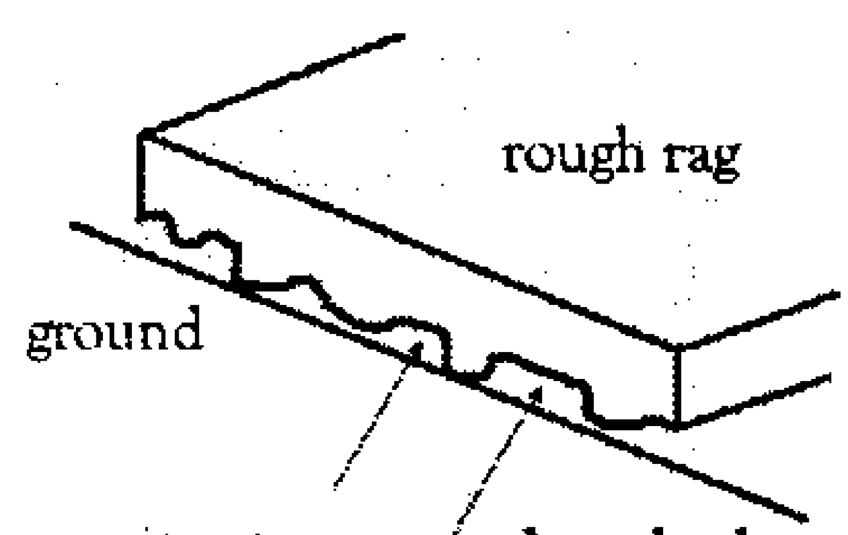

Figure.11 Diagram for contact area and paths between the rag and ground

V. Conclusion

This paper primarily focuses on investigating various factors which determine the frictional force. The first experiment dealt with the amount of water per unit area. Friction suddenly jumped when the dry friction changes into the wet friction. When the amount of water per unit are is in between 0.014g/cm^2 and 0.1g/cm^2, there was an irregular pattern since the increase in total water did not always lead to the increase in not-absorbed water (boundary lubrication). For the amount of water per unit area greater than 0.1g/cm^2, we could detect the gradual decrease in friction due to thickening water film(full-film lubrication). Moreover, hydroplaning also contributes to the gradual decrease since the wet rag has sufficient velocity.

There are other crucial variables influencing the resistive force. The greater pressure, less surface tension, and smaller contact area decrease the friction. Also, roughness of surface texture hindered the formation of water film and delays lubrication and hydroplaning..

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