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Materials for Pavement Marking and for Joints in Concrete Structures

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Subject Areas

34 General Materials
35 Mineral Aggregates

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CONTENTS

FOREWORD

The subjects covered in the 4 papers contained in this RECORD are varied and include evaluating paint stripes, sealing bridge expansion joints, compression-deflection testing of preformed elastomeric joint seals, and correlating properties of limestone.

Ritter presents a different approach for evaluating stripe materials on 2-lane rural roads. Approximately 16 miles of test stripes was placed as part of a reflectorized double yellow line. One stripe represented the control and was consistent throughout the test section; the other stripe varied. The increase in the highway death rate for rural 2-lane highways in comparison with other systems and the very high rate for night driving on those highways are reported. The report deals more with the approach used for evaluation than with the results. However, the author does point out the distinct advantage of the larger beads for nighttime driving on wet roads. This paper should be of particular interest to researchers, traffic and maintenance engineers, and safety experts.

Some relatively new developments for sealing bridge expansion joints are presented in an abridgment by Watson. Four systems are described and illustrated: a gland type of system that uses rubber block interfaces; an armored, skid-resistant, rubber-cushion system; a strip seal system with extruded steel interfaces; and an improved modular compression sealing system. This abridgment should be of special interest to bridge and maintenance engineers and to bridge contractors.

Huffman describes the research he performed in analyzing the compression-deflection test method for preformed elastomeric compression seals. This test method is becoming well established as a means of testing and evaluating preformed elastomeric joint seals. Huffman attempted to establish the number of load cycles a specimen should be subjected to before the curve was obtained for the compression-deflection test. He also looked at the effects of crosshead speed and load. He found that the third cycle of the test produces a curve that approximates the equilibrium compression-deflection curve. He suggests the establishment of maximum and minimum allowable forces for sealers from the compression-deflection curve. He was not able to establish a desired load level or crosshead speed but learned that they can be a significant cause of variability in the test results. Recommendations for further study on those 2 variables and the establishment of levels for use nationwide are made. In a discussion of this paper, Koslov questions the necessity for this research and presents a review of work previously done in this area including his own. Koslov states that the maximum allowable force for seals is of no consequence because the user is only concerned with the degree of compression at the limit of safe compressibility. Huffman counters in his closure that the purpose of his paper may have been misunderstood and that the maximum allowable force is essential to prevent overstressing of the sealers. This paper and discussion should be of interest to materials engineers, bridge engineers, pavement design engineers, and researchers.

The concluding paper by El-Rawi describes the correlation of the properties of limestone from different locations in Iraq. He established a relation among wear from the Los Angeles abrasion test and compressive strength, the impact value, the specific gravity, and the MgO and CaO contents. Because the properties of limestone may vary from country to country, the results should be verified for any new location. This paper should be of interest to materials engineers.

—Dale E. Peterson

A UNIQUE APPROACH TO EVALUATING ROAD STRIPE MATERIAL ON TWO-LANE RURAL ROADS

James R. Ritter, Potters Industries, Inc.

Comparisons were made of side-by-side double yellow lines on rural 2-lane roads. One line was a reference line of 0.015-in. wet paint film with 6 lb/gal of conventional glass spheres applied by the drop-on method. The experimental line either was unbeaded or had various amounts of several types and sizes of glass beads. One experimental line consisted of a 0.010-in. wet paint film with 4 lb/gal of glass spheres applied by the drop-on method. Evaluations were made under night driving conditions at normal speeds on dry and wet pavement. The methods of application, control, and evaluation are also described. Both colored movies and slides were made at regular intervals for a documentary record. Samples of the photographs are included. This approach has been found to have many advantages over existing techniques and few disadvantages.

•LITTLE emphasis has been placed on maximizing the effectiveness of stripe material for 2-lane rural roads. Those roads are inadequately designed for the traffic that they now carry and lack many basic safety improvements. Those who drive on rural 2-lane roads are familiar with the deficiencies and the dangers of traveling on them, particularly at night.

A rural 2-lane road at night frequently looks like the picture shown in Figure 1; a driver on such a road is uneasy because there is nothing to guide him. There is a high probability of cars running off the road, head-on collsions, intersection collisions, and pedestrian accidents. Almost 4 times as many deaths per 100 million vehicle-miles occur on rural 2-lane roads as on turnpikes. Nighttime travel on rural roads accounts for only 15 percent of all travel but for more than 35 percent of all highway deaths.

Figure 2 shows a well-delineated 2-lane rural road that has yellow reflectorized lines at the center and white lines at the edges. That picture was taken from the same location and under the same illumination as the one shown in Figure 1. The reflectorized lines help the driver by indicating passing zones, curves, pavement edges, and intersections.

Because of the need for good reflectivity and durability of stripes on rural 2-lane roads, a study was initiated to maximize the effectiveness of those markings. This test program was unique because of the following new and unusual approaches that were attempted:

1. All testing was performed on 2-lane rural secondary roads;
2. It was the largest commercially sponsored road-marking research project ever conducted;
3. More than 50 miles of rural roads were employed in the field tests;
4. Yellow paint was used according to the Manual on Uniform Traffic Control Devices, and its importance is highlighted by the new 2-lane road-marking system;
5. Observation of dual stripes, where one is a control stripe and one is a test stripe, has not been reported before;

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6. The stripes were visually evaluated under normal driving conditions;
7. Color movies and slides were obtained periodically from application to failure;
8. An accident-reduction study was conducted on a previously unmarked road that was marked and on other unmarked roads that served as controls; and
9. A survey of public response to new road markings was conducted.

Traditionally, the evaluation of the night-visibility performance of road-marking systems using paint and glass spheres has been by means of alternate skip lines or group skip lines. In Pennsylvania, for example, the practice is to apply a 50-ft skip line for each variable tested. The location is usually along a level and straight, divided 4-lane highway requiring white paint. Evaluations were made at night by drivers traveling at 5 to 10 mph because of the short length of the test sections.

In the spring of 1971, Potters Industries, Inc., conceived and instituted a road-striping test program directed toward evaluating the materials used on accident-prone rural roads. The purpose was to explore the performance of a variety of paint-sphere systems with regard to night visibility and durability and to accident reduction and motorist response.

The site chosen was in the township of West Milford, located in the northernmost portion of the state of New Jersey and containing a large number of rural arterial secondary bituminous concrete roads. There is sufficient daily traffic of 1,000 to 5,000 cars, depending on road sections, for normal wear to occur over a manageable period of observation. Overhead lighting is infrequent. A genuine interest was shown by county and municipal governments. The site also offered a variety of climatic conditions from heavy snow in the winters to hot and dry weather in the summers and typical annual rainfall.

The township of West Milford previously had either unmarked roads or roads marked with a single, solid, nonreflectorized white stripe. Local county and state authorities gave permission to apply the test stripes according to the then-current edition of the Manual on Uniform Traffic Control Devices. The single, solid, nonreflectorized white line was replaced by reflectorized double yellow lines in regular no-passing zones. The double, no-passing yellow line provided means for a unique way of assessing performance characteristics, i.e., the comparison of 2 side-by-side lines differing in some known and deliberate way.

One test site of 2.4 miles was divided into 6 sections and striped in sequence. The first section was striped, and the same type of beads was used in the center and edge lines. The next section was striped the same way, and a different type of beads was used. Those 6 sections could be compared with one another sequentially rather than side by side as in the other sections.

There were 28 test sections striped during the spring of 1971; each section averaged ½ mile in length. A total of 54 miles of stripes were applied, counting the double center and edge stripes. In the fall, the total number of sections was increased to 56. Test sections are shown in Figure 3.

Because of the magnitude of the many tests conducted in West Milford, certain results have been omitted from this report for the sake of brevity. Many results are being duplicated by additional tests added in the spring of 1972. Separate documentation is available on accident reduction and public response to road marking.

VARIABLES

In the comparative tests, one line was the reference line. It consisted of a 4-in.-wide yellow stripe applied at 0.015-in. wet thickness and on which were dropped the equivalent of 6 lb of glass beads per 1 gal of paint. One gallon of paint will produce about 310 ft of 4-in. stripe at 0.015-in. wet thickness. The beads had a 1.5 refractive index and a sieve analysis as given in Table 1. This is typical of drop-on specifications.

Variables tested and evaluated with this reference line are as follows:

1. A nonreflectorized line,
2. Different sphere gradations,
3. Beads with various coatings,

4. A wet paint film thickness of 0.010 in. with 4-lb/gal drop-on bead application,
5. Glass beads with other refractive indexes including 1.6 and 1.9,
6. Various quantities of beads,
7. Premix lines with and without drop-on beads, and
8. Thermoplastic lines.

All striping was placed on aged bituminous concrete roads in a reasonable state of repair. The lines were applied with commercially available standard equipment operated by experienced personnel. No stripes were applied unless air temperature was at least 50 F and relative humidity was below 80 percent.

EQUIPMENT AND PROCEDURES

A Wald model 36 striper was used for all the comparative test stripes. A Wald custom liner was employed for edge lining and sequential test sections.

The model 36 striper, having separate bead hoppers, is particularly adaptable to the simultaneous application of 2 different double yellow stripes. The stripes can differ in type of paint, thickness of paint, and type and quality of glass spheres applied. Calibrations of paint thickness and sphere quantity were carried out prior to each test section application.

Paint thickness adjustments were made with the aid of wet-paint thickness gauges. The paint was applied by the striper in motion at its normal traveling speed (about 8 mph). Bead quantity adjustments were made by weighing the quantity of beads ejected from the bead dispenser while the striping machine was moving at normal speed over a measured 20-ft distance. Duplicate and sometimes triplicate runs were made to ensure reproducibility. Weighings were made on a triple beam balance accurate to 0.1 gram.

The standard paint used was a high-grade, quality commercial paint that would meet most state specifications. In certain test sections, premix paint or thermoplastic binders were applied.

During application of each test section, 4- by 8-in. aluminum test panels were placed in the path of the striper, and the resulting striped panels became a permanent record of the stripe as initially applied to the road.

If, in the course of test section application, a malfunction was observed, the application was stopped, the malfunction was corrected, and the operation was then resumed. In no case, however, was a mistake or accident corrected by overstriping.

EVALUATION PROCEDURES

Formal evaluation of the test stripes was begun when applications were completed on the last test sections. A committee was appointed to conduct monthly evaluations and consisted of the township engineer, 2 township policemen having responsibility for traffic safety, and 3 employees of Potters Industries, Inc. Occasionally, interested visitors were invited to become part of the evaluation group. Two committee members were assigned to a car, and they were not allowed to discuss the ratings while traveling the test course at a normal speed. In every section, each of the yellow lines was rated on a 0 to 10 scale, 10 being the best. This procedure was followed once each ensuing month. In August, a heavy rain prevailed during the entire inspection. Consequently, a second inspection under dry conditions was made during the following week.

After each evaluation, the results were tabulated, and averages for each section were computed and plotted graphically. Some examples of results obtained will be described later.

PHOTOGRAPHIC DOCUMENTATION

An attempt was made to photographically document the history of test stripes from application to failure. Day and night color movies and slides were obtained at regular intervals from day of application until failure. In addition, color macrophotographs were taken of each stripe at regular intervals.

Colored movies and slides were made of all calibration and application procedures. The pictures include safety precautions, the coding of the roadways, equipment filling, adjustment and calibration of spray guns and bead dispensers, and actual road-striping procedures.

The colored movies and slides to be obtained at night presented special technical problems requiring professional assistance. Proper color balance and illumination for color movies were obtained with a van equipped with special high-intensity, balanced lights and camera mount (Fig. 4). That required some experimentation before satisfactory results were obtained. During actual filming, traffic in both directions of the test section was stopped by police cars. The van was driven at 35 mph over the section and was normally trailed by a police car. A portion of each test section of approximately 1,000 ft in length was chosen and marked in advance for repeated filming during the life of the stripes. Attempts made to take movies in wet as well as dry weather were not successful.

Colored slides were obtained under similar conditions at selected and constant positions for each test section. In addition, close-up colored photographs yielding a 1x magnification on the film were taken of each stripe at a preselected position. That position remained unchanged during the history of the test program. Wet weather slides were successful.

All photographs were used for documentation only and were not used as a basis for numerical evaluation.

TYPICAL RESULTS

A few examples have been chosen to demonstrate the usefulness of this evaluation technique. Those examples are from the side-by-side comparisons. One line in each case was the standard reference line of 15-mil wet paint film with 6 lb of typical drop-on specification beads. The other line was nonreflectorized, was flotation coated and had different bead gradation, or had smaller quantity of beads on a thinner paint line. All lines were inspected from May through December except for 2 sections that were resurfaced in late fall. All lines showed gradual deterioration in November. Just prior to Thanksgiving, the first major snowstorm occurred in the area and necessitated extensive plowing, sanding, and salting. Accelerated deterioration was observed from December on.

The first comparison is between the reflectorized line and the nonreflectorized line (Fig. 5). Their history in terms of night visibility evaluated as previously described is shown in Figure 6. The x-axis corresponds to the month in which the evaluation was conducted, and the y-axis corresponds to the average of the individual ratings. The vastly different ratings indicated between the beaded and unbeaded line are not unexpected.

It has been reported that a 10-mil wet line with 4 lb/gal of drop-on beads gives a satisfactory line. One of the test sections was devoted to examining that possibility. Figure 7 shows photographs taken in January of 2 test sections that had received applications in October. The evaluation results are shown in Figure 8. The performance of the test line was consistently below that of the standard line for the duration of this test. This may be due to the fact that the number of beads per linear foot in the test line is less than half the number in the standard line.

It has also been suggested that a narrow size gradation (40 to 80 mesh) with a flotation coating has desirable attributes. Test lines were applied to evaluate that concept. The beads were applied on both lines at the rate of 6 lb/gal and a wet thickness of 0.015 in. (Fig. 9). The evaluation results are shown in Figure 10. As observed in normal nighttime driving, the narrow gradation with a flotation coating was rated slightly higher than the adjacent reference line initially, but the rating tended to decrease at a somewhat more rapid rate. At the conclusion of the test, which was premature due to road resurfacing, the reference-line rating was actually somewhat higher than that of the narrow-gradation line. Figure 11 shows a test line that has 6 lb/gal of the standard gradation that was flotation coated, and Figure 12 shows the evaluation results. Its performance under dry conditions is essentially equal to that of the narrow gradation initially, and it did not deteriorate so fast.

Figure 1. Newly resurfaced road before being striped.

Figure 2. Same road as shown in Figure 1 after being striped with yellow lines at center and white lines at edge.

Figure 3. Test sections in West Milford, New Jersey.

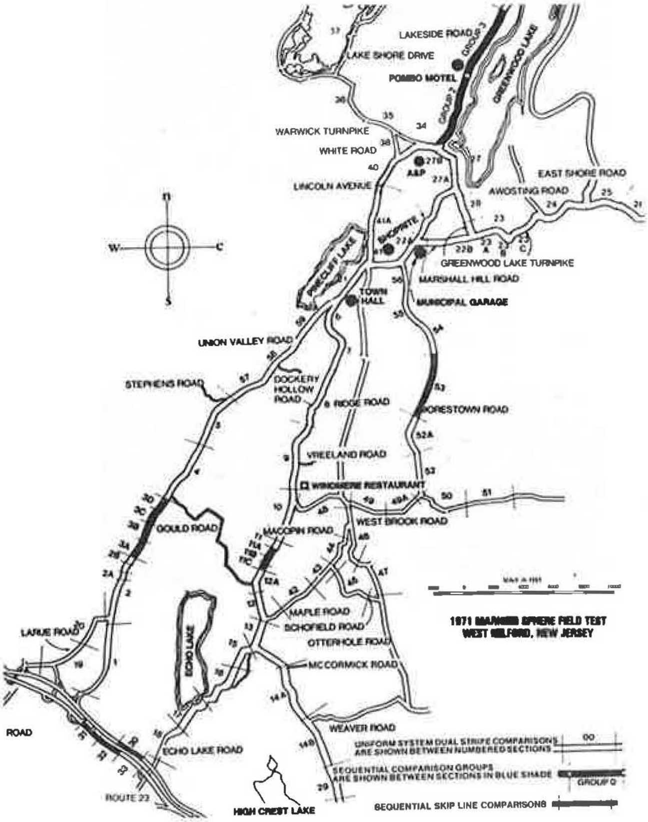


Table 1. Specification and analysis for standard spheres used in test.

U. S. Sieve	Specification (percent on)	Analysis (percent on)
20	Trace	—
30	10 to 15	12.2
50	45 to 55	50.4
80	15 to 25	21.0
100	5 to 15	11.3
Pan	5 to 10	5.1

Figure 4. Van used for motion picture photography.

Figure 5. Standard reflectorized line (left) and nonreflectorized line (right).

Figure 6. Monthly average night-visibility ratings of standard reflectorized line and nonreflectorized line.

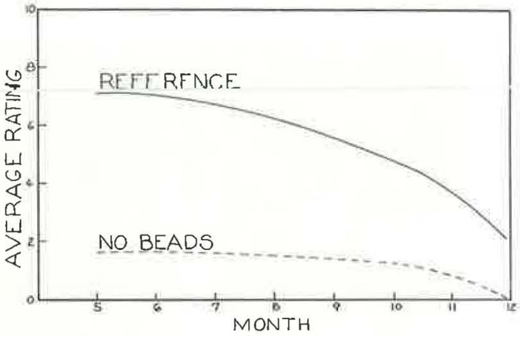


Figure 8. Monthly average night-visibility ratings of 0.010-in. beaded test line and standard reference line.

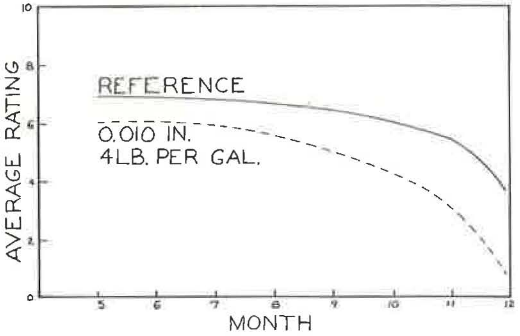


Figure 10. Monthly average night-visibility ratings of narrow-gradation, flotation test line and standard reference line.

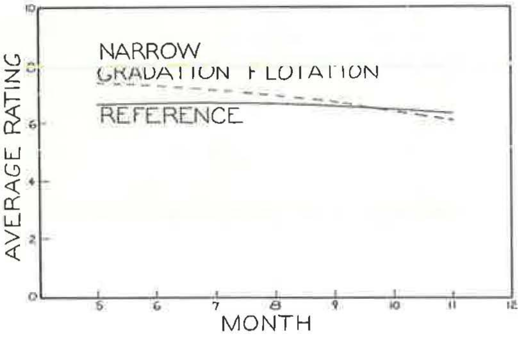


Figure 12. Monthly average ratings of standard-gradation, flotation test line and standard reference line.

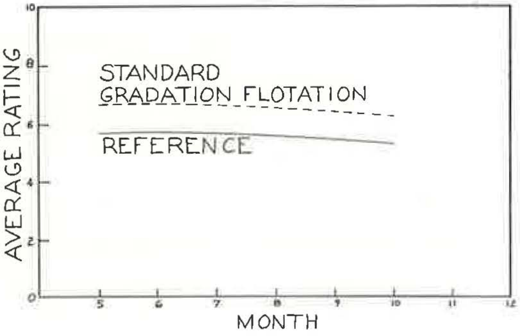


Figure 7. 0.010-in. beaded test line (left) and standard reference line (right).

Figure 9. Narrow-gradation, flotation test line (right) and standard reference line (left).

Figure 11. Standard-gradation, flotation test line (right) and standard reference line (left).

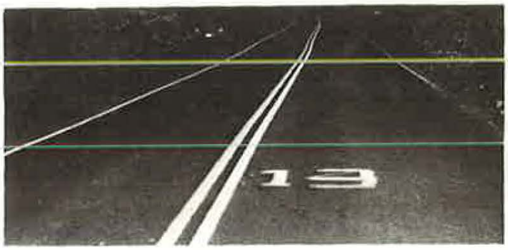


Table 2. Average night-visibility ratings for dry and wet conditions.

Line	Dry	Wet	Decreased (percent)
Standard reflectorized	5.5	2.5	55
Nonreflectorized	1.2	0.3	75
0.010-in. beaded	5.1	2.4	53
Narrow-gradation, flotation	6.8	2.0	71
Standard-gradation, flotation	6.3	3.5	45

The reference line used as a standard was comparable in most of the test sections. There were, however, differences from section to section because of road surfaces, viewing environment, and equipment variations. In almost all test sections, the difference between reference lines and the average of all 3 reference lines varied by less than 1 rating unit.

Inspection during a moderate rain in August 1971 revealed a surprisingly large decrease in night visibility of the narrow-gradation, flotation test line compared with the standard line. A subsequent inspection under dry conditions was made within 1 week. The dry and wet ratings for the 5 varieties of lines discussed previously are given in Table 2. The test lines that had the largest beads had the smallest percentage of decrease in visibility under wet conditions, and the lines that had narrow-gradation (smaller beads) or no beads had a significantly larger percentage of decreased visibility. The standard beads and narrow-gradation beads, both flotation coated, have essentially the same night visibility under dry conditions. Under wet conditions, however, the standard beads with a broader size range perform in a distinctly superior manner.

ADVANTAGES AND DISADVANTAGES

This double-yellow-line method compares favorably with the traditional alternate-skip-line method for the evaluation of road-marking systems. We have observed the following advantages and disadvantages of the dual-stripe method.

Advantages

1. It offers continuous comparison of a test line with an adjacent reference line and does not require recall of a previous test section.
2. Photographic records of the test can be made because the variables of photography are eliminated by the presence of the reference and the test lines together.
3. Exceptionally long straight roads are neither required nor desirable.
4. This test is useful for yellow paint systems.
5. The procedure is readily usable for smaller government units.
6. Test results are immediately useful on 2-lane rural roads.
7. Test evaluations are conducted under normal driving speeds and conditions.
8. The test stripes have a longer, useful life because of lower average daily traffic counts and, thus, offer longer evaluation periods.

Disadvantages

1. Greater distances are required for each test section.
2. Photographic documentation requires police protection and professional services and equipment.
3. Because of road topography where double yellow lines are painted, long-distance visibility becomes more difficult.
4. Uneven wear patterns occur on curves.

CONCLUSION

Based on experience obtained with the dual-stripe comparison method for road-marking evaluation, this method of test can be highly recommended. The test method is directly applicable for use on 2-lane rural roads; test stripes that conform to the Manual on Uniform Traffic Control Devices can be used, and, thus, motorists are spared undue confusion.

The road-marking testing began in West Milford in the spring of 1971 and has produced well-documented records and data because of the ease with which side-by-side lines can be compared and evaluated. The procedure was found to be so useful that the test program has been continued. Color photographs of the dual stripe comparisons are very useful for illustrative purposes.

REVIEW OF PAST PERFORMANCE OF AND SOME NEW CONSIDERATIONS IN BRIDGE EXPANSION JOINTS

Stewart C. Watson, Watson Bowman Associates, Inc.

ABRIDGMENT

TWO NEW TYPES OF RUBBER-CUSHION SYSTEMS

Gland Type of System Using Rubber Block Interfaces

Figure 1 shows a gland type of system consisting of two 10- to 12-ft, 75-durometer, extruded neoprene blocks incorporating integral steel bearing plates connected by a replaceable low-stress rolling gland that takes the movements. The neoprene rubber blocks are doweled end to end, and the gland is installed in a continuous piece across the deck.

Advantages of a system of this type are the complete elimination of plastic flow or upward buckling of the blocks during cycling, low stress transmission to the structure, noise elimination, attrition resistance, ideal suitability to vertical movements and skewed joints, simplified temperature width setting, adaptability to deck rehabilitation and joint reconstruction under traffic, and on-site variability of bolt spacing. The use of a continuous sealing gland in one piece across the bridge appears to ensure a high leakproofing potential. This type of system should be restricted to movements of 4 in. or less.

Armored, Skid-Resistant, Rubber-Cushion System

Significant design improvements over earlier concepts of high-stress, rubber-cushion systems have been incorporated into the armored, skid-resistant, rubber-cushion device shown in Figure 2. A high-strength, corrosion-resistant, alloyed aluminum extrusion wear plate protects and structurally supports the 45-durometer (shore A) neoprene molding, which is bolted to the deck over the joint opening. A number of sizes reflecting differing movement capabilities from 1½ to 13 in. are now being specified by bridge engineers.

Reduction in stress transmission to the structure, lessened long-term plastic flow potential, minimal deflection under live loading, and armoring for improved attrition and snowplow resistance are some of the advantages over previous concepts where unprotected neoprene is exposed to heavy traffic and environmental service conditions.

STRIP-SEAL SYSTEM WITH EXTRUDED STEEL INTERFACES

German bridge engineers are responsible for the strip-seal systems (Fig. 3) that are currently in wide use.

An optimization of parts, use of steel extrusions, and low cost have made this type of system attractive not only to designers of new bridges but also to bridge maintenance people.

It was developed for improved strength-to-weight ratios and reduced welding requirements, and a number of configurations of standard extruded steel interfaces with varying heights are now available. These ASTM A-242 steel extrusions are bolted to the deck ends or cast in place by using conventional anchorage after which a heavy-duty neoprene gland is snap-locked into the receptacle provided in the interfacial armor.

Publication of this paper sponsored by Committee on Sealants and Fillers for Joints and Cracks.

Figure 1. Gland type of system using rubber block interfaces.

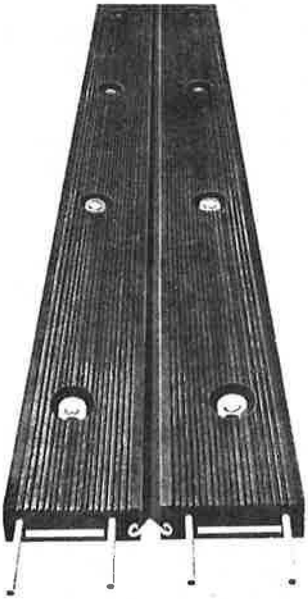


Figure 2. Armored, skid-resistant, rubber-cushion system.

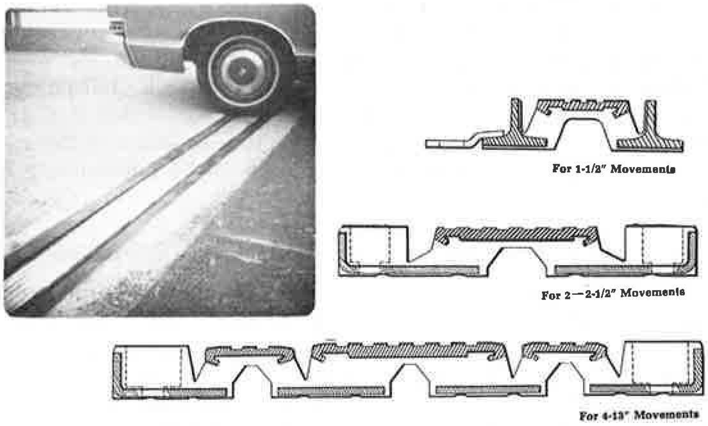


Figure 3. Strip-seal system with extruded steel interfaces.

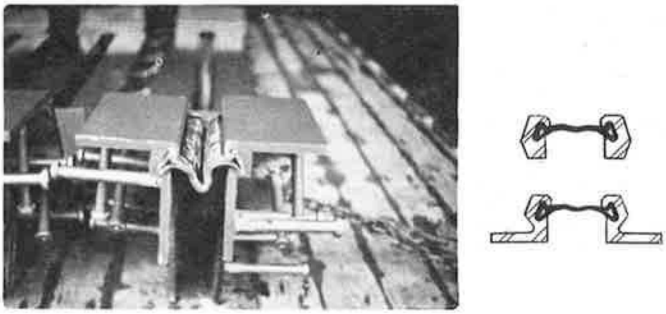
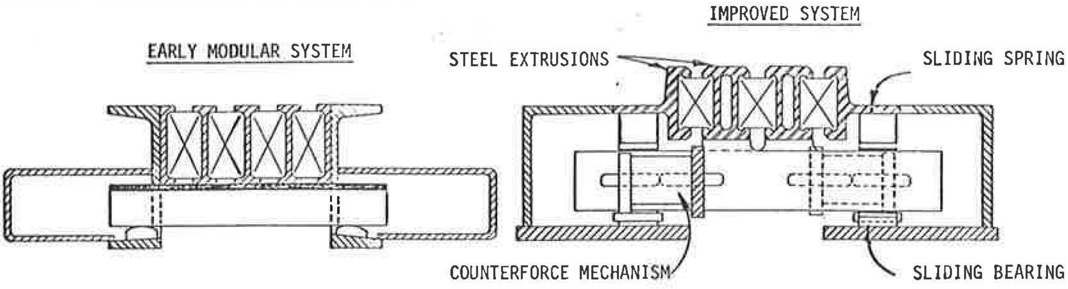


Figure 4. Early and improved modular systems.



Because the strip-seal element during movement cycling develops very low forces, it is ideally suited for skewed joints, vertical movements, and time-dependent and irreversible joint width changes of either progressively opening or closing type.

The simplicity of the strip-sealing system enhances quick, inexpensive fabrication of lateral and vertical changes in direction of curbs, gutters, and malls. Because the sealing gland is continuous throughout the deck, 100 percent leakproofing is achieved with relative ease as compared to sealing systems that arrive on site in discontinuous sections. An absolute minimum of steel to achieve the rubber armoring of interfaces so necessary to long-life performance is the outstanding feature of the strip-seal system.

IMPROVEMENTS IN MODULAR-COMPRESSION SEALING SYSTEMS

Performance surveys of the earlier generation of modular-compression sealing systems installed on North American bridges during the midsixties and early seventies have called attention to a critical need for certain improvements to correct problems such as (a) upward buckling or lifting of separation beams, (b) rotation or tilting of separation beams, (c) unequal distance between adjacent separation beams, (d) objectionable amplification of traffic-activated noise, (e) acceleration and deceleration cracking of components, (f) high cyclic forces in compression from heavily webbed seal elements and high friction sliding surfaces, (g) premature leaking from loss of interfacial contact, and (h) insufficient lateral or torsional strength of separation beams.

Figure 4 shows improvements that have been made to earlier systems. The early systems had free sliding parts operating out of control, wearing points, high noise potential, tilting plus lifting up of separation beams, bearings subjected to wear, and an uneven surface for traffic. They were potentially susceptible to premature failure from braking forces, snowplows, and long-term pressure decay. The advantages of the improved system are use of steel extrusions (greater strength-to-weight ratio), corner locking of seal elements, separation beams welded to support bars, positively noise-proofed system, teflon to stainless steel sliding surfaces, low-stress seal elements, equidistance control of elements, and fail-safe counterforce mechanism.

Details of the improved systems on prestigious bridges such as Pine Valley Creek Bridge, Auburn-Foresthill Bridge (record 26-in. movements), and Kolmar-Oland Bridge in Sweden (Europe's longest bridge) are described in another report (<u>1</u>).

REFERENCE

1. Watson, S. C. A Review of Past Performance and Some New Considerations in the Bridge Expansion Joint Scene. Watson Bowman Assoc., Inc., Buffalo, 1972.

ANALYSIS OF METHODS OF COMPRESSION-DEFLECTION TESTING OF PREFORMED ELASTOMERIC COMPRESSION SEALS

Douglas Huffman, The D. S. Brown Company

This paper is a study of some of the ways in which compression-deflection tests vary; specifically, the number of compression cycles that must be run and the effect of varying total deflection and crosshead speeds were studied. The study shows that 3 compression-deflection cycles must be run before the force-deflection curve produced approximates the equilibrium force-deflection curves. If fewer cycles are run, the results cannot be considered equal to the equilibrium values and hence characteristic of the seal's true performance in service. The study also pointed to 2 sources of variance in the test results. The first source was changing loads; as the loads or total deflection changes, values on the force-deflection curves also change. The result is that, if 2 different loads are chosen to test identical seals, values common to both force-deflection curves produced will not be equal. The second source was crosshead speeds. Though the speed variance was not so great as the variance caused by changing loads, it generally, for the speeds tested, produced results that were not equal. The results and accompanying conclusions show how those factors affected the tests and suggest possible solutions to the problem.

•A RELATIVELY new test for preformed elastomeric joint seals is the compression-deflection test. Its purpose is to measure the ability of the rubber seal to retain elastic properties and generate sealing forces after prolonged compressive stresses that might be encountered in actual use. Although this test is not an absolute indicator of performance, it serves as an excellent comparative test. Measurements taken show the minimum compression needed to make the seal remain in the joint, and the strength at the maximum compression indicates whether the seal can be installed properly without undue effort and indicates the seal's ability to resist deterioration of force generation as a result of overstressing.

Lack of standardization in the method of performing this test has led to uneconomical testing and a variability in the results obtained. This study attempted to find some of the sources of variability and wasted effort and to find a reliable and economic method of conducting the compression-deflection test.

PROCEDURE

Sample Preparation

In this study, random samples representing different types of joint seals from recently manufactured lots were secured for testing. A lot of a given type that was chosen for testing was used throughout the study to eliminate as much arbitrary variance as possible. Figure 1 shows the 4 types of seals used.

For each experiment, 10 samples were prepared. Preparation was done in accordance with ASTM D 15. Each specimen was cut to a length of 6 ± 0.1 in. These

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specimens were then washed with water and air-dried. No further preparation of the sample was conducted. Each sample was marked with a number to be used as identification.

After the test seals were prepared, an information sheet was written up for each specimen. The information consisted of type of seal, lot number, production date, sample number, maximum and minimum pressures at which deflection would be recorded, weight of the sample, and dimensions of the seal. The dimensions were measured by a dial micrometer to the nearest 0.001 in. Four width measurements were taken: at the lugs, at the top, at the bottom, and at the maximum width. Height was measured on each side of the test seal. The samples were then ready for testing.

Testing Procedure

Regardless of the experiment, the testing procedure was basically the same. For this study, an Instron universal testing instrument, model TT-D equipped with a graphical recorder, was used.

At the start of each day, and whenever necessary, the testing instrument was calibrated according to the operating instructions of the machine. Before each test, the calibration was checked and, when necessary, recalibrated. The crosshead and chart speeds were set according to the specifications of the experiment. The balance on the chart was adjusted so that the force on the graphical recorder read zero.

The sample to be tested was placed between the 2 plates of the testing machine in the center of the lower plate. (The upper plate is the crosshead.) The balance was readjusted so the force once again read zero. That procedure removes the effects of the weight of the sample on the results.

The information sheet, mentioned earlier, was used to record the test date, the crosshead and chart speed, and the operator's initials. Throughout the testing procedure, all data were recorded on that same information sheet.

The load selector was set on the lightest load, and the crosshead was lowered manually until the first complete contact along any edge of the seal was made. The separation between the plates was read from the gauge length dials to the nearest 0.001 in. and recorded. There should be very little pressure on the test seal at this point. Before anything else was done, the seal was adjusted between the plates so that the top of the seal was perpendicular to the plates. The crosshead was manually lowered farther until the force on the seal was 2 percent of the full-scale load that had been selected for the test. The load selector was turned to the selected load. When a load had been selected, the machine automatically controlled the stopping of the crosshead. As the crosshead traveled downward, it stopped when a force of 90 percent of the selected load was reached. When the crosshead traveled in the opposite direction, the machine stopped when the force became only 2 percent of the selected load.

The graphical recorder was engaged. The graph paper used was divided into 1-in. squares, which were subdivided into $^1/_{10}$-in. squares. For convenience, the recorder was engaged so that when the test began the recording of the deflection started at the edge of one of the inch squares. The machine was now ready to begin the test.

The crosshead was started at the preselected crosshead speed. The chart was activated simultaneously. The crosshead stopped at 90 percent of the selected load; that was the maximum deflection. At that point, the distance between the plates was read and recorded. The whole operation of reading the separation between the plates took only a matter of seconds, and then the crosshead was started again. When the force was only 2 percent of the selected load, the crosshead once again stopped and the separation of the plates was read and recorded. That completed 1 cycle. This procedure was repeated for the number of cycles that were selected. At the end of every other cycle, however, the process was stopped momentarily so that a new graph could be started. That facilitated the reading of the graphs.

When a graph was completed, the machine was zeroed to check for changes in the balance. A new graph was then started in like manner. When all the cycles were completed, the machine was zeroed, and the graphs were removed in a group. They were labeled with the date, the full-scale load, the crosshead and chart speeds, the type of seal, and the number of the test sample. The graphs and the information sheet were used to analyze results.

The crosshead was raised, the sample was removed and dated, and the machine was then ready for the next test.

Test to Determine Adequate Number of Cycles

"It has been known for many years that deformation in softening of rubber and the initial stress-strain curve determined during the first deformation are unique and cannot be retraced. Further the effect of repeated deformation is to cause rubber asymptotically to approach a steady state with a constant or equilibrium stress-strain curve" (1).

The purpose of this set of experiments was to determine how many force-deflection cycles are necessary to achieve at least a statistical equilibrium.

A set of 10 samples of preformed joint seals was tested. In each case a crosshead speed of 0.5 in./min was used in accordance with ASTM D 575. In practice, The D.S. Brown Company uses 3 loads when testing each seal.

The middle load was chosen for the tests. Previous experience had shown that equilibrium is reached by at least the sixth cycle, so 6 cycles were run on each specimen.

This test was run on 4 types of preformed elastomeric joint seals in case the seals behaved differently under force-deflection. Successive cycles were compared to determine the cycles necessary before 2 cycles could be considered statistically equal.

Test to Check Effect of Different Loads

Currently the states do not specify any load to be used in the testing of the road seals. Because different loads result in different total deflection, the question arises as to whether the final force is affected at points of deflection of importance. This set of experiments was designed to answer that question.

The results of the first group were used as a control. Ten new samples of each type of seal were tested again in a similar manner. A crosshead speed of 0.5 in./min was used to compress the seals, but a different load was chosen. The results of that experiment were then compared with the original set of results to determine whether the load chosen could affect the final result.

Test to Determine the Effect of Crosshead Speeds

ASTM Test D 575 recommends a crosshead speed of 0.5 in./min when force-deflection tests are performed. Nevertheless, state specifications for this test vary from 0.2 in./min to no specified speed. There is a possibility that a seal may fatigue differently when different crosshead speeds are used and, therefore, affect the final results. This set of experiments was an attempt to determine whether there would be such an effect over a narrow range of crosshead speeds that might be used to run the force-deflection test.

Ten new samples were prepared for testing. They were divided into 2 sets of 5 specimens each. The first set was tested with a crosshead speed of 0.2 in./min, and the second set was tested at 1.0 in./min. For the given type of seal, the load chosen was the same as that chosen for the test to determine the adequate number of cycles. The results of the tests were compared to see whether they were statistically equal. When they proved not to be equal, each set was then individually compared to the results of the test to determine the adequate number of cycles because the only condition that was different in the 2 tests was the crosshead speed. Unequal results indicated that crosshead speeds could affect the results.

EVALUATION OF TEST RESULTS

Every graph of a force-deflection curve of a preformed joint seal has several points that are characteristic of that seal. For the purposes of this test, points x and y were used. x is the breaking point on the return cycle and represents the pressure at the widest opening at which a seal will remain in place. y, or the point of safe compressibility, is defined as the pressure at the point at which all webs initially make contact. Figure 2 shows the 4 seals compressed to y. x and y were read off the graph for every cycle. Figure 3 shows the points for the 6 cycles run on one seal sample. For those cycles, the load was 400 lb, the crosshead speed was 0.5 in./min, and the chart speed was 2.5 in./min. When the values are read, the base line is used as the reference for the force readings. The nearest 1-in. square line at the start of the graph is used as a reference for the deflection readings. Every $1/10$-in. square represents one unit. The x and y values for every cycle are recorded on the appropriate form.

A balance line reading was also taken. The balance line reading equals the force reading at A minus the force reading at B plus the force reading at C (Fig. 3).

Two more readings taken from the graph for each cycle were the initial chart and the final chart readings (Fig. 3). Those readings were taken on the deflection scale. The initial chart reading is at the start of the downward movement of the crosshead, and the final chart is the reading at the completion of the crosshead's downward movement.

The dimensions of the test seal, the full-scale loading used for the test, and all information read from the chart are fed into the programmed calculator. The pounds per square inch at x and y are calculated in the following manner:

$$\text{psi at x} = \frac{F_x}{L \times H}$$

$$\text{psi at y} = \frac{F_y}{L \times H}$$

where

F_x = force at x = $(f_x - BL)\ FS/100$,
F_y = force at y = $(f_y - BL)\ FS/100$,
H = average height = $(h_1 + h_2)/2$,
f_x = force reading at x from graph,
f_y = force reading at y from graph,
BL = balance line reading,
FS = loading selected for test,
L = length of test seal, and
h_1, h_2 = 2 recorded heights of test seal.

For each group of 10 samples, the above information was determined, and then a sample mean $\overline{x}$ and sample variance S^2 were calculated for the pounds per square inch at both x and y.

All 3 sets of tests conducted required calculations to determine whether 2 groups of samples were statistically equal. For this purpose a 2-sample t-test for the difference between 2 means was used whenever possible. This test was used rather than normal distribution tests because the population variance was unknown and small samples were being used. The t-test requires the assumption that the 2 population variances σ_1^2 and σ_2^2 are equal. Therefore, before the 2-sample t-test is used, this assumption must be tested. This was done by using an F-statistic.

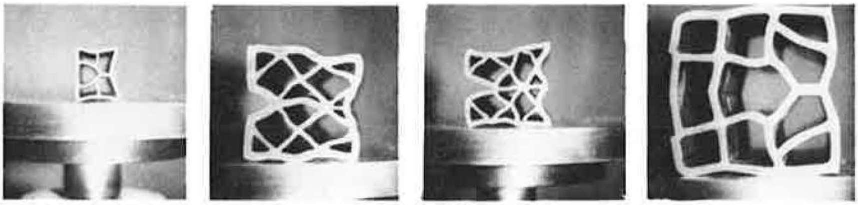
$$F = \frac{S_M^2}{S_m^2}$$

where

S_M^2 = larger of the sample variances, and
S_m^2 = smaller of the sample variances.

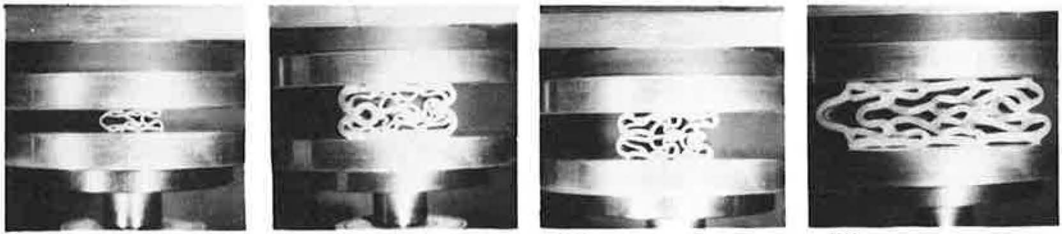
F is the value of the test statistic having an F-distribution with $(n_M - 1)$ and $(n_m - 1)$ degrees of freedom, where n_M and n_m are the respective number of values in each sample group. The null hypothesis H_0 is that $\sigma_1^2 = \sigma_2^2$, and the alternative hypothesis H_1 is that

Figure 1. Uncompressed samples of test seals.



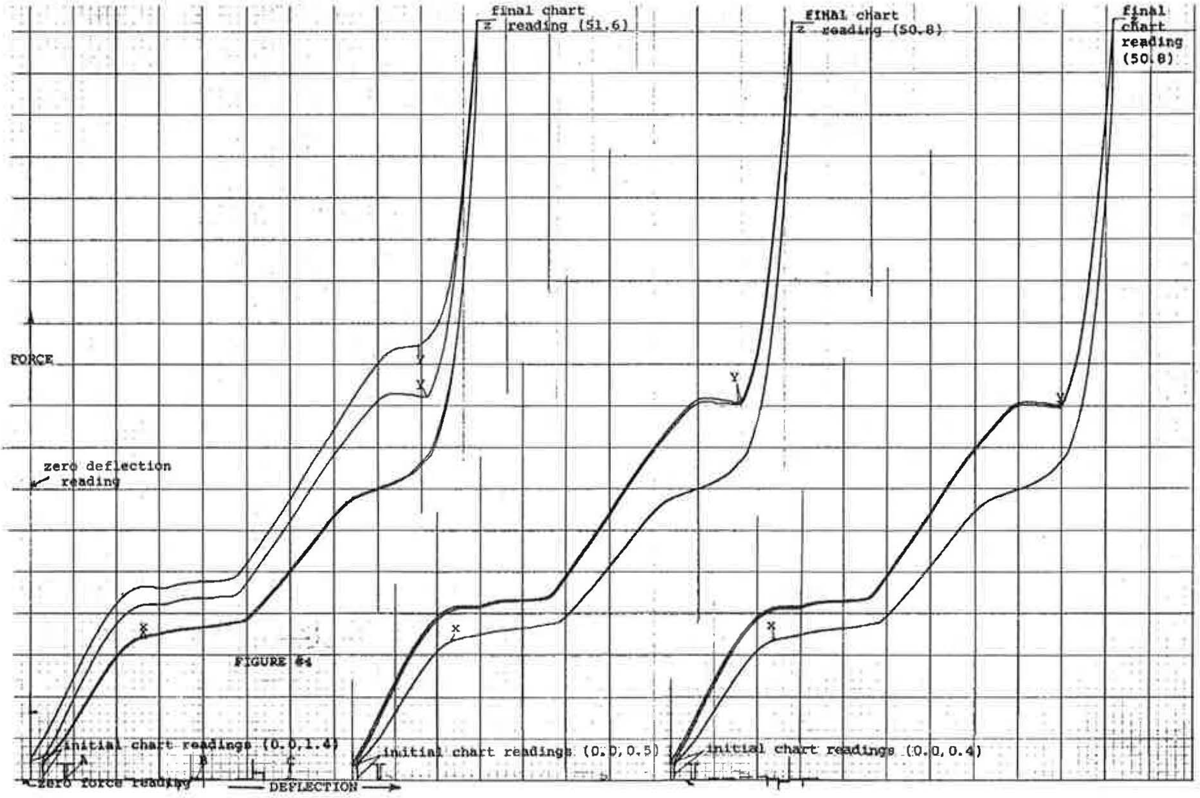
E-1250 CV-2500 B-2000 H-4000

Figure 2. Test seals compressed to limit of safe compressibility.



E-1250 CV-2500 B-2000 H-4000

Figure 3. Force-deflection curves for sample 8 of seal B-2000.



$\sigma_1^2 \neq \sigma_2^2$. A confidence value α of 95 percent was used. If $F < F_{\frac{\alpha+1}{2}}$, then the null hypothesis could not be rejected and it was justifiable to use the 2-sample t-test for that comparison. At this point, the assumption is made that the populations are normally distributed.

After it was determined that the population variances were equal, a 2-sample t-test could then be used based on the statistic

$$t = \frac{(\bar{x}_1 - \bar{x}_2) - \delta}{\sqrt{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}} \cdot \sqrt{\frac{n_1 n_2 (n_1 + n_2 - 2)}{n_1 + n_2}}$$

where

$\bar{x}_1, \bar{x}_2$ = sample mean of either x or y, in psi, of the 2 groups of data being compared,
δ = theoretical difference between the means (in all tests, $\delta = 0$),
S_1^2, S_2^2 = sample variances, and
n_1, n_2 = sample size.

The null hypothesis here is that the population means μ_1 and μ_2 are equal. In most cases, the alternative hypothesis was that the means were not equal. In the test for determining the necessary number of cycles, the alternative was that μ_1 was greater than μ_2 because during force-deflection cycles the seal will generally only lose strength until equilibrium is reached. Once again a confidence value of 95 percent was used. If $t > t_\alpha$ for $(n_1 + n_2 - 2)$ degrees of freedom, then the null hypothesis is rejected. Otherwise, it is accepted, and the 2 population means are considered equal.

In cases where the 2-sample t-test could not be used because the sample variances could not be considered equal, the Smith-Satlerthwaite test was used instead.

The test statistic is given by

$$t' = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}}$$

This sampling distribution can be approximated by a t-distribution having

$$\frac{\left(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right)^2}{\frac{(S_1^2/n_1)^2}{n_1 - 1} + \frac{(S_2^2/n_2)^2}{n_2 - 1}}$$

degrees of freedom, where

$\bar{x}_1, \bar{x}_2$ = 2 values being compared for equality,
s_1^2, S_2^2 = 2 respective sample variances, and
n_1, n_2 = 2 respective sample sizes.

If t′ lay between the critical values for a confidence value of 95 percent, the 2 values could be considered equal.

In the case of the test to determine an adequate number of cycles, the pounds per square inch at x and y in successive cycles were compared by the 2-sample t-tests until the means of those values were equal. When this had occurred it showed, temporarily, that the force-deflection curve had reached equilibrium and no further cycles were needed.

For the test to determine whether the size of the load has an effect on results, the pounds per square inch at x and y were compared for the same type of seal but with 2 different loadings. If the statistical test used showed that the means were equal, it proved that the loadings had no significant effect on the characteristic values on the force-deflection curve and therefore on the curve itself.

The same procedure was followed for the test to determine the effect of crosshead speeds on the force-deflection curve. In this case, the means of values for the tests with different crosshead speeds were compared. If the means were found to be equal, it could be assumed that the crosshead speeds tested had no significant effect on the force-deflection curves.

RESULTS

All 4 seals tested showed that the fourth cycle of the force-deflection curve was statistically equal to the third cycle curve. This indicates that the force-deflection curve of the third cycle approximates the equilibrium force-deflection curve.

In all the tests involving changes in loads, it was found that different loads gave different results. This indicates that the amount of total deflection will affect the entire force-deflection curve. No definite trend could be seen as the loads changed. The results seemed largely dependent on the type of seal being tested.

The results of the tests involving the crosshead speeds were inconclusive. In one test, the force-deflection curves for the 2 widely varied crosshead speeds proved to be equivalent. With the other 2 types of seals tested for force-deflection, curves were not equivalent. The one feature all 3 types had in common was a trend for the force at x and y to increase as the crosshead speed increased.

The values for the pounds per square inch at x and y are given in Tables 1 through 8.

CONCLUSIONS AND RECOMMENDATIONS

Many of the aspects affecting the compression-deflection test have been scrutinized in this study in an effort to determine a reliable and economic method of conducting this test. Experiments involving the proper number of cycles to run, the effect of different full-scale loads or total deflection on the preformed joint seals, and the effect of varying crosshead speeds have been conducted and analyzed.

The results show several things. First, only 3 cycles of the force-deflection test need to be run before the curve produced approximates the equilibrium force-deflection curve. The curve of the first deflection is unique and often even has a shape all its own. Generally this curve produces values that are not conclusive.

One of the greatest sources of errors or variance in results was the changing of the load or the total deflection used in the tests. Few states specify a load for testing seals, yet this study showed that the force-deflection curves are greatly affected by this factor. This calls for one of two things. Either a national or agreed-on standard load for different sizes of seal should be specified, or a standard that specifies compression to a given percentage of nominal width should be agreed on. Further study and consideration are needed before specific loads can be chosen for different sizes of seals. This study alone does not give sufficient data to set those loads. However, in respect to a standard for compressing to a given percentage of the nominal width of a seal, 35 percent seems like a reasonable value because all present state requirements could be met by using that compression.

Results involving crosshead speeds were inconclusive but did show that this factor may also be a substantial source of variance in the results. Further study needs to be done to determine conclusively the ranges that crosshead speeds can vary without affecting the final force-deflection curve.

REFERENCE

1. Mullins, L. Softening of Rubber by Deformation. Rubber Chem. and Technol., Feb. 1969, pp. 339-362.

Table 1. x-values for seal B-2000 at chart speed of 2.5 in./min.

Loading (lb)	Crosshead Speed (in./min)	Cycle	Sample														
			1	2	3	4	5	6	7	8	9	10	Σx	$(\Sigma x)^2$	$\bar{x}$	Σx^2	s_x^2
400	0.5	1	5.63	5.62	5.56	5.53	5.67	5.81	5.64	5.70	5.62	5.73	56.51	3,193.4	5.65	319.39	0.006667
		2	5.57	5.59	5.56	5.53	5.64	5.71	5.51	5.64	5.58	5.66	55.99	3,134.88	5.60	313.52	0.004000
		3	5.50	5.56	5.56	5.46	5.64	5.71	5.54	5.64	5.58	5.63	55.82	3,115.87	5.58	311.64	0.005778
		4	5.50	5.56	5.52	5.46	5.64	5.71	5.54	5.57	5.58	5.63	55.71	3,103.60	5.57	310.41	0.005444
		5	5.50	5.52	5.52	5.43	5.60	5.61	5.54	5.57	5.55	5.59	55.43	3,072.49	5.54	307.27	0.002889
		6	5.50	5.52	5.52	5.43	5.60	5.61	5.54	5.64	5.55	5.59	55.50	3,080.25	5.55	308.06	0.003889
1,000	0.5	1	5.73	5.77	5.71	5.47							22.68	514.38	5.67	128.65	0.01650
		1					5.81	6.27	5.96	5.96	5.68		29.68	880.90	5.94	176.37	0.04840
		Total											52.36	2,741.57	5.82	305.02	0.05076
		2	5.65	5.77	5.71	5.39							22.52	507.15	5.63	126.87	0.02817
		2					5.81	5.85	5.88	5.96	5.59		29.09	846.23	5.82	169.32	0.01910
		Total											51.61	2,663.59	5.73	296.19	0.02992
		3	5.65	5.77	5.63	5.31							22.36	499.97	5.59	125.11	0.03850
		3					5.81	5.85	5.88	5.88	5.51		28.93	836.94	5.79	167.49	0.02475
		Total											51.29	2,630.66	5.70	292.60	0.03750
		4	5.65	5.77	5.63	5.31							22.36	499.97	5.59	125.11	0.03850
		4					5.81	5.85	5.88	5.88	5.51		28.93	836.94	5.79	167.49	0.02475
		Total											51.29	2,630.66	5.70	292.60	0.03750
400	0.2	1	5.66	5.71	5.68	5.62	5.81						28.48	811.11	5.70	162.24	0.005250
	1.0	1						5.91	5.69	5.75	5.79	5.64	28.78	828.29	5.76	165.70	0.01060
	0.2	2	5.66	5.61	5.65	5.59	5.74						28.25	788.49	5.62	159.63	0.003350
	1.0	2						5.87	5.66	5.72	5.75	5.61	28.61	818.53	5.72	163.75	0.009900
	0.2	3	5.62	5.58	5.68	5.49	5.71						28.08	788.49	5.62	157.73	0.007450
	1.0	3						5.87	5.69	5.72	5.69	5.71	28.68	822.54	5.74	164.53	0.005900
	0.2	4	5.62	5.58	5.68	5.49	5.71						28.08	788.49	5.62	157.73	0.007450
	1.0	4						5.87	5.69	5.72	5.69	5.71	28.68	822.54	5.74	164.53	0.005900

Table 2. y-values for seal B-2000 at chart speed of 2.5 in./min.

Loading (lb)	Crosshead Speed (in./min)	Cycle	Sample														
			1	2	3	4	5	6	7	8	9	10	Σ_y	$(\Sigma y)^2$	$\bar{y}$	Σy^2	s_y^2
400	0.5	1	17.04	17.28	17.08	17.29	16.99	17.20	17.20	17.32	17.06	17.09	171.55	29,429.40	17.16	2,943.07	0.01389
		2	14.89	15.16	14.95	15.12	14.72	15.11	15.18	15.25	14.84	15.00	150.22	22.566.05	15.02	2.256.87	0.02900
		3	14.69	14.93	14.75	14.98	14.45	14.91	14.92	14.71	14.92	14.84	148.10	21,933.61	14.81	2,193.60	0.02622
		4	14.56	14.80	14.62	14.91	14.28	14.84	14.92	14.85	14.58	14.74	147.10	21,638.41	14.71	2,164.20	0.04022
		5	14.49	14.76	14.55	14.85	14.18	14.74	14.85	14.72	14.41	14.70	146.25	21,389.06	14.62	2,139.32	0.04622
		6	14.39	14.70	14.49	14.78	14.15	14.69	14.79	14.41	14.64	14.78	145.81	21,260.56	14.58	2,126.47	0.04556
1,000	0.5	1	17.36	17.65	16.80	15.93							67.74	4,588.71	16.94	1,148.90	0.5733
		1					18.37	18.47	18.40	17.15	16.46		88.85	7,894.32	17.77	1,582.21	0.8369
		Total											156.59	24,520.43	17.40	2,731.11	0.8271
		2	14.20	14.19	14.07	13.78							56.24	3,162.94	14.06	790.85	0.03817
		2					14.54	14.71	14.58	14.83	14.28		72.94	5,320.24	14.59	1,064.22	0.04280
		Total											129.18	16,687.47	14.35	1,855.07	0.1132
		3	14.04	14.02	13.74	13.53							55.33	3,061.41	13.83	765.53	0.05958
		3					14.38	14.54	14.34	14.66	14.12		72.04	5,189.76	14.41	1,038.12	0.04240
		Total											127.37	16,223.12	14.15	1,803.65	0.1354
		4	13.87	13.86	13.57	13.53							54.83	3,006.33	13.71	751.68	0.03326
		4					14.21	14.38	14.17	14.50	13.95		71.21	5,070.86	14.24	1,014.35	0.04430
		Total											126.04	15,886.08	14.00	1,766.03	0.1140
400	0.2	1	16.84	17.46	16.72	17.91	16.89						85.82	7,365.07	17.16	1,474.04	0.2554
	1.0	1						17.66	17.99	16.77	17.11	18.46	87.99	7,742.24	17.60	1,550.27	0.4560
	0.2	2	14.54	14.74	14.56	14.59	14.46						72.89	5,312.95	14.58	1,062.63	0.01065
	1.0	2						14.93	15.21	14.37	14.86	14.90	74.27	5,516.03	14.85	1,103.58	0.09235
	0.2	3	14.25	14.44	14.29	14.42	14.26						71.66	5,135.16	14.33	1,027.06	0.008200
	1.0	3						14.69	14.84	14.14	14.62	14.77	73.06	5,337.76	14.61	1,067.86	0.07655
	0.2	4	14.05	14.34	14.16	14.29	14.12						70.96	5,035.32	14.19	1,007.12	0.01440
	1.0	4						14.52	14.74	14.01	14.49	14.64	72.40	5,241.76	14.48	1,048.66	0.07900

Table 3. x-values for seal CV-2500 at chart speed of 2.0 in./min.

Loading (lb)	Crosshead Speed (in./min)	Cycle	Sample										Σx	$(\Sigma x)^2$	$\bar{x}$	Σx^2	s_x^2
			1	2	3	4	5	6	7	8	9	10					
1,000	0.5	1	4.40	4.42	4.47	4.32	4.23	4.33	4.39	4.29	4.38		39.24	1,539.78	4.36	171.13	0.005569
		2	4.40	4.31	4.35	4.32	4.17	4.21	4.33	4.23	4.32		38.64	1,493.50	4.29	165.94	0.005444
		3	4.34	4.31	4.23	4.26	4.11	4.15	4.39	4.23	4.26		38.28	1,465.36	4.25	162.88	0.007681
		4	4.34	4.19	4.23	4.26	4.11	4.09	4.27	4.17	4.26		37.92	1,437.93	4.21	159.82	0.006556
		5	4.28	4.25	4.29	4.20	4.11	4.03	4.21	4.17	4.26		37.80	1,428.84	4.20	158.82	0.007375
		6	4.28	4.25	4.29	4.20	4.11	4.03	4.21	4.17	4.26		37.80	1,428.84	4.20	158.82	0.007375
2,000	0.5	1	4.11	4.36	4.23	4.40	4.23	4.14	4.29	4.22	4.23		38.21	1,460.00	4.25	162.29	0.008792
		2	4.11	4.23	4.23	4.03	4.11	4.14	4.29	4.10	4.23		37.47	1,404.00	4.16	156.06	0.007236
		3	3.99	3.99	4.23	4.03	3.88	4.02	4.17	3.97	4.23		36.51	1,332.98	4.06	148.23	0.01539
		4	3.99	3.99	4.23	4.03	3.88	4.02	4.17	3.97	4.23		36.51	1,332.98	4.06	148.23	0.01539
1,000		5	3.92	4.11	4.23	4.10	3.94	3.90	4.05	3.97	3.99		36.21	1,311.16	4.02	145.78	0.01176
		6	3.92	4.11	4.23	4.10	3.94	3.90	4.05	3.97	3.99		36.21	1,311.16	4.02	145.78	0.01176
400	0.2	1	4.65	4.61	4.49	4.61	4.69						23.05	531.30	4.61	106.28	0.005600
	1.0	1						4.69	4.64	4.78	4.84	4.79	23.74	563.59	4.75	112.74	0.006600
	0.2	2	4.58	4.61	4.49	4.55	4.57						22.80	519.84	4.56	103.98	0.001950
	1.0	2						4.63	4.52	4.66	4.78	4.66	23.25	540.56	4.65	108.15	0.008600
	0.2	3	4.52	4.43	4.55	4.55	4.57						22.62	511.66	4.52	102.35	0.003050
	1.0	3						4.51	4.46	4.60	4.66	4.60	22.83	521.21	4.57	104.27	0.006300
	0.2	4	4.52	4.43	4.55	4.49	4.57						22.56	508.95	4.51	101.80	0.003050
	1.0	4						4.51	4.46	4.60	4.60	4.60	22.77	518.47	4.55	103.71	0.004350

Table 4. y-values for seal CV-2500 at chart speed of 2.0 in./min.

Loading (lb)	Crosshead Speed (in./min)	Cycle	Sample										Σy	$(\Sigma y)^2$	$\bar{y}$	Σy^2	s_y^2
			1	2	3	4	5	6	7	8	9	10					
1,000	0.5	1	20.57	20.26	20.29	20.48	21.04	20.76	20.51	20.71	20.32		184.94	34,202.80	20.55	3,800.83	0.06518
		2	18.12	18.94	18.25	18.88	17.83	18.13	18.34	18.62	18.31		165.44	27,370.39	18.38	3,042.23	0.1340
		3	17.94	18.46	17.53	18.29	17.35	17.64	17.74	17.90	18.07		160.92	25,895.25	17.88	2,878.28	0.1282
		4	17.82	18.28	17.41	18.29	17.23	17.64	17.50	17.72	17.95		159.84	25,548.83	17.76	2,839.84	0.1347
		5	17.63	18.40	17.35	18.29	17.23	17.70	17.50	17.36	17.64		159.10	25,312.81	17.68	2,813.88	0.1677
		6	17.51	18.40	17.35	18.23	17.17	17.52	17.50	17.36	17.64		158.68	25,179.34	17.63	2,799.06	0.1699
2,000	0.5	1	20.83	21.43	21.42	21.79	20.35	19.28	21.24	21.10	20.71		188.15	35,400.42	20.91	3,937.85	0.5583
		2	17.08	17.92	17.91	17.87	17.40	17.33	17.92	17.48	17.68		158.59	25,150.79	17.62	2,795.31	0.09675
		3	17.08	17.44	17.91	17.99	16.93	17.20	17.31	17.48	17.68		157.02	24,655.28	17.45	2,740.52	0.1308
		4	17.08	17.44	17.79	17.87	16.82	17.20	17.19	17.48	17.56		156.43	24,470.35	17.38	2,719.85	0.1158
1,000		5	17.33	17.74	17.79	17.68	16.46	17.08	17.62	17.24	17.50		156.44	24,473.47	17.38	2,720.69	0.1773
		6	17.33	17.68	17.73	17.68	16.43	17.08	17.62	17.18	17.50		156.21	24,401.56	17.36	2,712.73	0.1804
400	0.2	1	22.76	22.60	23.40	22.85	22.55						114.16	13,032.51	22.83	2,606.96	0.1152
	1.0	1						23.71	25.13	23.85	24.85	24.89	122.43	14,989.11	24.49	2,999.54	0.4293
	0.2	2	19.10	20.32	20.50	20.11	19.92						99.95	9,990.00	19.99	1,999.18	0.2951
	1.0	2						20.78	22.36	20.76	22.21	22.09	108.20	11,707.24	21.64	2,344.01	0.6400
	0.2	3	18.42	19.15	20.38	19.38	19.07						96.40	9,292.96	19.28	1,860.61	0.5053
	1.0	3						19.99	21.52	20.76	20.92	21.78	104.97	11,018.70	20.99	2,205.70	0.4908
	0.2	4	18.35	19.09	19.64	19.38	19.01						95.47	9,114.52	19.09	1,823.85	0.2352
		4						19.93	21.46	20.82	20.92	21.78	104.91	11,006.11	20.98	2,203.22	0.5006

Table 5. x-values for seal E-1250 at chart speed of 4.0 in./min.

Loading (lb)	Crosshead Speed (in./min)	Cycle	Sample														
			1	2	3	4	5	6	7	8	9	10	Σx	$(\Sigma x)^2$	$\bar{x}$	Σx^2	s_x^2
200	0.5	1	2.17	2.11	2.14	2.09	2.10	2.10	2.14	1.96	2.16	2.27	21.24	451.14	2.12	45.17	0.006222
		2	2.17	2.11	2.11	2.06	2.10	2.07	2.14	1.93	2.12	2.20	21.01	441.42	2.10	44.19	0.005444
		3	2.10	2.07	2.07	2.27	2.06	2.13	2.07	2.10	1.86	2.16	20.89	436.39	2.09	43.74	0.01067
		4	2.10	2.07	2.07	2.27	2.06	2.13	2.07	2.10	1.86	2.16	20.89	436.39	2.09	43.74	0.01067
		5	2.04	2.11	2.11	2.06	2.13	2.07	2.10	1.90	2.16	2.23	20.91	437.23	2.09	43.79	0.007556
		6	2.04	2.11	2.11	2.06	2.13	2.07	2.10	1.90	2.16	2.23	20.91	437.23	2.09	43.79	0.007556
400	0.5	1	2.21	2.35	2.28	2.07	2.35	2.34	2.27				15.87	251.86	2.27	36.22	0.04024
		1								2.49	2.37	2.44	7.30	53.29	2.43	17.77	0.003833
		Total											23.17	536.85	2.32	53.99	0.03412
		2	2.21	2.28	2.22	2.07	2.28	2.27	2.20				15.53	241.18	2.22	34.49	0.005429
		2								2.42	2.24	2.38	7.04	49.56	2.35	16.54	0.009167
		Total											22.57	509.41	2.26	51.03	0.009500
		3	2.28	2.21	2.22	2.07	2.22	2.34	2.20				15.54	241.49	2.22	34.54	0.006857
		3								2.49	2.31	2.38	7.18	51.55	2.39	17.20	0.008000
		Total											22.72	516.20	2.27	51.74	0.01336
		4	2.28	2.21	2.22	2.07	2.22	2.34	2.20				15.54	241.49	2.22	34.54	0.006857
		4								2.36	2.31	2.38	7.05	49.70	2.35	16.57	0.001167
		Total											22.59	510.31	2.26	51.11	0.008600
200		5	1.98	2.05	2.08	2.17	2.12	2.27	2.10				14.77	218.15	2.11	31.22	0.008548
		5								2.29	2.34	2.38	7.01	49.14	2.34	16.38	0.002000
		Total											21.78	474.37	2.18	47.60	0.01813
		6	1.98	2.05	2.08	2.17	2.12	2.27	2.10				14.77	218.15	2.11	31.22	0.008548
		6								2.29	2.34	2.38	7.01	49.14	2.34	16.38	0.002000
		Total											21.78	474.37	2.18	47.60	0.01813
200	0.2	1	2.64	2.74	2.77	2.72	2.79						13.66	186.60	2.73	37.33	0.003450
	1.0	1						2.64	2.48	2.51	2.64	2.65	12.92	166.92	2.58	33.41	0.006700
	0.2	2	2.64	2.78	2.74	2.68	2.76						13.60	184.96	2.72	37.01	0.003500
	1.0	2						2.58	2.44	2.48	2.54	2.58	12.62	159.26	2.54	31.87	0.003800
	0.2	3	2.64	2.78	2.74	2.65	2.76						13.57	184.15	2.71	36.85	0.004250
	1.0	3						2.44	2.38	2.38	2.41	2.58	12.19	148.60	2.44	29.75	0.006950
	0.2	4	2.64	2.78	2.74	2.65	2.76						13.57	184.15	2.71	36.85	0.004250
	1.0	4						2.44	2.35	2.35	2.41	2.58	12.13	147.14	2.43	29.46	0.008900

Table 6. y-values for seal E-1250 at chart speed of 4.0 in./min.

Loading (lb)	Crosshead Speed (in./min)	Cycle	Sample														
			1	2	3	4	5	6	7	8	9	10	Σy	$(\Sigma y)^2$	$\bar{y}$	Σy^2	s_y^2
200	0.5	1	6.39	6.39	6.40	6.39	6.30	6.35	6.29	6.38	6.31	6.37	63.57	4,041.15	6.36	404.13	0.001556
		2	6.05	6.06	6.09	6.09	5.99	6.02	6.02	6.07	5.98	5.99	60.36	3,643.33	6.04	364.35	0.001667
		3	6.02	5.99	6.02	6.02	5.99	5.95	5.96	6.04	5.94	5.99	59.92	3,590.41	5.99	359.05	0.001111
		4	6.02	5.95	6.02	6.02	5.99	5.95	5.96	6.04	5.94	5.99	59.88	3,585.61	5.99	358.57	0.001444
		5	5.99	5.99	6.05	6.05	5.99	5.95	5.96	6.04	5.91	5.99	59.92	3,590.41	5.99	359.06	0.002222
		6	5.99	5.99	6.05	6.05	5.99	5.95	5.96	6.04	5.91	5.95	59.88	3,585.61	5.99	358.58	0.002444
400	0.5	1	6.31	6.52	6.39	6.47	6.52	6.15	6.41				44.77	2,004.35	6.40	286.44	0.01748
		1								5.44	5.67	5.75	16.86	284.26	5.62	94.81	0.02583
		Total											61.63	3,798.26	6.16	381.25	0.1578
		2	5.97	6.18	6.06	6.07	6.05	5.88	6.08				42.29	1,788.44	6.04	255.55	0.008833
		2								5.37	5.34	5.42	16.29	260.18	5.38	86.73	0.001667
		Total											58.42	3,412.90	5.84	342.27	0.1094
		3	5.97	6.05	5.99	6.01	5.99	5.82	6.01				41.84	1,750.59	5.98	250.12	0.005381
		3								5.44	5.28	5.35	16.07	258.25	5.36	86.10	0.006667
		Total											57.91	3,353.57	5.79	336.21	0.09491
		4	5.97	6.05	5.99	5.75	6.01	5.99	6.01				41.77	1,744.73	5.97	249.31	0.009738
		4								5.24	5.28	5.35	15.87	251.86	5.29	83.96	0.003333
		Total											57.64	3,322.37	5.76	333.27	0.1142
200		5	5.97	6.05	6.02	6.07	5.99	5.88	6.11				42.09	1,771.57	6.01	253.12	0.005643
		5								5.34	5.37	5.38	16.09	258.88	5.36	86.30	0.001000
		Total											58.18	3,384.91	5.82	339.41	0.1023
		6	5.97	6.04	6.02	6.07	5.99	5.88	5.98				41.95	1,759.80	5.99	251.42	0.003762
		6								5.34	5.37	5.38	16.09	258.88	5.36	86.30	0.001000
		Total											58.04	3,368.64	5.80	337.72	0.09509
2.00	0.2	1	5.83	6.03	5.98	5.86	6.05						29.75	885.06	5.95	177.05	0.009850
	1.0	1						6.15	6.02	6.15	6.21	6.09	30.62	937.58	6.14	187.54	0.005300
	0.2	2	5.54	5.73	5.68	5.54	5.72						28.21	795.80	5.64	159.18	0.009050
	1.0	2						5.72	5.99	5.82	5.85	5.76	29.14	849.14	5.83	169.87	0.01075
	0.2	3	5.47	5.66	5.59	5.44	5.66						27.82	773.95	5.56	154.83	0.01090
	1.0	3						5.65	5.85	5.76	5.81	5.70	28.77	827.71	5.75	165.57	0.006600
	0.2	4	5.44	5.62	5.55	5.41	5.62						27.64	763.97	5.53	152.83	0.009750
	1.0	4						5.62	5.85	5.76	5.78	5.70	28.71	824.26	5.74	164.88	0.007550

Table 7. x-values for seal H-4000 at chart speed of 1.2 in./min.

Loading (lb)	Crosshead Speed (in./min)	Cycle	Sample														
			1	2	3	4	5	6	7	8	9	10	Σx	$(\Sigma x)^2$	$\bar{x}$	Σx^2	s_x^2
1,000	0.5	1	3.87	3.77	3.82	3.69	3.81	3.87	3.78	4.01	3.98	4.04	38.64	1,493.05	3.86	149.42	0.01300
		2	3.79	3.69	3.73	3.65	3.73	3.79	3.70	3.93	3.89	3.96	37.86	1,433.38	3.79	143.44	0.01144
		3	3.66	3.52	3.65	3.56	3.69	3.62	3.57	3.93	3.68	3.75	36.63	1,341.76	3.66	134.30	0.01344
		4	3.66	3.52	3.65	3.52	3.69	3.62	3.53	3.93	3.68	3.75	36.55	1,335.90	3.66	133.73	0.01556
		5	3.66	3.52	3.56	3.48	3.65	3.58	3.53	3.93	3.64	3.79	36.34	1,320.60	3.63	132.23	0.01911
		6	3.66	3.52	3.56	3.48	3.65	3.58	3.53	3.93	3.64	3.79	36.34	1,320.60	3.63	132.23	0.01911
400	0.5	1	4.09	4.20	4.05	4.10	4.31	4.25	4.03	3.92	3.94	4.62	41.51	1,723.08	4.15	172.70	0.04300
		2	4.02	4.13	4.00	4.03	4.23	4.15	4.00	3.86	3.89	4.57	40.88	1,671.17	4.09	167.49	0.04140
		3	4.02	4.05	4.03	3.96	4.21	4.13	3.90	3.88	3.90	4.57	40.65	1,652.42	4.07	164.25	0.04311
		4	4.02	4.05	3.95	3.95	4.21	4.11	3.90	3.88	3.86	4.55	40.48	1,638.63	4.05	164.25	0.04311

Table 8. y-values for seal H-4000 at chart speed of 1.2 in./min.

Loading (lb)	Crosshead Speed (in./min)	Cycle	Sample														
			1	2	3	4	5	6	7	8	9	10	Σy	$(\Sigma y)^2$	$\bar{y}$	Σy^2	s_y^2
1,000	0.5	1	12.01	11.41	11.58	11.46	11.78	11.71	11.62	11.95	11.48	11.72	116.72	13,623.56	11.67	1,362.72	0.04089
		2	11.29	10.90	10.86	10.65	11.08	10.99	10.90	10.13	10.73	10.97	109.50	11,990.25	10.95	1,199.34	0.03533
		3	11.33	10.48	10.56	10.61	10.92	10.49	10.86	10.56	10.73	11.05	107.59	11,575.6	10.76	1,158.26	0.07767
		4	11.25	10.40	10.48	10.52	10.84	10.44	10.82	10.52	10.73	10.97	106.97	11,442.5	10.70	1,144.94	0.07567
		5	11.29	10.44	10.39	10.57	10.71	10.44	10.73	10.52	10.63	11.01	106.79	11,404.10	10.68	1,141.13	0.08022
		6	11.21	10.40	10.39	10.52	10.63	10.44	10.65	10.52	10.69	10.97	106.42	11,325.22	10.64	1,133.15	0.06944
400	0.5	1	11.79	11.93	11.85	11.80	12.16	12.10	12.16	11.78	11.95	11.71	119.23	14,215.79	11.92	1,421.83	0.02763
		2	11.24	11.49	11.13	11.37	11.97	11.55	11.78	11.22	11.60	11.20	114.55	13,121.70	11.46	1,312.85	0.07574
		3	10.94	11.15	11.05	11.28	10.95	11.38	11.39	11.08	11.20	11.22	111.64	12,463.49	11.16	1,246.58	0.02578
		4	10.89	11.07	11.04	11.28	10.95	11.36	11.06	11.17	11.22	11.37	111.41	12,412.18	11.14	1,241.47	0.02758

DISCUSSION

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To recap the history of the compression-deflection test, one should begin with the 1967 paper by Hall, Ritzi, and Brown (2). In that paper, the authors have directed attention, for the first time, to what is now recognized as the characteristic shape of pressure-deflection curves for preformed elastomeric sealers. In 1969, after considerable laboratory and field investigation, I proposed that this test be employed by sealer users as one of the means for judging the acceptability of an elastomeric sealer (3).

The compression or pressure-deflection test has been part of the New Jersey Department of Transportation specification for preformed elastomeric joint sealer since 1969.

Huffman's paper should be welcomed because he rightfully sets forth several important factors affecting pressure-deflection testing. However, certain of his resulting recommendations for test standardization are ill-conceived and will tend to confuse and possibly mislead the uninformed.

In essence, he has studied 3 factors:

1. Number of cycles necessary to achieve an equilibrium pressure-deflection curve,
2. Effect of "some loads" on this curve, and
3. Effect of crosshead speed or load application rate on the pressure-deflection curve.

The results of his study can be summarized as follows:

1. A reasonable equilibrium pressure-deflection curve is achieved on the third cycle, and
2. The investigations of "load effect" and "crosshead speed" were inconclusive.

However, in spite of the nature of his findings, he rather surprisingly concludes that

1. The force-deflection curve is greatly affected by the load factor, or, in essence, the amount of total deflection will significantly alter the magnitude of key parameters obtained from the curve; and
2. The factor of crosshead speed may also be a substantial source of variance in magnitude of key curve parameters.

Of further bewilderment is his recommendation for the establishment of national standards for either loads or degree of compression. Yet, at the same time he admits that this study does not give sufficient data to set these loads or deflections.

The question in my mind is, Why all this work? I can see a possible need for advising sealer users of the cycle level at which curve equilibrium is achieved, although it should already be widely known that equilibrium is reached between the third and fifth cycles, 3 cycles obviously being the least number that must be run. But what is the logical basis for considering the testing of sealers to a "specific load or loads"?

The amount of pressure needed to compress a sealer depends on

1. The amount of compression;
2. The ingredients from which a sealer is compounded, their quality and relative quantity, and batching techniques;
3. The sealer's extrusion techniques and quality;
4. The sealer's state of cure and possibly the curing procedures; and
5. The sealer's structural design.

All of those parameters vary from lot to lot, and some are different for each individual sealer.

The parameters given above are just some that affect a sealer's performance characteristics, of which structural strength is one. The various tests proposed and explained in my aforementioned paper to some degree control the parameters. However, the involved tests provide parameter limits broad enough to permit, literally, for each sealer a very wide variation of pressure (or loads, as Huffman terms it) for the same degree of compression. But most important, there is no evidence that this latitude of pressures in any way impedes or governs a sealer's efficiency. In essence, there is no possible way that any "specific load" could be used as a pass-failure criterion for a specific size of sealer in the pressure-deflection test. However, it remains quite obvious that, for any sealer to perform efficiently, a certain minimum pressure at the minimum degree of compression must be required.

Now to the subject of crosshead speed.

For sealers installed in the field and exposed to design limits, a full cycle lasts about 1 year. The speed of the cycle depends on the time and movement limits. A 4-in.-wide sealer, which is compressed 1.2 in., undergoes 2.4 in. of movement in one year. Therefore, the speed would be approximately 4.6×10^{-6} in./min, very slow indeed. If we could attain such a yearly pressure-deflection curve, its familiarity with the laboratory curve would not be surprising.

Huffman submits that his inconclusive research established "a trend for the force of x and y to increase as the crosshead speed increased," and "that this factor may also be a substantial source of variance in the results." If there is a variance, it is doubted that it is substantial or that it is in any way significant, unless of course tests are run haphazardly. However, the important word in the above quote is not "variance" but "results." Before a study is conducted on factors affecting variation of results, a determination must first be made as to the exact results that are desirable and meaningful.

The maximum value (the y-value), i.e., the pressure at the limit of safe compressibility (LSC), is of no practical consequence in reference to sealers and sealer users' application of the pressure-deflection test. The user is interested only in the degree of compression at the LSC and not in the pressure or force because the degree of compression is the factor that governs the field capabilities of the sealer. The identification of the degree of compression at LSC is independent of loading rate although a slow crosshead speed of 0.2 in./min does simplify somewhat the LSC identification process.

In this case, it is felt that, if there were a variance of pressure-deflection test results, it is of concern only in the determination of the minimum permitted pressure (Huffman's x-value).

In general, the relevance of Huffman's paper to furthering the sealer users' understanding of the compression-deflection test is questioned. The information available on load-cycling equilibrium is already widely known and understood. The data on testing to a specific load and on loading rate are in an area that can hardly be of any practical consequence to the industry; they are unrelated to sealer capabilities or current test usage.

Data to support such contentions have been presented in the aforementioned paper; additional supporting information obtained since that paper, but too complex for presentation in this discussion, is readily available upon request from the New Jersey Department of Transportation and was previously presented to ASTM Task Group J of Subcommittee D-4.34.

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AUTHOR'S CLOSURE

Kozlov's discussion of my paper indicates that its intent and purpose might be misunderstood. Therefore, I offer, in rebuttal, the following comments.

Compression deflection testing of elastomeric seals is a means of characterizing different designs of seal by measuring the resistance force of deflection generated when a given shape is compressed. Because the seal functions in service under compression, it is desirable to know not only that the seal design retains sufficient force to effectively keep a joint watertight at the widest anticipated opening of a given joint but also that it will retain sufficient force to accomplish that purpose after being exposed to heat and compression far in excess of this minimum requirement when it is compressed during its service life to the minimum opening of the joint in question. Because rubber under stress loses its ability to rebound or recover in direct relation to the degree of overstressing (the higher the stress is, the faster the decay or loss of recovery force will be), it is desirable to undertake laboratory analysis to determine the optimum degree of stress the seal can resist so that a seal with a given design will not be placed in a joint configuration where excessive stressing will destroy at too fast a rate its ability to function and keep a joint watertight.

To measure the overstressed conditions of a seal requires that different loads for different sizes and designs be used to deflect the seal enough to reach a point where rubber-to-rubber contact across the cross-sectional design of a seal occurs. The pounds per square inch required to overstress any seal design is relatively the same and should not be confused with the loading applied to the sample to get the seal to the overstressed state. Overstressing does not occur until a given design is deflected to a point where rubber-to-rubber contact across the cross section occurs and the rubber making that cross section begins to flow or extrude. It is at that point that a rapid rise in force occurs, and the degree or amount of deflection varies from one style or design of seal to another. It should be pointed out that the service application of a given seal should avoid this area or degree of deflection.

It is my opinion that in this testing Kozlov has always disregarded the forces generated when various seal designs are deflected to given percentages of their nominal width; or, putting it another way, he has greatly overstressed seals and established limits of overstressing far exceeding the true working range of a given seal design.

His approach has been that bridge designers design in a structure a joint that should accommodate a seal capable of 50 percent deflection. What the force is to reach that deflection or whether the rubber is highly overstressed in reaching that deflection is apparently of no concern. To quote Kozlov, "The user is interested only in the degree of compression at the LSC and not in the pressure or force because the degree of compression is the factor that governs the field capabilities of the sealer." Thus, we ignore the resultant shortened life span of an overstressed seal and the fact that the seal will lose its ability to seal the joint at maximum opening quicker as a result of this overstressing in the warm or closed part of the joint cycle.

Because the forces required to deflect various seal designs, as well as sizes, to the point of overstressing vary with the style and size of the sample to be tested, I have suggested that all seals be deflected to 35 percent of their nominal width as a basis of standardization. It will take different loadings to accomplish this, but the point at which overstressing occurs will always be discernible—the total loadings will be different, but the point of overstressing will be relatively the same in pounds per square inch. From this, working limits of a given design of seal can be ascertained.

To have reproducibility among laboratories requires that the crosshead speeds used be constant. Varying the crosshead speeds changes the values along the curve. That is another reason for deflecting to 35 percent of nominal width to give reproducibility among laboratories in the pressure results. These simple standardizations would provide a worthy base to operate from.

In view of the foregoing, I respectfully submit that Kozlov's discussion is not pertinent to my paper.

CORRELATION OF PROPERTIES OF IRAQI LIMESTONE

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Test results obtained on limestone from different locations were used to investigate the relations of properties of limestone. A relation was found between abrasion wear obtained in the Los Angeles abrasion test and each of the following: compressive strength, impact value, and specific gravity. A nomographic solution for the physical properties is presented; once one of the properties is known, the other properties can be estimated by using the nomograph. An investigation was made of the relation between abrasion wear and chemical composition, and no significant relation was found.

• CALCITIC and dolomitic limestone is widely distributed in various regions of Iraq. The formation of limestone is divided into 3 groups according to their locations, as shown in Figure 1 (1, 2):

1. West of the Euphrates from the Syrian border to south of Samawa,
2. East of the Tigris from Mosul in the north to south of Kafri, and
3. The mountainous region in Sulaimania and Arbil.

Limestone has diverse uses in industry, agriculture, and construction. In the field of civil engineering, limestone is used for manufacturing materials such as portland cement and lime; it is also used as a building stone and as crushed aggregate for highway bases.

The properties of limestone are determined in a number of physical and chemical tests. Some of these tests are tedious and difficult to perform; others are time-consuming. The purpose of this paper is to present a nomographic solution correlating the physical properties of limestone. The values of other properties can be estimated if the value of any one of the following is known: Los Angeles abrasion (percentage of wear), compressive strength, impact value, apparent specific gravity, and bulk specific gravity.

MATERIALS

Eighteen samples of limestone from different locations were obtained and tested, as discussed below, by the Building Research Centre (3). The method prescribed in ASTM D 75-59 for sampling was adopted.

Los Angeles Abrasion Test

The Los Angeles abrasion test was carried out according to ASTM C 131; gradation A was used. The percentage of abrasion wear of the aggregates was found after 500 revolutions at a speed of 30 to 33 rpm with 12 steel spheres.

Compressive Strength Test

The compressive strength of limestone was found by crushing 7.5-cm cubes cut from pieces not smaller than 15 × 15 × 10 cm in size. A universal testing machine with a rate of loading of 1.25 cm/min was used. The average of 3 cubes was determined for each limestone sample tested.

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Impact Test

The resistance of stones to impact was determined according to ASTM D 3-18-58. Test values are empirical and indicate the distance in centimeters through which a 2-kg hammer falls to cause failure of the specimens (4).

Specific Gravity

Bulk and apparent specific gravities were determined in accordance with ASTM C 127.

Chemical Analyses

Chemical analyses were conducted according to ASTM C 25-58 to find CaO, MgO, SiO_2, Al_2O_3, Fe_2O_3, SO_3, R_2O_3, and loss on ignition.

TEST RESULTS

The test results reported by the Building Research Centre are given in Tables 1 and 2 (3).

Regardless of its location, Iraqi limestone shows a hyperbolic relation between the abrasion wear obtained in Los Angeles abrasion test and the crushing compressive strength. As the compressive strength increases, the percentage of wear decreases (Fig. 2). The relation could be explained since both tests indicate rock hardness. Figure 2b shows that the reciprocal of the abrasion wear and the compressive strength has a linear relation. The least squares method of analysis (5) was used for the linear equation

$$y = a + bx$$

where

$$b = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n} (x_i - \bar{x})^2}$$

and $a = \bar{y} - b\bar{x}$, to obtain Eq. 1.

$$\frac{10^4}{W} = 22.6 + 1.134\sigma \tag{1}$$

where W is the percentage of abrasion wear and σ is compressive strength in kg/cm^2. The correlation coefficient r was found to be 0.91 ($r = 1$ indicates perfect correlation, and $r = 0$ indicates no correlation). The expression for r is

$$r = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}}$$

If 1/W represents the y-axis, then, for regression with respect to y, the standard error of estimate (6) is equal to 0.0055 as given in Table 3.

Figure 1. Location of limestone in Iraq.

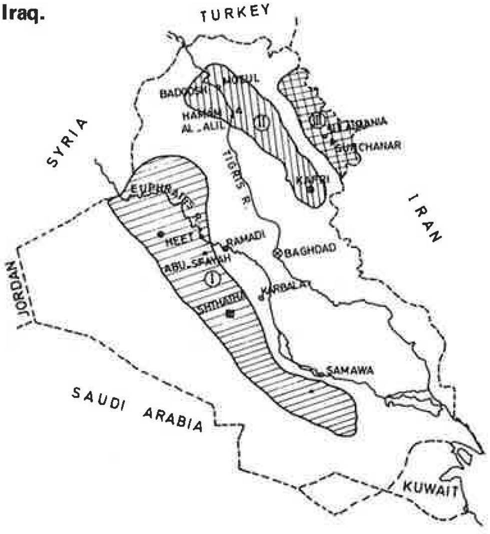


Table 1. Physical properties of limestone.

Sample	Area	Location	Specific Gravity		Absorption (percent)	W (percent)	1/W	Compressive Strength (kg/cm^2)	Impact (cm)
			Bulk	Apparent					
1	Ramadi	Abu-Sfayyah-1	1.84	1.93	2.75	43.9	0.0228	144	10
2		Abu-Sfayyah-2	2.05	2.12	1.54	46.7	0.0214	125	6
3		Heet	2.07	2.16	1.99	—[a]	—[a]	168	5
4	Karbala	Kalat Mazloom-1	1.76	2.18	10.92	54.6	0.0183	114	4
5		Kalat Mazloom-2	1.77	2.08	8.27	82.0	0.0122	92	2
6		Kalat Mazloom-3	1.65	2.08	9.89	76.9	0.0130	125	3
7		Shthatha-1	—[b]	—[b]	—[b]	97.3	0.0103	85	4
8		Shthatha-2	1.15	1.55	22.63	92.6	0.0108	86	3
9		Shthatha-3	1.55	1.95	13.15	96.5	0.0104	85	3
10	Sulaimania	Surchanar-1	2.25	2.40	2.81	16.4	0.0610	396	10
11		Surchanar-2	2.17	2.36	3.58	23.1	0.0433	319	9
12		Surchanar-3	2.11	2.37	3.60	26.9	0.0371	333	10
13	Mosul	Badoosh-1	2.25	2.37	2.25	38.0	0.0263	210	9
14		Badoosh-2	2.05	2.04	1.87	33.1	0.0302	209	8
15		Badoosh-3	1.95	2.19	5.62	42.0	0.0238	190	10
16		Hammam Alil-1	2.56	2.58	0.47	43.2	0.0232	272	9
17		Hammam Alil-2	2.46	2.54	1.29	24.8	0.0403	372	12
18		Hammam Alil-3	2.34	2.44	1.73	32.1	0.0311	343	11

[a] Asphaltic mat. [b] Disintegrated.

Table 2. Chemical analyses of limestone.

Sample	Area	Location	Loss on Ignition	SiO_2	R_2O_3	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
1	Ramadi	Abu-Sfayyah-1	42.29	0.80	1.41	0.28	1.13	54.90	0.14	0.36
2		Abu-Sfayyah-2	42.00	0.78	1.48	0.48	0.10	55.07	0.15	0.30
3		Heet	43.66	2.64	1.18	0.62	0.56	47.07	0.34	2.30
4	Karbala	Kalat Mazloom-1	43.72	2.06	2.61	1.10	1.56	47.55	1.27	0.58
5		Kalat Mazloom-2	42.14	1.48	1.03	0.25	0.74	54.10	0.89	0.34
6		Kalat Mazloom-3	40.65	0.69	0.86	0.02	0.70	52.52	2.32	0.58
7		Shthatha-1	42.02	0.66	1.12	0.64	0.47	55.01	0.86	0.30
8		Shthatha-2	42.60	1.68	0.50	0.27	0.27	54.00	0.69	0.30
9		Shthatha-3	43.21	1.04	0.43	0.27	0.16	54.16	0.57	0.52
10	Sulaimania	Surchanar-1	37.26	12.02	1.84	0.83	0.96	47.76	0.54	0.45
11		Surchanar-2	35.00	18.82	2.18	1.04	1.12	43.12	0.46	0.32
12		Surchanar-3	33.64	17.02	2.13	0.99	1.14	44.18	0.33	0.30
13	Mosul	Badoosh-1	42.70	1.63	1.12	0.50	0.62	53.10	1.07	0.21
14		Badoosh-2	39.50	8.06	4.53	2.18	2.25	47.04	0.46	0.28
15		Badoosh-3	39.90	6.45	3.14	1.49	1.68	49.43	0.72	0.30
16		Hammam Alil-1	40.00	4.33	2.42	1.16	1.26	51.74	0.74	0.43
17		Hammam Alil-2	43.50	1.88	3.22	0.45	0.72	50.58	1.93	0.37
18		Hammam Alil-3	44.32	1.32	1.20	0.58	0.62	50.51	1.86	0.41

A plot of abrasion wear versus impact values (Fig. 3a) shows that, as wear decreases, the impact value increases. The reciprocal of the percentage of wear gives a linear relation. The impact value is represented by Eq. 2 and is shown in Figure 3b.

$$\frac{10^4}{W} = 29.07 + 31.39\ I \tag{2}$$

where I is the impact value, in cm. The correlation coefficient for Figure 3b was found to be 0.76. The standard error of estimate with respect to the y-axis is 0.0090. Although Los Angeles abrasion and impact tests are empirical, both tests indicate rock toughness. Wear appears to result from both impact and surface abrasion; impact causes more loss (4). That could explain the relations shown in Figure 3.

A linear relation exists between bulk and apparent specific gravities of Iraqi limestone as shown in Figure 4. The relation, expressed by Eq. 3, has a correlation coefficient of 0.93.

$$G_b = 1.28\ G_a - 0.81 \tag{3}$$

The standard error of estimate with respect to the y-axis is 0.055.

The relation between percentage of wear and specific gravity is shown in Figure 5. The band between the dashed lines indicates that the scattering of points tends toward linear relations. The solid line halfway between the dashed lines uses the least squares method of analysis; thus, Eqs. 4 and 5 are obtained.

$$W = 202 - 70\ G_a \tag{4}$$

$$W = 162 - 57\ G_b \tag{5}$$

Figure 5 compares reasonably well with Figure 4. The scattering of points in Figure 5 seems to be reasonably acceptable for practical estimations; correlation coefficients are 0.74 and 0.83 respectively.

Figures 2a, 3b, 4, and 5 are combined to obtain the nomograph shown in Figure 6. Once the specific gravity of limestone is known, the nomograph can be used to estimate the compressive strength, the impact value, and the abrasion wear in the Los Angeles abrasion test. If the abrasion wear is known, the nomograph can also be used to estimate the other properties. The equations presented relate abrasion wear to other physical properties because the Los Angeles abrasion test is characterized by the quickness with which a sample may be tested and the applicability of the method to all types of aggregate.

Figure 7 shows that there seems to be a relation between SiO_2 content and abrasion wear. The wear increases as the SiO_2 content decreases. That is to be expected because SiO_2 is regarded as a hard mineral compared with other minerals that constitute limestone.

No relation exists between MgO content and abrasion wear as shown in the scattered points on Figure 8.

Figure 9 shows that CaO content has a certain tendency toward a linear relation with abrasion wear; however, more data are required before a definite conclusion can be reached.

No significant relation seems to exist between abrasion wear and Al_2O_3, Fe_2O_3, R_2O_3, and SO_3 contents.

CONCLUSIONS

The following conclusions may be drawn from the tests on Iraqi limestone:

1. Relations exist between abrasion wear in the Los Angeles abrasion test and the following physical properties: compressive strength, impact value, and specific gravity;
2. Equations relating abrasion wear to compressive strength, impact value, and specific gravity were derived;

Figure 2. Abrasion wear and compressive strength.

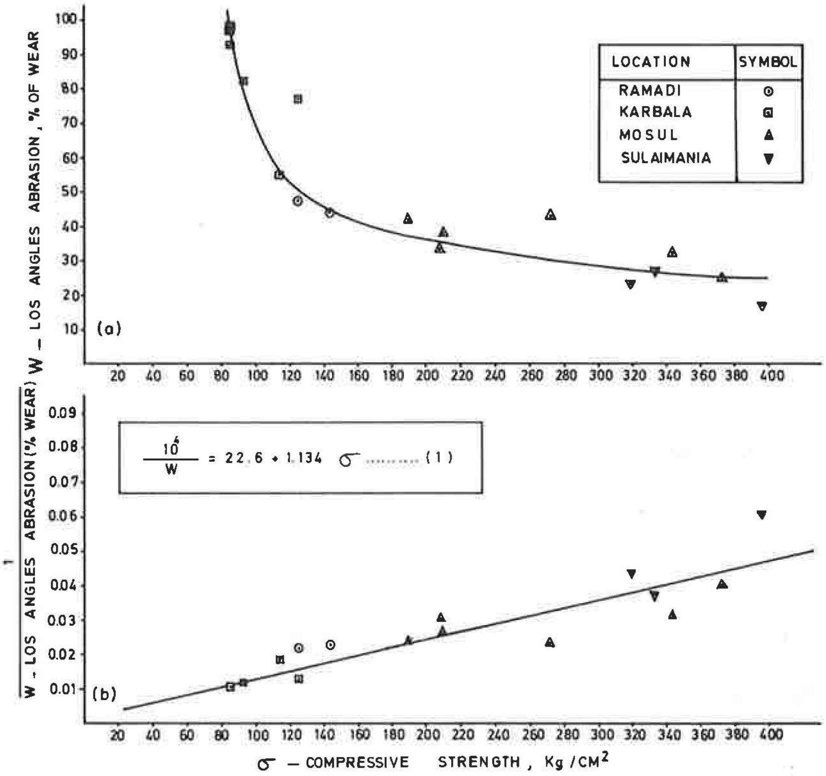


Table 3. Statistical analyses.

Figure	y	x	$\bar{y}$	$\bar{x}$	σ_y	σ_x	r	S_y
2a	1/W	σ	0.0256	205.8	0.0139	111.3	0.91	0.0055
3b	1/W	I	0.0256	7.24	0.0139	3.4	0.76	0.0090
4	G_b	G_a	2.00	2.20	0.26	0.35	0.93	0.055
5a	W	G_a	48.3	2.20	25	0.26	0.74	17
5b	W	G_b	48.3	2.00	25	0.36	0.83	14

Note: W = abraison wear, percent; σ = compressive strength, kg/cm²; I = impact, cm; y, x = standard deviation with respect to y and x; r = correlation coefficient; and S_y = standard error of estimate with respect to y axis = $\sigma_y \sqrt{1 - r^2}$.

Figure 3. Abrasion wear and impact value.

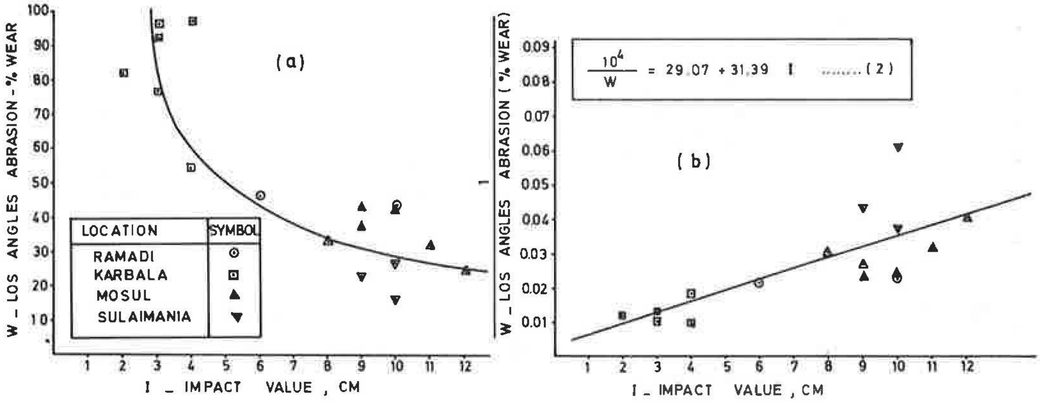


Figure 4. Bulk and apparent specific gravities.

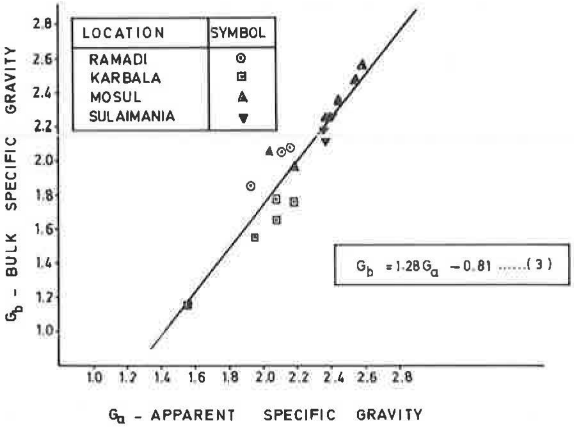


Figure 5. Abrasion wear and specific gravity.

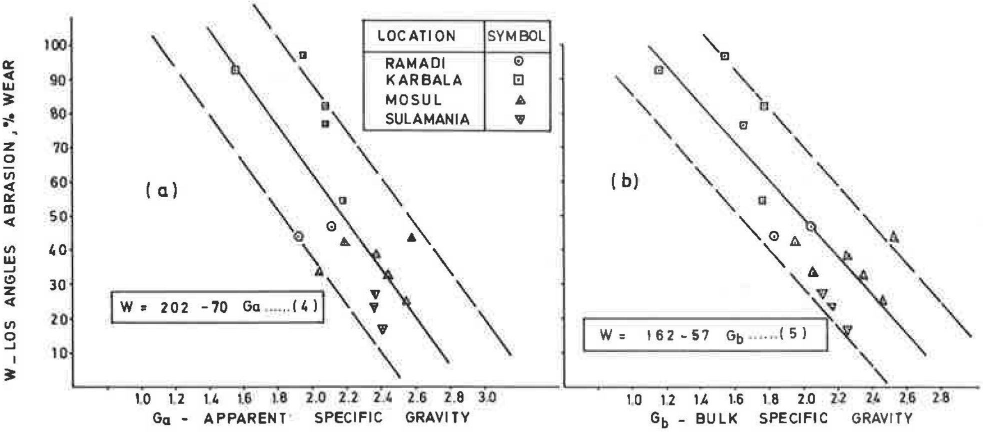


Figure 6. Correlation of physical properties.

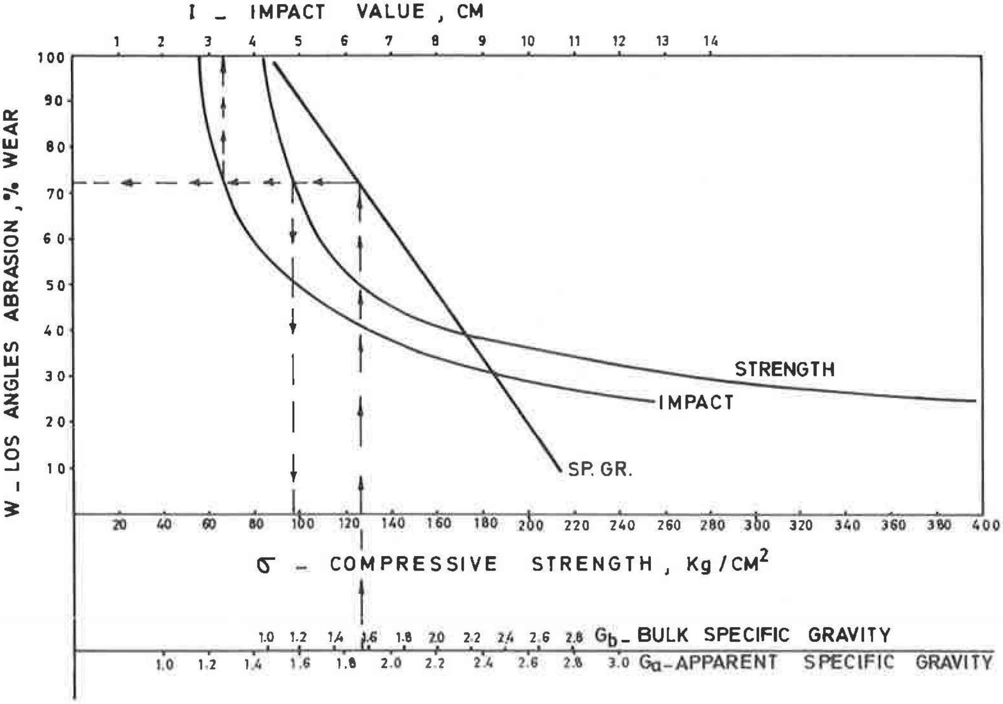


Figure 7. SiO_2 content and abrasion wear.

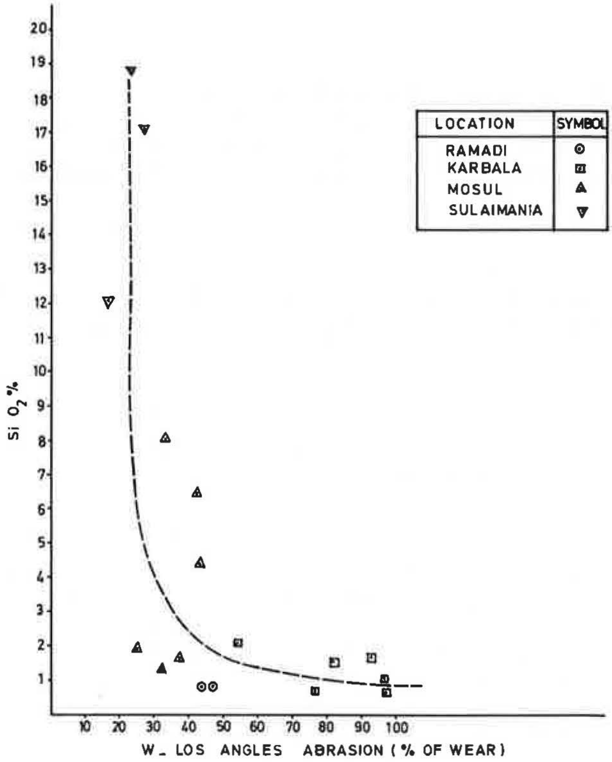


Figure 8. MgO content and abrasion wear.

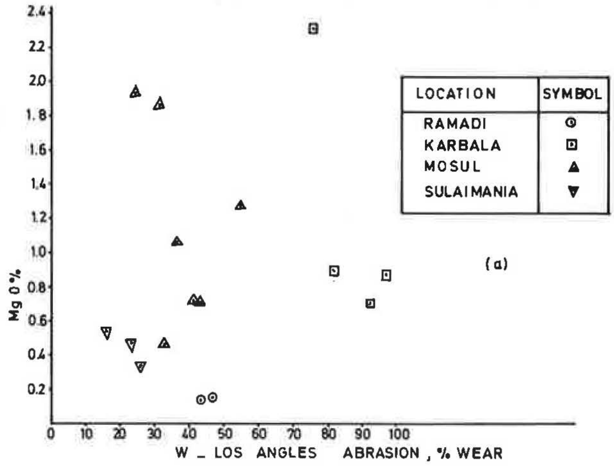
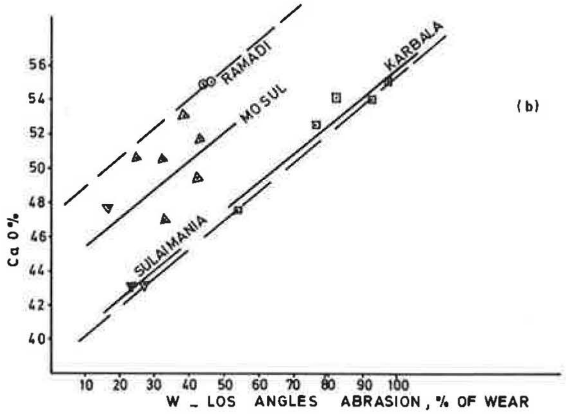


Figure 9. CaO content and abrasion wear.



3. A nomographic solution was presented that can be used to correlate the physical properties of Iraqi limestone and that will reduce the effort, tedious work, and time consumed in sample preparation and testing of limestone aggregates; and
4. SiO_2 and CaO contents influence the hardness and toughness of limestone.

RECOMMENDED RESEARCH

It is recommended that research be undertaken to investigate the applicability of the nomograph and equations presented to limestone from other regions; to expand the nomograph to include results of durability tests; and to investigate other gradations used in the Los Angeles abrasion test.

ACKNOWLEDGMENT

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