Strength of Bonding of Food Soils to Dishes[1]

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ABSTRACT

The material which is baked onto ovenware and casseroles is probably more strongly bound than any other food soil. A method has been developed for measuring the relative bonding strength using a calibrated hydraulic jet. Soil-to-soil bonds are more readily weakened by aqueous action than soil-to-substrate bonds; both types of bonds are stronger on aluminum than they are on glass. Rate of soil removal was increased by increasing the concentration and alkalinity of the detergent. Temperature had the usual exponential effect, doubling the rate each 10.5 C. Time naturally was effective and a number of soaking studies showed this. Time and temperature yielded excellent results in steaming studies. Rather large amounts of energy were necessary to loosen and remove food soil. Some combination of 3 energy inputs was required. Chemical input ranged from water to high concentrations of highly alkaline detergent. Thermal levels ranged from moderate increase in temperature (40 C) to the latent heat of vaporization in steam applications (100 C). Mechanical energy was supplied by impingement of a hydraulic jet at forces from 40 to 350g.

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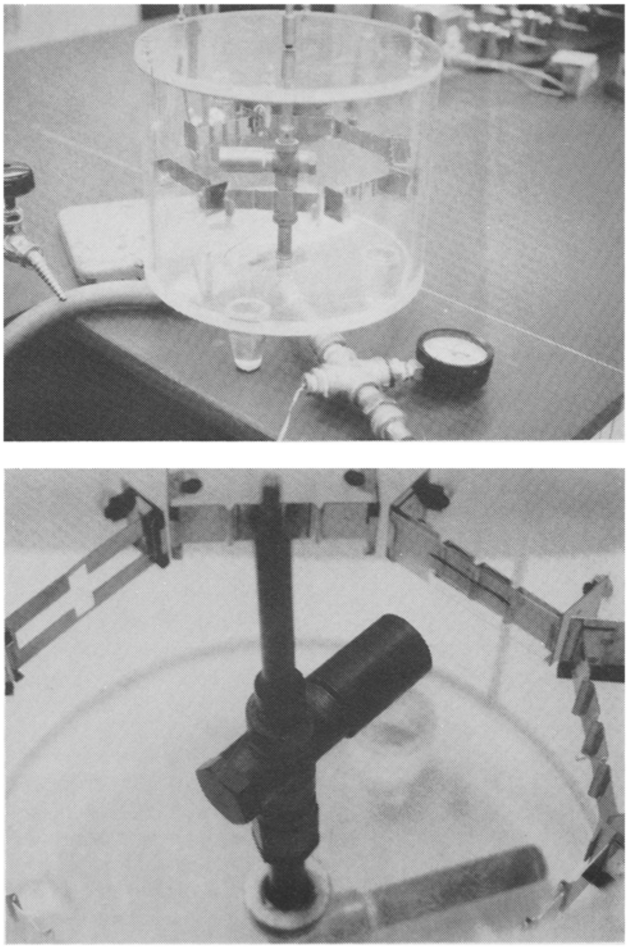

FIG. 1. Two views of experimental apparatus.

INTRODUCTION

The most difficult soil to remove from dishes is the material baked onto casseroles and ovenware. In this study, we measured the relative strength of the adhesive bonds between food and substrates such as glass and aluminum. In addition, various means of reducing bond strength were evaluated.

Because this food is strongly bound to the surfaces, it follows that relatively large amounts of energy are required to remove it. The energy forms have been classified as thermal (steam, elevated temperature), chemical (various detergents at various concentrations), and mechanical (impact of the spray). The force of impingement of a water jet on the surface of a soiled substrate has been used to measure the relative strength of these adhesive bonds, and this action is comparable to that occurring in a dishwasher.

McFarlane and Tabor (1) showed a correlation between adhesion and the surface tension of a liquid film. The adhesive force is independent of film thickness above about 20 molecular layers. Force of adhesion also increases proportionally with the radius of the particle being held. However, the force also decreases markedly with surface roughness. It is very likely that hydration of potato particles greatly reduces the effective surface roughness. Therefore, adhesive force would vary due to particle size variations and would be especially great for large, thoroughly hydrated particles. Incompletely hydrated soil would adhere less tenaciously and also would cover a more narrow range of bonding strength. The latter is true because the smaller particles will be more thoroughly smoothed and, therefore, more tenaciously held, while the larger particles will have their inherently greater adhesive force partially decreased by surface roughness.

EXPERIMENTAL PROCEDURES

Apparatus

A laboratory device (Fig. 1) was designed and built to

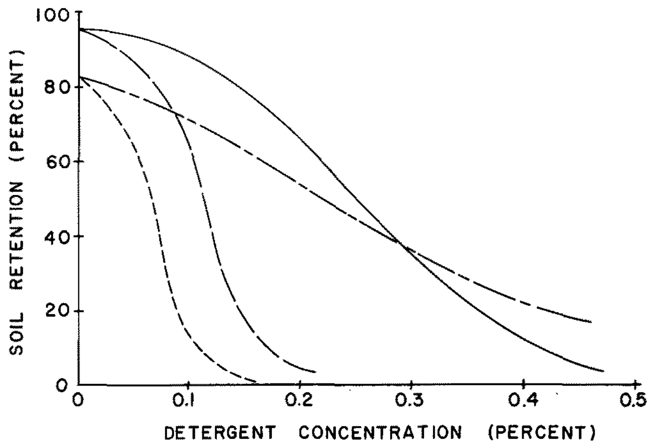

FIG. 2. Effect of detergent on soil retention by soft glass. (–) = Hard water detergent in tap water; (—-–) = hard water detergent in deionized water; (–––) = soft water detergent in tap water; (—) = soft water detergent in deionized water. Tap water, 170 ppm as $CaCO_3$; deionized water, <1 ppm as $CaCO_3$; washing time, 15 min; water impingement force, 234g; temperature, 70 C.

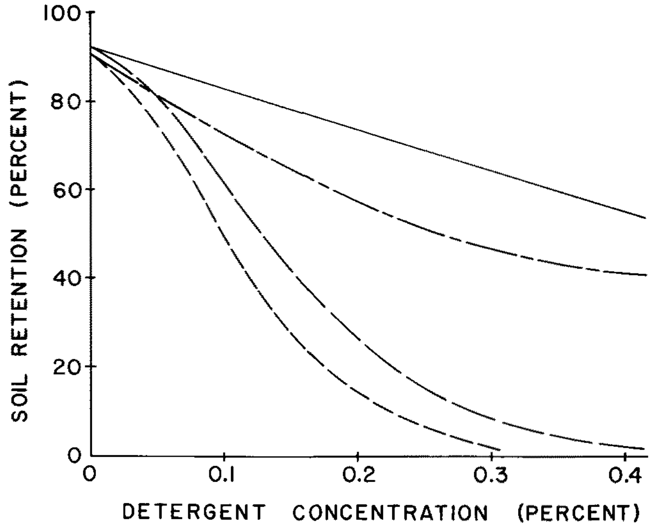

FIG. 3. Effect of detergent on soil retention by aluminum. (–) = Hard water detergent in tap water; (–––) = hard water detergent in deionized water; (– – –) = soft water detergent in tap water; (—) = soft water detergent in deionized water. Washing conditions were the same as for Fig. 2.

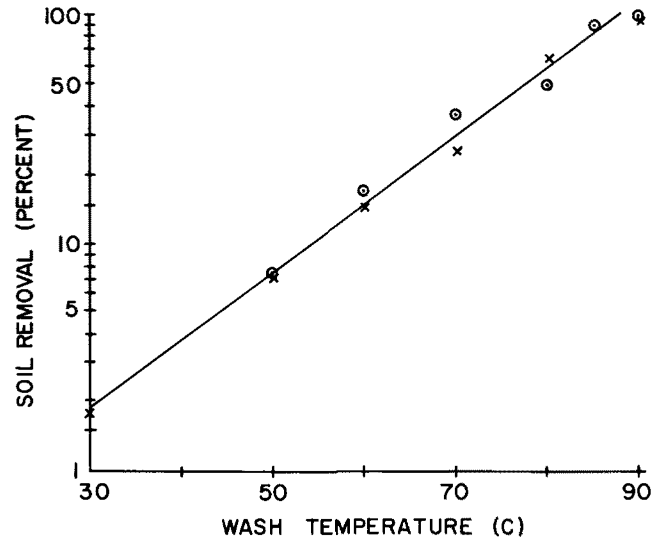

FIG. 4. Soil removal as a function of temperature. X = Soft glass; ⊙ = Pyrex glass.

provide a regulated jet of water or detergent solution to wash soiled specimens 25 mm x 75 mm. The angle of impingement varied from 90 degrees at the center to 75 degrees at the ends of the soiled area. The shaft supporting the nozzle was rotated by a stirring motor at 60 rpm. The nozzle was designed to minimize flaring, and, thus, deliver a jet of measurable and constant cross section. Lowering of the surface tension of water by detergent usually disrupted this cohesiveness, however.

The force of the jet was measured as a function of system pressure using a very simple calibrator, which was based on a water level switch from an automatic washing machine. The jet was pointed at the surface of the switch, and water pressure was increased until the switch closed. The switch then was turned to a vertical position and loaded with sufficient class S balance weights to close the switch. Then the switch was adjusted, and the procedure repeated. The force of impingement was measured at angles of 90 and 80 degrees with the transducer surface. The data were fitted with a straight line by the method of least squares. For 90 degrees impingement, the equation was:

$$F = 23.2P + 1.2, \qquad (I)$$

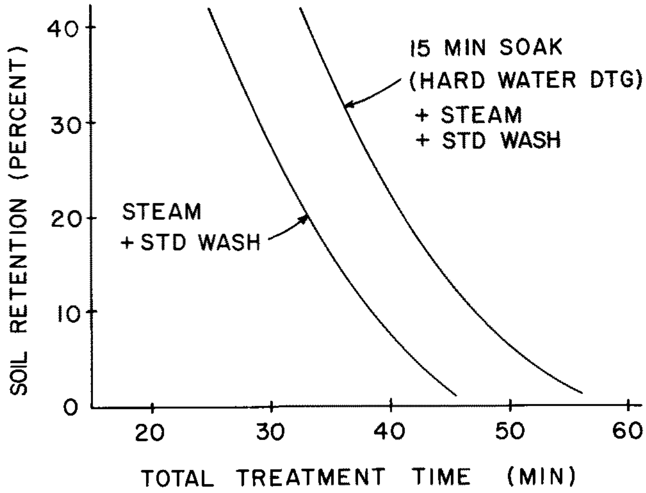

FIG. 5. Effect of steaming on soil retention. Total treatment time includes standard wash after initial treatment(s). DTG = detergent.

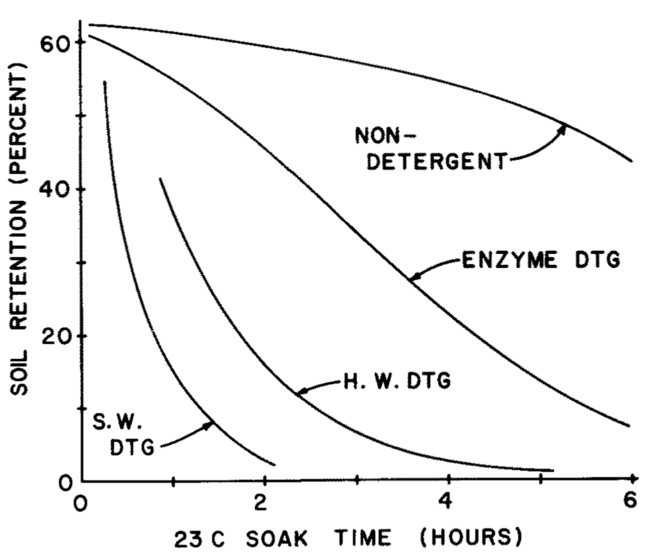

FIG. 6. Soil removal by soaking at 23 C, glass substrate. All soaks at 0.33% detergent (DTG) concentration followed by standard wash. S.W. = Soft water; H.W. = hard water.

and for 80 degrees:

$$F = 8.3P + 41.8, \qquad (II)$$

where F = force (g)
P = pressure (psig)

Procedure

Development of a suitable test soil is essential in any dishwashing project. It was decided initially to use a potato-milk combination which adheres tightly to glass surfaces when baked on. Mixtures of Carnation Instant Nonfat Dry Milk, Instant "Potato Buds," and distilled water were prepared and evaluated. Fresh whole milk was also substituted for the dry milk to introduce a fat content into the soil, but this gave no appreciable change in results. The test soil selected for use was of instant milk:instant potato:distilled water (1:1:6, w/w). This gave a thick slurry which was applied easily to the slides with an eyedropper. The soil was applied in a narrow band, measuring ca. 45 x 10 mm, using 75 x 25 mm microscope slides as the glass substrate. Aluminum specimens were cut to the same dimensions for subsequent tests.

The above soil was aged for at least 30 min before baking to allow complete hydration of the soil particles. Then it was baked on at 232 C for 30 min in a forced convection oven. After baking, a porous superficial crust was removed by spraying with water. The samples then were dried in air and weighed. Various treatments then were evaluated gravimetrically.

A typical home machine dishwasher detergent was selected as a standard and was purchased in case lots. Performance of each batch was checked, using the standard washing procedure described below. No change was seen within a given case over a period of several months nor in an opened box over a 2-3 week period. This has been designated Hard Water Detergent.

A second detergent was selected for stronger chemical action. This was a highly alkaline detergent, containing 65% sodium carbonate, 27% sodium metasilicate, and 3% surfactant; the pH of a 0.2% solution was 11.1. It was suitable for normal use only in water of zero hardness. It therefore, was, designated Soft Water Detergent, even though it was sometimes used in hard water.

A commercial enzyme prewash product was used for enzyme soak studies. For some studies, 1% enzyme was added to this product. The enzyme added was 50% protease, 50% amylase.

Standard wash conditions involved use of 0.20% Hard Water Detergent in laboratory tap water (170 ppm hardness). This solution was circulated at 70 C and a pressure of 10 psi (234 g impingement force) for 15 min. A standard wash followed all supplementary treatments, such as soaking and steaming.

RESULTS

Effect of Detergent Action

Figure 2 shows the dependence of soil retention on detergent concentration. It can be seen that 95% of the soil withstood a force of 234 grams for 15 min. A concentration of 0.1% detergent was necessary to sequester the 170 ppm hardness ions in laboratory tap water. Any further increase in detergent concentration led to a reduction in retained soil. Deionized water caused a reduction in retained soil even without detergent; a detergent effect was noted for even small amounts of detergent.

The highly alkaline Soft Water Detergent showed much more chemical action at 0.2%. Concurrent chemical action on the substrate (drastic etching of glassware and corrosion of aluminum) would prevent practical use at this concentration.

The standard wash conditions described above removed 37% of the initial soil. These conditions were used for evaluating such supplemental treatments as soaking, enzyme treatment, and steaming.

The S-shaped curves suggest that there were 2 distinct ranges of adhesive bond strength. These might be described as soil-to-substrate bonds, i.e., bonding between soil particles and the substrate, and a larger percentage of weaker soil-to-soil bonds. The former were less responsive to the effects of detergent. Detergent action on aluminum showed a similar pattern (Fig. 3), but a smaller fraction of soil was removed for any given condition. Both types of binding were stronger than with glass, but the difference in strength was much less.

Thermal Effects

Figure 4 shows the temperature dependence of soil removal in 0.2% detergent. Differences between Pyrex and soft glass were almost certainly experimental variance, which would be expected to be greatest near 50% retention. The slope of the curve in Figure 4 indicates a doubling of soil removal rate for each 10.5 C rise in temperature; this increase persisted remarkably close to 100% removal. The last residue, however, appears to have been much more stongly bound.

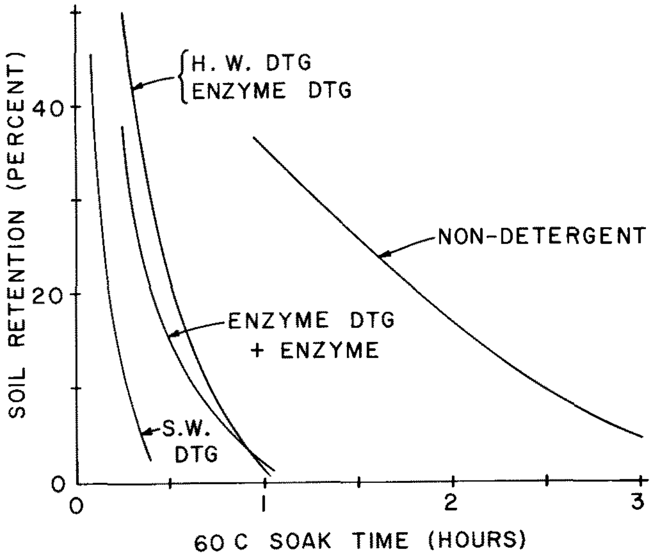

FIG. 7. Soil removal by soaking at 60 C, glass substrate. All soaks at 0.33% detergent (DTG) concentration followed by standard wash. S.W. = Soft water; H.W. = hard water.

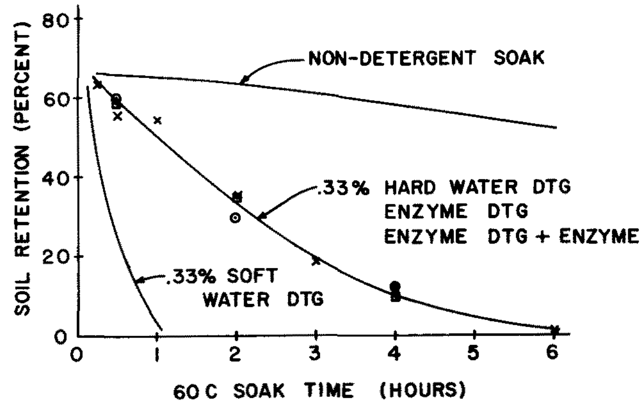

FIG. 8. Soil removal by soaking at 60 C, aluminum substrate. X = Hard water detergent (DTG); ⊡ = enzyme detergent; ⊙ = enzyme detergent plus enzyme.

A different thermal action was observed in steaming. Here, there was a strong thermal input (latent heat of condensation), and a weak chemical input (distilled water) prior to the standard chemical and mechanical inputs. A combination of soaking and steaming, i.e., steaming in the presence of detergent, proved more effective but only at the expense of additional time. The results are plotted on the basis of elapsed treatment time in Figure 5. As steam time increased, the effect of the detergent decreased until no appreciable improvement was observed in 30 min steaming results.

Soaking

Still greater chemical action was realized when the soil was soaked in detergent for a period of time prior to application of mechanical force. In all cases, the standard wash procedure followed the soak period. The effect of soak temperature, soak time, and detergent are shown in Figures 6 and 7. Ease of soil removal increased with increasing soak temperature and with longer soak times. Use of an enzyme detergent in the presoak was not as effective as the Hard Water Detergent at lower temperatures, but was more effective at 60 C. Addition of more enzyme to the enzyme detergent had an adverse effect at all temperatures except 60 C. In every case, the Soft Water Detergent maintained its distinct superiority.

TABLE I

	Energy Characteristics[a]			Time for 99.5% removal (min)
	Thermal	Chemical	Mechanical	
Steam + 15 min Wash	High + 15 min Std	Very low + 15 min Std	None + 15 min Std	46 (31 steam + 15 wash)
90 C Soak, H W dtg[b] + 15 min Wash	High + 15 min Std	Moderate + 15 min Std	None + 15 min Std	33 (18 + 15)
90 C Soak, S W dtg[c] + 15 min Wash	High + 15 min Std	High + 15 min Std	None + 15 min Std	23 (8 + 15)
90 C Flush[d], S W dtg[c] + 15 min Wash	High + 15 min Std	High + 15 min Std	Low + 15 min Std	21 (6 + 15)
90 C Wash	High	Moderate	Std	14
90 C Flush[d] + 5 min 90 C Wash	High	Moderate	Low + 5 min Std	14 (9 + 5)

[a]Std = standard wash.

[b]HW dtg = Standard Hard Water Detergent.

[c]SW dtg = Highly Alkaline Soft Water Detergent.

[d]Flush = gentle flow of solution over surface, with no appreciable mechanical action.

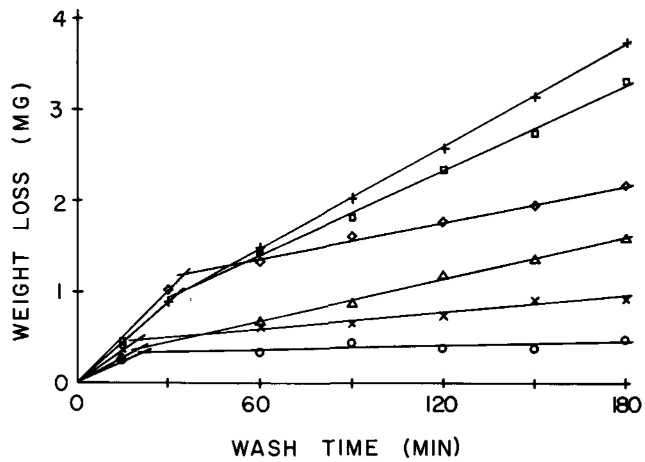

FIG. 9. Erosion of soft glass by detergent solutions. + = 90 C Deionized water; □ = 90 c soft water; ◇ = 80 C deionized water; △ = 80 C soft water; X = 70 C soft water; 0 = 60 C soft water. Washing conditions were the same as for Fig. 2.

Aluminum Substrates

The rapid heat transfer to the metal-soil interface during baking produced a much stronger adhesive bond than was produced with glass. Figure 3 shows this at all detergent concentrations. The behavior of soil baked onto aluminum also is seen in Figure 8, where the effect of soaking at 60 C is presented for several detergents. Comparison with Figure 7 shows the markedly greater strength of soil-to-aluminum bonds, as well as soil-to-soil bonds on aluminum. In this case, the solutions containing enzyme were not appreciably different from the Hard Water Detergent. Comparison of soak times with those shown in Figure 7 shows the markedly greater difficulty of removing soil from aluminum.

High Energy Treatments

All of the above show a need for considerable amounts of energy to bring about the removal of food soil from substrates. The energy must be supplied in a combination of thermal, mechanical, and chemical forms. Some minimum of each is required, and a large amount of one or more must be added.

Table I shows the overall effect of various high energy treatments. The best comparative criterion seems to be time to remove 99.5% of the soil from the surface. The flushing process referred to in Table I was a flow of fluid over a surface at a rate sufficient to continually renew the solution at the soil surface without supplying any appreciable mechanical energy. A measured force of 40 g was spread over an extensive area. It is noted that as with all low or zero inputs of mechanical energy in pretreatment, a subsequent period of application of moderate mechanical energy was required to remove the loosened soil.

Erosion of Substrates

In all cases, it was found that the more highly effective treatments produced higher amounts of wt loss from the glass substrate (Figure 9). The effect was greatly magnified in softened or deionized water. It is seen from Figure 9 that the wt loss was more rapid in the first 20-30 min. This was undoubtedly caused by a greater concentration of soluble oxides in the surface layer. This loss was not necessarily bad for the appearance of the surface, but it was a source of error for gravimetric determinations.

REFERENCE

1. McFarlane, J.S., and D. Tabor, Proc. Roy. Soc. 202:224 (1950).

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