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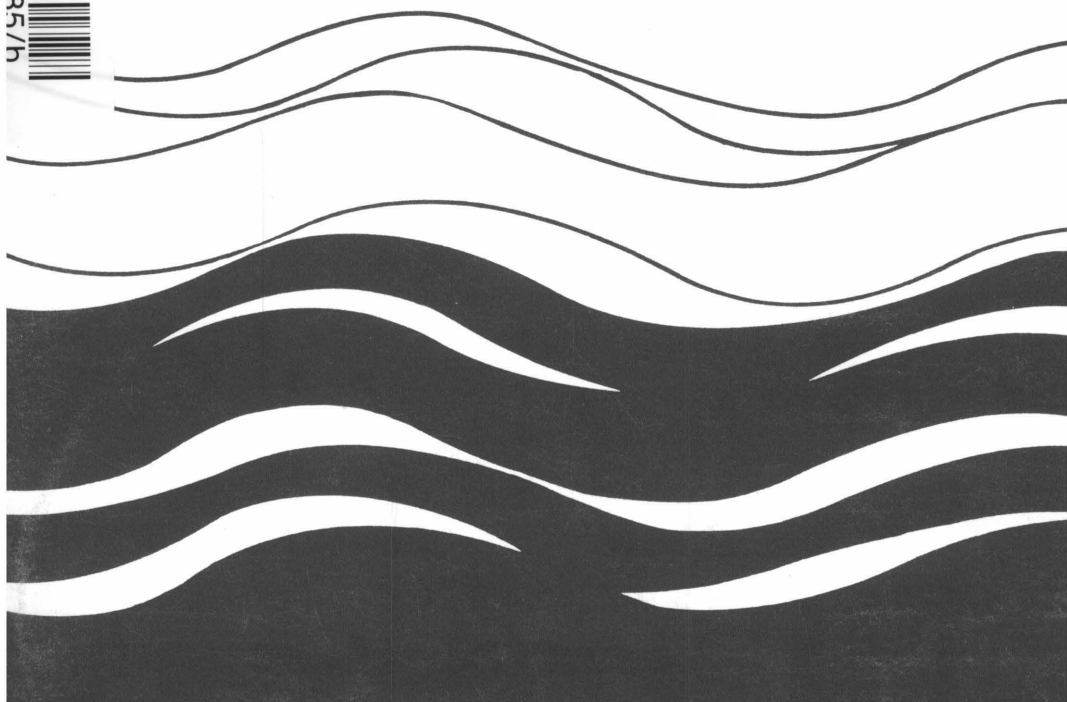
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Bulletin 156

Performance of Three Types of Laundry Detergents in Soft and Hard Water

R.P. Lovingood, J.E. Woodard, I.E. Leech,
D.E. Hinkle, and J.D. Barber



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ABSTRACT

This study was designed to evaluate the performance of current formulations of three types of laundry detergents in soft (60 ppm) and hard (172 ppm) water using home laundry equipment. Standard loads were washed with two brands from each of three types of detergents (phosphate-built and carbonate-built granular, and unbuilt liquid) to measure soil removal, soil deposition, and carbonate deposition. For the 5 replications of the soil removal test, swatches of soiled test cloth in 100% cotton, 50% cotton/50% polyester with no finish, and 50% cotton/50% polyester with permanent press finish were used. Untreated swatches of the same fabrics were used for the 10 replications of the soil deposition test and soil was introduced via a solution of Bandy black research clay and hot water. Swatches of the test cloth were attached to items in the test load. Carbonate deposition was observed after 5, 10, and 15 washings of a load composed of nine dark blue items (three 100% cotton terry washcloths, three men's 100% cotton T-shirts, and three boy's 50% cotton/50% polyester sport shirts) plus sufficient filler cloths of unbleached muslin to complete the load.

Numerous significant interactions indicate that the results are not clear cut. However, the following conclusions were reached. The unbuilt liquid detergent was most effective in soil removal, especially in hard water, and the carbonate-built granular product was least effective. The phosphate detergent was the best of the three types in holding soil in suspension. Soil deposition increased with the number of washings and the increase was greater in hard water than in soft water. The appearance of "tattletale gray", which results as suspended soil is deposited on fabrics, was most noticeable for fabrics of untreated 100% cotton.

Carbonate deposition was more apparent in hard water than in soft, but the buildup of the white precipitate occurred in both soft and hard water. Deposition of the carbonate precipitate was progressive and occurred at a faster rate in hard water than in soft. Items washed in hard water felt harsher than those washed in soft water, and the presence of the precipitate was more noticeable in areas with irregular surface texture or thickness.

Detergent formulations change frequently and the differences in detergent types are becoming increasingly blurred. Therefore, when purchasing and using laundry detergents, consumers need to be aware of the properties of their water supply, laundry detergent, and washing machine, plus the articles to be washed, including types of soil. Laundering clothes is a complex process; satisfactory results depend on appropriate combinations of variables in the laundry system. At present, unbuilt liquid products are a practical and effective alternative to phosphate-built laundry detergents.

Key Words: Phosphate-built and Carbonate-built Granular Detergents, Unbuilt Liquid Detergents, Soil Removal and Deposition, Carbonate Deposition, Water Properties, Laundering

INTRODUCTION

Undesirable changes in the quality of water in the Chesapeake Bay and other bodies of water in Virginia have occurred, in part, as a result of nutrient enrichment from the element phosphorus. This situation, documented in studies sponsored by the Chesapeake Bay program and others, has caused public policy makers to investigate the potential of alternative strategies that would provide effective nutrient control.

One source of phosphorus entering lakes and streams is the effluent from home laundering processed through wastewater treatment plants and poorly functioning septic systems. Strategies to overcome the problem of high levels of phosphorus are to impose a ban on the sale of laundry detergents that contain phosphates and to alter treatment of sewage at wastewater treatment plants. It has been estimated that use of nonphosphate detergents by consumers would potentially reduce the phosphorus loadings from municipal point sources in the Chesapeake Bay tributaries by about 25% (Costs and Benefits of a Phosphate Detergent Ban 1985). Members of the Chesapeake Bay Program's Scientific and Technical Advisory Committee working on nutrient control have stated that "chemical precipitation of phosphorus (at wastewater treatment plants) is very reliable and can achieve the desired effluent quality, but it increases the cost of wastewater treatment by adding the cost of the chemicals and substantially increasing waste sludge disposal costs" (Nutrient Control in the Chesapeake Bay 1986, p. 17). An alternative method of treating sewage is biological phosphorus removal, the linkage of anaerobic and aerobic units in the same activated sludge system. Developed by Randall, Brannan, and Benefield (1985), this method has been used experimentally with results which indicate substantial savings.

A ban on the sale of phosphate-built detergents, first legislated in the 1970s, is now in effect in seven states (Indiana, Maryland, Michigan, Minnesota, New York, Vermont, and Wisconsin) plus the District of Columbia and parts of Illinois and Ohio. Legislation to prohibit by law the sale of detergents having more than 0.5% phosphorus was discussed during sessions of the Virginia General Assembly in 1985 and 1986 and finally enacted in 1987 to become effective January 1, 1988.

Manufacturers have changed and continue to change the formulations of detergents used in home laundering in response to legislation as well as to concerns about the impact of phosphate-built products on the quality of water in lakes and rivers in areas of the United States other than those with a mandated sales ban.

Phosphates are added to detergents and other cleaning materials to improve ("build") the cleaning power of the surfactant in water. Other materials used as

builders in granular detergents include sodium carbonate and zeolite. A citrate builder is used in some liquid detergents, and currently, unbuilt liquids are popular. These are products formulated to perform well without a builder through the use of other ingredients. Each of the builders has certain advantages and limitations, depending on the mineral content of water and type of soil in the laundry load.

This project was designed to augment the body of knowledge about the performance in soft and hard water of three types of laundry detergents currently sold in Virginia. Information generated can be used as the basis for an education program to help consumers recognize changes that may occur following the mandate to limit the phosphate content of laundry products marketed in the Commonwealth.

BACKGROUND INFORMATION

The process of restoring clothing and other household items to useable condition through home laundering requires complex decisions and actions. If the laundering process is viewed as a system, interacting inputs to the system are the items in the wash load (composed of various fibers and types of fabrics and finishes along with accessories such as buttons), soil on the items, water, detergents, and other laundry additives. In the washing machine, the water, detergent, and other laundry additives provide chemical energy; heat (if warm or hot water is used) provides thermal energy; and the washing machine itself provides mechanical energy to the process. Outputs from the laundering process include items that are restored to useable condition, water, detergent, and other additives drained into the sewage system. Removal of soil, and consequently the appearance of items laundered, is affected by all three forms of energy — chemical, thermal, and mechanical — in the washing process.

While the interactions among all three variables affect laundry performance, only the interactions among soils, water, and detergents will be mentioned here.

I. Soils

Soils involved in the laundry system are of four types: water soluble; insoluble, organic — saponifiable; insoluble, organic — not saponifiable; and insoluble, inorganic. Table 1 summarizes information on soils common in home laundering.

II. Water

A. Hardness

The mineral content or hardness of water affects the performance of laundry detergents. Expressed in parts per million (ppm) of calcium carbonate (CaCO_3), water with a hardness level of 60 ppm or below is generally considered soft. That with a hardness level above 120 ppm is considered hard.

The majority of the population of Virginia (71%) is served by surface water (Costs and Benefits of a Phosphate Detergent Ban 1985). Overall, about 64% of the population of Virginia live in soft water areas. The remaining 36% live in areas with water of varying degrees of hardness from medium hard to very hard (Table 2). The hardness level in the groundwater is generally the lowest in the coastal plain area and increases progressively in the landward direction. In general, high hardness levels are found near the Blue Ridge mountains and Shenandoah Valley areas where limestone predominates the geologic makeup. Water hardness level is also higher in nonurban areas of the state served by groundwater than in urban areas served by surface water. Figure 1 shows the

distribution of hardness levels in the groundwater for the nonurban areas in Virginia on a county-by-county basis.

It should also be noted that even when clothes are washed in soft water, some hardness minerals are introduced into the water by the soil on the clothes. Such soil may contribute hardness ions equivalent to 35-85 ppm, according to Williams (1984a).

B. Temperature

The temperature of water used in laundering influences the amount of cleaning accomplished, the energy consumption, and, in some cases, the extent of wrinkling of fabrics and fading of colors. Higher temperatures generally remove more soil, require more energy to heat the water, may leave more wrinkles, and may remove more dye.

With the current need to reduce the cost of heating water, using warm water for washing and cold water for rinsing has been recommended for all but heavily soiled articles.

III. Detergents

The composition of laundry detergents varies with type of detergent and brand but, in general, all laundry detergents contain surface-active agents (i.e., surfactants) and other ingredients to improve cleaning (Table 3). At present, granular laundry detergents contain one or more builders; liquid products generally contain no builders and are referred to as "unbuilt" products. Table 4 shows a comparison of the ingredients in built and unbuilt laundry detergents.

The builder, called the second most important ingredient in a detergent formula, enhances or "builds" the cleaning efficiency of the surfactant by deactivating water hardness minerals. Used alone or in combination, builders soften water by sequestration, precipitation, or ion exchange.

Phosphate, usually in the form of sodium tripolyphosphate, is the most frequently used builder. Phosphates soften water by sequestration — inactivating water hardness mineral ions and holding them tightly in solution. Phosphates also hold dissolved iron in the water in suspension. This helps to prevent discoloration of fabrics which occurs in some areas of Virginia where dissolved iron often is present in hard water (Lung 1984).

The level of phosphate in detergents has been reduced voluntarily by the industry since 1970. As reported by Procter and Gamble, the level of phosphorus in all laundry detergents in 1970 averaged about 11%; in 1984, about 5%

(Williams 1984b). Liquid detergents which did not contain any phosphorus were included in calculating the overall average of 5%. The level of phosphorus in several granular detergents marketed in Blacksburg area stores early in 1987 was:

Brand	Phosphorus	
	Percent	Grams/amount recommended per load
Ajax	0.5	0.4 per 1C.
All	< 0.5	—
Arm & Hammer	0.25	0.37 per 1C.
Bold 3	7.1	6.0 per 1C.
Cheer	9.5	6.1 per $\frac{3}{4}$ C.
Fab	7.1	6.0 per 1C.
Gain	7.1	6.0 per 1C.
Oxydol	8.6	5.5 per $\frac{3}{4}$ C.
Surf	7.5	6.0 per 1C.
Tide	9.8	6.3 per $\frac{3}{4}$ C.

Another sequestering builder that performs well in laundry detergents is sodium citrate. While not as effective a sequestrant as a phosphate, sodium citrate is used in liquid detergents.

Sodium carbonate and sodium silicate are precipitating builders that remove water hardness ions by a nonreversible reaction which forms an insoluble residue or precipitate that can adhere to fabrics and washer parts. Sodium carbonate does not hold iron in solution and is ineffective in preventing discoloration of fabrics caused by iron in the water (Hobbs, Cowan, and Hurwitz 1984).

Zeolite (sodium aluminosilicate) is an ion exchange builder. It ties up calcium ions, the primary source of hardness, but an additional builder is needed to control magnesium ions.

Consumers can determine which builder(s) are in a detergent by examining the ingredients label on a package. Those containing phosphate provide specific information as to the amount (proportion) contained while those with another builder usually identify it but do not disclose the quantity. Due to the distribution systems of some large supermarket chains, it is possible for nonphosphate formulations of detergents to be distributed in areas which do not have a phosphate sales ban. Since packaging is identical (i.e., some national brands come in both phosphate and nonphosphate forms), it is important to check the label for information about ingredients.

REVIEW OF RELATED RESEARCH

Published empirical studies sponsored by independent organizations to compare the effects of phosphate and nonphosphate detergents in home laundering have been limited. The earliest studies (Avery and Harabin 1975; Morris and Prato 1975) were conducted following the first wave of publicly voiced concerns about the ecological impact of the use of phosphate detergents on water quality, especially on the Great Lakes. Two of the most recent studies (Spivak, Smith, and Kim 1982; Hobbs, Cowan, and Hurwitz 1984) were conducted during a period of controversy about the ecological impact of the use of phosphate detergents on water quality in the Chesapeake Bay and its tributaries.

Avery and Harabin (1975) compared the effectiveness of two phosphate and two nonphosphate detergents, used alone or in combination with a perborate bleach and an enzyme presoak, in laundering three white shirting fabrics. The phosphorus content of the phosphate detergents was 10.84 and 15.26 grams phosphorus per load. One of the nonphosphate detergents contained sodium carbonate; the other, a combination of sodium carbonate and sodium metasilicate. The three fabrics were a 100% cotton broadcloth with an easy care finish, a 50% polyester/50% cotton shirting with permanent press finish and a 65% polyester/35% cotton broadcloth with permanent press finish. Three common substances — catsup, salad oil, and coffee containing sugar and cream — were used as soiling materials.

Two sets of fabric specimens were prepared for laundering — one for laundering alone 20 times and one for soiling and laundering five times after the initial soiling. A part of each fabric was set aside as a control and not laundered. All fabric specimens were laundered in soft water (38 ppm) in a household automatic washer and dried in a household electric dryer. The washer options chosen were permanent press cycle with 8 minutes wash, normal agitation, and normal spin speed. Water temperature was 120° ($\pm 5^\circ$) F for the wash cycle and 105° ($\pm 5^\circ$) F for the rinse cycle. Color change after laundering alone and after laundering and subsequent exposure to light were evaluated statistically in analysis of variance and t-tests.

Conclusions of this study were:

1. In most of the analyses of the laundering of unsoiled and soiled samples, fabrics accounted for the major portion of the variance. A comparison of the overall changes which took place within each of the three fabric groups suggest that cotton was relatively sensitive and polyester relatively insensitive to the effects of different combinations of detergents and additives.

2. The number of launderings was a significant factor in four of the five analyses. Breaking strength and yellowing increased with two of the fabrics and decreased with one. Reflectance also tended to increase over the 20 launderings while the ratings for soil and stain removal gradually improved over five launderings. The results of individual launderings tended to be erratic and uneven.
3. The main effect for detergents was statistically significant in all but one of the analyses (warp breaking strength). The differences, however, were not necessarily related to the phosphate content of the detergents but could have been due to the action of optical brighteners and other detergent ingredients or to variations in fabric structure. In some of the analyses the differences between the two nonphosphate detergents were sometimes greater than the differences between the phosphate and nonphosphate products. No one detergent was best for removing all soiling and staining compounds. All detergents appeared to be equally affected by exposure to light.

The most crucial difference in the phosphate and nonphosphate detergents was in their ability to sequester the iron and manganese minerals that cause yellowing. Even after one laundering with the phosphate detergents, the blended fabrics were considerably less yellow than those laundered with the nonphosphate detergents.

Morris and Prato (1975) analyzed the effects of laundering with phosphate-built (48% sodium tripolyphosphate) and carbonate-built (55% sodium carbonate) detergents on the edge abrasion of durable press cotton fabric and the buildup of a precipitate deposit on samples of durable press cotton and nylon. Technical grade sodium tripolyphosphate (STPP) and reagent grade sodium carbonate were used alone to represent the builders for four of the launderings. In laundering, distilled water was used to simulate soft water. The hard water used had a hardness level of 300 ppm. The four detergent treatments were repeated with artificial soil which was a mixture of Bandy black clay and synthetic sebum.

Samples (3" x 6") of a durable press cotton fabric and a nylon fabric were used for the test loads which were washed and rinsed in a Terg-O-Tometer for 15 minutes with water at 120° F. Samples were dried in a household clothes dryer.

Edge abrasion was evaluated on the cotton samples after 20, 30, and 40 launderings by a visual method and the buildup of a deposit on both cotton and nylon fabrics was determined by atomic absorption spectrophotometer analyses for calcium and magnesium, scanning microscope examination, and weight change determinations.

Conclusions of this study were that:

1. A significantly greater amount of edge abrasion was found on cotton samples laundered in hard water than on those laundered in soft water with comparable detergent or builder.
2. The greatest amount of abrasion was on samples laundered in hard water with carbonate detergent, followed in descending order of abrasion damage by carbonate builder, phosphate detergent, and phosphate builder.
3. The amount of edge abrasion was similar on all cotton samples laundered in soft water regardless of the laundry treatment.
4. A heavy buildup of calcium deposit (precipitate) was found on both cotton and nylon fabrics laundered in hard water with carbonate detergent or builder. Lower levels of the buildup were found on samples laundered in hard water with phosphate detergent but no indications of the deposit were found on samples laundered in soft water or in hard water with the phosphate builder. Thus, Morris and Prato concluded that neither carbonate nor phosphate builders caused deleterious effects to the fabric when soft water was used.

The removal of soil that accumulates during wearing is critical to satisfaction with the appearance of white apparel. Retention of whiteness at acceptable levels has become increasingly complex with the general use of cotton fabrics with a durable press finish or blends of polyester and cotton in fabrics with or without a permanent press finish, and laundry detergents that contain no phosphates. Consequently, Mohamed (1982) attempted to determine the effect of various commercial laundering formulas on 150 white hospital uniforms of 65% polyester/35% cotton or 50% polyester/50% cotton with a durable press finish. Specifically, the objectives were to: 1) compare the effect of phosphate- and carbonate-built detergents in laundering polyester/cotton; 2) to determine the effects on whiteness retention, durable press appearance, and tearing strength; and 3) to compare the combined effect of wear and laundering with the effect of laundering alone on tearing strength.

All laundry treatments were commercially performed using medium hard water (100 ppm) and two types of detergents — sodium tripolyphosphate-built or sodium carbonate-built — and no chlorine bleach or brighteners.

The uniforms were subjected to five treatments: 1) no laundering or wear; 2) laundering with phosphate-built detergent; 3) laundering with carbonate-built detergent; 4) worn for 8 hours and laundered with phosphate detergent

(repeated for a total of 25 cycles); and 5) worn for 8 hours and laundered with carbonate detergent (repeated for a total of 25 cycles).

Conclusions of this study were that:

1. Laundering with phosphate-built detergent produced a significantly higher level of soil removal, and higher durable press appearance ratings and strength retention after 25 cycles than laundering with carbonate-built detergent.
2. Wear and laundering had more effect than laundering alone upon strength retention, but laundering was the major contributor to loss of strength.
3. A powdery deposit of calcium carbonate was visible on the surface of the garments. Observation with a scanning electron microscope also revealed severe abrasion of cotton fibers with the use of the carbonate-built detergent.

Spivak, Smith, and Kim (1982) evaluated soil removal, soil redeposition, and calcium carbonate deposition as a function of detergent type. One brand of each of three nationally distributed detergents were used in the study: phosphate-built granular (6.1% phosphorus), carbonate-built granular, and unbuild liquid.

Two different wash loads were used during the study. A five-pound white load composed of three boy's 100% cotton T-shirts, three boy's 50% polyester/50% cotton sport shirts, and three 100% cotton washcloths plus filler fabrics was used for the soil removal and soil redeposition tests. A five-pound load of dark colored items — three men's 100% cotton dark green T-shirts, three boy's 50% polyester/50% cotton dark blue sport shirts, and three 100% cotton burgundy washcloths plus filler fabrics — was used for the carbonate deposition test.

Maryland type clay soil was used for the soil removal test; clay soil plus vacuum cleaner soil for the soil redeposition test; and no soil for the carbonate deposition test. Test loads were washed in a household automatic washer for 10 minutes in warm water ($100^{\circ} \pm 2^{\circ}$ F) and rinsed in cold water. All loads were dried in a household clothes dryer.

For the soil removal and soil redeposition tests, the hardness of the water was almost identical, 104 and 105 ppm, respectively. For the carbonate deposition test, hardness of the water was 87 to 120 ppm.

Items were washed once for the soil removal test, five times for the soil redeposition test, and 15 times for the carbonate deposition test. The dark items

were prewashed separately three times with AATCC Standard Detergent 124 to remove any loose dye and thus prevent dye transfer.

Findings of this study were that:

1. Samples laundered once with the phosphate detergent retained only a small amount of clay soil while samples laundered with the two nonphosphate detergents still showed heavy staining.
2. In preventing soil redeposition, the phosphate detergent was most effective. The unbuil and carbonate-built detergents ranked correspondingly lower, with some loss of appearance after five launderings.
3. In assessing calcium carbonate deposition, the phosphate and unbuil detergents showed little or no change while buildup of deposits resulting from the interaction of water with the carbonate detergent continued to accumulate throughout the 15 launderings tested. The findings also suggested a somewhat stiffer "feel" of the wash load that corresponds to increasing carbonate deposition.

Hobbs, Cowan, and Hurwitz (1984) studied the effect of iron in the water supply on the acceptability of textiles laundered with phosphate granular, carbonate-built granular, and liquid citrate-built detergents. White fabrics included in the study were bath size terry towels of 100% cotton, men's knit T-shirts of 100% cotton and 50% polyester/50% cotton, and men's shirts of 60% cotton/40% polyester with a permanent press finish. Each wash load weighed 5.5 pounds. The test loads were not soiled before laundering. Water hardness was adjusted to 59.5 ppm and the iron concentration was adjusted to 0.8 ppm.

Test loads were laundered in a household automatic washer and dried in a household automatic dryer. Warm water (100° F) was used for the wash cycle and cool water (78° F) was used for the rinse cycle. Washing time was 10 minutes with the regular cycle. Data were collected and analyzed after 5, 15, and 30 wash and dry cycles.

The authors concluded that:

1. In water averaging 0.8 ppm iron, phosphate-built granular detergent was more effective than either the carbonate-built granular detergent or citrate-built liquid detergent in maintaining textile whiteness through repeated wash/dry cycles. The reduction in whiteness noted after repeated use of the nonphosphate detergents over a number of wash/dry cycles was readily apparent to the casual observer.

2. The most marked changes in whiteness occurred by the time the textiles had been laundered 15 times.
3. During the subjective rating for whiteness, observers noted that the items laundered using the carbonate-built detergent had a noticeably harsher "hand" or "feel" than the items laundered with the other two types of detergent.

Jubinsky (1984) assessed the effectiveness of three granular detergents and one unbuilt liquid detergent in removing oily and particulate soil. Builders in the granular detergents were: 1) NTA/sodium carbonate/zeolite; 2) phosphate/carbonate/zeolite; and 3) carbonate/zeolite.

Squares of 65% polyester/35% cotton fabric with a durable press finish were used for the testing. Soiling materials were triolein, the representative of single component oily soils, and black kaolinite research clay, the particulate soil component. Some fabric samples were soiled with a mixture of clay and oily soil. Each fabric sample was washed and rinsed separately in distilled water using a Launder-Ometer. A 10-minute wash cycle was used with two wash water temperatures, 81° F and 120° F.

Jubinsky reported that:

1. In terms of soil removal, the performance of the NTA/zeolite/carbonate detergent was significantly better than the other detergents.
2. In whiteness retention and removal of particulate soil, the phosphate/carbonate detergent was second, closely followed by the carbonate/zeolite detergent.
3. For removal of oily soil, the order for second and third place was reversed with the carbonate/zeolite detergent outranking the phosphate/carbonate product.
4. By all measures of cleaning, all three of the built powdered detergents were better than the unbuilt detergent.
5. The synergistic effect of the surfactant and the builder was greater than the effect of the surfactant alone.

In 1978, Consumer's Research Magazine included a report of a study of the performance of 46 different detergent products, both powdered and liquid, in phosphate and nonphosphate types (Laundry Detergents 1978). The detergents were studied with three different water temperatures and with hard and soft

water. Overall, the group of phosphate detergents performed better than the nonphosphate products, especially in hard water. On an individual basis, there were phosphate and nonphosphate detergents that received below average ratings for soil removal and others which were rated above average.

This study has several limitations:

1. Formulation of the detergents studied by CRM have changed since 1978 (although this is the most recently published evaluation of a large number of detergents).
2. A single artificial soil was used which, because it may react differently from the variety of natural soils found in a home laundry, may produce unrealistic results.
3. Only light reflectance was used as a measure of soil removal. In the home, other aspects of laundering must be considered such as visual appearance, edge abrasion, and "hand".

More recently, Consumer Reports (Laundry Detergents 1986) carried a report of an evaluation of major detergent products. The 11 products tested were chosen for their broad spectrum of formulations. White polyester/cotton shirts were worn long enough to appear dirty around collar and cuffs and then washed in an automatic washer. All detergents were effective in cleaning the lightly soiled areas, but performed less satisfactorily on the soiled collars and cuffs.

In additional tests, 1000 foot-square swatches of woven 50% cotton/50% polyester fabric with a durable press finish and 1000 swatches of nylon knit were treated with one of 10 hard-to-wash stains. No product was rated very good or excellent in removing all the stains from both fabrics.

In summary, although a number of researchers have studied the effects of phosphate and nonphosphate builders on laundry performance, it is recognized that research methodology and detergent product formulation have been so varied that generalizations for all laundry conditions are almost impossible. Consequently, the results of the studies reviewed do not provide the information needed to evaluate the effect of using nonphosphate detergents in home laundering in Virginia in 1986. Primary limitations of the previous research include:

1. length of time since most of the research was conducted.
Because manufacturers change product formulations frequently, products available at present are likely to be significantly different from the products used in research published even as recently

as three years ago. Also, as Consumers Union writers point out (Laundry Detergents 1986), "Detergent makers ...tailor their formulas by geographical area, to account for differences in the mineral content of water" (p. 80).

2. the quality of the water used.

A number of researchers have used hard or distilled water; few have reported studies with water classified as naturally soft.

3. data collection techniques.

Some researchers have approached the topic in controlled laboratory tests using simulated laundry conditions; little work has been done with laboratory experiments to determine the effect of nonphosphate detergents on laundry performance in soft and hard water using a standard test load of clothing items representative of the items laundered at home.

METHODOLOGY

I. Test Conditions

Performance of three types of laundry detergents — phosphate-built and carbonate-built granular and unbuild liquid — was evaluated by using standard procedures for measuring soil removal, soil deposition, and carbonate deposition in soft and hard water. Tests were conducted by trained technicians using identical procedures in the household equipment laboratory at Virginia Tech and in a home outside the town of Blacksburg.

The water used for all tests was taken directly from the water system at each of the test sites. In the household equipment laboratory, water is obtained from the New River, purified at a pumping station and treatment center operated by the Blacksburg-Christiansburg-VPI Water Authority, and piped to the campus with an average mineral content of 60 ppm. On occasion, the mineral content is as low as 50 ppm or it may reach 70 ppm. Thus, the water in the household equipment laboratory generally falls within the range of soft water as classified by Lung (1984).

Because hard water was not available in the laboratory, a site approximately five miles from the university was selected at which to evaluate detergent performance in hard water. At that site, the water is pumped from a drilled well and used without treatment of any kind. When tested in the Environmental Engineering Laboratory at the university, average mineral content was 171.66 ppm (10 gpg), thus the classification of hard water.

The automatic washers used at each site were identical in wash, rinse, and extraction programs as well as size and configuration of tub and agitator. For all tests, washing machine controls were set for warm wash and cold rinse. Thus the temperature of the wash water was determined by the temperature of water from the water heater and in the cold water line. Launderings were conducted between July and November 1985, when water temperatures fluctuated through a narrow range. Soil removal, soil deposition, and carbonate deposition were determined by measuring the light reflectance of samples before and after laundering with a Hunter Lab Spectrocolorimeter (model LS 5100, Hunter Associates Laboratory, Inc., Reston, VA). Subjectively, "hand" and visual appearance were evaluated. The six brands of detergent (two brands in each of the three types) were selected from approximately 20 national brands available in a Blacksburg supermarket in the summer of 1985. Selection criteria were:

1. Formulation - granular or liquid
2. Builder - phosphate, carbonate, none
3. Additives - no bleaches, enzymes, or softeners

4. Density - amount recommended per normal load in top-loading automatic washer for granular, 1 C; for liquid, 1/2 C.
5. Suds level - normal
6. Manufacturer - as many as possible

Information about product formulations and recommended usage is given in Table 5.

Standard loads, as specified in the American National Standards Institute/ Association of Home Appliance Manufacturers (ANSI/AHAM) procedure for evaluation of washing machine performance (AHAM 1980), were assembled for the soil removal and soil deposition tests. For each series, an eight-pound load of white clothing and other household items was used. In the series of tests for carbonate deposition, each load included nine dark blue items — three 100% cotton washcloths, three boy's 50% cotton/50% polyester knit sport shirts, and three men's 100% cotton knit T-shirts with enough 24" x 36" white 50% cotton/50% polyester muslin filler cloths to complete the eight-pound load. (See Table 6 for a more detailed description of test loads.) Prior to testing, all white items were washed through three normal cycles — an eight-minute warm water wash with phosphate granular detergent followed by a cold rinse — with an additional cold water rinse following the third cycle. Dark items were given the same treatment with the exception of detergent. Items then were dried in an automatic dryer and stored in plastic bags.

Based on protocol specified in the ANSI/AHAM procedure, items in the white test load were carriers for a designated number of 4" x 4.5" swatches of standard soiled or unsoiled test cloth of 100% cotton with no finish, 50% cotton/50% polyester with no finish, and 50% cotton/50% polyester with a permanent press finish (United States Testing Company, Inc., Instrument Marketing Division, Hoboken, NJ). The standard soiled cloth is impregnated with a special formula composed of carbon black, vegetable oil, and mineral oil, and reflectance is controlled at a value of $25\% \pm 2\%$ as measured by a reflectometer.

Before testing began, fabric swatches sufficient for all tests were cut, marked for identification within a specific test series in soft or hard water, placed in random order, and wrapped by sets in plastic film. Prior to use, L, a, and b reflectance readings using the D₆₅ illuminant were recorded for each swatch.

II. Description of Tests

A. Soil Removal and Soil Deposition

Tests of soil removal and soil deposition are designed to evaluate the effec-

tiveness of a detergent in removing and holding soil in suspension during the laundry process. In this study, two separate series of tests were run with each type of detergent in soft and hard water using ANSI/AHAM procedures (1980).

In the soil removal tests, soil was introduced to the wash solution via 12 swatches of standard soiled cloth (4 cotton, 4 cotton/polyester, and 4 cotton/polyester with permanent press finish) attached at specified locations in the white test load (Table 7). The procedure for each of the five replications in this series was:

1. Mark soiled swatches to identify fiber swatch number, water type, detergent, and test replication.
2. Record reflectance.
3. Attach soil swatches in random order to items in test load as described in Table 7.
4. Record temperature and humidity in test environment.
5. Add premeasured detergent. Allow washer to fill with warm water for 0.5 min.
6. Select items from test load at random and loosely place into washer tub.
7. Set washer control for a large load, normal wash cycle, 10 min. agitation (wash), warm wash and cold rinse.
8. After the washer has filled with water for the wash cycle, stop the machine and record the temperature of water in the tub.
9. Repeat temperature measurement after the washer has filled for the rinse cycle.
10. Following the final spin, remove the swatches. Spread flat on brown paper on counter and allow to dry for at least 24 hours.
11. Treat test load with an additional deep rinse (cold water).
12. Dry load in automatic dryer using a regular dry cycle (be sure lint filter is clean before each load).
13. Attach fresh set of soiled swatches and perform next test.

14. Following each third replication, recondition test load using a normal cycle with warm wash and cold rinse water and no detergent.
15. After final replication, recondition load in preparation for next series or for storage.
16. Measure and record reflectance for each swatch.

Ten replications of the soil deposition test were conducted with a procedure similar to that used in the soil removal test except that untreated swatches were attached as shown in Table 7 and soil was introduced into the wash solution via a slurry of .85 oz. Bandy black clay dissolved in 1 qt. of hot water (140° F). Fifteen swatches (5 cotton, 5 cotton/polyester, and 5 cotton/polyester with permanent press finish) were used in each replication. In order to determine possible progression in soil deposition, one swatch of each fiber type, selected at random, was removed after each of the first five replications and replaced with an identical unwashed swatch. The original 15 swatches were used with no replacement in tests 6-10. The procedure used in the soil deposition tests was to:

1. Prepare swatches as in soil removal test except to use untreated white fabrics.
2. Record reflectance readings of all swatches.
3. Randomly select and attach 15 swatches to items in the white test load in locations described in Table 7.
4. Record room temperature and humidity.
5. Set washer for hand wash, regular cycle and allow washer to fill with warm water for 0.5 min.; add slurry of clay and hot water.
6. Allow washer to fill and agitate for 1 min. to mix slurry through wash water.
7. Stop washer. Add premeasured detergent.
8. Select items from test load at random and loosely place into washer tub.
9. Set washer control for large load, normal wash cycle, 10 min. agitation (wash) with warm wash and cold rinse.

10. After washer has filled with wash water, stop machine and record temperature of water in the tub.
11. Repeat for rinse water temperature.
12. After final spin, remove the swatches, spread flat on brown paper on counter and allow to dry for 24 hours.
13. Treat load with an additional deep rinse (cold water), and extra spin.
14. Dry using regular cycle, removing items as they dry.
15. From the dry (washed) swatches, randomly select 3 (one of each fiber type) for evaluation. (None of these should be replacement swatches.) Mark with designation for number of times washed. Measure and record reflectance.
16. Replace the 3 swatches removed with 3 unwashed swatches (one of each type) which have been marked with replacement code.
17. Attach the 12 washed swatches and 3 replacement swatches (total of 15) to items in the test load.
18. Repeat the process 4 times for a total of 5 replications.
19. Recondition test load after each fifth replication using a normal cycle with warm wash and cold rinse water and no detergent.
20. For replications 6 - 10, attach the original 15 swatches to items in the test load. Wash as above with no replacement.
21. After final replication, recondition load in preparation for next series or for storage.
22. Measure and record reflectance for each swatch.

B. Carbonate Deposition.

A deposit of the precipitate formed by the interaction of the carbonate builder and minerals in water is most apparent on dark fabrics, particularly fabrics with an irregular surface texture or in areas of extra thickness (e.g., pockets or collars).

In the carbonate deposition series, 15 replications were specified to evaluate the

extent of a buildup of the precipitate on the dark blue items in the test load, as determined by an increase in reflectance. The number of replications was set arbitrarily in an attempt to determine the effect of repeated exposure of test items to these laundry conditions. Assuming an average of two to three launderings per month, 15 tests would represent the effect on test items over a period of approximately four to five months. For this series, four sets (one set for each of the two carbonate-built detergents in soft and hard water) of dark blue items were assembled (3 terry washcloths, 3 boy's knit sport shirts, 3 men's knit T-shirts). Enough 24" x 36" white stuffer cloths were added to each set of dark blue items to make an eight-pound load. Generally, 24 cloths were used at the beginning of tests for each detergent with an additional cloth after the first and tenth test.

Because prior observations have shown that the precipitate is not evenly distributed, each dark blue item was marked for reflectance reading in a different location. The location for each item was:

Washcloth	Boy's Shirt	Man's T-Shirt
1. center	1. seam	1. pocket
2. corner	2. collar	2. center front
3. edge	3. center front	3. sleeve front seam

Following are the steps in the procedure for carbonate deposition tests:

1. Assemble an 8-pound load of dark blue items and stuffer cloths.
2. Record reflectance in center of each area marked on the dark blue items.
3. Record temperature and humidity.
4. Allow washer to fill with warm water for 0.5 min.; add premeasured detergent.
5. Selecting items at random, load loosely into the washer tub.
6. Set machine for large load, normal wash cycle, 10 min. agitation, warm wash and cold rinse.
7. After the washer has filled for the wash cycle, stop the machine and measure the temperature of water in the tub.
8. Repeat temperature measurement after the washer has filled for the rinse cycle.

9. At end of test, dry load in automatic clothes dryer using a regular cycle (be sure lint filter is clean before each load.)
10. After every five wash and dry cycles, measure and record reflectance in center of specified areas on dark blue test items.
11. Repeat for a total of 15 washes and dry cycles.

III. Data Analysis

After tests were completed, L (measuring lightness), a (measuring redness or greenness), and b (measuring yellowness or blueness) readings, determined with the Hunter Spectrocolorimeter, were coded for computer analysis. Delta (Δ) E values, which combine the L, a, and b, were computed to represent overall color change (Billmeyer, Jr. and Saltzman 1981). The formula for ΔE was the square root of $L^2 + a^2 + b^2$.

The SAS statistical package was utilized in analysis. Descriptive statistics including mean, standard deviation, range, and variance were computed for each test. The analysis of each test will be discussed individually.

A. Soil Removal

Although six different detergents were used, they represented three general detergent types. Therefore, a nested analysis of variance design, with two detergents nested in each detergent type, was used. It is an expansion of designs found in Kirk (1982) and Keppel (1982). Because detergent selection was not truly random, a fixed effects model was used. The design included detergent group, detergent within detergent group, water, and fabric and all combinations of these independent variables. The dependent variable was color change as represented by ΔE .

Simple main effects were analyzed for significant interactions (Kirk 1982). If simple main effects were significant, the Tukey HSD test was used to test differences between means.

B. Soil Deposition

A repeated measures nested ANOVA design was required because color was measured before washing, after 5 washes, and after 10 washes. The independent variables, water, fabric, detergent group, detergent within detergent group, and time, plus all combinations of these variables, were included in the design. The dependent variable was color change as represented by ΔE . Again a fixed effects model was used. Simple main effects were analyzed for signif-

ificant interactions (Kirk 1982). If simple main effects were significant, the Tukey HSD test was used to test differences between means.

C.. Carbonate Deposition

A fixed effects repeated measures design was also utilized for these tests which only included the carbonate detergents. The independent variables were detergent, item, water, and time. The design included these variables, their combinations and a factor named subject number (consisting of detergent, item, and water) which was used as the error term. Again, the dependent variable was color change as represented by ΔE . Simple main effects were analyzed for significant interactions (Kirk 1982). If simple main effects were significant, the Tukey HSD test was used to test differences between means.

RESULTS AND CONCLUSIONS

The effects of water hardness, type of detergent, and type of fabric were apparent in results of tests for soil removal, soil deposition, and carbonate deposition. General trends observed as well as statistically significant results of the nested ANOVA procedure are reported for each series of tests. Differences between specific detergents will not be discussed because it was the purpose of this study to compare one type to another, not to make comparisons between specific brands. However, it is important to recognize that there were differences between products within detergent groups.

I. Soil Removal

Some soil was removed in all tests (Table 8). The degree of soil removal was significantly influenced by detergent, detergent group, and fabric (Table 9). The interaction of various factors is important. For example, effectiveness of the detergents in removing soil varied with the hardness of the water and was apparent in visual observation as well as in measurement of reflectance. The most soil was removed by the unbuil liquids, especially in hard water. In soft water, results with the phosphate-built detergents were similar to those of the unbuil liquids. The carbonate-built detergents were always the least effective in either soft or hard water, but results were only slightly lower than the phosphate-built detergents in hard water (Figure 2, Table 10).

When laundering the 50% cotton/50% polyester fabric with no finish, the unbuil liquid detergents gave the best results followed in decreasing effectiveness by carbonate-built and phosphate-built detergents. In laundering the permanent press fabric (50% cotton/50% polyester with a permanent press finish) phosphate-built detergents removed the most soil followed in decreasing order of effectiveness by the unbuil liquids and carbonate-built detergents (Figure 3, Table 11).

The effectiveness of the detergents in removing soil also varied with the fiber content and finish of the fabrics laundered, regardless of whether the water was hard or soft. When laundering 100% cotton fabric with no finish, soil removal was greatest with the unbuil liquids. In this instance, the phosphate-built and carbonate-built detergents were similar to one another and less effective than the liquid product.

Regardless of detergent type, the cotton fabric gave up soil most readily in both hard and soft water. In hard water, results were the same for the 50% cotton/50% polyester fabrics with and without the permanent press finish. However, in soft water, results were better for the cotton/polyester fabric with

the permanent press finish than for the samples of the cotton/polyester blend that did not have the permanent press finish (Figure 4, Table 12).

II. Soil Deposition or Whiteness Retention

Tests of the effectiveness of a detergent in holding soil in suspension in the wash water, i.e., in preventing the deposition of suspended soil on white fabric, are often used as a proxy for tests of soil redeposition or retention of whiteness during laundering. In these tests, white fabric samples were laundered in water containing Bandy black clay and evaluated for a decrease in reflectance after 5 and 10 washings (Table 13).

Based on visual observation, it was apparent that some soil was deposited on all fabric samples in soft and hard water but, in general, whiteness retention was better in soft water than hard.

Based on statistical analysis of the objective measurement of change in reflectance, water, fabric, and times washed significantly influenced soil deposition (Table 14). Increased levels of soil deposition were common in hard water. This was especially true for the 100% cotton regardless of detergent type. Whiteness retention of cotton/polyester fabric with permanent press finish was least affected by soil deposition regardless of water (Figure 5, Table 15) or type of detergent (Figure 6, Table 16). Graying of the white fabrics was progressive from five to 10 washings and the increase occurred at a faster rate in hard water than in soft (Figure 7, Table 17, Figure 8, Table 18). The detergent groups did not perform consistently when times washed and water were considered together (Figure 9, Table 19).

III. Carbonate Deposition

A carbonate residue was deposited on all of the items (Table 20). Item, water, and times washed all significantly influenced carbonate deposition (Table 21). The deposition of an insoluble white precipitate on clothes washed in a carbonate-built detergent is detected by a change in reflectance and "hand" of a garment. Based on objective measurements of reflectance, items such as wash cloths had more obvious collections of the precipitate during the first 10 washings, but the change in T-shirts was almost the same as washcloths by 15 washings. The knit sport shirts showed the least buildup (Figure 10, Table 22). Items washed with a carbonate-built detergent in hard water felt harsher than those washed in soft water. The presence of the precipitate was more apparent in areas with irregular surface texture or thickness.

A buildup of the precipitate on dark items washed with carbonate-built detergents occurred in both soft and hard water, but was more apparent in hard

water. In addition, the buildup was progressive in both types of water and progressed more rapidly in hard water than in soft (Figure 11, Table 23). One might assume that the harder the water, the greater the buildup of the precipitate and the sooner it would become apparent.

IV. Conclusions

The results of this study are similar to those of previous studies. The factors involved — detergent, fabric, water, and times washed — all influenced the outcome and interacted with each other. Based on analysis of data for all tests, it was concluded that:

1. All types of detergents performed better in soft water than in hard water.
2. The unbuilt liquids and phosphate-built powders were more effective in soil removal and whiteness retention than the carbonate-built powders.
3. Untreated cotton fabric had a greater tendency both to give up and to absorb soil than did the cotton/polyester blends with or without a finish.
4. Differences in results were magnified as the number of washings increased.

SUMMARY AND RECOMMENDATIONS FOR FURTHER STUDY

I. Summary

This study was designed to evaluate the performance of current formulations of three types of laundry detergents in soft and hard water using home laundry equipment. Using procedures which are standard in the detergent and appliance industries and in independent laboratories, clothes were washed with two brands of each of three types of detergents (phosphate-built and carbonate-built granular and unbuilt liquid) to obtain measures of soil removal, soil deposition, and carbonate deposition. Mineral content of the soft water used in the study averaged 60 ppm; the hard water averaged 171.66 ppm.

For the five replications of the soil removal test, swatches of soiled test cloth in 100% cotton, 50% cotton/50% polyester with no finish, and 50% cotton/50% polyester with permanent press finish were used. Untreated swatches of the same fabrics were used for the 10 replications of the soil deposition test and soil was introduced via a solution of Bandy black clay and hot water. In both series of tests, the swatches of test cloth were attached at locations specified in the test procedures on unsoiled white items in a standard eight-pound load of garments and household linens. Carbonate deposition was observed after 5, 10, and 15 washings of a load composed of nine dark blue items (three 100% cotton terry washcloths, three men's 100% cotton T-shirts, and three boy's 50% cotton/50% polyester sport shirts) plus sufficient filler cloths of unbleached muslin to complete the load.

When data were analyzed using a nested analysis of variance technique, significant interactions were found between detergent, fabric, and water in all tests. The unbuilt liquid detergent was most effective in soil removal, especially in hard water, while the carbonate-built granular product was least effective. Soil removal was more effective for the cotton than for either of the cotton/polyester fabrics.

There was deposition of soil on samples of unsoiled cloth with all three types of detergent in both soft and hard water. Cotton samples picked up the most soil in both soft and hard water; permanent press samples, the least. While soil deposition was lowest on the cotton/polyester with permanent press finish with all three types of detergent, the phosphate detergent was the best of the three types in holding soil in suspension. Soil deposition increased with the number of washings and was greater in hard water than in soft water. The appearance of "tattletale gray", which results as soil suspended in the wash water is deposited on fabrics, was most noticeable for fabrics of untreated 100% cotton.

Carbonate deposition was more apparent in hard water than in soft, but the

buildup of the white precipitate occurred in both soft and hard water. Observations following 5, 10, and 15 washings showed that deposition of the carbonate precipitate was progressive and occurred at a faster rate in hard water than in soft. Items washed in hard water felt harsher than those washed in soft water, and the presence of the precipitate was more noticeable in areas with irregular surface texture or thickness.

II. Implications

Trends observed in this study were similar to those previously reported by researchers at other universities and at Consumers Union (Laundry Detergents 1986) in tests with artificially soiled cloth and with naturally soiled clothing. The unbuilt liquids and phosphate-built powders out-performed the products with a carbonate builder in both soft and hard water. The actual amount of soil removed or precipitate deposited was not measured, therefore it is not possible to make absolute statements about the amount of change that occurred as a result of using the different detergents. One cannot say, for example, that one product was "twice as good" or removed "twice as much soil" as another. Neither is it possible to say with confidence that each unit of difference in the purchase price was related to an absolute level of change in the cleaning ability (effectiveness) of the detergents used.

Judging from the results of this study, consumers can expect good performance in laundering with present formulations of either phosphate-built powders or unbuilt heavy-duty liquid detergents. Carbonate-built detergents may give poor results, especially because of the deposit which builds up on washed articles. This deposit will be most noticeable if the wash load contains dark colored fabrics and the wash water is hard. Based on national reports from consumers living in hard water areas, another problem which can occur with carbonate-built detergents is a buildup of carbonate deposit on the agitator and other parts of the washer.

In price, there was little difference in the cost per load between the phosphate-built and unbuilt liquid detergents used in this study (Table 5). Carbonate-built detergents tended to be less expensive than the other two choices, with the average cost per load being about 40% less than the phosphate and liquid detergents. However, the disadvantages of the lower level of effectiveness and problems in use of carbonate-built products, especially in hard water, could outweigh savings in the purchase price of these detergents.

Consumers who have iron in their water supply may find that the results of this study do not apply to their situation. Research conducted elsewhere indicates that phosphate-built products are more effective than carbonate-built powders and liquids containing sodium citrate (Hobbs, Cowan, and Hurwitz 1984). The

phosphate-built detergents also hold dissolved iron in suspension and thus prevent stains on fabrics better than detergents which do not contain builders. Generally, consumers with an iron-free water supply who want to use a nonphosphate detergent can choose a heavy-duty liquid product and not sacrifice cleaning quality.

III. Recommendations for Further Study

Although the results of these tests provided answers for the questions implied in the objectives, the number of significant interactions implies that the results are not clear cut. Other questions remain to be answered. Therefore, recommendations for further study are:

1. Repeat this study with more replications in order to provide a measure of detergent effectiveness over a longer period of time.
2. Conduct this study in harder water with and without dissolved iron.
3. Measure the effectiveness of various types of detergents in combination with hot and cold wash water (only warm wash water was used in this study).
4. Use objective and subjective methods to evaluate the effectiveness of phosphate and nonphosphate formulations of the same brand of detergent in laundering loads of clothes worn by people who encounter varying types of soil.
5. Survey specifically defined groups of consumers to determine: a) knowledge about detergents and other laundry aids as well as fibers, finishes, and fabric construction; and b) laundry standards and practices (e.g., standards for acceptable appearance and wear life of clothing and household items, frequency of laundering pieces of clothing and household items, number and description of loads laundered, washing machine settings — including water temperature, type and quantity of detergents and other laundry aids).

Findings from all of these studies would provide valuable baseline data to be used in planning educational programs targeted for specific audiences.

Finally, will the phosphate detergent ban adversely affect consumers? The results of this study suggest that at the present time the unbuilt liquid products are a practical and effective alternative to phosphate-built detergents. One further suggestion would be for consumers with very hard water to invest in a mechanical water softener.

Detergent formulations are changed frequently and the differences in detergent types are becoming increasingly blurred. Therefore, when purchasing and using laundry detergents, consumers need to be aware of the properties of their water supply, laundry detergent, and washing machine, plus the articles to be washed and the soil they contain. Laundering clothes is a complex process; satisfactory results depend on appropriate combinations of the variables in the system.

FIGURES

FIGURE 2
Soil Removal: Interaction of Detergent Group with Water

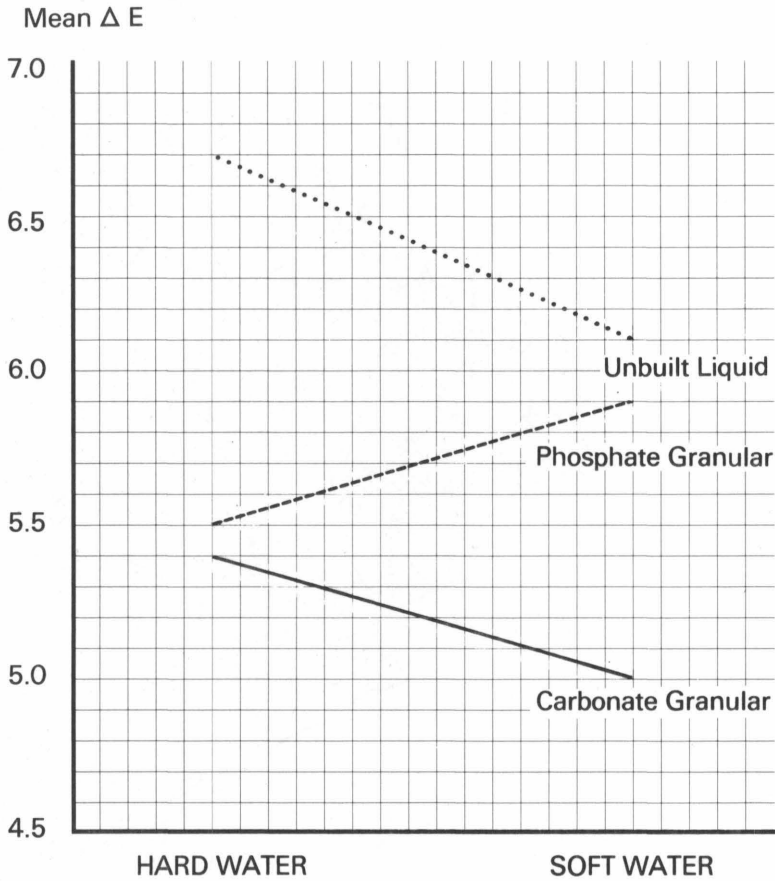


FIGURE 3
Soil Removal: Interaction of Detergent Group with Fabric

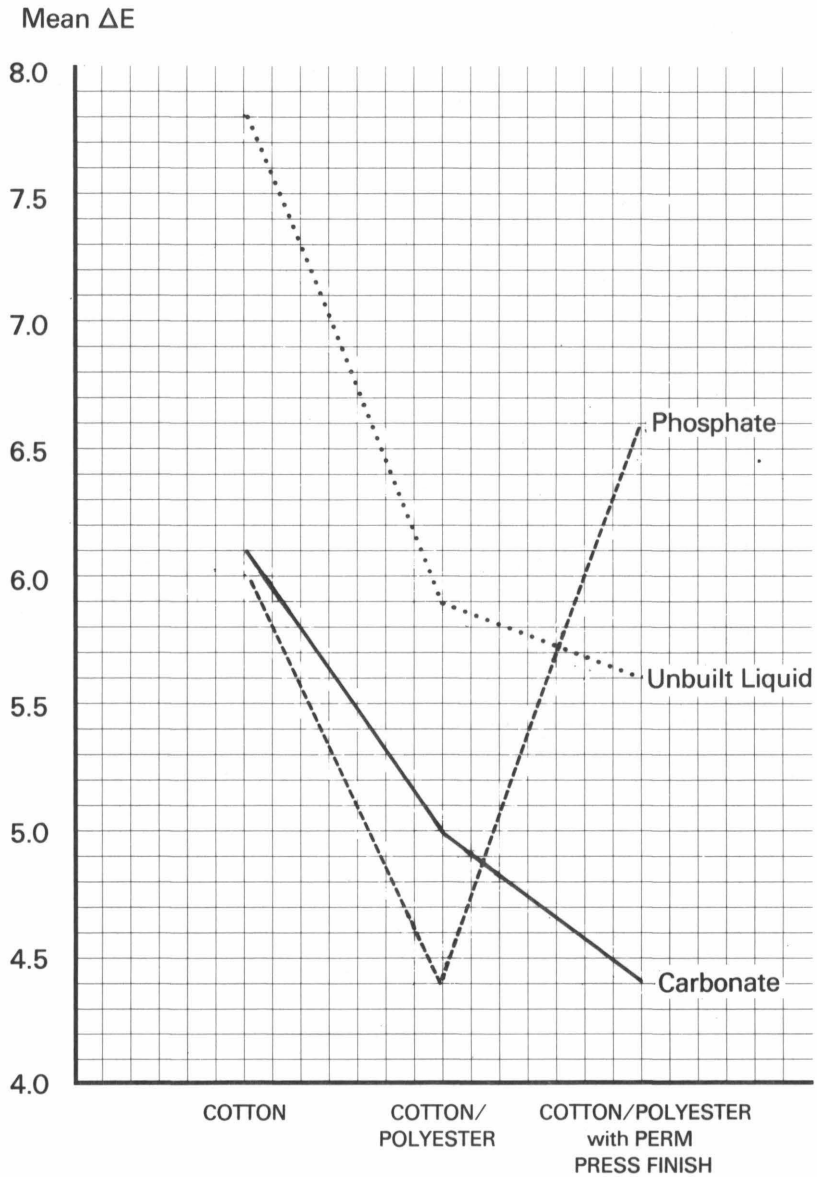


FIGURE 4
Soil Removal: Interaction of Water with Fabric

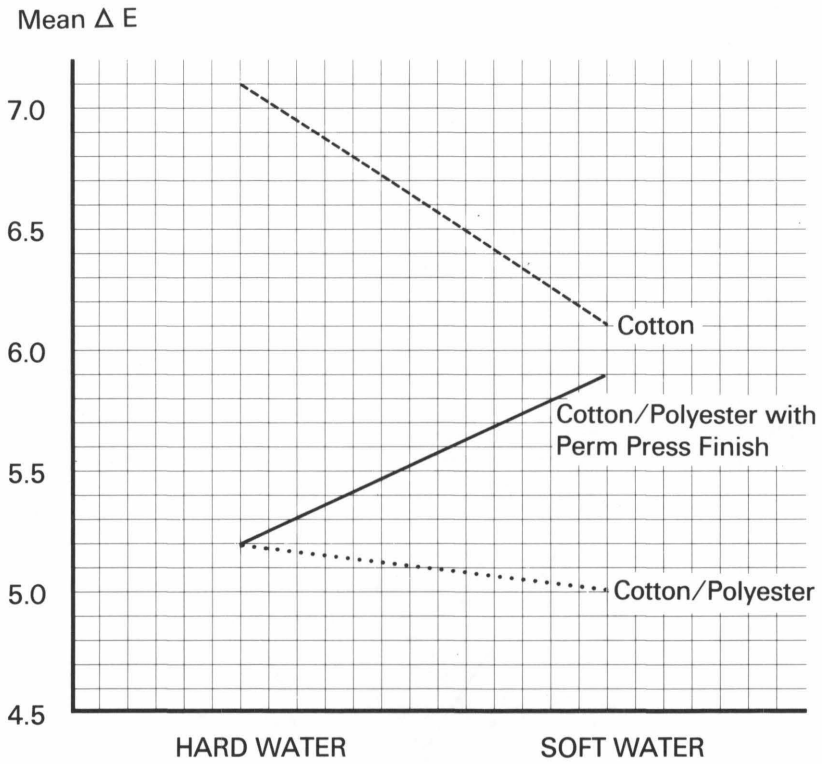


FIGURE 5
Soil Deposition: Interaction of Fabric with Water

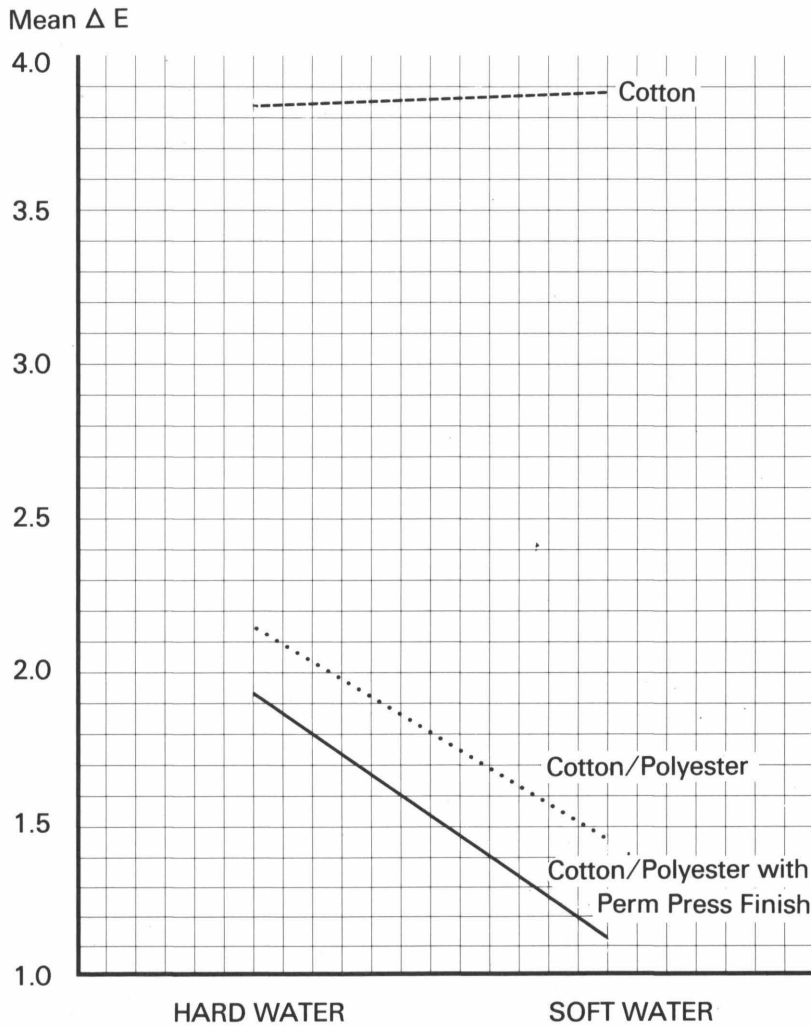


FIGURE 6

Soil Deposition: Interaction of Detergent Group with Fabric

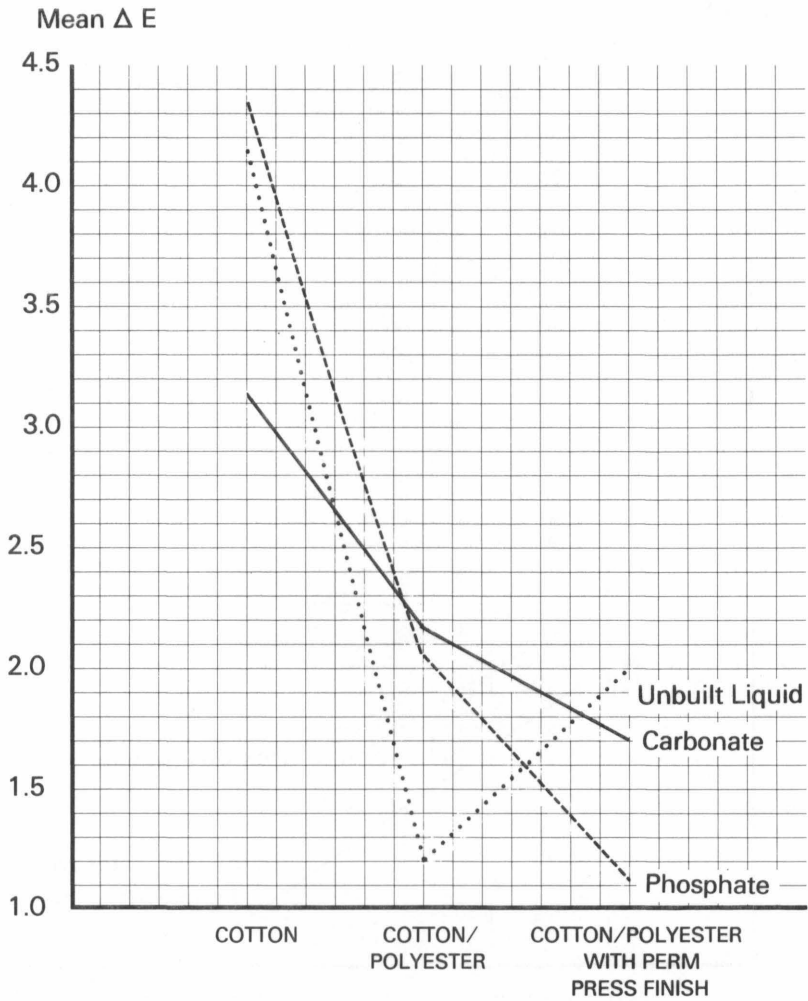


FIGURE 7
Soil Deposition: Interaction of Water with Times Washed

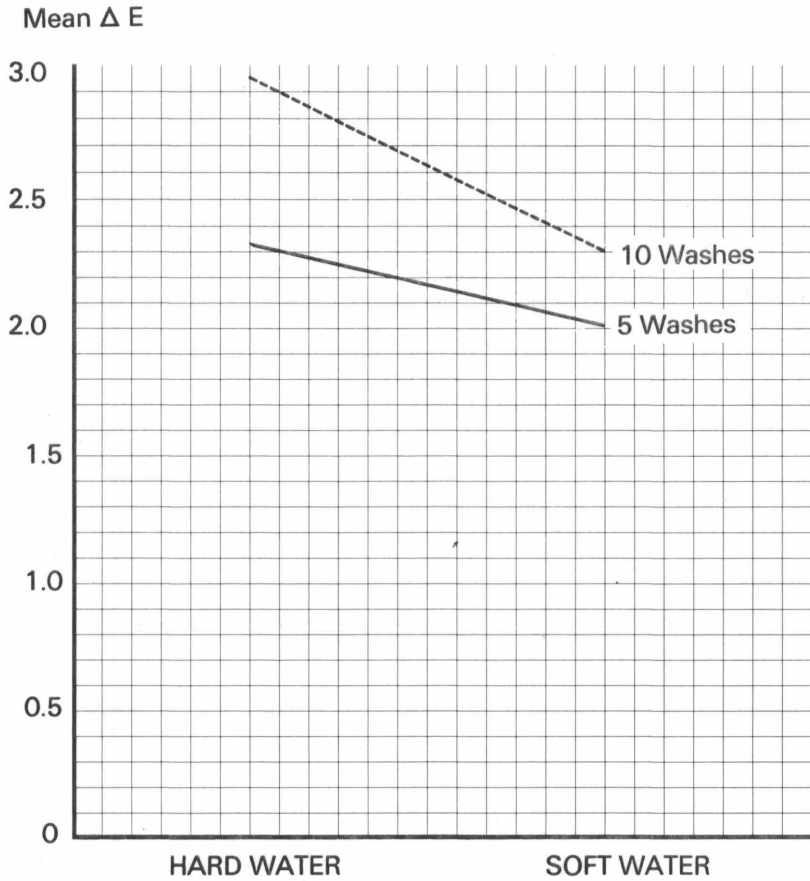


FIGURE 8
Soil Deposition: Interaction of Fabric with Water with Times Washed

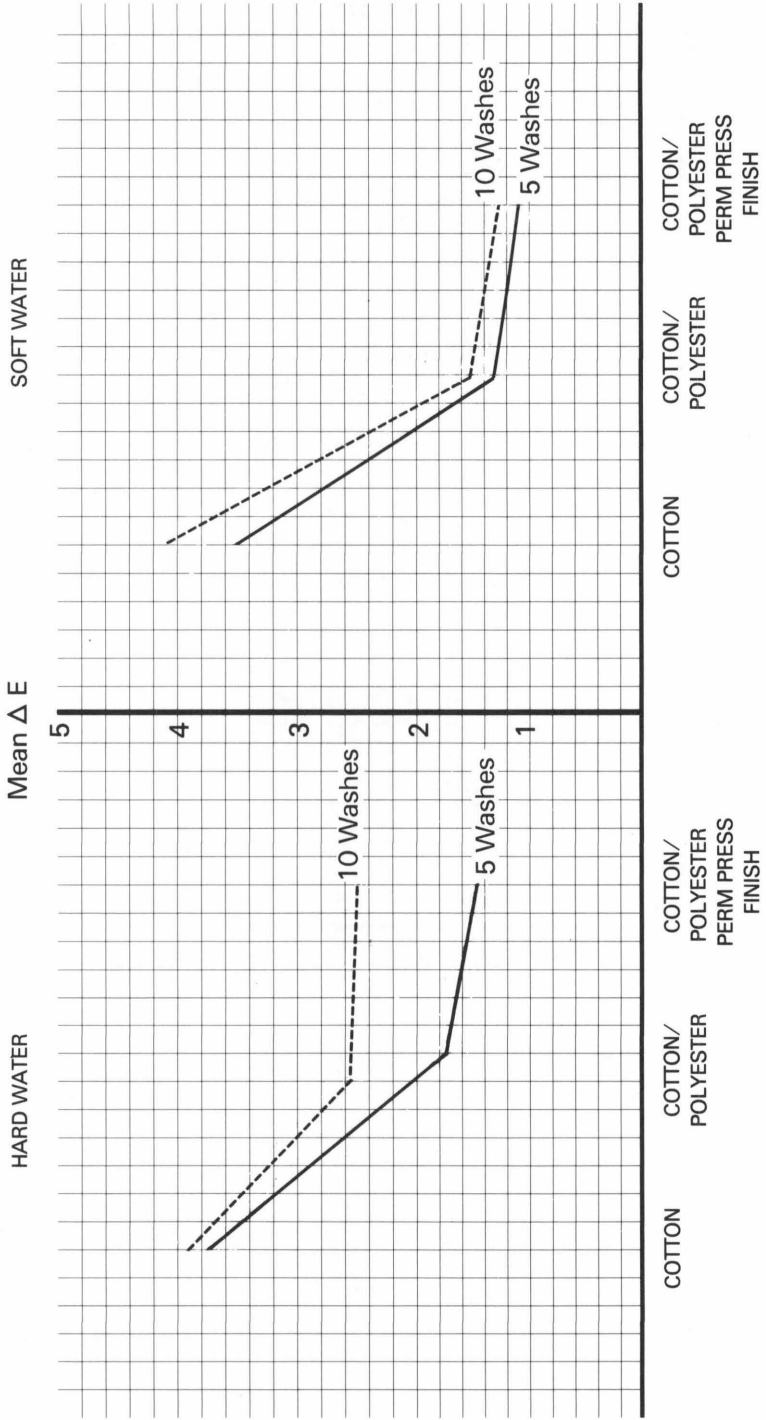


FIGURE 9
Soil Deposition: Interaction of Detergent Group with Water with Times Washed

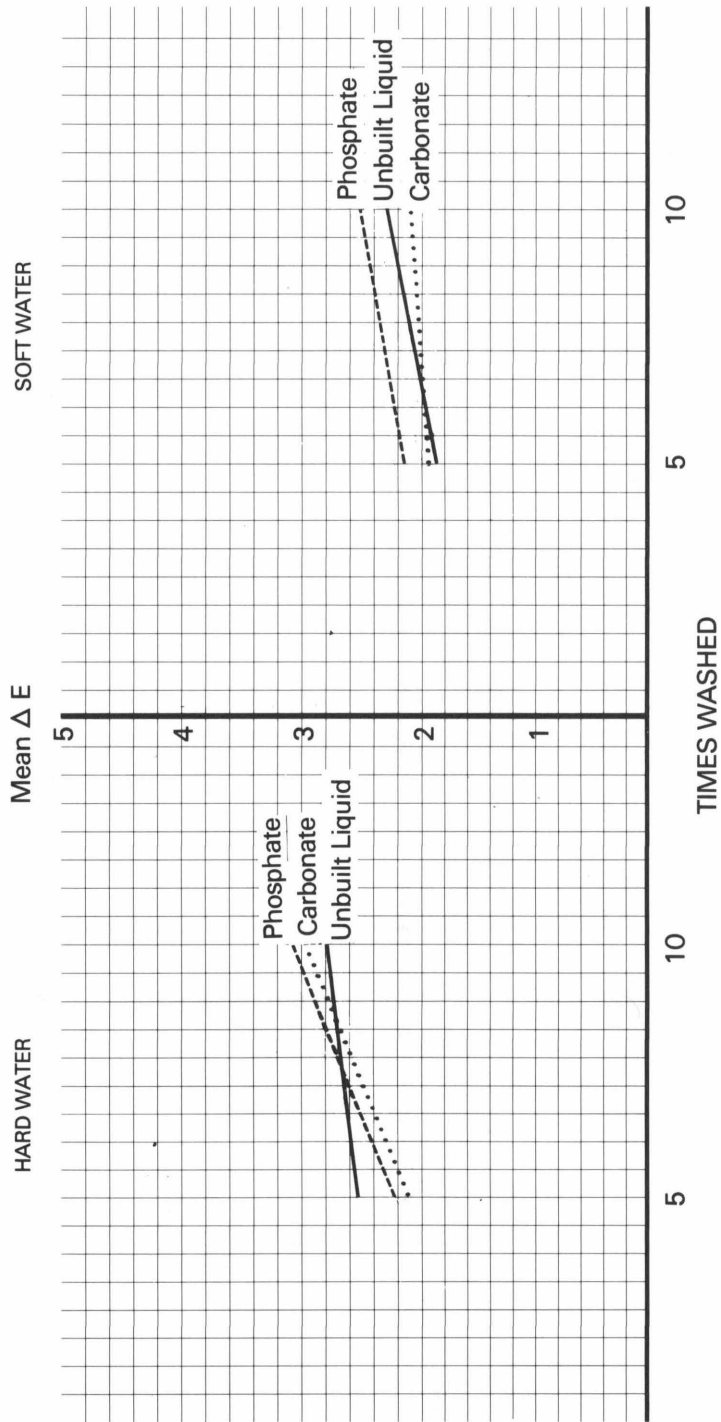


FIGURE 10
Carbonate Deposition: Interaction of Item with Times Washed

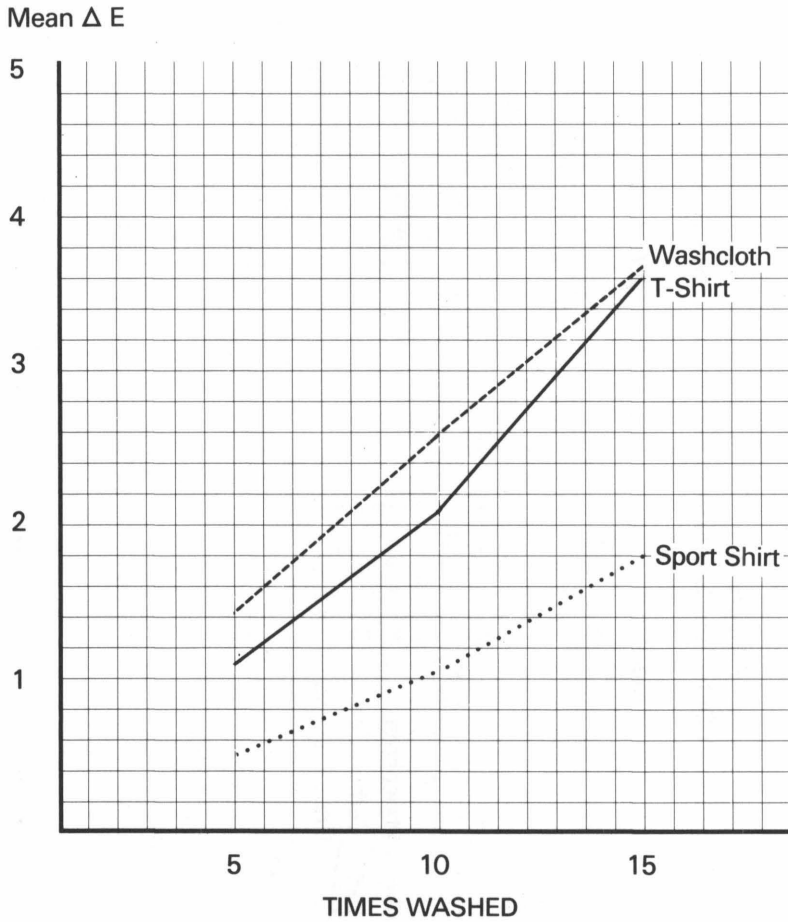
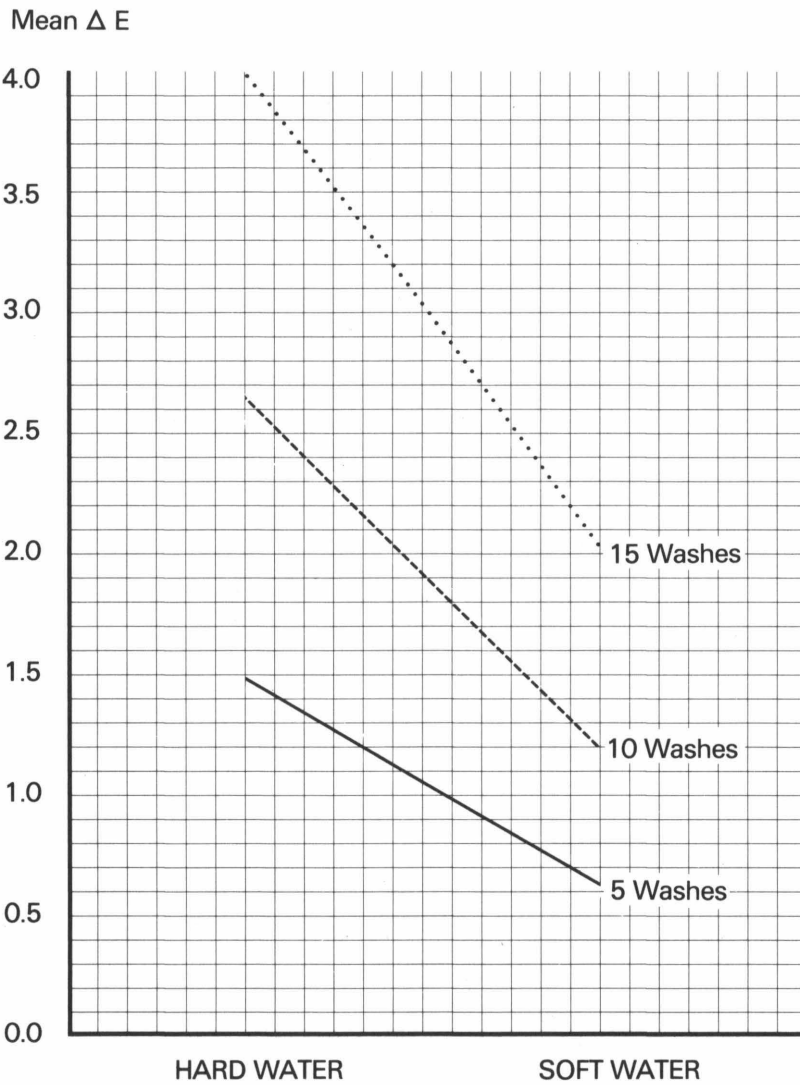


FIGURE 11
Carbonate Deposition: Interaction of Water with Times Washed



TABLES

TABLE 1
Soils Commonly Found in Home Laundry

Soil Groups	Examples	Suggestions for Removal
Water soluble soils	Salt, sugar, fresh tea and coffee, some components of perspiration, some proteins	Easily removed by water alone; hot water aids in dissolving soils
Insoluble, organic soils — saponifiable	Oils; fats; fatty acids from food, the skin, hair dressings, and cosmetics	Removal more difficult as soil ages. Soap or detergent required for removal; heavy duty detergents more effective than mild detergents. Builders in detergents react with this soil; abundant detergent required to react with, solubilize, and emulsify this soil. Hot water speeds soil removal and results in more complete soil removal.
Insoluble, organic soils — not saponifiable	Mineral oil, car grease, some body oil, lint, skin particles, tar, wax, protein, dyes	Removal more difficult as soil ages. Soap or detergent required for removal; abundant detergent required to solubilize and emulsify this soil. Hot water speeds removal and results in more complete soil removal.
Insoluble, organic soils	Dust, mud, clay, smoke, soot, mineral ash, metals, metal oxides	These soils are often held on fabric by oily soils; need detergent to remove oil and release this soil. Soil not soluble in wash water; requires much agitation by washer and an adequate suspending agent in detergent to prevent redeposition.

Source: The Laundry System (1984)

TABLE 2
Water Hardness in Virginia*

Hardness Ranges (ppm)	Population on Surface Water	Population on Groundwater	Total Population
0-60 Soft	3,092,146	394,808	3,486,954 (64.4%)
61-120 Medium Hard	762,307	480,649	1,242,956 (23.0%)
121-180 Hard	—	434,575	434,575 (8.0%)
Over 180 Very Hard	—	250,514	250,514 (4.6%)
Totals	3,854,453 (71.2%)	1,560,546 (28.8%)	5,414,999 (100%)

*Source: Lung, W. (1984, p. 7)

TABLE 3
Components of Laundry Detergents*

Component	Function	Comments
Surfactants (surface active agents)	Allow water to wet both fabric and soil quickly and thoroughly. Remove oily soil and emulsify or solubilize it. Remove particulate soil and help suspend it.	Both anionic and non-anionic surfactants are used. Hard water diminishes cleaning ability of anionic surfactants. When the concentration is sufficiently high, surfactants form groups, called micelles, that solubilize oily soil.
Builders	Control water hardness. Increase and maintain alkalinity of wash water. React with (saponify) some oily soils. Suspend particulate soil.	Builders are commonly found in powdered detergents. Polyphosphates are preferred because they serve all functions well and control hardness without forming a precipitate. Where phosphates are prohibited, sodium carbonate, sodium aluminosilicate, and sodium nitrilotriacetate (NTA) may be used. In hard water, carbonates form a crystalline precipitate, which adheres to fabrics, makes fabrics feel stiff and harsh, and changes the appearance of colored fabrics.
Suspending agents	Prevent redeposition of particulate soil	Polyphosphates, NTA, and a special component called CMC help to suspend soil. The carbonates are not effective in preventing redeposition of soil.
Corrosion inhibitor	Protects metal parts of washer	Without an inhibitor, detergent solution would attack or corrode some metal parts in washing machines.
Fluorescent whitening agents	Make white fabrics look whiter and colored fabrics brighter. Cover up yellowing of white fabrics.	Fluorescent whitening agents (FWA) "work" in the presence of ultraviolet light, such as sunlight and light from fluorescent lamps. Invisible ultraviolet light is converted by FWAs to blue light, which improves the appearance of fabrics.
Coloring, fragrance	Provide distinctive color, fragrance to detergent	These are added for aesthetic purposes only.

*Source: The Laundry System (1984)

TABLE 4
Comparison of Built and Unbuilt Laundry Detergents*

Component	Built Detergent	Unbuilt Detergent
Surfactants	Lower concentration, perhaps half as much as in unbuilt detergents. Anionic surfactants likely to predominate.	Higher concentration, perhaps twice as much as in built detergents. Nonionic surfactants likely to predominate
Builders	High concentration of builders, usually alkaline	No builders
Soil suspending agents	Carboxymethyl-cellulose (CMC), polyphosphates, NTA	No phosphates or NTA; higher concentrations of CMC likely than in built detergents
Fluorescent whitening agents	Built and unbuilt detergents similar	
Coloring matter and fragrance	Built and unbuilt detergents similar	

*Source: The Laundry System (1984)

TABLE 5
Description of Detergents Used in Study

Product Type	Ingredients	Amt./load	Cost
Phosphate-built A	anionic surfactants complex sodium phosphates sodium carbonate sodium sulfate sodium silicates fabric whitener masking fragrance deposition agent phosphates — 9.8% by volume 8.4 grams per cup	1 C. (78 g. or 2.75 oz.)	\$0.0545/oz. \$0.1499/load
Phosphate-built B	anionic surfactants complex sodium phosphates sodium carbonate sodium sulfate sodium silicates fabric whitener soil suspending agents colorant perfume phosphates — 9.5% by volume 8.1 grams per cup	1C. (77 g. or 2.75 oz.)	\$0.0517/oz. \$0.1422/load
Carbonate-built A	sodium carbonate sodium sulfate anionic surfactants sodium silicate	1C. (85 g. or 3 oz.)	\$0.0264/oz. \$0.792/load

TABLE 6
Description of Test Loads

No.	Item and Description
White Test Load (ANSI/AHAM, HLW-1 1980)	
2	Sheets — 81"x99", flat double, 65% polyester/35% cotton
1	Tablecloth, 52"x52", 50% cotton/50% polyester
3	Bath towels, 22"x44", 100% cotton
2	Men's shirts, size 16, 65% polyester/50% cotton
2	T-shirts, size 46, 50% polyester/50% cotton
3	Boxer shorts, size 44, 50% polyester/50% cotton
2	Handkerchiefs, 16"x16", 65% polyester/35% cotton
1	Washcloth, 12"x12", 100% cotton
2	Pillowcases, 20"x30", 65% polyester/35% cotton
Dark Test Load (Spivak, Smith, and Kim 1982)	
3	Boy's shirts, size 14 (12), 50% polyester/50% cotton
3	Men's T-shirts, size 46, 100% cotton
3	Washcloths, 12"x12", 100% cotton

TABLE 7
Swatch Placement for Soil Removal and Soil Deposition

All Locations Were Marked with a Safety Pin.

Sheet	One — wide hem end, right of center
Sheet	One — narrow hem end, left of center
Man's shirt	One — center of collar
Man's shirt	One — center of tail
Bath towel	One — left of center
Bath towel*	One — center
Bath towel	
Tablecloth	One — 12 inches from an end
Handkerchief	
Handkerchief	
Boxer shorts	One — right front waistband
Boxer shorts	One — left front leg, bottom
Boxer shorts*	One — right front leg
T-shirt	One — back neck
T-shirt	One — right front bottom, off center
Pillowcase	One — hem end, center
Pillowcase*	One — hem end, center
Washcloth	One — center, side without border

* Used for soil deposition only

TABLE 8
Soil Removal: Means and Standard Deviations for ΔE 's

	100% Cotton			Cotton/Polyester			Finished Blend			All Fabrics		
	Hard	Soft	Mean	Hard	Soft	Mean	Hard	Soft	Mean	Hard	Soft	Mean
Phosphate	Mean	5.70	6.01	4.68	4.06	4.37	5.39	7.88	6.64	5.46	5.88	5.67
	SD	0.63	0.60	0.43	0.60	0.60	0.64	0.55	1.40	0.88	1.69	1.35
Unbuilt Liquid	Mean	8.45	7.05	5.79	5.93	5.86	5.69	5.43	5.56	6.65	6.13	6.39
	SD	0.81	0.88	0.56	0.30	0.44	0.21	0.46	0.37	1.41	0.90	1.20
Carbonate	Mean	6.56	5.62	5.13	4.95	5.04	4.47	4.41	4.44	5.39	4.99	5.19
	SD	0.52	0.81	0.70	0.76	0.72	0.39	0.61	0.50	1.04	0.87	0.97
All Detergents	Mean	7.11	6.12	5.20	4.98	5.09	5.19	5.91	5.55	5.83	5.67	5.67
	SD	1.16	1.00	0.72	0.96	0.85	0.68	1.57	1.26	1.26	1.30	1.30

TABLE 9
Analysis of Variance for Soil Removal Tests

Source	Sum of Squares	DF	Mean Square	F Value
Main Effects				
Detergent Group	43.7365	2	21.8683	64.99**
Detergent within Detergent Group	2.8099	3	0.9366	2.98*
Water	1.2112	1	1.2112	3.60
Fabric	73.5137	2	36.7569	109.23**
Two-way Interactions				
Detergent Group X Water	7.6696	2	3.8348	11.40**
Detergent within Detergent Group X Water	4.3772	3	1.4591	4.34
Detergent Group X Fabric	65.3005	4	16.3251	48.51**
Detergent within Detergent Group X Fabric	2.0816	6	0.3469	1.03
Water X Fabric	21.9964	2	10.9982	32.68**
Three-way Interaction				
Detergent within Detergent Group X Water X Fabric	20.7555	6	2.0756	6.17**
Residual	48.4558	144	0.3365	
Total	291.9076	179		

* Significant at .05 level

** Significant at .01 level

TABLE 10
Soil Removal: Means and Standard Deviations for Δ E's for the Interaction of
Detergent Group and Water (N=30/cell)

		Detergent Group*					
		Phosphate Granular		Carbonate Granular		Unbuilt Liquid	
		Mean	SD	Mean	SD	Mean	SD
Water	Hard	5.46aA	0.88	5.39bA	1.04	6.65cA	1.41
	Soft	5.88aB	1.69	4.99bB	0.87	6.13cB	0.90

* Means in the same row followed by a different lower case letter are significantly different at the .01 level (Tukey's HSD). Means in the same column followed by a different upper case letter are significantly different at the .01 level.

TABLE 11
Soil Removal: Means and Standard Deviations for ΔE 's for the Interaction of
Detergent Group and Fabric (N=20 cell)

Fabric	Detergent Group*								
	Phosphate Granular			Carbonate Granular			Unbuilt Liquid		
	Mean	SD		Mean	SD		Mean	SD	
Cotton	6.01aA	0.68		6.09aA	0.82		7.75bA	1.09	
Cotton/polyester	4.37aB	0.60		5.04bB	0.72		5.86cB	0.44	
Cotton/polyester w/Perm Press	6.64aC	1.40		4.44bC	0.50		5.56cB	0.37	

* Means in the same row followed by a different lower case letter are significantly different at the .01 level (Tukey's HSD). Means in the same column followed by a different upper case letter are significantly different at the .01 level.

TABLE 12
Soil Removal: Means and Standard Deviations for Δ E's for the Interaction
of Water and Fabric (N=30/cell)

	Fabric*						
	Cotton		Cotton/polyester		Cotton/polyester w/Perm Press Finish		
	Mean	SD	Mean	SD	Mean	SD	
Water	Hard	7.11aA	1.16	5.20b	0.72	5.19bA	0.68
	Soft	6.12aB	1.00	4.98b	0.96	5.91aB	1.57

*Means in the same row followed by a different lower case letter are significantly different at the .01 level (Tukey's HSD). Means in the same column followed by a different upper case letter are significantly different at the .01 level. If the simple main effect was not significant, there are no letters.

TABLE 13
Soil Deposition: Means and Standard Deviations for ΔE 's

Times Washed	100% Cotton			Cotton/Polyester			Finished Blend			All Fabrics		
	Hard	Soft	Mean	Hard	Soft	Mean	Hard	Soft	Mean	Hard	Soft	Mean
5	Mean	4.02	4.05	1.85	1.51	1.68	0.99	0.88	0.94	2.29	2.15	2.22
	SD	0.33	0.08	0.20	0.33	0.10	0.28	0.20	0.00	1.42	1.51	1.40
10	Mean	4.54	4.64	3.25	1.61	2.43	1.50	1.14	1.32	3.10	2.50	2.80
	SD	0.55	0.28	0.37	1.01	0.25	1.12	0.42	0.01	1.47	1.76	1.58
Mean	SD	4.28	4.34	2.55	1.56	2.05	1.25	1.01	1.13	2.69	2.33	2.51
	SD	0.47	0.42	0.42	1.02	0.17	0.86	0.40	0.15	1.44	1.57	1.47
5	Mean	4.49	3.62	4.05	1.34	0.97	1.15	1.20	1.54	2.57	1.93	2.25
	SD	0.35	0.61	0.65	0.02	0.16	0.23	0.28	0.29	1.52	1.35	1.41
10	Mean	3.92	4.48	4.20	1.39	1.20	1.29	3.19	1.25	2.22	2.31	2.57
	SD	0.22	0.00	0.35	0.30	0.06	0.21	0.08	0.02	1.12	1.68	1.41
Mean	SD	4.21	4.05	4.13	1.36	1.08	1.22	2.53	1.22	1.88	2.12	2.41
	SD	0.41	0.61	0.49	0.18	0.17	0.22	0.78	0.17	0.87	1.47	1.39
5	Mean	2.83	3.09	2.96	2.10	1.67	1.89	1.69	1.14	2.21	1.97	2.09
	SD	0.07	0.28	0.23	0.15	0.18	0.28	0.39	0.25	0.55	0.92	0.74
10	Mean	3.35	3.31	3.33	3.05	1.76	2.41	2.66	1.42	3.02	2.16	2.59
	SD	0.07	0.39	0.23	0.06	0.21	0.76	0.45	0.00	0.37	0.92	0.81
Mean	SD	3.09	3.20	3.14	2.58	1.72	2.15	2.17	1.28	2.61	2.06	2.34
	SD	0.31	0.30	0.29	0.56	0.16	0.60	0.65	0.22	0.62	0.89	0.80
5	Mean	3.78	3.59	3.69	1.76	1.38	1.57	1.52	1.07	2.35	2.02	2.19
	SD	0.80	0.53	0.65	0.38	0.35	0.40	0.48	0.23	1.18	1.21	1.18
10	Mean	3.94	4.18	4.06	2.56	1.53	2.04	2.45	1.27	1.86	2.32	2.65
	SD	0.60	0.72	0.64	1.03	0.29	0.90	0.82	0.13	0.83	1.42	1.27
Mean	SD	3.86	3.88	3.87	2.16	1.45	1.81	1.99	1.17	1.58	2.17	2.67
	SD	0.68	0.67	0.66	0.85	0.32	0.73	0.80	0.20	0.71	1.31	1.14

TABLE 14
Analysis of Variance for Soil Deposition Tests

Source	Sum of Squares	DF	Mean Square	F Value
Water	4.4932	1	4.4932	28.98**
Fabric	76.5978	2	38.2989	247.00**
Detergent Group	0.3514	2	0.1757	1.13
Detergent within Detergent Group	0.1816	3	0.0605	0.39
Fabric X Water	2.5094	2	1.2547	8.09*
Detergent Group X Water	0.1620	2	0.0810	0.52
Detergent within Detergent Group X Water	0.3631	3	0.1210	0.78
Detergent Group X Fabric	12.8423	4	3.2106	20.71**
Detergent within Detergent Group) X Fabric	1.3111	6	0.2185	1.41
Detergent Group X Fabric X Water	1.6854	4	0.4214	2.72
Error 1	0.9303	6	0.1551	
Time	3.9468	1	3.9468	93.03**
Water X Time	0.4628	1	0.4628	10.91*
Fabric X Time	0.1137	2	0.0569	1.34
Detergent Group X Time	0.2000	2	0.1000	2.36
Detergent within Detergent Group x Time	0.0922	3	0.0307	0.72
Fabric X Water X Time	1.2646	2	0.6323	14.90**
Detergent Group X Water X Time	0.4504	2	0.2252	5.31*
Detergent within Detergent Group X Water X Time	0.1391	3	0.0464	1.09
Detergent Group X Fabric X Time	0.4847	4	0.1211	2.85
Detergent within Detergent Group X Fabric X Time	0.2286	6	0.0381	0.90
Detergent Group X Fabric X Water X Time	1.1923	4	0.2981	7.03*
Error 2	0.2546	6	0.0424	
Total	110.2570	71		

** Significant at .01 level

* Significant at .05 level

TABLE 15
Soil Deposition: Means and Standard Deviations for Δ E's for the Interaction
of Fabric with Water (N=12/cell)

Water	Hard Soft	Fabric*					
		Cotton		Cotton./polyester		Cotton./polyester	
		Mean	SD	Mean	SD	Mean	SD
		3.86a	0.68	2.16bA	0.85	1.99bA	0.80
		3.88a	0.67	1.45	0.32	1.17bB	0.20

*Means in the same row followed by a different lower case letter are significantly different at the .01 level (Tukey's HSD). Means in the same column followed by a different upper case letter are significantly different at the .01 level. If the simple main effect was not significant, there are no letters.

TABLE 16
Soil Deposition: Means and Standard Deviations for ΔE 's for the Interaction of
Detergent Group with Fabric (N=8/cell)

Fabric	Detergent Group*					
	Phosphate Granular		Carbonate Granular		Unbuilt Liquid	
	Mean	SD	Mean	SD	Mean	SD
Cotton	4.34aA	0.42	3.14bA	0.29	4.13aA	0.49
Cotton/polyester	2.05 B	0.85	2.15 B	0.60	1.22 B	0.22
Cotton/polyester w/Perm Press	1.13 C	0.31	1.73 B	0.66	1.88 C	0.87

* Means in the same row followed by a different lower case letter are significantly different at the .05 level (Tukey's HSD), means in the same column followed by a different upper case letter are significantly different at the .05 level. If the simple main effect was not significant, there are no letters.

TABLE 17
Soil Deposition: Means and Standard Deviations for ΔE 's for the Interaction of
Water with Times Washed (N=18/cell)

	Number of Washes*				
	Five		Ten		
	Mean	SD	Mean	SD	
Water	Hard	2.35aA	1.18	2.98bA	1.05
	Soft	2.02aB	1.21	2.32bB	1.42

* Means in the same row followed by a different lower case letter are significantly different at the .01 level (Tukey's HSD). Means in the same column followed by a different upper case letter are significantly different at the .01 level.

TABLE 18
Soil Deposition: Means and Standard Deviations for ΔE 's for the Interaction of
Fabric with Water with Times Washed (N=6/cell)

Fabric	Hard Water*					
	Five Washes		Ten Washes		Ten Washes	
	Mean	SD	Mean	SD	Mean	SD
Cotton	3.78 A	0.80	3.94 A	0.60	3.94 A	0.60
Cotton./Polyester	1.76aB	0.38	2.56bB	1.03	2.56bB	1.03
Cotton./Polyester w./Perm Press	1.52aC	0.48	2.45bB	0.82	2.45bB	0.82

Fabric	Soft Water*					
	Five Washes		Ten Washes		Ten Washes	
	Mean	SD	Mean	SD	Mean	SD
Cotton	3.59aA	0.53	4.18bB	0.72	4.18bB	0.72
Cotton./Polyester	1.38 B	0.35	1.53 B	0.30	1.53 B	0.30
Cotton./Polyester w./Perm Press	1.07 C	0.23	1.27 C	0.13	1.27 C	0.13

* For each water type, means in the same row followed by a different lower case letter are significantly different at the .01 level (Tukey's HSD). For each water type, means in the same column followed by the same upper case letter are significantly different at the .05 level. If the simple main effect was not significant, there are no letters.

TABLE 19
Soil Deposition: Means and Standard Deviations for ΔE 's for the Interaction of
Detergent Group with Water with Times Washed (N=6/cell)

		Hard Water*					
Times Washed		Phosphate Granular		Carbonate Granular		Unbuilt Liquid	
		Mean	SD	Mean	SD	Mean	SD
Five	Five	2.29A	1.42	2.21	0.55A	2.57	1.52
	Ten	3.10B	1.47	3.02	0.37B	2.83	1.18
		Soft Water*					
Times Washed		Phosphate Granular		Carbonate Granular		Unbuilt Liquid	
		Mean	SD	Mean	SD	Mean	SD
Five	Five	2.15A	1.51	1.97	0.92	1.93A	1.35
	Ten	2.50aB	1.76	2.16a	0.92	2.31aB	1.68

* For each water type, means in the same row followed by a different lower case letter are significantly different at the .05 level (Tukey's HSD). For each water type, means in the same column followed by a different upper case letter are significantly different at the .05 level. If there are no letters, the simple main effect was not significant.

TABLE 20
Carbonate Deposition: Means and Standard Deviations for ΔE 's

Times Washed	Washcloth			T-Shirt			Knit Shirt			All Items				
	Mean	SD	Hard	Soft	Mean	Hard	Soft	Mean	Hard	Soft	Mean	Hard	Soft	Mean
5	Mean		1.88	1.12	1.50	1.82	0.50	1.16	0.76	0.39	0.58	1.49	0.67	1.08
	SD		1.19	0.88	1.07	0.71	0.44	0.89	0.52	0.19	0.42	0.96	0.63	0.90
10	Mean		3.31	1.88	2.60	3.16	1.15	2.15	1.49	0.67	1.08	2.65	1.23	1.94
	SD		0.47	0.67	0.93	0.79	0.52	1.23	1.06	0.25	0.85	1.14	0.70	1.18
15	Mean		4.81	2.53	3.67	4.79	2.52	3.65	2.51	1.10	1.81	4.04	2.05	3.04
	SD		1.07	0.63	1.45	1.02	0.49	1.41	1.10	0.30	1.20	1.56	0.83	1.59
All	Mean		3.33	1.84	2.59	3.26	1.39	2.32	1.59	0.72	1.15	2.73	1.32	
	SD		1.53	0.91	1.45	1.48	0.98	1.56	1.23	0.38	1.00	1.61	0.91	

TABLE 21
Analysis of Variance for Carbonate Deposition Tests

Source	Sum of Squares	DF	Mean Square	F Value
Detergent	1.3341	1	1.3341	1.12
Item	41.9981	2	20.9991	17.70 **
Water	53.5422	1	53.5422	45.13 **
Detergent X Item	0.9381	2	0.4691	0.40
Detergent X Water	3.3879	1	3.3879	2.86
Item X Water	4.6493	2	2.3247	1.96
Detergent X Item X Water	4.3660	2	2.1830	1.84
Error 1	28.4725	24	1.1864	
Time	69.6130	2	34.8065	142.24 **
Detergent X Time	1.7427	2	0.8714	3.56 *
Item X Time	5.4407	4	1.3602	5.56 **
Water X Time	6.1531	2	3.0766	12.57 **
Detergent X Item X Time	0.3827	4	0.0957	0.39
Detergent X Water X Time	0.6794	2	0.3397	1.39
Item X Water X Time	0.3900	4	0.0975	0.40
Detergent X Item X Water X Time	0.7745	4	0.1936	0.79
Error 2	11.7461	48	0.2447	

* Significant at .05 level

** Significant at .01 level

TABLE 22
Carbonate Deposition: Means and Standard Deviations for ΔE 's for the
Interaction of Item with Times Washed (N=12/cell)

Times Washed	Washcloth			T-Shirt			Sport Shirt		
	Mean	SD	Item*	Mean	SD	Item*	Mean	SD	Item*
Five	1.50aA	0.94		1.16aA	0.78		0.58bA	0.23	
Ten	2.60aB	0.88		2.15aB	1.18		1.08bB	0.49	
Fifteen	3.67aC	1.49		3.65aC	1.33		1.81bC	0.88	

* Means in the same row followed by a different lower case letter are significantly different at the .05 level (Tukey's HSD). Means in the same column followed by a different upper case letter are significantly different at the .05 level.

TABLE 23
Carbonate Deposition: Means and Standard Deviations for Δ E's for the Interaction
of Water with Times Washed (N=18/cell)

Water	Hard Soft	Number of Times Washed*					
		Five		Ten		Fifteen	
		Mean	SD	Mean	SD	Mean	SD
	Hard	1.49aA	0.82	2.65bA	0.92	4.03cA	1.33
	Soft	0.67aB	0.46	1.23bB	0.60	2.05cB	0.75

* Means in the same row followed by a different lower case letter are significantly different at the .05 level (Tukey's HSD). Means in the same column followed by a different upper case letter are significantly different at the .01 level.

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The Virginia Water Resources Research Center is a federal-state partnership agency attempting to find solutions to the state's water resources problems through careful research and analysis. Established at Virginia Polytechnic Institute and State University under provisions of the Water Research and Development Act of 1978 (P.L. 95-467), the Center serves six primary functions.

- It studies the state's water and related land-use problems, including their ecological, political, economic, institutional, legal, and social implications.
- It sponsors, coordinates, and administers research investigations of these problems.
- It collects and disseminates information about water resources and water resources research.
- It provides training opportunities in research for future water scientists enrolled at the state's colleges and universities.
- It provides other public services to the state in a wide variety of forms.
- It facilitates coordinated actions among universities, state agencies, and other institutions.

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