Experiences with Gyratory Testing Machine

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•IN 1961, the Department of Civil Engineering of West Virginia University established a bituminous mixtures laboratory as a part of the facilities of the new Engineering Sciences Building. The equipment obtained for the laboratory included a Model 4-C gyratory testing machine (Engineering Development Co., Inc., Vicksburg, Miss.) to permit instruction and research with the most recently available and promising test equipment.

Late in 1961, a research contract was initiated between West Virginia University, the West Virginia State Road Commission, and the U. S. Bureau of Public Roads to develop a bituminous mixture design procedure suitable for West Virginia aggregate and gradation and to reproduce the successful experience designs developed through state experience. The general approach to the mixture design study was to utilize the gyratory testing machine for laboratory sample compaction and to measure the engineering properties of the samples using stabilometer, cohesiometer, air voids, and density techniques. As the research program progressed, it became apparent that there were numerous aspects of the gyratory testing machine that should be investigated. Initial studies dealt with uniformity of compaction as reported by several laboratories, effect of various angles of gyration, ram pressure, and number of revolutions with the fixed roller and the air roller. The latter investigations opened still other areas of interest, including the effect of air-roller pressure and the significance of results.

Very little is contained in the literature with respect to gyratory compaction and testing since the initial studies by the Texas Highway Department (7) and the development by the Corps of Engineers (1) of the present-day form of the equipment. The available literature deals primarily with fixed-roller compaction. It has also been noted that there is appreciable interest in the results obtained by the work at West Virginia University. This paper is presented in an effort (a) to define the character of the studies performed to this date at West Virginia University, (b) to present the problems encountered with the equipment, (c) to illustrate the type of results that have been obtained, (d) to discuss the tentative conclusions reached from the results, and (e) to indicate the present trend and probable future aspects of the West Virginia University research with the gyratory testing machine.

LIMITATIONS OF EXISTING BITUMINOUS MIXTURE DESIGN METHODS

There are numerous factors that limit the use of the various bituminous mixture design procedures employed today. The following discussion is not intended to consider all of these factors but has been limited to comments of particular interest to the authors' studies with the gyratory testing machine.

Present methods of bituminous mixture design consider the influence of vehicular traffic by changing the design criteria or the amount of laboratory compaction. Materials that fail to meet the design criteria are either discarded or altered by changing the aggregate gradation, mineral filler content, and/or grade of asphalt cement to attain the desirable mixture characteristics. The modification of a bituminous mixture may be desirable if it is assumed that the various test measurements are accurate and that the design criteria are applicable to existing conditions.

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Variations due to materials, equipment, and the skill of the technician may result in erroneous selection of design asphalt contents. Elimination of complex and numerous test procedures would be beneficial in reducing much of this variation.

Certain aggregate types and gradations yield inadequate stability but when subjected to a slight increase in compactive effort show an appreciable increase in stability. Laboratory compaction should simulate the density and stability characteristics that are reasonably and economically attainable by field compaction of the mixture. Is it feasible to increase stability with a greater amount of compactive effort, or is it more desirable to alter the aggregate gradation without increasing compactive effort? Current design methods consider only the alteration of the grading to obtain satisfactory stability, although inadequate stability may still exist after construction (because of a low degree of field compaction) or failure of the pavement surface may develop with traffic (as a result of 100 percent or more of laboratory compaction). Certainly the existing design procedures do not define the minimum acceptable stability or the maximum density for construction to assure reasonable compaction requirements and adequate stability for the life of the pavement. Existing procedures attempt to do this by a middle-of-the-road approach.

Limitations of existing bituminous mixture design methods may be summarized as follows:

1. Design procedures do not establish a minimum field-compacted density based on a stability criterion;
2. Design procedures do not establish a maximum field-compacted density based on stability considerations for the densities developed during the life of the pavement; and
3. Design procedures do not evaluate the stability characteristics of mixtures through a wide range of density conditions.

OPERATIONAL ASPECTS OF MODEL 4-C GYRATORY TESTING MACHINE

The major operational aspects of the gyratory testing machine have been thoroughly discussed in the literature (1, 3); however, certain significant aspects of operation have been neglected. The ensuing discussion pertains to the utilization of different upper rollers and to the operational difficulties encountered in the studies performed at West Virginia University.

Fixed-strain operation may be attained by using either the fixed roller or the oil-filled roller, as shown in Figure 1. The oil-filled roller offers the advantage of direct measurement of roller pressure for constant angles of gyration. Pressure changes provide more sensitive measurements of variation in the character of the sample than may be obtained by observing changes in the width of the gyrograph and, thus, provide a direct comparison between different aggregates, gradations, and asphalt contents. If pressure readings are not utilized, the only recourse is to assume that the mixture will have adequate stability at the design asphalt content selected on the basis of the gyrograph.

Flushing, or widening of the gyrograph, results when the force exerted by the off-center weight of mold and mold chuck exceeds the resisting force of the mixture being compacted. If the angle of gyration is increased, the force exerted by the mold chuck increases so that flushing will be observed at a higher level of mixture resistance. This effect is most desirable since it provides a basis for establishing arbitrary levels of stability for different contact pressures to evaluate mixtures for a wide range of traffic conditions.

McRae states:

> The 100 ram pressure, 1 ½° angle of gyration, and 20 revolutions may be a better selection for heavy highway traffic (75 blow Marshall). In general, increasing the angle of gyration produces a lower optimum for the same density. (6)

The logical design procedure would be to utilize a ram pressure and an angle of gyration similar to actual contact pressures and strains to produce stabilities sufficient for each level of traffic service. This assumes that a criterion is available to define

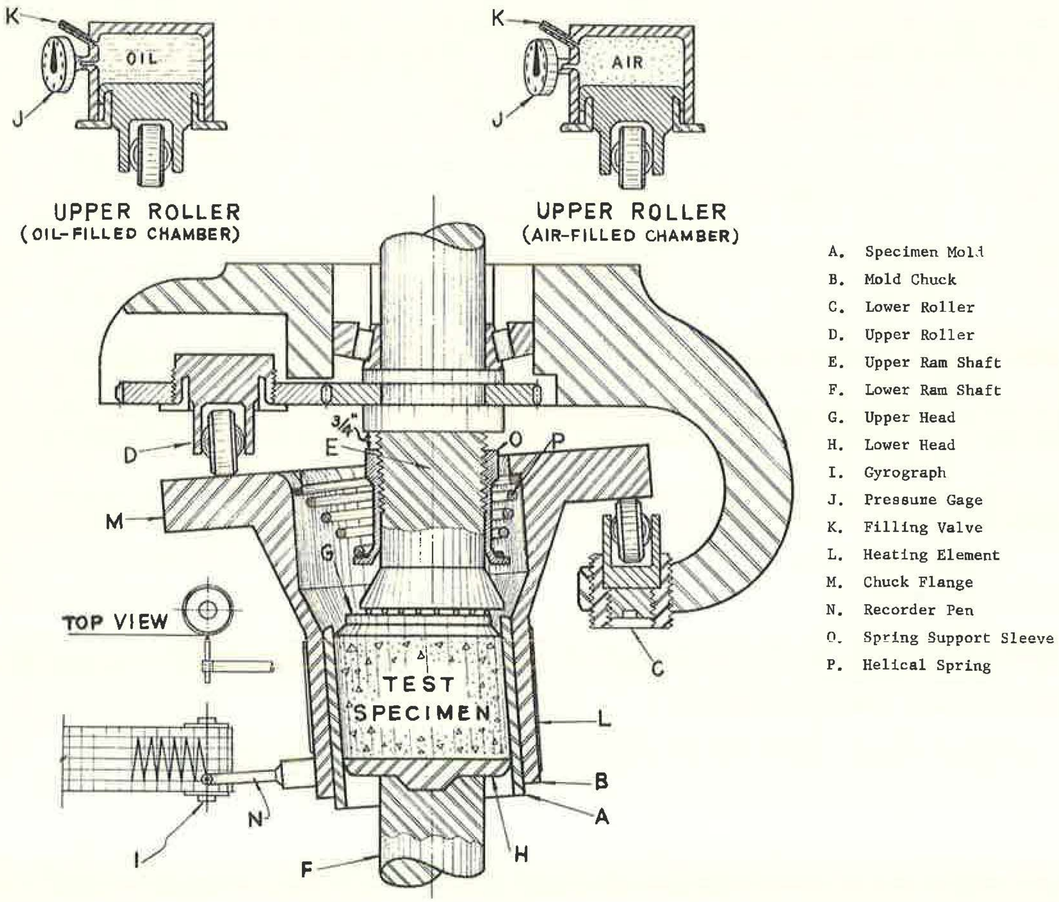

Figure 1. Schematic side view of section through gyrating mechanism (from U. S. Corps of Engineers).

the optimum number of revolutions that must be attained without reducing stability below the acceptable standard.

Normal procedure for setting the angle of gyration is to: (a) insert the sample into the mold chuck, allowing several revolutions to seat the sample; (b) place the upper and lower roller in line with the recording pen; (c) allow sufficient time to record a line on the chart; (d) rotate the rollers 180 deg; and (e) record another line on the chart. If the desired angle was 1 deg, the lower roller would be adjusted until the distance between the two lines was exactly 8 divisions. Each chart division is 7.5 min of angle. It should be remembered that the recorder chart is offset from the center of the mold. The top view of the recorder pen and chart is shown in Figure 1. If the rollers are not aligned properly, the recording pen will indicate a larger angle than actually exists.

When setting large angles of gyration, the sample must have adequate stability to accept the greater load. As previously mentioned, flushing will occur at higher stability when the angle of gyration is increased. Greater difficulty in the setting of accurate and reproducible large angles of gyration may be experienced unless this condition is recognized.

The effect of sample height on the performance of a mixture also must be considered. Kallas (2) reports that heights from $2\frac{1}{4}$ to $2\frac{3}{4}$ in. had no significant effect on the recorded angle of gyration when using a 1-deg and 200-psi setting. Although less likely,

TABLE 1

AGGREGATE GRADATION FOR COMPARATIVE COMPACTION STUDIES

Sieve Size	Passing Sieve (%)	
	1st Series	2nd Series
¾ in.	100	-
½ in.	90	100
⅜ in.	80	95
No. 4	60	65
No. 8	40	45
No. 16	32	32
No. 30	21	-
No. 50	12	14
No. 100	11	8
No. 200	8	4

this may be the case at 2 or even 3 deg. This condition further indicates the lack of sensitivity provided by the gyrograph. Consequently, it is believed that gyrograph widening should be used only as a general guide in the design of asphaltic mixtures.

Another factor of interest is the use of the gyratory testing machine air roller (Fig. 1) for variable strain compaction and testing. This method of operation provides a variable degree of angle kneading which is dependent on the nature of the material (1). Adjustment of the air-roller pressure permits the use of a wide range of strains which are dependent on the initial setting of the angle, air-roller pressure, and the resistance of the specimen. Changes in sample stability are accompanied by changes in the pressure developed in the air roller. If the air-roller pressure is initially set too high, the operation reverts to the fixed-strain condition and flushing will occur without a change in pressure. In this case, the air roller remains in a fixed position and widening of the gyrograph occurs in the same manner as with the fixed roller. The angle of gyration is set by using the fixed roller following established procedures or by using the air roller at high pressures, assuming that the roller is fully extended. The first method is more reliable, but care must be taken to assure that the dimensions of both rollers are the same. A height gage can be used to measure the distance from the roller mount plate to the bottom of the roller. Model 4-C gyratory testing machine rollers should be interchangeable without affecting the angle of gyration.

The maximum recorded angle that can be attained during operation is approximately 5 deg. The actual angle is less than 5 deg since the recorded angle value includes the effect of the recorder pen during operation. As the angle is increased, the neutral axis of the mold chuck raises and displaces the recorder pen upward with respect to the chart. At 5 deg the chuck mold will hit the spring support sleeve near point 0 and the upper portion of the gyrograph will be on the margin of the chart paper. Excessive angles are not normally encountered unless air-roller pressures are being recorded for high levels of strain. Tests of this type may, over a period of time, further restrict the angle of gyration by moving the threaded spring support sleeve downward and hitting the helical spring. The distance between the upper lock rings and the spring support sleeve should be set at ¾ in.

COMPARATIVE COMPACTION STUDIES

A comparative study of gyratory compaction was initiated in 1962 in cooperation with the Asphalt Institute and the U. S. Bureau of Public Roads. The first series of tests utilized material furnished by the Asphalt Institute. The material for the second series was furnished by West Virginia University. The aggregate gradations for these mixtures are given in Table 1. Duplicate samples for each of three different asphalt contents were prepared for each participant by the laboratory furnishing the material. These samples were compacted by the three laboratories using the fixed roller, 100-psi ram pressure, 1-deg angle, and 30 rev plus 3 for leveling. The comparison of the differences in unit weight is given in Table 2.

The first series appeared to give reasonable variation in density values except that the maximum density difference for the average of two samples for each laboratory was approximately twice as large as the difference between the samples compacted at any one laboratory. For example, the maximum density differences for the 4.5 percent

TABLE 2

DIFFERENCES IN UNIT WEIGHT

Series	% Asphalt[a]	Max. Density Diff. (pcf)	
		Between Labs.	Between Samples[b]
1st	4.5	1.8	0.9
	5.5	1.1	0.5
	6.5	0.1	0.15
2nd	5.66	2.3	2.2
	6.54	0.4	1.2
	7.41	0.3	0.4

[a] By weight of total mix.
[b] At any one lab.

asphalt content specimens from different laboratories was 1.8 pcf, and the difference at any one laboratory was 0.9 pcf. This discrepancy was attributed to variation in the procedure used at each laboratory. The method for setting the angle of gyration and the procedure used in putting the mixture into the mold were considered the major sources of error.

A second series of samples was prepared following a detailed materials handling and compaction procedure. In the second series, the loose material was heated to 250 F for 4 hr and then was transferred into heated compaction molds using a large funnel to allow the mixture to be dumped into the mold without excessive delay. The flat side of a metal spatula was used to press the mixture into the mold so that the funnel could be removed. A 4-in. diameter metal plunger was inserted in the mold and the mix was compressed by hand to provide approximately ½ in. of clearance between the top of the mold and top of the sample. The chuck heater was not used because of the short time required for compaction and the negligible effect of temperature within the normal operating range (2).

The results as given in Table 2 indicate that the variation in density between samples from different laboratories did not exceed that obtained in samples from any one laboratory; in fact, it is considerably smaller for the samples with 7.0 percent asphalt content. Comparison of samples compacted at any one laboratory illustrates that the gradation has a pronounced effect on the uniformity of compaction. The finer grading, as used in the first test series, logically produces more uniform compaction characteristics resulting in less variation in density.

It is not intended that the results or comparisons presented in the previous discussion be considered as applicable to different materials, gradings, or laboratories. The most significant fact is that the gyratory testing machine does provide a method of compaction which will give reproducible results and that the method of sample preparation does influence the obtained results. The latter may be significant when comparing results from more than one laboratory.

FIXED-ROLLER DESIGN

Prior research appears to have been concentrated on the fixed-strain application of the gyratory testing machine using either the fixed roller or the oil-filled roller for compaction. Research by McRae and other personnel at the U. S. Army Engineer Waterways Experiment Station (1) has established gyratory compaction criteria that are essentially equivalent to 50 and 75 blow Marshall compaction, i.e. 100-psi and 200-psi ram pressure, respectively, with a 1-deg angle and 30 rev plus 3 for leveling. With this procedure, the design asphalt content is determined by selecting an asphalt content 0.5 percent below that where flushing occurs as indicated by the widening of the gyrograph. The design asphalt content selected in this manner provides the maximum unit weight attainable for any specified compactive effort.

Design of bituminous mixtures using this generalized approach may be inadequate since the amount of gyrograph widening necessary to denote a loss in stability or flushing of the mixture is not specified. Another approach to the selection of a design asphalt content is to utilize the gyratory testing machine as a compactor and, for those cases where the gyrograph does not widen appreciably, select the design value on the basis of air voids in the compacted specimen.

Kallas (2) describes a procedure combining both of these approaches for the selection of a design asphalt content. This gyratory design procedure, using the equivalent 50 and 75 blow Marshall compaction for medium and heavy traffic, respectively, defines the design asphalt content as 1 percent less than the critical asphalt content, determined as that asphalt content causing a 14-min increase in the width of the gyrograph. Test results obtained in establishing this criterion indicate that the optimum asphalt contents are essentially the same as those determined by the Marshall and Hveem method of mix design and apparently provide desirable air void contents. Kallas reports that slag aggregate mixtures and open-graded or coarse mixtures did not perform in the same manner as the dense-graded mixtures and are, therefore, excluded from consideration in the design approach.

Studies performed at West Virginia University verify, within certain limitations, the design approach presented by Kallas. Typical results from different materials and gradations are illustrated by the comparative curves of four different mixtures shown in Figures 2 and 3. Table 3 summarizes the values of the design asphalt content selected by the Kallas procedure and by the air-roller design procedure discussed later in this paper. These design asphalt contents were readily determined from the gyrographs with the exception of the slag-sand mixture, TR-9.

An example of the gyrographs (Fig. 4) for mixture TR-1 at 7.5 percent asphalt content shows a uniform width of 13 chart divisions corresponding to a gyratory angle of 1 deg 37.5 min. At 8.5 percent asphalt content, the width of the gyrograph is 15 divisions, which is an increase of 2 divisions or 15 min. Therefore. disregarding the relatively insignificant difference between the 15-min increase and the 14-min increase design criterion, the design asphalt content is 7.5 percent. A close inspection of the three gyrographs for the 8.0 percent asphalt content samples demonstrates the variation in angle that may occur with certain mixtures with the same asphalt content and prepared by identical compaction procedures. The widths of the gyrographs are 14, 13, and 14.5 divisions, respectively. The variation is probably due to slight differences in particle orientation between samples. The density for the second sample is lower than that of the other 8.0 percent asphalt content. It may be considered that the critical asphalt content is found at the point of incipient failure where a slight change in the structural arrangement within the sample creates a notable reduction in one or more of the physical properties.

Variations in the gyrographs of most slag mixtures, especially those that yield a flat density curve throughout a wide range of asphalt content, make it difficult to apply the Kallas design criterion. For example, the gyrograph produced with mixture TR-9 under fixed-roller operation showed variable amounts of widening at sample asphalt contents of 10.0, 10.5, and 11.0 percent. This condition is a direct result of the surface texture, angularity and porosity of the slag aggregate. In addition, mixtures of this type are characterized by high mineral aggregate voids and stability with little effect on the density. Further research may explain the mechanism of slag mixture performance. At present it is logical to assume, from the standpoint of economics and design, that reduction of asphalt content by the addition of fine aggregate (sand, not necessarily slag) will improve the characteristics of the mix so that existing design procedures can be utilized.

The problems associated with the use of the fixed roller in the design of bituminous mixture may be summarized as follows:

1. The fixed-strain method of testing may not be compatible to field compaction because of the sample restraint in the mold;

SIEVE SIZE / MIXTURE NO.	PERCENT PASSING								
	1/2	3/8	4	8	16	30	50	100	200
TR-1 LIMESTONE	100	94	65	47	27	18	11	6	2
TR-7 CRUSHED GRAVEL & OHIO RIVER SAND	100	96	67	43	36	21	8	4	1.5
TR-8 LIMESTONE & L. S. ROCK DUST	100	96	69	47	40	26	14	10	6
TR-9 SLAG & OHIO RIVER SAND	100	97	66	46	37	21	8	4	1.5

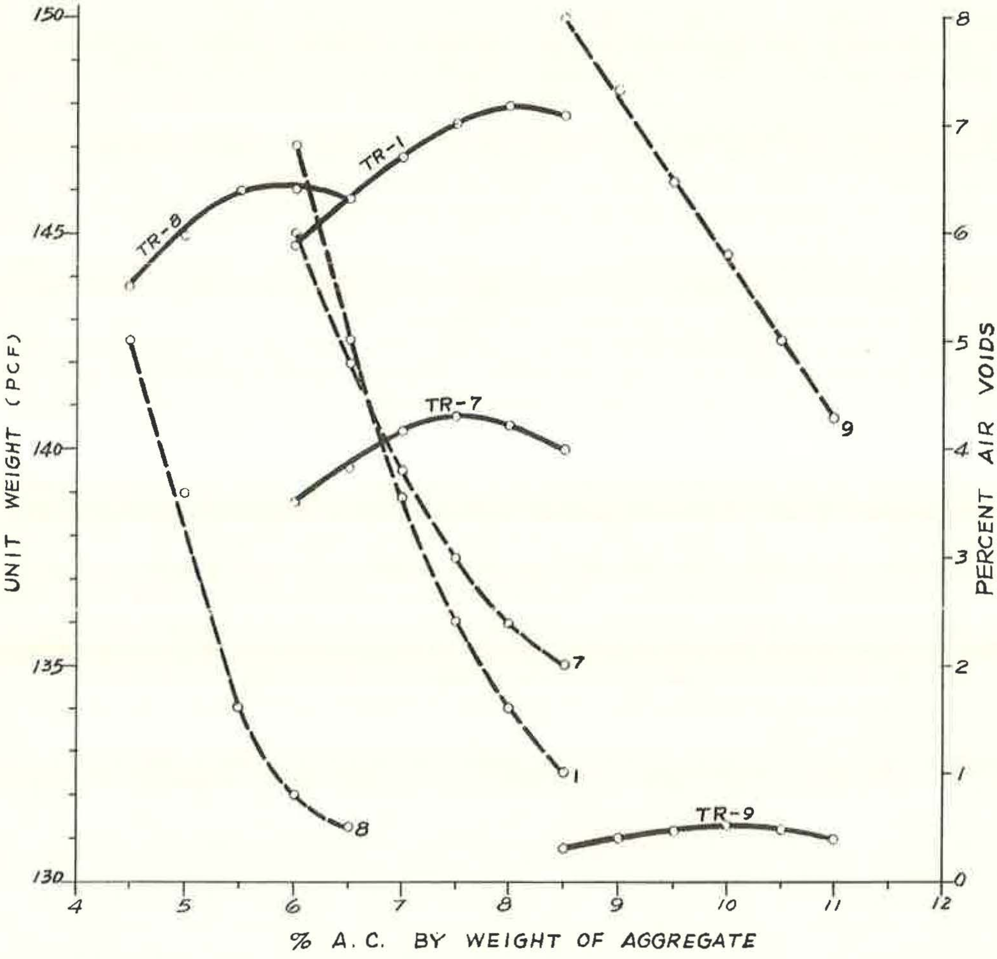

Figure 2.

2. The gyrograph does not provide adequate sensitivity;
3. Widening of the gyrograph to determine the design asphalt content is dependent on material type and gradation and, consequently, does not evaluate the relative stability of different mixtures; and

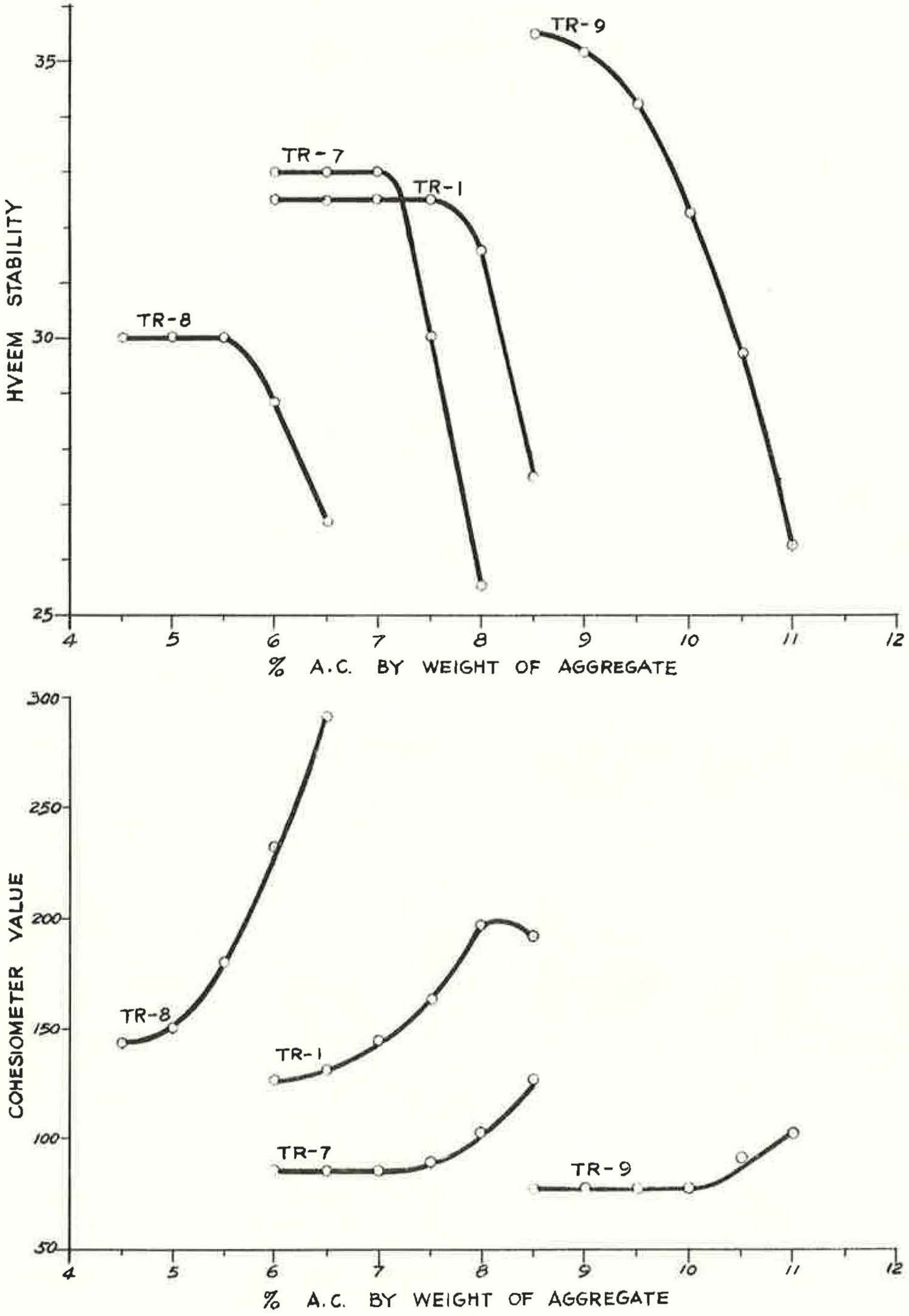

Figure 3.

4. The mechanism of flushing with fixed-strain operation is entirely dependent on the weights of the mold and mold chuck which become more critical as the angle of gyration is increased.

TABLE 3

DESIGN DATA FOR TEST MIXTURES

Mix No.	Design Procedure	Design Asphalt Content[a] (%)	Unit Weight (pcf)	Air Void Content[a] (%)	Min. Agg. Voids (%)	Hveem Stability	Cohesiometer Value
TR-1	Fixed roller	7.5	147.4	2.4	18.7	35	155
	Air roller	6.5	145.7	5.0	19.2	34	130
TR-7	Fixed roller	7.5	140.7	3.0	18.5	30	90
	Air roller	7.2	140.0	3.6	18.4	32.5	85
TR-8	Fixed roller	5.5	146.0	1.5	13.6	30	185
	Air roller	5.0	144.8	3.8	14.6	30	150
TR-9[b]	Fixed roller	11.0	131.0	4.6	25.5	26.5	100
	Air roller	10.5	131.4	5.0	25.2	30	90

[a] All mixtures using 85-100 penetration asphalt cement.

[b] Gyrograph showed 11-min increase in angle at 11.5 percent asphalt content; 12.0 percent asphalt content was not compacted so design asphalt content corresponding to 1 percent below the 14-min increase in angle may be closer to 10.5 percent than to 11.0 percent.

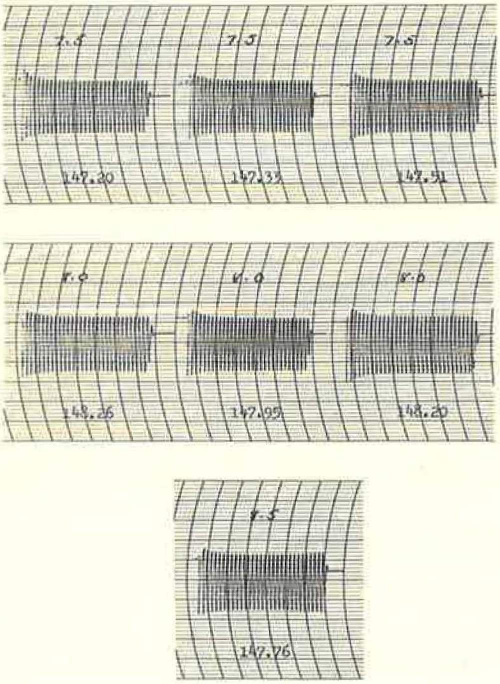

Figure 4. Mixture TR-1 gyrographs.

STUDY OF AIR-ROLLER CAPABILITIES

Application of the air roller for compaction or simulation of traffic has received very little attention in the literature, though it has been suggested that variable strain testing may be a useful tool for these purposes (1). Goode (5) investigated the effect of angle, revolutions, and initial air-roller pressure on the hot-mix compaction of two different aggregate gradations. Busching (4) used the fixed roller for initial compaction and the air roller for secondary compaction. These studies were limited in scope and, consequently, were not used to establish a design procedure.

Air-roller studies at West Virginia University were initiated in 1962. At that time, two possible approaches using the air roller appeared to warrant investigation. The first of these used the air roller to evaluate samples previously compacted by the fixed roller. It was thought that air-roller revolutions would simulate the effect of traffic on the compacted mixture and that some concept of the stability of the mixture under long-time repetitive loading might be obtained. The second approach was based on available field densification data for certain of the mixtures under laboratory study. Since construction compaction does not achieve the same density as obtained in the laboratory, it appeared to be reasonable to compact a sample in the laboratory with the fixed roller

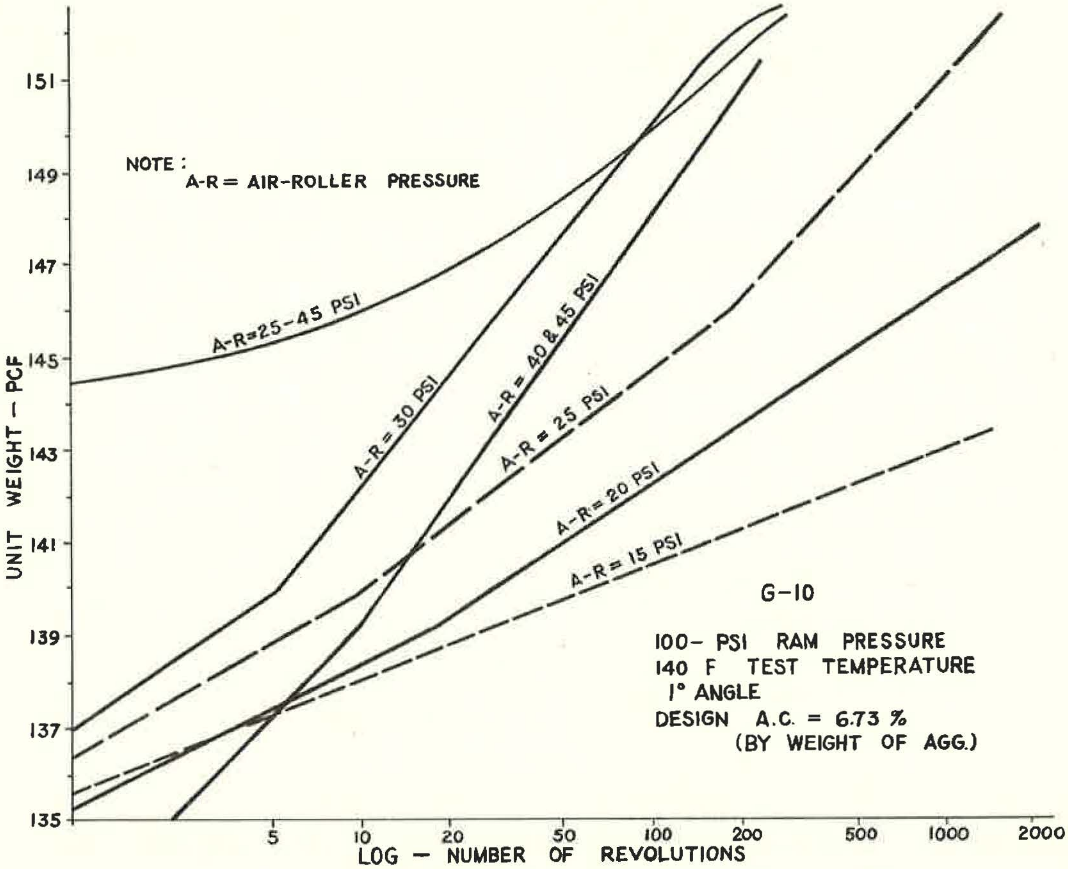

Figure 5. Effect of air-roller pressure on densification and revolutions.

to a density equal to that expected in the field and then to apply air-roller compaction until the density of the sample equaled that obtained in the field after a given length of time.

The two approaches were studied first from the standpoint of the effects of initial air-roller pressure on densification of samples for various numbers of revolutions using a 1-deg angle of gyration. Standard laboratory compacted samples were prepared using fixed-roller compaction with 1-deg angle of gyration, 100-psi ram pressure, and 30 rev plus 3 for leveling. Compaction of samples for duplicating field-compacted densities used the same procedure, except that 4 rev were used instead of 30. All samples were then densified at 140 F using different initial air-roller pressures and varied numbers of gyrations. Bulk specific gravities were obtained for each sample before and after air-roller compaction following the procedure outlined in paragraphs 4a and 4b of ASTM Designation: D 1075. Sample height values obtained during air-roller compaction were used to calculate intermediate densities. The results (Fig. 5) show increasing rates of densification for the low-density samples as the initial air-roller pressure was increased from 15 to 30 psi.

Air-roller pressures of 30 psi and greater produced similar rates of densification. The lateral shift between the 30- and 45-psi lines is attributed to the difference in initial densities. The slight difference in slope may be a direct result of difficulties encountered in measuring the bulk density of low-density samples. During the tests with 30- to 45-psi initial air-roller pressures, there was no discernible air-roller pressure change. Pressure fluctuations were readily observed in tests where the initial air-roller pressure was less than 30 psi. If there is no change in pressure

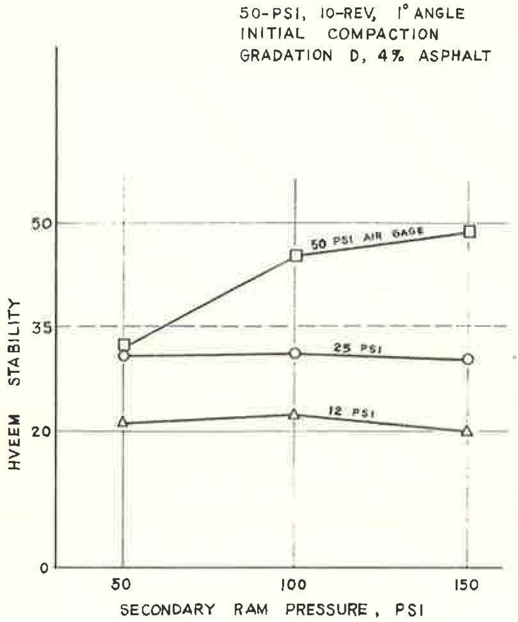

Figure 6. Hveem stability vs secondary ram pressure, air-filled upper roller, 400-rev secondary compaction (4).

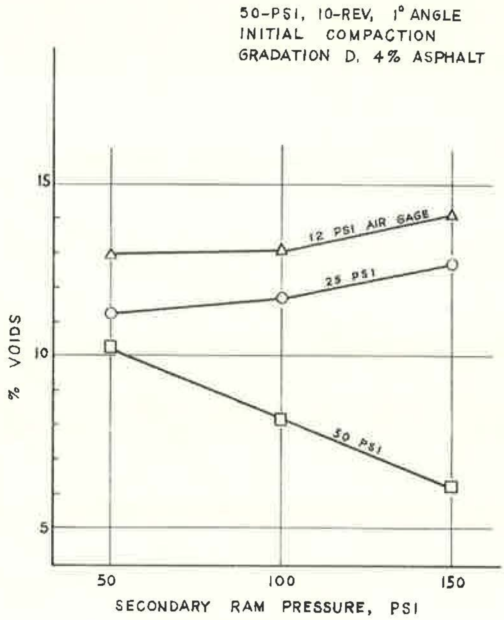

Figure 7. Percent voids vs secondary ram pressure, air-filled upper roller, 400-rev secondary compaction (4).

during air-roller densification, the test is actually a fixed-strain test instead of a variable-strain test. This condition occurs at different initial air-roller pressures, depending on the characteristics and temperature of the mixture.

One of the most significant aspects of Figure 5 is the change in rate of densification at 25-psi air-roller pressure. From 0 to 10 rev there is a tendency to parallel the 15-psi densification curve, between 10 and 200 rev to parallel the 20-psi curve, and above 200 rev to parallel the 30- to 45-psi curve. These changes are the result of the combined effects of changes in air-roller pressure which directly influence the angle of gyration and the characteristics of the mixture at different densities. At low initial air-roller pressures, the angle of gyration, as recorded on the gyrograph, was very small, indicating that the strain was also small. With this condition a great number of revolutions would be necessary to achieve any appreciable densification. At high initial air-roller pressure, the strain was so great that there were no observable air-roller pressure changes as the number of revolutions increased. With this condition, the test was essentially one of fixed strain. The 25-psi initial air-roller pressure was apparently of the right order of magnitude, for the mixtures and test conditions used, to produce increasing densification and resistance to strain with increasing numbers of revolutions and to reflect these increases with observable changes in the air-roller pressure. It was tentatively concluded, therefore, that the range of strain through which changes in the physical characteristics of the test mixture could be observed most readily could be obtained best with an initial air-roller pressure of 25 psi for initial angles of gyration of 1 deg.

Results obtained by Busching (4) further illustrate some of the effects of air-roller densification (Figs. 6 and 7). Busching concludes:

> **These figures indicate that for a constant ram pressure stability is a function of the angle of gyration. It appears that densities and stabilities produced by air-filled roller compaction would be equivalent to those produced by fixed-roller compaction provided air pressures were high enough.**

Tests performed on high-density samples showed similar rates of densification at air-roller pressures of 25 to 45 psi. Samples 1 and 2 (Fig. 5) illustrate the typical densification curves obtained for this range of pressures. The rate of densification above 100 rev is about the same as that obtained with low-density samples tested at 25 and 30 psi.

It should be mentioned that similar tests performed on this mixture at different asphalt contents did not show an appreciable difference in rates of densification. It is difficult to identify such changes because the initial density varies with asphalt content.

DEVELOPMENT OF TENTATIVE AIR-ROLLER DESIGN PROCEDURE

The results obtained in the study of air-roller capabilities clearly demonstrated that stability and rate of densification are dependent on the magnitude of strain for constant ram pressure, revolutions, and mixture type. If two mixtures of different stability-densification characteristics are tested at an initial angle of 1 deg and an air-roller pressure of 25 psi, for example, it would be possible for the high-stability sample to resist further densification so that no change in stability would occur. The low-stability sample may respond to air-roller densification and indicate trends in stability with increasing revolutions. Therefore, the problems associated with the air-roller testing procedure are twofold and may be stated as follows:

1. The 1-deg initial angle of gyration is not adequate to produce variable strains of sufficient magnitude to overcome the high resistance of certain mixtures without the increased use of air-roller pressure. If the air-roller pressure is increased to a satisfactory level for these mixtures, the testing of low-resistance mixtures will be essentially a fixed-roller test.
2. The change in angle, even if the angle is reduced from 1 to 0 deg, does not produce a large change in air-roller pressure. Therefore, the measurement of the angle of gyration by either air-roller pressures or gyrograph is not sufficiently sensitive for observing changes in the physical characteristics of a sample during densification.

A study was initiated for the purpose of minimizing these undesirable effects. The same mixture that was used in the previously described air-roller tests was compacted to a low density by fixed-roller compaction at a 1-deg angle of gyration. These samples were heated to 140 F and tested with initial angles of gyration of 2 and 3 deg, using air-roller pressures of 15, 20, and 30 psi for the 2-deg tests and 5 to 10, 15, and 20 psi for 3-deg tests. (The air-roller pressure gage was graduated in 5-psi increments so that precise settings or readings could not be obtained.) The results of this study showed that for the 3-deg angle of gyration, even with air-roller pressures as low as 5 to 10 psi, a minimum angle of approximately 2 deg was maintained during the initial stages of densification and an extreme increase in angle occurred within a short period of time. These tests were stopped when the mold chuck started hitting the spring support sleeve and the gyrograph indicated an angle of gyration of approximately 5 deg. At this point in the test, the top of the gyrograph was in the upper margin of the chart and the air-roller pressure for the initial setting of 5 to 10 psi was 27 psi. The undesirable aspects of the 3-deg test are as follows:

1. The air-roller pressure did not drop to the original setting before the capabilities of the gyratory testing machine were exceeded; and
2. Low-stability mixtures would be subjected to excessive strain (angle of gyration).

The first statement suggests that lower air-roller pressures at a 3-deg angle of gyration may alleviate the problem. It is not practical, however, to use an initial pressure of 0 psi since it is virtually impossible to attain a reliable setting. The frictional resistance and effectiveness of the seal in the pneumatic cell would likewise prevent the use of very low pressures. Also, it is apparent that the contact pressure on the chuck flange, for a given angle of gyration, must be adequate to prevent premature overstraining of the sample.

The second statement suggests that the angles of gyration would be in excess of 2 deg for low-stability mixtures and the samples would not exhibit normal stability or

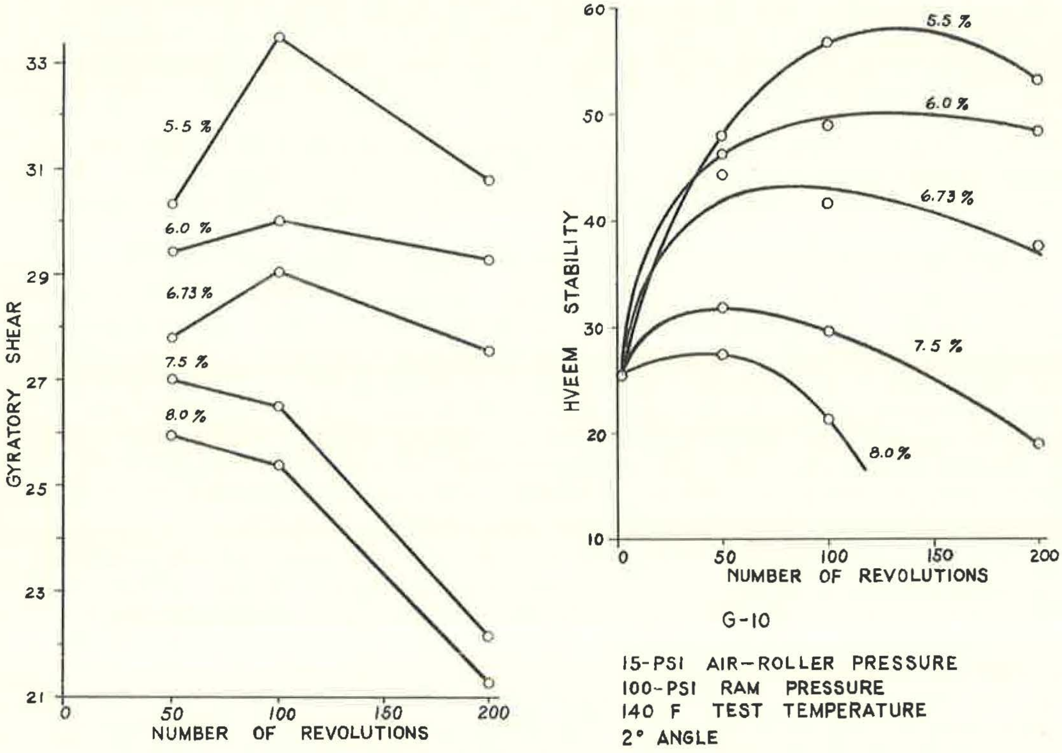

Figure 8. Stability vs revolutions for different asphalt contents.

densification characteristics. In studies performed by the U. S. Corps of Engineers (1), the following observation was made:

> Increase in gyration angle from 1 to 2 degrees causes an increase in both unit weight and stability, and an increase in angle beyond 2 degrees causes a decrease in both unit weight and stability.

This pertinent characteristic may be either a benefit or a hindrance in air-roller testing of bituminous mixtures. If, as indicated, the strain remains excessive throughout the test, the results probably are not representative of conditions existing in the field. If the strain never exceeds 2 deg, assuming a static condition where density and stability remain constant, the test is valueless because no change in mixture characteristics can be observed. Somewhere between these two extremes lies the optimum or most desirable testing procedure.

The results of the 2-deg angle of gyration tests indicated that air-roller pressures of 15 or 20 psi appeared to give the largest range in pressure variation throughout a given increase in density. It was decided to use the 2-deg angle of gyration and an air-roller pressure of 15 psi for the testing of different mixtures. It should be emphasized that the observed angle of gyration is produced by the combined effect of air-roller pressure and the force exerted by the weight of the chuck at that particular angle.

The first tests using this concept were made on mixture G-10 which was the same as used in earlier air-rolling testing. Correspondence from J. L. McRae (6) provided information that was utilized in all air-roller studies. McRae suggested the use of a gyratory shear value to indicate stability. This parameter is defined as follows:

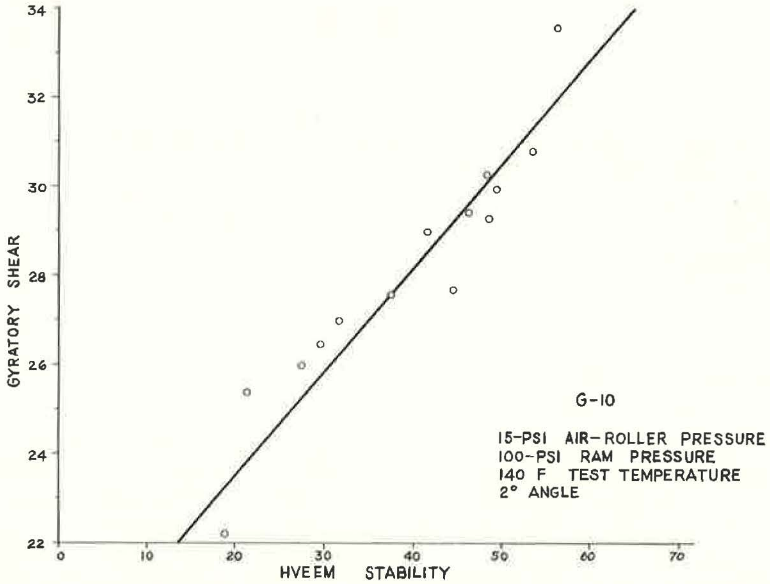

Figure 9. Gyratory shear vs Hveem stability.

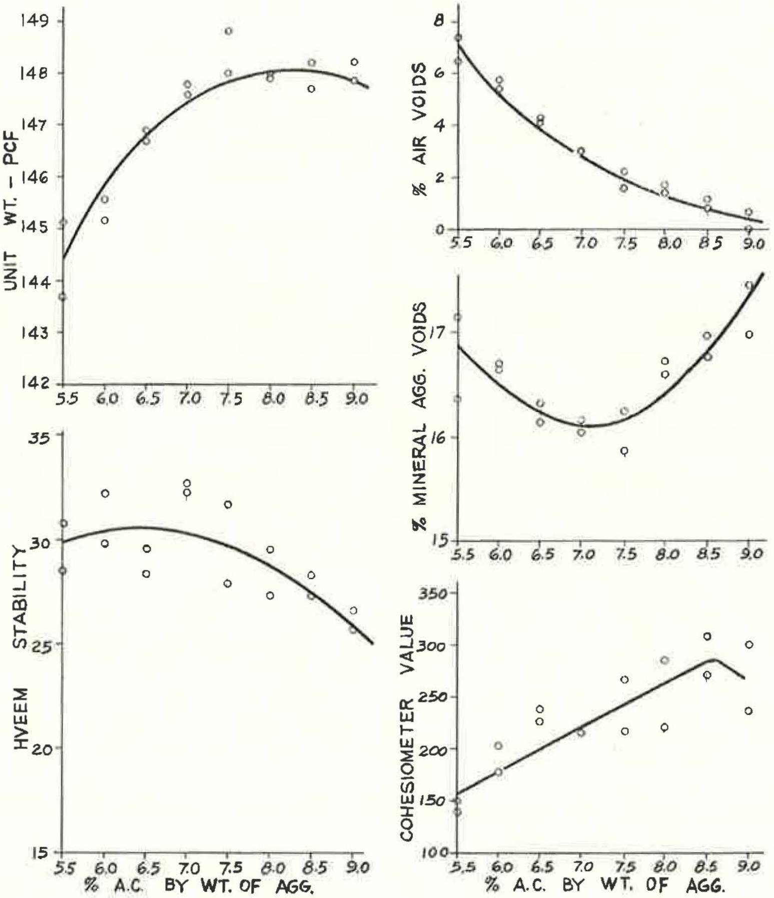

Figure 10. Mixture G-12 results.

$$G_S = \frac{P \cdot L}{V} \tag{1}$$

where

P = load in upper roller (lb) = effective area of upper roller times unit pressure, p, on upper roller = $5.28 \times p$;
L = distance from center of sample to center of roller = 5 in.;
V = volume of sample = area times height, $H = 12.56 \times H$; and
$G_S = \frac{5.28 \times p \times 5}{12.56 \times H} = \frac{2.1p}{H}$,

where

p = roller pressure (psi), and
H = height of samples (in.).

The results of the G-10 series (Fig. 8) showed a remarkable similarity between plots of gyratory shear and stability vs number of revolutions. In both cases, the relative order of magnitude of stability values is the same for the different asphalt contents. At the 7.5 percent asphalt content, gyratory shear and stability values do not exceed 27.0 and 32.0, respectively. Comparisons of G_S and stability values (Fig. 9) indicate a reasonably good correlation. Unfortunately, further tests on higher stability mixtures were not satisfactory because the strain was not sufficient to produce changes beyond a certain stability level even though the samples were run for 250 rev. This implied that a higher level of strain was needed to facilitate testing of all mixtures within a reasonable period of time.

The air-roller pressure was increased to 20 psi for all subsequent testing and appeared to yield better results throughout a wide variety of mixtures. In an effort to improve the accuracy of pressure measurements, a 3-in. pressure gage, reading directly to 0.2 psi, was installed on the air-roller cell. Pressure readings were easily estimated to 0.1 psi with this gage. The procedure used in evaluating the different mixtures is briefly outlined as follows:

1. Two or three samples were compacted at each asphalt content using the fixed roller, 1-deg angle of gyration, 100-psi ram pressure, and 30 rev plus 3 for leveling. The upper limit in asphalt content was based on flushing as indicated by the gyrograph. These samples were then evaluated for density, stability, cohesiometer value, air void content, and mineral aggregate voids. The data were plotted and the design asphalt content determined from the curves by Hveem medium traffic criteria with due consideration given to a desirable range of air void values. Mixture G-12 (Fig. 10) illustrates the typical curves obtained from the testing procedure.
2. After the compaction of samples in the first step, three or four different asphalt contents were selected and eight samples were compacted for each asphalt content using fixed-roller compaction. These samples were extruded for density determination and were reinserted into the mold for air-roller testing at 140 F. The samples were ranked from low to high density for each asphalt content.
3. The angle of gyration was adjusted for 2 deg using the fixed roller before installing the air roller. The air-roller press was set at 20 psi. The lowest density sample was densified for 10 rev and succeeding higher density samples were densified by greater numbers of revolutions to eliminate some of the variation in test results that would otherwise occur with random sample selection. Sample heights and air-roller pressures were recorded on the data sheet (Fig. 11) for each specified number of revolutions. Readings were obtained by stopping the gyratory testing machine at the desired number of revolutions. Density, stability, and cohesiometer values were determined for each sample. Average gyratory shear and stability values vs revolutions were plotted (Figs. 12 and 13) for comparison.

Six different gradations, as shown in Table 4, were compacted following this procedure. Curves of stability vs number of revolutions for the mixtures illustrate definite trends with increasing asphalt content. At low asphalt contents, stability values con-

GYRATORY AIR-ROLLER DENSIFICATION DATA SHEET

Gradation: G-12 Date 8-9-63

Angle of Gyration 2 ° Ram Pressure 100 psi

Sample Number	A.C.%		Revolutions										Hveem Stability
			0	10	25	50	100	150	200	250	350		
7	6.5	Press.	20	34.8									
		Ht.	2.587	2.532									
		G_s	—	28.86									34.05
2	6.5	Press	20	33.8	33.6								
		Ht.	2.576	2.519	2.489								
		G_s	—	28.18	28.35								37.76
5	6.5	Press.	20	34.0	33.4	33.6							
		Ht.	2.591	2.539	2.510	2.480							
		G_s	—	28.12	28.36	28.45							39.08
6	6.5	Press	20	33.3	33.0	32.8	32.8						
		Ht.	2.576	2.528	2.500	2.472	2.437						
		G_s	—	27.66	27.72	27.86	28.26						41.97
4	6.5	Press.	20	33.7	33.8	33.9	33.7	33.7					
		Ht.	2.566	2.519	2.490	2.463	2.431	2.410					
		G_s	—	28.09	28.51	28.90	29.11	29.37					46.84
1	6.5	Press.	20	33.8	32.5	32.3	32.0	31.8	31.3				
		Ht.	2.555	2.505	2.473	2.450	2.406	2.384	2.368				
		G_s	—	28.34	27.60	27.72	27.93	28.01	27.76				50.45
3	6.5	Press.	20	32.7	32.5	32.5	32.0	31.4	31.2	30.5			
		Ht.	2.548	2.516	2.485	2.456	2.421	2.400	2.385	2.373			
		G_s	—	27.24	27.46	27.79	27.76	27.91	27.47	26.99			51.75
8	6.5	Press.	20	32.0	31.8	31.7	31.7	31.3	30.8	30.1	28.2		
		Ht.	2.553	2.505	2.478	2.448	2.414	2.394	2.379	2.369	2.353		
		G_s	—	26.83	26.45	27.14	27.58	27.46	27.14	26.68	25.17		43.46

Average G_s 27.42 27.85 28.04 28.13 28.19 27.47 26.84 25.17

Figure 11.

tinued to increase with densification throughout the test range of number of revolutions. With increased asphalt content, the stability values increased with densification to a critical density. Additional revolutions beyond this point produced a continuous reduction in stability. In general, stability and the number of revolutions to achieve maximum stability decreased with increased asphalt content. It was assumed that the peaks defined a satisfactory condition before failure of the mixture. The number of revolutions for each peak was used to obtain the corresponding gyratory shear value. Table 5 summarizes the data obtained in this fashion. A gyratory shear value of 27.0 was considered indicative of a strain condition immediately before failure for those mixtures tested.

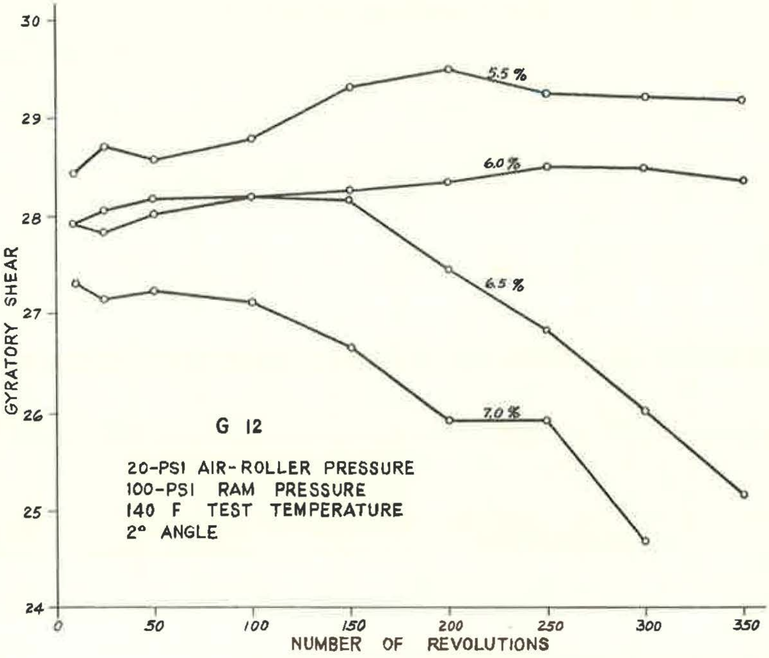

Figure 12. Gyratory shear vs revolutions.

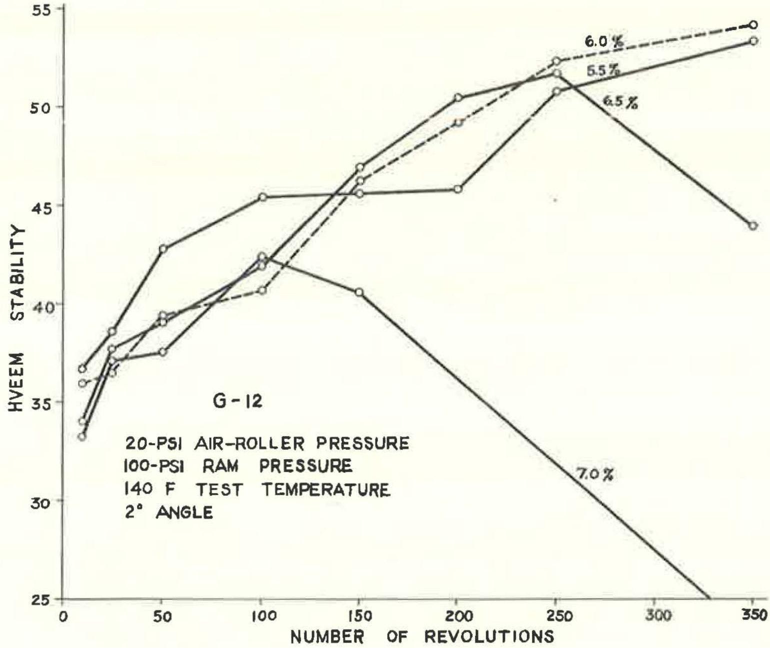

Figure 13. Hveem stability vs revolutions.

TABLE 4

Mixture	Passing Sieve (%)								
	½ In.	⅜ In.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
G-12	100	95	65	40	25	-	8	5.2	3
G-50	100	96	67	53	37	-	17	10.6	6
G-75	100	98	84	75	53	37	23	13.6	7
R-1	100	90	67	50	37	-	16	12.0	8
S-1	100	92	65	45	30	22	12	5.8	4
S-2	100	92	65	45	35	26	18	14.3	10

TABLE 5

Mixture	Values at Peak of Curve			Hveem Std. Gyratory Compaction			
	Asphalt Content (%)	Hveem Stability	No. Rev	Corresponding Gyratory Shear (G_s)	Design Asphalt Content	% Air Voids	No. Rev at G_s = 27.0
G-12	6.5	53	250	26.8	6.5	4.0	250
	7.0	45	100	27.2			
G-50[a]	7.5	49	150	28.5	8.0	5.8	200
	8.0	51	200	27.2			
G-75[a]	10.0	45	100	26.3	-	-	-
	11.0	43	125	27.5			
R-2	5.5	36	25	27.0	5.0	4.0	125
	6.0	28	10	27.0			
S-1	9.5	44	150	27.0	9.0	3.4	350
	10.0	44	50	26.8			
S-2	6.5	48	200	26.8	7.0	4.6	50
	7.0	38	50	26.5			
Avg.	-	-	-	27.05	-	-	195

[a] Revolutions increase with asphalt content for peak values; this phenomenon appears to be unique with the limestone-slag sand mixtures.

The next step in the analysis was to determine the number of revolutions to define the desired asphalt content corresponding to that established by Hveem design criteria using fixed-roller compaction. Numerous problems arise when one attempts to obtain design asphalt contents using gyratory rather than kneading compacted samples. Although the densities obtained by both methods of compaction may be about the same, the stability values are not similar for certain mixtures. Busching reports (4) an instance of a mixture giving inadequate stability when prepared by kneading compaction but showing a definite increase in stability when prepared by gyratory compaction and densified by 400 rev with the air roller.

Variability in data and selection of a design asphalt content further complicate the problem. Therefore, although the numbers of revolutions given in Table 5 show extreme variability, an arbitrary value of 200 rev was selected to define the point at which the sample would be evaluated. Limited studies of other mixtures indicate that this is a reasonable value for the mixtures and test conditions used in this study.

APPLICATION OF TENTATIVE AIR-ROLLER DESIGN PROCEDURE

During a period of 2 years, only limited information could be obtained on the field-compacted densities and the effect of traffic densification for typical asphaltic concrete surfacing mixtures in West Virginia. The need for test roads was apparent, but a test road program was complicated by the wide variety of aggregate types and combinations in use. The use of different construction projects for different materials was not desirable because time, location, and traffic variables would be introduced.

This problem was solved through the joint efforts of the West Virginia State Road Commission and the U. S. Bureau of Public Roads. A test road site was selected near Beckley, W. Va., on a 3-mi section of new construction of W. Va. 54. One 12-ft lane, 3 mi long, was subdivided into fourteen 1,200-ft sections with the surfacing for each section consisting of a different design mixture. Design asphalt contents for the ten sections to be used were determined by the tentative air-roller design procedure described earlier in this paper. The asphalt contents used in the remaining four sections were established by the West Virginia State Road Commission. Design asphalt contents were obtained from the gyratory shear vs numbers of revolutions curves (Figs. 14 to 23, Table 6) by interpolating between the two asphalt contents bracketing the design criterion ($G_s = 27.0$ at 200 rev).

The design of the slag and silica sand mixture, TR-9, did not follow the defined procedure. The TR-9 mixture (Fig. 21) maintains approximately the same value of gyratory shear for the different asphalt contents up to 200 rev. This condition is typical of slag mixtures having a low percentage of fines. The 10.5 percent design asphalt content was selected for this mixture even though the G_s value did not exceed 26.7 at 200 rev. Lower asphalt contents developed G_s values in excess of 27 and maintained this level of stability well beyond the 200-rev point.

Six of the test road mixtures were compacted at the design asphalt content and tested by the air roller as a check on the design. The results showed excellent reproducibility with the exception of mixtures TR-7 and TR-10. Time limitations prevented further investigation of these discrepancies before the test road construction. A review of G_s values for the different mixtures indicated that the variability for TR-7 and TR-10 was much larger than that for the other mixtures. Although air void content is not considered in this design procedure, it is of interest to note that it varied from 2.4 to 6 percent (Table 3) for samples compacted at the design asphalt content by standard fixed-roller procedures which provide the reference level for field compaction.

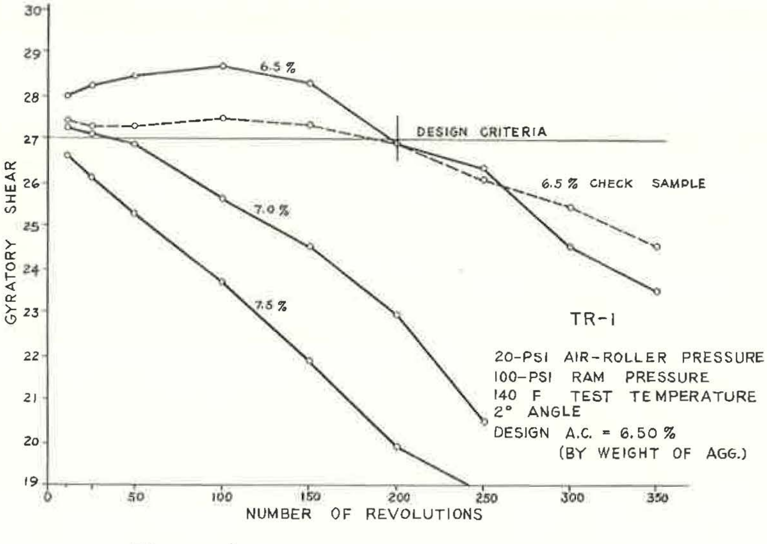

Figure 14. Gyratory shear vs revolutions.

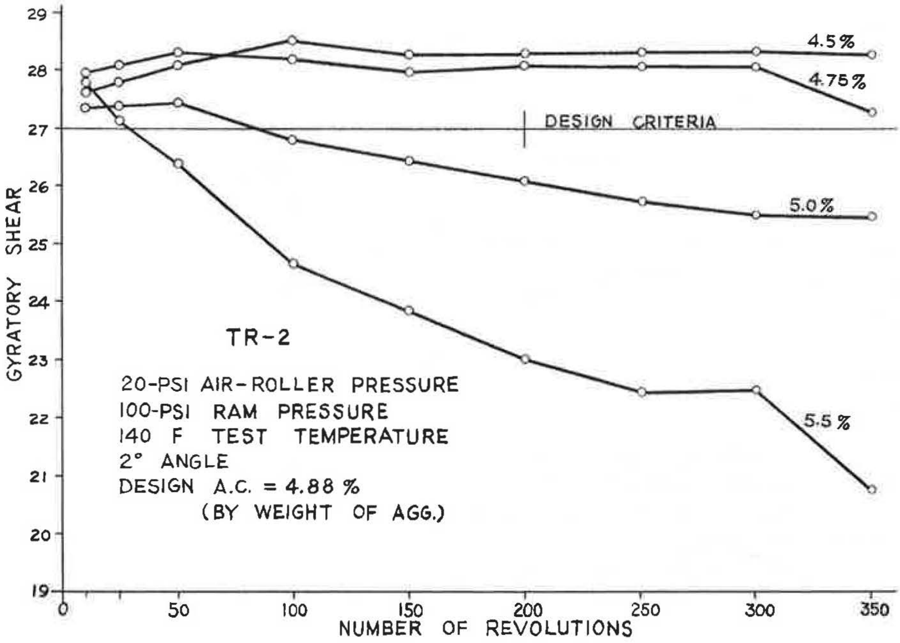

Figure 15. Gyratory shear vs revolutions.

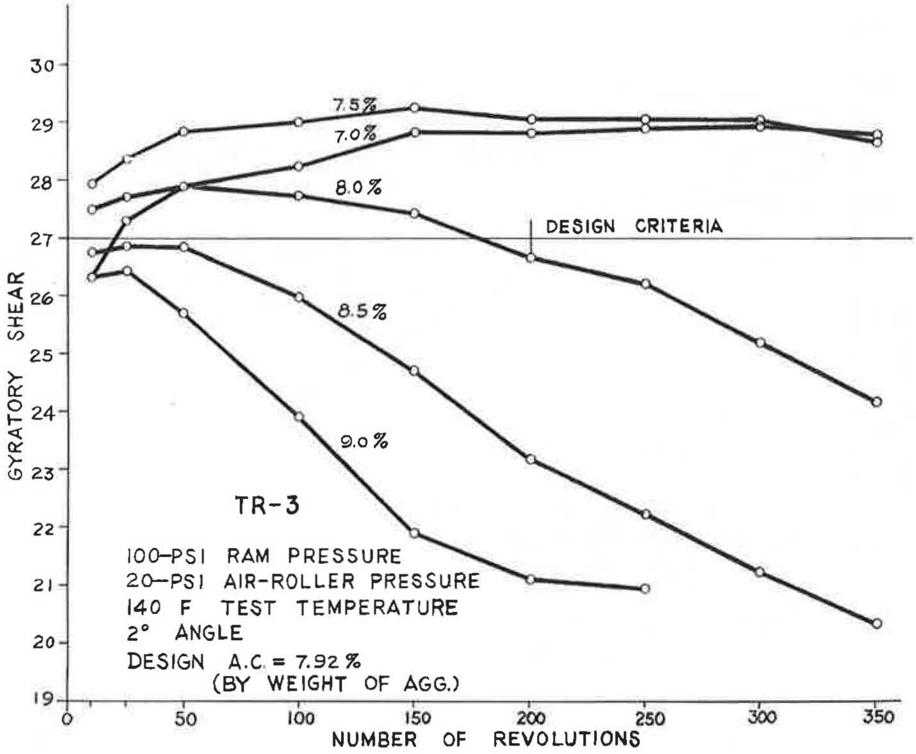

Figure 16. Gyratory shear vs revolutions.

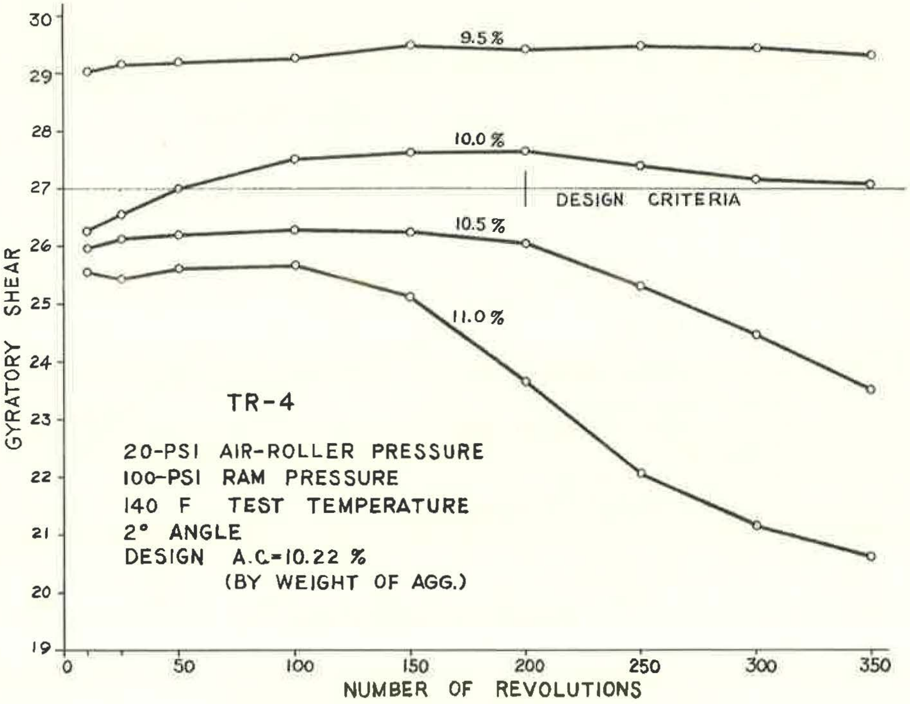

Figure 17. Gyratory shear vs revolutions.

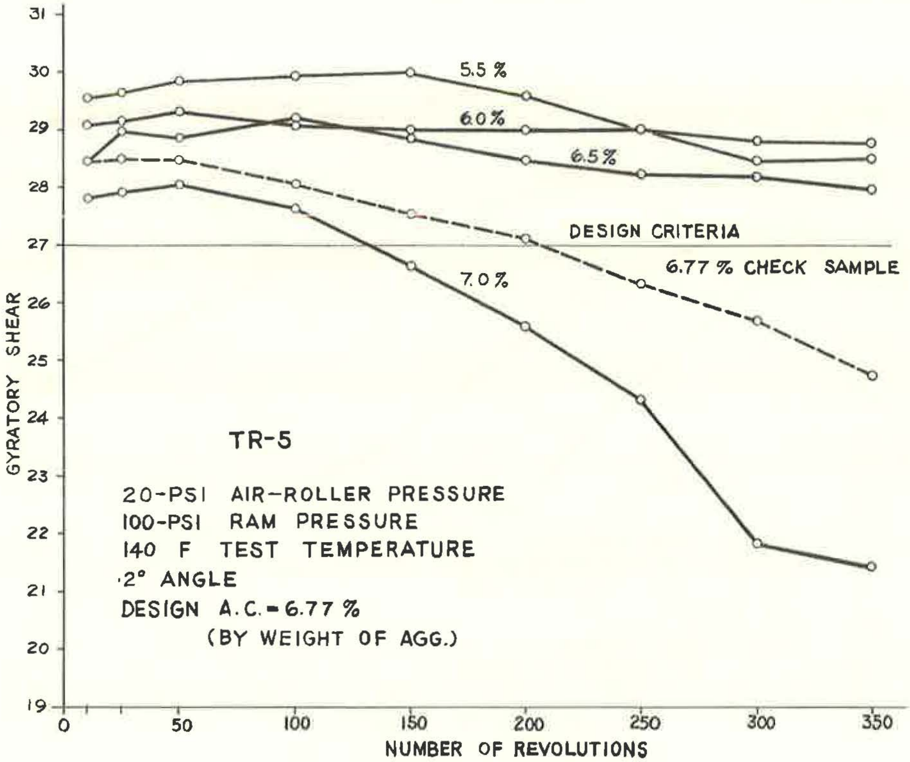

Figure 18. Gyratory shear vs revolutions.

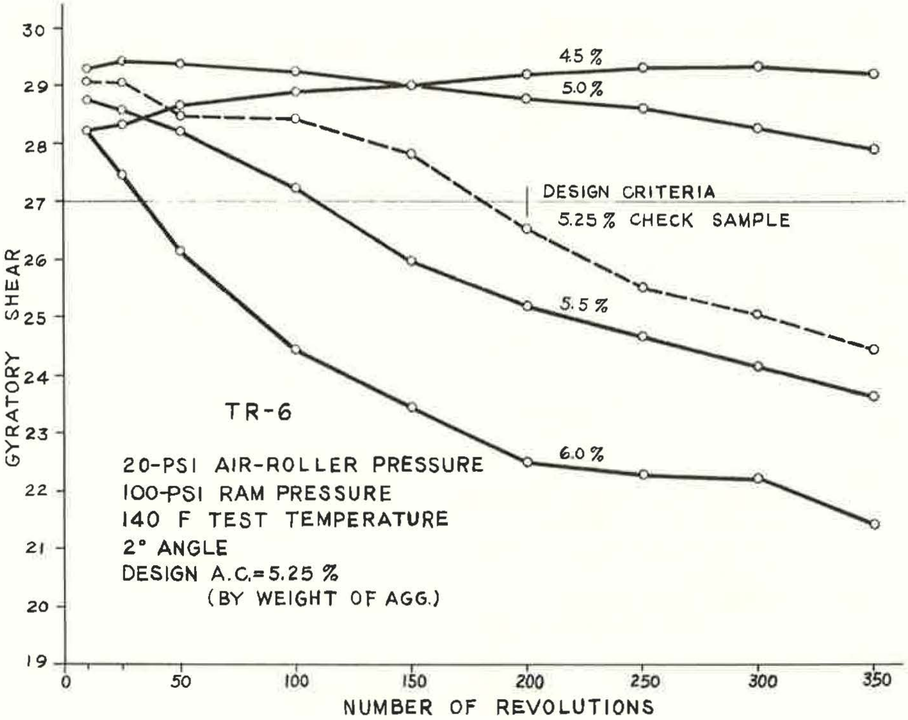

Figure 19. Gyratory shear vs revolutions.

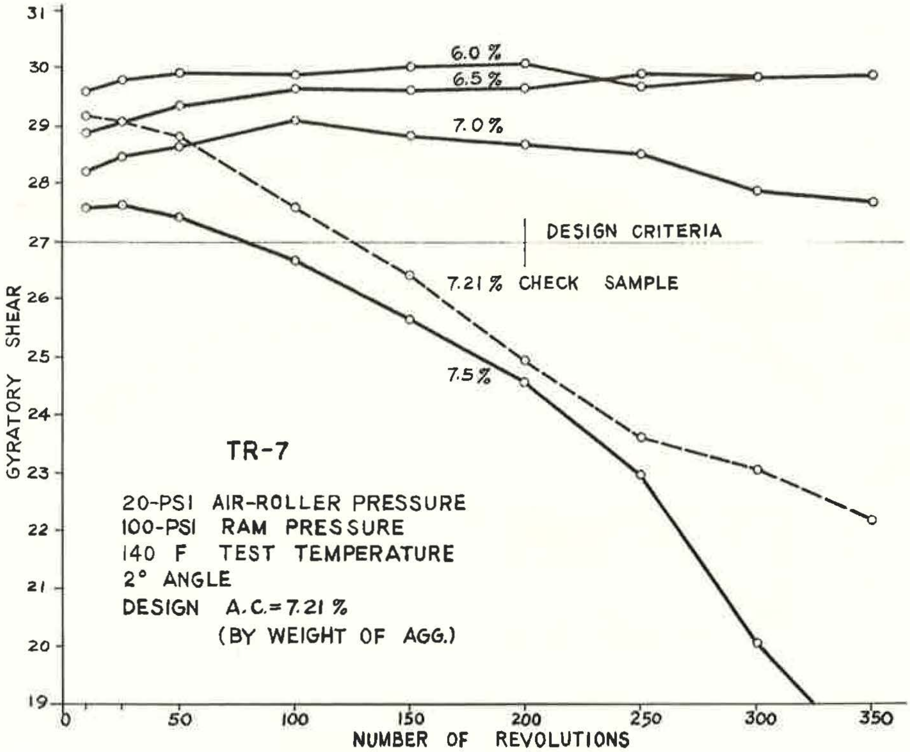

Figure 20. Gyratory shear vs revolutions.

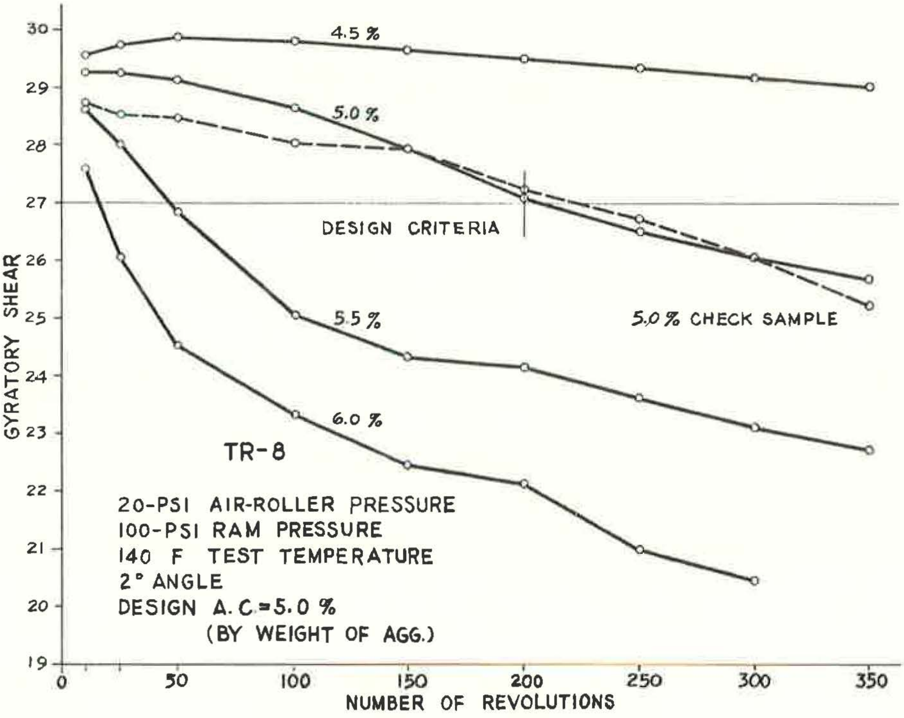

Figure 21. Gyratory shear vs revolutions.

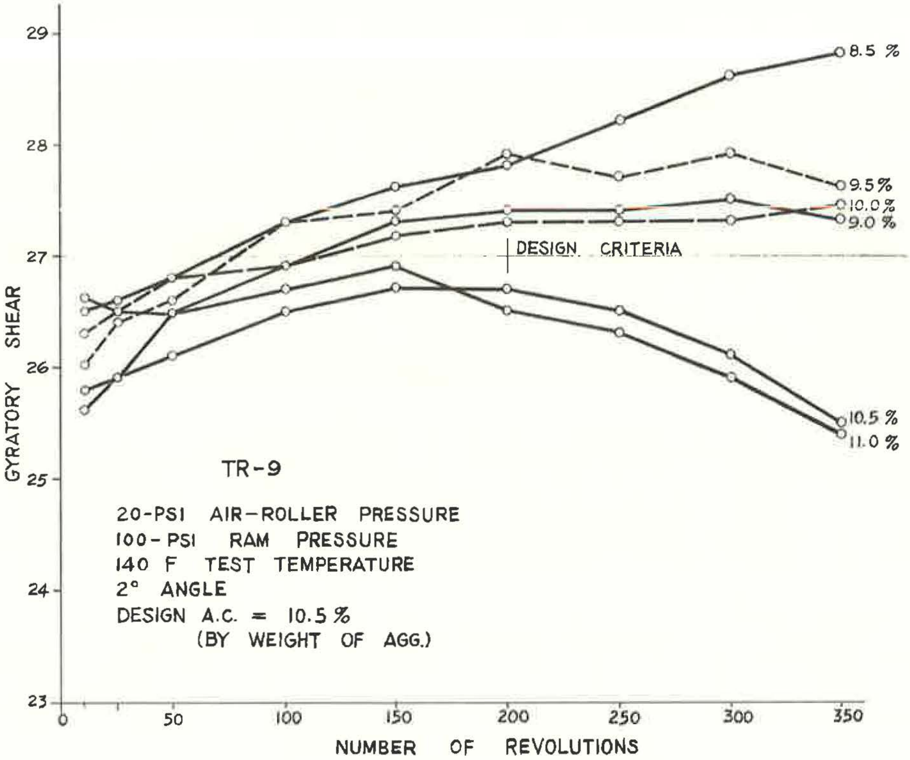

Figure 22. Gyratory shear vs revolutions.

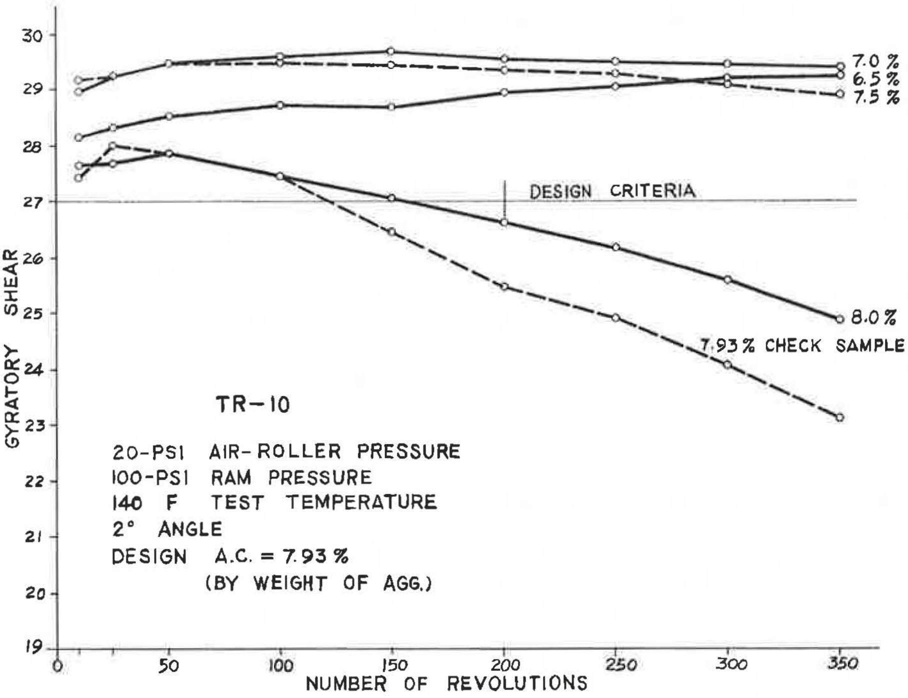

Figure 23. Gyratory shear vs revolutions.

TABLE 6
GRADATIONS FOR TEST ROAD MIXTURES

Mixture		Passing Sieve (%)								
		½ In.	⅜ In.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
TR-1	No. 12 limestone, L. S. sand	100	94	65	47	27	18	11	6	2
TR-2	No. 12 limestone, L. S. sand, L. S. rock dust	100	94	67	50	31	23	16	11	6
TR-3	45% No. 12 L. S., 50% No. 13 slag, 5% L. S. rock dust	100	95	67	53	37	25	17	11	6
TR-4	20% No. 12 L. S., 75% No. 13 slag, 5% L. S. rock dust	100	98	84	75	53	37	23	14	7
TR-5	No. 12 limestone, silica sand	100	96	68	45	35	20	8	4	2
TR-6	No. 12 limestone, silica sand, L. S. rock dust	100	96	70	49	39	25	14	9.7	6
TR-7	No. 12 gravel, silica sand	100	96	67	43	36	21	8	4	1.5
TR-8	No. 12 gravel, silica sand L. S. rock dust	100	96	69	47	40	26	14	10	6
TR-9	No. 12 slag, silica sand	100	97	66	46	37	21	8	4	1.5
TR-10	No. slag, silica sand, L. S. rock dust	100	98	74	56	46	32	15	8.6	6

Little difficulty was experienced in the compaction of the test road mixtures during construction. One of the most interesting situations encountered during construction was in the hauling and compaction of mixture TR-9. This mixture was so fluid that the load shifted in the truck bed on curves and slopped over the tail gate when the trucks accelerated. The laying and rolling operations were not significantly hindered by this fluid condition.

Outwardly it appears that the designed mixtures were adequate from the standpoint of field construction, but only time will determine the suitability of these mixtures and the adequacy of the design procedure. Roller pass, air permeability, nuclear density, and temperature data were obtained for each section during construction of the road. Cores of the compacted materials and samples of the loose mixtures were obtained for laboratory testing. Laboratory studies and observation of the test road will be continued to provide data on traffic densification for future use in conjunction with air-roller testing and to evaluate the performance of the various mixtures under field conditions.

PROPOSED STUDIES

The ever-increasing need for better methods to evaluate highway materials rationally has resulted in the continual development of new equipment and procedures. Research is needed to develop the necessary methodology and equipment for identifying, both quantitatively and qualitatively, the important parameters which govern the performance of asphaltic mixtures. The gyratory testing machine is relatively new. It is felt that the potential of this equipment has not been fully realized and that it offers an excellent tool for further detailed studies of the mechanism of mixture performance.

The authors suggest that future use of the gyratory testing machine, particularly with the air roller, may include the following applications: (a) to simulate field construction compaction, (b) to simulate traffic densification, (c) to evaluate effects of binder viscosity, (d) to evaluate effects of aggregate surface texture, (e) to evaluate effects of mineral filler-asphalt ratios, (f) to evaluate effects of grading, and (g) to act as an accelerated serviceability test.

It is not intended to imply that all of these problems listed can be satisfactorily solved by the gyratory testing machine. This list is merely intended to illustrate the wide variety of problems that appear suitable for study with the gyratory equipment.

ACKNOWLEDGMENTS

The authors wish to express their appreciation for the efforts and invaluable assistance provided by personnel of the West Virginia State Road Commission. In particular, Mark Fara, former Research Coordinator and R. T. Hughes, Materials Control Engineer, should be commended for their assistance in the planning of the test road and in the control of plant production. The comments and suggestions offered by personnel of the U. S. Bureau of Public Roads were especially helpful in the research study.

REFERENCES

1. Development of the Gyratory Testing Machine and Procedures for Testing of Bituminous Paving Mixtures. U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Tech. Rept. No. 3-595, 1962.
2. Kallas, B. F. Gyratory Testing Machine Procedures for Selecting the Design Asphalt Content of Paving Mixtures. Paper presented at 1964 Ann. Mtg. AAPT.
3. Busching, H. W., and Goetz, W. H. Use of a Gyratory Testing Machine in Evaluating Bituminous Mixtures. Highway Research Record No. 51, pp. 19-43, 1964.
4. Busching, H. W. Stability Relationships of Gyratory-Compacted Bituminous Mixtures. M.S.C.E. thesis, Purdue Univ., 1963.

5. Goode, J. F. Unpub. report to Highway Research Board Committee on Mechanical Properties of Bituminous Paving Mixtures, Department of Materials and Construction, 1964.
6. McRae, J. L. Personal correspondence, Dec. 4, 1961.
7. Ortolani, Lawrence, and Sanberg, Harry A., Jr. The Gyratory Method of Molding Asphaltic Concrete Test Specimens; Its Development and Correlation with Field Compaction Methods, A Texas Highway Department Procedure. Proc. AAPT, Vol. 21, 1952.