lished. Since pavement surfaces almost always contain rather large amounts of dust and dirt, time spent in carefully cleaning the surface before application of the paint will often prolong the service life of the paint and therefore prove profitable. The air temperature at the time of painting is important in that it materially affects drying time.

Conclusion

In conclusion, it may be pointed out that it is the job of the purchasing and testing agencies to provide the best paint possible consistent with cost and serviceable life on the road. It is the duty of the maintenance agency to apply the marking paint in the best way possible. Co-operation between these two agencies and care in the selection and application of a marking paint are essential to satisfactory results. The research of the Joint Highway Research Project is designed to provide basic information that will enable the co-operating agencies to give the motoring public more service and greater safety for their marking-paint dollar.

FUNDAMENTALS OF SURFACE-TREATMENT CONSTRUCTION

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Bituminous surface treatment may be defined as the application of bituminous material and mineral aggregate to an existing road surface or pavement. The term "surface treatment" as used in this paper applies to the use of these materials to form a wearing course less than one inch in thickness. The purposes of such a treatment are as follows: to eliminate dust, to harden and improve the ability of the wearing surface to withstand the abrasive action of traffic and disintegration by weathering, and to maintain a smooth-riding, skid-proof wearing surface. This paper reviews briefly the development and extent of this type of work in Indiana and summarizes some of the more important findings of the Joint Highway Research Project affecting surface treatment, design, construction, and performance.

Development in Indiana

While the practice of surface treating existing road or pavement surfaces was first started early in the twentieth century, it was not until after the World War and the universal use of pneumatic tires that this type of work received a great amount of attention. With increased automobile speeds, the traveling public demanded safe roads that were smooth-riding, dustless, and skid-proof. The improvement of construction equipment, as well as a more thorough knowledge of bituminous materials and the behavior of bituminous-coated aggregate, has added much to the progress of this type of work.

Indiana, having an abundance of aggregates well distributed throughout the state, had developed a good system of traffic-bound gravel and stone roads at the time of the establishment of the State Highway Commission. It was only logical when better roads were demanded that many of these roads should be salvaged wherever possible and converted into higher types. This salvaging, particularly on the intermediate and secondary-type highways, has been possible by the use of stage construction—i. e., traffic-bound, dust-palliative, oil-mat, and successive surface treatments. Some of these highways having good alignment and grades have been converted into primary roads by the construction of a higher-type surface. The necessity for salvaging old bases and pavements wherever possible is apparent when we consider that during the past ten years the mileage of the state system has been doubled. At the same time, the amount of available highway funds has not been materially increased.

Bituminous surface treatments have been constructed extensively in Indiana, particularly during the past ten years. A review of the annual reports of the State Highway Commission shows that for this period from 800 to 1600 miles (8-16%) of the state system is classified under this type. Likewise, many miles of the more heavily traveled county roads and some of the streets in the smaller cities and towns are grouped in this classification. Assuming an average of 50 miles for each county, it is estimated that the total mileage of bituminous surface treatments in Indiana is in excess of 6,000. With such a mileage there is justification for research dealing with the improvement of this type of construction as well as the determination of some of the fundamentals which influence performance. Therefore, a few of the studies conducted by the Joint Highway Research Project will be described.

Associated Laboratory Studies

Adhesion. The results of preliminary inspections and surveys, which will be described later, led to the establishment of certain detailed laboratory studies, one of which was on adhesion. A study of the factors affecting the adhesion of various types of bituminous films to the surfaces of mineral aggregates was conducted and the results were published in bulletin form.[1] It was found that highly siliceous aggregates, such as quartz, chert, and granite, exhibited the least resistance to stripping in the presence of water and that porosity of the aggregate had no appreciable effect on their ability to resist stripping. Also, the adhesion of bituminous-coated aggregate could be improved by prolonging the curing period.

Bituminous Mixtures. To facilitate more uniform patching, and at the request of the Maintenance Department, a series of tests was conducted to determine the optimum bitumen content for aggregates commonly used in patch work.[2] Using a pugmill, several sizes of aggregates were coated with various types of bituminous materials and tested on the minitrack under moving-wheel-loads to determine what bitumen content gave the greatest strength. Results of these tests indicated that there is an optimum bitumen content for each aggregate which varies directly with the surface area of the aggregate and is lower for hard aggregates than for soft ones. A dense grading required a higher bitumen content than an open grading, but also gave higher strengths. Another feature of this investigation was the determination of the best shape of a patch from a performance standpoint. It was found that if a patch was shaped so that traffic enters on a feather edge and leaves on a vertical edge, very little rutting or shoving results.

Field Studies

Preliminary Surveys. The State Highway Commission recognized the need for fundamental information regarding bitumous surface treatments because of the numerous failures which developed during the spring of 1936. Accordingly, when the co-operative research project was established in June, 1936, the first investigation and study started was that on surface treatments. Field inspections were made during that summer in each of the six highway districts. These inspections were for the purpose of determining the type and extent of failures, and whether failures could be traced to the use of any particular type of material. They also served to determine whether failures were general in extent or more pronounced in some particular geographical area. Pictures were taken of typical failures and also of the various surface textures encountered.

Ratings according to performance were given both the surface and the base of over 100 of these surface-treated roads, covering several hundred miles. These surveys indicated that, in general, failures could not be attributed to any

[1] O. R. Tyler, "Adhesion of Bituminous Films to Mineral Aggregates," *Purdue University Engineering Experiment Station Bulletin No. 62*, 1938.

[2] L. D. Graves, "Bituminous Road Mixtures Study," an unpublished report to the Advisory Board, 1939.

particular material, since some satisfactory treatments were found with practically all types of the materials commonly used. However, approximately 75 per cent of the surface-treatment failures could be attributed, at least partially, to inadequate base support. In many cases poor provisions for drainage were contributing factors to poor bases. No satisfactory treatment was found on a poor base; however, some treatments giving poor performance were found on roads with adequate bases. It was indicated that subgrade soil type was an influencing factor affecting performance. Exclusive of base failures, the most prevalent type of failure was raveling. Many fat spots and edge failures were also observed as typical failures.

Field Samples. Over 200 samples were collected from these treatments. After the treatment had been separated from the base, a determination was made of the bitumen content and also of the gradation of the aggregate. These treatments varied in thickness from nothing up to one and one-half inches. The bitumen content ranged from two to twelve per cent. Also, it was found that the gradation of the aggregates was entirely different from that used in construction. For example, the surface area of the bitumen-free aggregate ranged from 1000 to 7000 sq. cm. per 100 grams, while that used for construction was approximately 300. A wide variation both in bitumen content and gradation was found in samples from the same road taken at half-mile intervals. These variations both in bitumen content and aggregate gradation raised the question whether plant-mixed resurfacing with a depth greater than $\frac{3}{4}$ of an inch might not produce more uniform results and be more economical over a period of years.

Condition Surveys. While these samples represented the material left on the road, it was impossible to determine how much of the original surface was represented by the sample. For this reason it was believed that more could be learned regarding performance by observing all of the processes of surface-treatment construction. Accordingly, inspections were made and records kept during construction of 100 miles of surface treated in the fall of 1936. Condition surveys were also made the following spring to determine performance. The results of these surveys showed that surface-treatment performance is dependent, first of all, upon adequate base support. The thin treatment serves the purpose of transferring the load to the base, resisting the abrasive action of traffic, and the destructive elements of weathering, and preventing the entrance of surface moisture. It should not, therefore, be expected to add strength to the base except as it does so in performing the above functions.

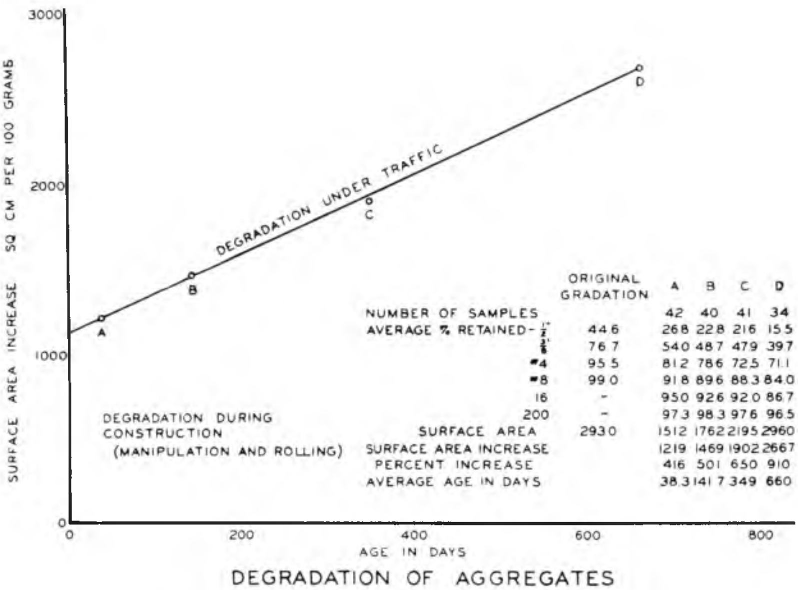
These surveys revealed the fact that surface-treatment performance is dependent also upon weather conditions during construction and immediately afterward. Increased raveling was found on those roads treated late in the season. For example, on one road observed, 60 per cent of the surface of the last mile treated raveled within six months, while on the first mile of this same road constructed under more favorable weather conditions only 20 per cent of the surface had raveled. The weather conditions during the construction of the last mile were very unfavorable for this type of work, the average temperature being below 60° F. Surface treatments should be constructed early enough in the summer to allow proper curing under traffic during warm weather. The warm weather is necessary for proper curing, and the traffic under such conditions gives additional compaction resulting in a denser, better-sealed surface.

Successful performance is also dependent upon adequate provisions for drainage. These surveys indicated that base failures can be, in most cases, attributed to inadequate provisions for drainage. For example, the survey made in April, 1937, showed that at every place where a base failure was noted, water was found standing in the ditch. The value of building a grade, even two or three feet, above the surrounding ground was emphasized by comparing two of these roads which were parallel and only three miles apart. The treatment on the one with the higher profile (two to three feet above the surrounding ground) was performing quite satisfactorily when last observed, while the other road was scarified and rebuilt the following summer. These surveys also showed that a large number of edge settlements or failures had developed, and that the wider shoulders of impervious materials were contributing factors to poor performance.

Some of these roads that raveled excessively were given a light seal coat of approximately .15 to .20 of a gallon per square yard of bituminous material and 10 or 15 pounds of size No. 11 aggregate the following spring. Later surveys showed that these light seal coats gave better performance and that the amount of raveling was reduced very materially by the use of smaller-sized aggregate. This suggested the possibility that less expensive seal coats might be more serviceable and more economical than the standard treatment when applied to roads with suitable bases.

Degradation. As previously mentioned, samples of surface treatments which had been subjected to traffic for a year or so showed a great amount of breakage of aggregate particles. To learn more about this breakage, samples were taken of some of the 1937 surface treatments at periodic intervals of one, three, twelve, and twenty-two months after construction. It was found that a large amount of crushing had resulted from manipulation and rolling during construction. Also, there was a gradual break-down of the aggregates under traffic which showed a straight-line relationship with time (Fig. 1). This led to the establishment of a comprehensive series of tests on a number of aggregates.

A series of field tests was conducted and reported on the degradations produced by road rollers on typical surface-treatment aggregates.[3] It was found that the resistance of aggregates to crushing under road rollers is a characteristic of each aggregate and, hence, varies with different aggregate types and sources. The Los Angeles abrasion machine at 100 revolutions gives a good indication of the amount of degradation under road rolling and presents substantiating evidence that this laboratory test can be used satisfactorily in predicting aggregate degradation under field conditions. The degradation



	ORIGINAL GRADATION	A	B	C	D
NUMBER OF SAMPLES		42	40	41	34
AVERAGE % RETAINED - 1/2"	44.6	26.8	22.8	21.6	15.5
3/8"	76.7	54.0	48.7	47.9	39.7
#4	95.5	81.2	78.6	72.5	71.1
#8	99.0	91.8	89.6	88.3	84.0
16	-	95.0	92.6	92.0	86.7
200	-	97.3	98.3	97.6	96.5
SURFACE AREA	293.0	1512	1762	2195	2960
SURFACE AREA INCREASE		1219	1469	1902	2667
PERCENT INCREASE		416	501	650	910
AVERAGE AGE IN DAYS		38.3	141.7	349	660

Fig. 1. Progressive degradation of aggregates as determined from periodic samplings of 12 state roads surface-treated in 1937. (Each sample taken adjacent to previous sample.)

of aggregates under conditions of mixing, rolling, and traffic, as well as in the Los Angeles abrasion machine, approaches a maximum density curve, such as Fuller's, as an ultimate. This fact suggests a desirable trend in the design of surface-treatment mixtures toward longer gradings which approach maximum density.

Test Road No. 3. Because of the variations existing in quantities and types of materials and methods of construction, it was decided that, by constructing a number of test sections,

[3] Tilton E. Shelburne, "Crushing Resistance of Surface Treatment Aggregates." *Engineering Bulletin of Purdue University, Research Series No. 76,* Sept., 1940.

some of these variables could be evaluated. Consequently, during the summer of 1939, in co-operation with the Highway Commission, 51 test sections, each approximating 1000 feet in length, were constructed by the maintenance forces of the LaPorte District on State Road 8 in northern Indiana. This particular road was chosen because of its uniform base and subgrade conditions, the underlying soil being quite sandy. The amount of traffic throughout the length of this test road is also fairly constant. Three types of bituminous materials, namely, rapid curing asphalt cut-back RC-3, asphalt emulsion AES-3, and tar TH were combined with crushed stone from two sources and of four gradings. The amounts of these bituminous materials were varied for the different aggregate gradations. Samples of the covering aggregate were taken from the road immediately before the application of bituminous material for moisture-content determination. Complete records were kept during construction on each of the sections as to the quantity of materials, construction procedures, etc. Photographs were taken of the various construction operations and of the surface textures of typical sections after construction. Measurements of surface textures by means of the profilometer were made immediately after construction and also after seven and twelve months' service. Periodic inspections and ratings have been made of these sections since construction.

Fig. 2. A general view of a portion of J.H.R.P. Test Road No. 3.

These sections have now been in service for nearly eighteen months and have given satisfactory performance. That the appearance of these sections is not greatly different from that shortly after construction is perhaps caused not only by adequate base and drainage conditions, but also by the relatively small amount of traffic carried by this road. No difference is apparent between the performance of the crushed limestone from the two sources. In spite of the great difference in characteristics of the three types of bituminous materials, only slight variations can be observed in their performance. However, the liquid asphalt RC-3 and asphaltic emulsion AES-3 sections have functioned slightly better than the tar TH with the coarser, more open-graded aggregate (8F).

The variation in surface textures of the different sections secured by the use of various sizes of aggregates is particularly significant. Measurements of texture by the profilometer showed that the use of finer-sized covering aggregates (No. 9) produced better textures which were subject to less change than the coarser ones. Some scuffing and slight raveling were noted on the sections where the coarser-sized covering aggregates (8F) were used. It was observed that the sections where the finer-sized, longer-graded aggregates were used dried quicker after a rain, indicating a tighter seal.

Results

It is hoped that these findings may prove useful to all public officials and engineers entrusted with the construction and maintenance of city streets and county and state highways. The results of the preliminary inspections served the purpose of giving a perspective of the various surface-treatment problems as well as of determining the type and extent of failures. Later condition surveys emphasized certain factors which affect performance. All of these have been invaluable in establishing detailed studies on certain problems. Of particular significance are the studies on the degradation of aggregates. These studies brought to light the fact that aggregates have a fixed manner of degrading, approaching a maximum density curve, such as Fuller's, as an ultimate. This also suggested a desirable trend, in the design of surface-treatment mixtures, toward longer gradings which approach maximum density. This can be approximated in road mixing by using a combination of sizes and the correct sequence of applications. These studies also showed that the Los Angeles abrasion machine can be used to predict aggregate breakage under field conditions. The development of the profilometer as a means of determining surface texture also bears considerable promise. It is possible that such a device may be used not only for determining when a given surface needs a retreatment but also the desirable size of covering aggregate that should be used.

In conclusion, it should be remembered that surface-treatment performance is dependent, first of all, upon adequate base support and drainage. Performance is also dependent upon weather conditions during construction and immediately afterward. Surface treatments should be constructed early enough in the summer to permit curing under traffic during warm weather. The warm weather is necessary for proper curing of the bituminous material, and the traffic under such conditions gives additional compaction resulting in a denser, better sealed, longer-life surface.

APPLICATION OF PHOTOGRAPHY TO HIGHWAY RESEARCH

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The value of photographic records and the importance of photographs as a medium of description have made the use of pictures indispensable in the proper presentation of technical papers, reports, and bulletins.

The growth of the Joint Highway Research Project and the multiplicity of studies have made the centralization and standardization of the photographic work most desirable. As a

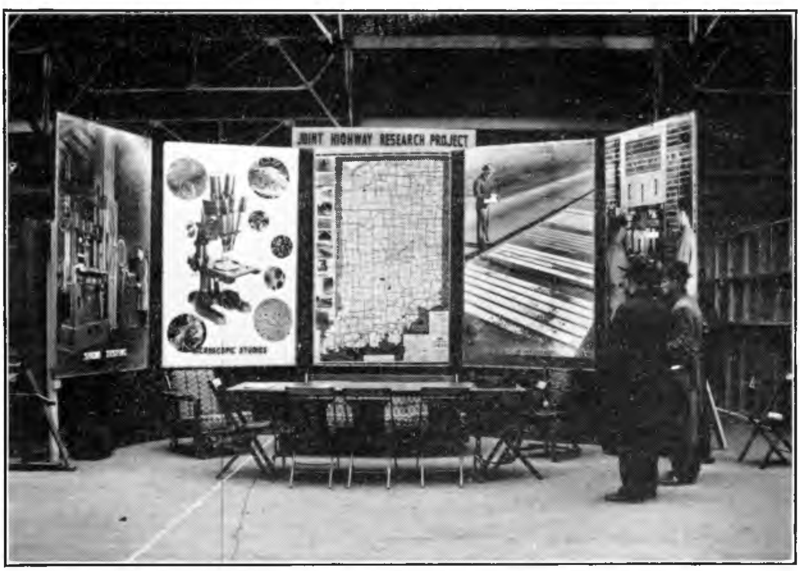

Fig. 1. Photographic exhibit of Joint Highway Research Project at the Road Show.