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Control of asphaltic concrete mixtures at hot-mix plants

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CONTROL OF ASPHALTIC CONCRETE MIXTURES

AT HOT-MIX PLANTS

by

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INTRODUCTION

As highways became one of the most important means of transportation in the daily life of human beings, the construction and maintenance of road surfacing received greater attention from peoples in every country. The use of asphalt as the cementing agent for road aggregates was started in 1835 in Paris (1). During the past century, increased knowledge about bituminous materials and their mixtures has made the so-called "Black Top" one of the most popular road surfacing. There are low-cost, medium-cost, and high-cost types of asphalt roads to meet different demands. Asphaltic concrete belongs to the high-cost type which has been extensively used in recent years for primary roads. The success of asphaltic concrete paving depends upon the sound engineering design of the mix and the road as a whole, wise choice of materials needed, proper preparation of subgrade and base course (if there is any), controlled plant operation in producing the mix, careful delivery, laying, and compaction, etc. Among the above factors, only the plant control will be discussed in this study.

There are two types of asphalt paving plants in common use, namely the stationary plant and the traveling plant. They can be further classified, according to their operation, as continuous and batch type. In either type, the aggregate and asphalt may be mixed at low or high temperature. In this study, most of the discussions will be concentrated upon the stationary continuous hot-mix plant only. Since the basic principle in operating either the continuous or batch plant is the same, primary control methods which are good for continuous plants can usually be applied equally well for batch plants. This is particularly true in the application of "Plant Stability Test", the development of which forms the main part of this thesis.

The necessity of a quick plant stability test is obvious to most field engineers. According to prevailing practice for asphaltic concrete plant inspection, samples are sent by the inspector to a laboratory, where it will be reheated, molded, and tested. The inspector cannot get the results until one or more days after the delivery of the sample. In case the mix was found to be unsatisfactory by laboratory stability test, it would be too late for adjustment because a large quantity of mix has already been produced and laid. Furthermore, the delayed adjustment based upon the mix of one day might be improper for the mix of other day since it is almost impossible to keep everything constant, especially in continuous plants. If a fairly accurate plant test can be run within 10 minutes right at the plant, proper timely adjustment for the mix would not be difficult.

Besides the defects as mentioned in the last paragraph, there might be even more serious trouble which is likely to be encountered at the plant. Let us imagine what happens in an asphaltic concrete plant if no quick stability test is available. The plant inspector and his assistant are busy all day in measuring temperature of mix, running rapid field extraction tests, making sieve analysis of heated aggregates, and watching plant operators working properly to bring everything possible within specifications. However, strict control of the above items cannot always assure the desired stability of the mix. Finally all the plant inspector can do is to judge the mix by eye and wait for praise or blame from the paving inspector in charge of laying and compacting the mix. It is not unusual that a fair looking mix could be proved as inferior after laying and rolling. In some extreme case, a few truckloads of mix, which have passed the visual examination by plant and paving inspector, spreaded and rolled into the road, may be found very unstable. Then it has to be removed. In asphaltic concrete plant operation there are so many factors to affect stability of mix that the plant inspector really cannot help very much if his tool for immediate judgement is only a pair of naked eyes.

From the above description, it is seen that delayed laboratory stability tests cannot help immediate plant control. They are good only for preliminary design and occasional check. However, a rapid plant stability test can be a helpful guidance for effective plant operation.

Before the presentation of this suggested control test, a general description and discussion about plant operation and inspection will be given. The necessity of plant stability test will be more obvious after such a review of prevailing engineering practice. As regards the suggested test in particular, every possible effort has been made in developing a test method as simple and reliable as possible. However, it is believed that, as the case of any other engineering test, continuous study and improvement will be necessary in order to make it a perfect testing device.

PLANT OPERATION IN MANUFACTURING ASPHALTIC CONCRETE MIXTURES

Manufacturing of mixtures plays an important role in the whole procedure of asphaltic concrete paving. Careful work in delivering, laying, and compaction will be all in vain if the mixture produced is unsatisfactory. Batch plants have been used in manufacturing asphaltic concrete mixture for years. Continuous plants were introduced with the purpose of getting faster and larger production. There are advantages and disadvantages in each type. It will be out of the scope of this study to compare their values and draw any conclusion. As it has been mentioned in the introduction, only the continuous hot-mix plant will be reviewed. Descriptions are referred to the recent model made by Barber-Greene Company.

Plant operation in producing asphaltic concrete mixtures involves the feeding of cold aggregate to the dryer, heating and drying of aggregate, screening and proportioning of heated aggregate, and finally mixing the heated aggregate with hot asphalt cement. It is not intended to give detailed description regarding plant operation as manufacturers usually do in their handbooks. The purpose to include plant operation in this thesis is just to emphasize the need of a rapid plant stability test. It will be seen later that, in the manufacturing of asphaltic concrete mixture, there are many hard-to-control factors which would influence stability of the mixture. Unless the plant inspector has some means to check the stability right in the plant within a short time, he is not in a position to assure the satisfactoriness of any mix (The term "Mix" will be used with the same meaning as "Mixture" in all subsequent descriptions).

In order to facilitate discussions about various parts of a continuous hot-mix plant, a flow diagram and some pictures of an actual plant are shown in Fig. 1-6. Plant operation will be discussed under four units, namely, cold aggregate feeder, dryer, gradation unit, and mixer.

Cold Aggregate Feeder

In most asphaltic concrete plants, two aggregates, coarse and fine, are used as raw material. They are introduced by cold aggregate feeder to the continuously moving mechanical system. Mineral filler is usually added to the system at later stage as shown in the flow diagram. Since the fuction of gradation unit is quite limited, it is impossible to produce a uniform mix unless cold aggregates are fed properly and uniformly. Various factors affecting uniformity of cold aggregate will be listed. It is understood that only the factors involved in plant operation are included. In other words, aggregates delivered from other places are assumed to be uniform in gradation, shape, and quality from time to time and free from segregation in every car-load or truck-load.

Formation of stockpiles

If aggregates received at the plant are stockpiled in an incorrect way, segregation of particles will be the result. Rolling of aggregate along the edge of a stockpile is one reason for such segregation. It can be corrected by stockpiling in layers. Sometimes the plant site is not big enough so that steep and high stockpiles are unavoidable. In such case, the possibility of aggregate segregation is increased due to the steeper and longer slope along the edge of stockpile. Therefore, a large space should always be reserved for stockpiles in order to asure efficient and proper handling of aggregates.

Setting of gate opening

Coarse and fine aggregates are fed to the dryer by a reciprocating feeder. Gate setting for both coarse and fine aggregate should be properly adjusted to meet the designed proportion. If the setting for either coarse or fine aggregate is too high, two undesirable results will occur. First, there would be overflow from one or more storage bins in the gradation unit due to excess of aggregate of a certain size. Second, the gradation of aggregate in certain bins might be changed. In the former case, means should be provided to remove the overflowed material. Consequently, material handling cost would be increased. In the latter case, change in gradation of aggregate in bins will cause the gradation change in the final mix and affect the rate of flow of heated aggregate which is to be carried from gradation unit to the mixer. Particular discussion related to such effects will be given under the heading "Gradation Unit".

Furthermore, the clearance of gate opening deserves particular attention. Sometimes, wet fines in sand might stick on sides of the chute so as to reduce the clearance of gate opening. Occasionally, the gate may be clogged up, partially or entirely, by some wood strips or other wasted material. Such clogging up of gate opening would cause similar results as previously described.

Of course, variation in moisture content of aggregate should be taken into consideration in determining the gate setting for cold aggregate feeder.

Dryer

Dryer is considered to be one of the most important parts in a hot-mix plant. The success in plant operation depends largely upon the efficient work of a patient and careful dryer operator. His negligence may cause a fluctuation in temperature and dryness of aggregate. Consequently, a bad mix will be produced. As regards type of dryer, there are single and dual drum in the Pacific Counter Flow model. A single drum dryer is shown in Fig. 5.

Capacity of dryer

Manufacturers usually furnish some tabular information about the capacity of their dryer. This information is based upon specific conditions. Actually, different aggregates have different properties in regard to ease of drying and size of aggregate would affect rate of drying too. Therefore, actual capacity of dryer should be carefully checked.

One thing that occasionally causes confusion is the temperature and dryness of heated aggregate. People might think that two groups of aggregate heated to a certain temperature, say 300° F, should always have the same degree of dryness. This is true when these two groups of aggregate belong to the same kind and they have the same amount of absorbed moisture. However, if the absorbed moisture of one group is much higher than that of the other, they might have different degree of dryness even if both are heated to the same temperature. This is due to the fact that more time or better condition is needed to evaporate more absorbed moisture. For example, heated aggregate at 300° F is satisfactory during dry weather. In case the aggregate is saturated with moisture during wet weather, 300° F might not give good result if the dryer carries the same load. (If dryer carries same load, the burner has to be adjusted in order to heat the wet aggregate to 300° F). Remedy for this case is to cut down gate setting for cold aggregate feeder so as to let each individual particle have more chance to evaporate the moisture during its passage through the dryer.

<u>Control of burner</u>

Since fuel oil is used for the burner in aggregate dryer, either ordinary-pressure or high-pressure injection burner can be adopted. Dryer operator should constantly watch the burner. If necessary, he has to make proper adjustments of the oil and steam valve so as to keep the heated aggregate at desired temperature and dryness. Furthermore, complete combustion of fuel oil should be maintained otherwise heated aggregate will be coated with free carbon. This will be discussed under next heading.

In general case, temperature alone is good enough to be used as a guide for dryer control except some particular instance as pointed out under last heading. A pyrometer is usually adopted to indicate the temperature.

It has to be checked very often to assure its accuracy and its active end must be located at the right place in the chute between dryer and gradation unit. When steam is used on the burner, steam pressure recorded at the boiler should be kept constant. A fluctuation of steam pressure would cause many troubles to the dryer operator.

Dust collector

Since dust from dryer can be used as filler in the final mix, it is usually collected by specially designed stacks, known as dust collector. Of course, the collector would also help to reduce nuisance. Material collected in the dust collector generally contains more than 75 per cent fines passing No. 200 sieve. Sometimes, incomplete combustion of fuel oil in the dryer would introduce free carbon which will mix with the aggregate. Such dark-colored aggregate impairs stability of mix. Therefore, dryer operator should make proper adjustment of the burner in order to maintain complete combustion of oil. This is particularly important at the starting of plant operation in the morning.

The amount of fines collected in the dust collector varies from time to time. Moisture content of original aggregate, humidity of atmosphere, intensity of heating, speed of air current in the dryer, and condition of dust collector itself would influence the amount at certain extent. Variation in the amount of fines collected in dust collector should receive particular attention.

Gradation Unit

Gradation unit may be also called aggregate proportioning unit. This unit involves the vibrating screen, the hot aggregate bins, and the conveying system. It is the most bulky unit in the whole plant. If everything is under control, no particular operator has to be employed to take care of this unit. Some particular points related to this unit will be discussed as follows:

Vibratory screen

Capacity of gradation unit is mostly controlled by capacity of vibratory screen. The capacity of certain combination of screens can be computed by referring to screen manufacturer's manual. Efficiency of screen varies inversely as the load to be carried if conditions are constant for other factors such as frequency and amplitude of vibration, length and inclination of screen, shape, roughness, and dryness of aggregate. Since it is necessary to maintain the gradation of heated aggregate in each bin as constant as possible, the efficiency of screen deserves particular attention by plant inspector. Occasional inspections should be made in order to avoid clogging up or wearing out of screens.

Segregation of fine bin

Sometimes mineral filler is not introduced by separate feeder but combined with other aggregates to be carried by the cold aggregate feeder. A particular example to illustrate this is the use of finely crushed agricultural lime in which there is usually over 25 per cent fines passing No. 200 sieve. For instance, three bins are furnished in the gradation unit. No. 1 bin is used for large-size aggregate, 1 in. to 3/8 in., No. 2 bin for intermediate-size, 3/8 in. to No. 8, and No. 3 bin for fines passing No. 8 sieve. At the beginning of operation, everything might be under control. After a while, fine particles, which have been suspended in air, gradually settle out at all possible places in No. 3 bin. When these settled fines accumulated to a certain degree, they flow out in an uncontrollable manner. The result is clogging up of bucket elevator and, consequently, shutdown of plant. This defect can be avoided by an entirely new plant design as regards shape and position of bins, arrangement of discharging and conveying system, etc. But, in case of existing plant, many possible efforts have been proved as failure. An indirect measure is to by-pass the fines from dust collector so as to reduce the amount of fines carried by the fines bin. Separate conveyor system is established to feed dust collector fines directly to the elevator beside mixer. This arrangement leads to a new trouble. The fluctuation in the amount of fines gathered by the dust collector (refer to the paragraph discussing dust collector) would make plant operation complicated and more difficult to control.

Control of flow

One of the special features in continuous plant is the proportioning of asphalt and aggregate by volume. Since mix design is always based upon proportion by weight, the change from weight to volume often introduces some uncertainty. This is not too serious so far as the asphalt is concerned. A little change in temperature will cause very small difference in its specific gravity (more discussions will be given later). Therefore, a properly designed direct-displacement pump is considered as satisfactory for the supply of asphalt to the mixer. The pump must be calibrated with the asphalt which will be used for the mix. In the case of aggregate, volumetric control always causes confusion. In order to illustrate this fact, control about the flow of heated aggregate will be described briefly.

Since weighing batches are omitted in continuous plants, the only possible control applies to rate of flow. Under each hot storage bin, there are gates to regulate quantity of aggregate flowed out from bins to conveyor. Aggregates are then transported by bucket elevators to the mixer. Gate setting for each bin has to be calibrated with the same kind of aggregate (at the same temperature) that will be used for the job. An example of calibration curves for a set of three bins is shown in Fig. 7. With calibration curves on hand, plant inspector can determine what gate settings are necessary to meet the requirements of a given mix formula.

It is seen from calibration curves that, for any particular gate setting, there is a definite weight of heated aggregate which will flow through the gate when the reference counter has one complete revolution. However, what the gate really controls is not the weight but the volume of aggregate. Volumetric control at continuous plants could be as good as the control by weighing batch if two conditions are satisfied. In the first place, the flow of aggregate, expressed in volume per revolution, must be constant. Secondly, aggregates flowing through the gate must be gathered in the same degree of compactness. In other words, it requires that equal volumes of aggregate (including air voids) should always have equal weight. Both requirements can be fulfilled if depth of aggregate in storage bin is kept nearly constant and aggregates during continuous operation are absolutely uniform in every respect. The factor regarding depth is considered less important when the top level of aggregate is above the line indicated by a bar outside each bin. But the influence in regard to uniformity of aggregate deserves great attention.

Unfortunately, fluctuation in the condition of aggregate is almost unavoidable. When the fluctuation exceeds certain degree, trouble will occur accordingly. This is due to the fact that degree of compactness, as referred to aggregates in the bin, is influenced by their gradation, shape, roughness, etc. These factors are nearly impossible to be exactly constant from time to time. Therefore, the flow of aggregate, expressed in weight per revolution, will be changed even if there is no change in flow as regards volume per revolution. Actually the flow, expressed in volume per revolution, might also be changed if conditions of aggregate are different.

In summarizing all discussions, it can be stated that fluctuation in the condition of aggregate may alter the rate in feeding aggregate to the mixer. Consequently, percentage of asphalt in the mix will be changed. On the other hand, non-uniform aggregate would naturally affect the stability of mix directly. This is why uniformity of aggregate has its double significance at continuous plants.

Mixer

Mixing of asphaltic concrete has received great attention from asphalt paving technologists. The purpose is to get a uniform mix that is least impaired by secondary effects such as oxidation of asphalt, degradation of aggregate, etc. Factors affecting stability of mix during mixing will be reviewed briefly. Descriptions are referred to pug mixer as it is always used at asphaltic concrete plants.

Spraying of asphalt

Asphalt is supplied to the mixer by a direct-displacement pump connected to a spray bar. There are two adverse requirements as regards the size of discharging orifices on the spray bar. In order to get a uniform spraying, orifices have to be as small as possible. On the other hand, they should not be too small if the flow of asphalt is concerned. Since medium penetration asphalt cement is generally used at hot-mix plants, its high viscosity even at ordinary heated condition may interfere with the flow in case orifices are too small. Recently, developments have been made to improve the supply of asphalt by utilizing high pumping pressure to discharge asphalt through special nozzle. With such arrangement, asphalt can be atomized to enable the formation of extraordinary thin coating over aggregates (2). A new field in asphaltic concrete paving might be established in view of this invention.

It has been mentioned under the heading "Control of flow" that volumetric control for asphalt is not likely to cause serious difficulty.

A change of 15° F in the temperature of asphalt will make a difference of only about one-half per cent in its specific gravity. Nevertheless, temperature variation in asphalt has to be avoided due to additional reasons, especially the influence related to oxidation and viscosity. Higher temperature gives more chance for oxidation. Lower temperature means higher viscosity and, consequently, more resistance to flow. Both the spray bar and the pump will be affected by viscosity of asphalt.

Intensity, time and temperature of mixing

In the pug mill type mixer, intensity of mixing is influenced by shape and diminsion of blades, distance between consecutive blades and their difference in phase during rotation, clearance between blade tip and mixer lining, speed of rotation, etc. Investigations have been made to adjust all factors so as to give maximum efficiency without impairing the quality of output. For example, Gerlack (3) found that, beyond certain limit, raising speed of rotation does not accelerate the mixing process but impairs quality of mix. Actually, among the above factors, only the difference in phase of consecutive blades can be adjusted by plant inspector. All the rest are fixed at certain condition. However, occasional inspection is indispensable in order to make sure that everything has been kept in right order. Very often, rotating blades wear out or even separate from the axis. If that happens, intensity of mixing will be substantially reduced. Furthermore, mixer linings may be worn out so that steam could get into the mixing chamber. Of course, this escaped steam would affect adhesion between aggregate and asphalt. Cleaning of mixing chamber is also important, otherwise the clearance between blade tip and mixer lining will be reduced.

During plant operation, time and temperature of mixing should be watched carefully. If mixing time is too long or mixing temperature is too high, loss of penetration in asphalt will be the direct result. On the contrary, if it is too short in time and too low in temperature, a non-uniform mix might be produced. Schaub and Parr (4) have made extensive investigations as regards such effects.

In short, a satisfactory and uniform mix can be produced only if all factors are kept in the right track. Requirements in regard to temperature, time and intensity of mixing are somewhat interrelated. For example, lower temperature has to be combined with longer time or higher intensity. At this point, it seems appropriate to mention that some confusion regarding stability of mix is often caused by high mixing temperature. It is obvious that penetration and ductility of asphalt will drop down if mixing temperature is too high. This means a reduction in durability of the mix. However, the immediate stability test at specified temperature might record a higher stability value due to harder asphalt.

Besides considerations related to quality and uniformity of mix, there is one more requirement in regard to temperature of output. Since temperature of asphaltic concrete mat must be within certain range during initial compaction, arrangements have to be made to meet such constructional requirement. The most ideal temperature of output is such that, after delivering and spreading, the mix would be just right for initial compaction without waiting.

Degradation and segregation

The term degradation refers to the breaking up of aggregate. For comparatively soft aggregates degradation in the mixer has to be taken into consideration. When aggregates are maintained at uniform quality and mixing conditions unchanged, the degree of degradation would naturally stay constant. If there are variations related to intensity, temperature and time of mixing as well as quality of aggregate, change in degree of degradation will occur accordingly. Usually such change is not big enough to cause significant difference in the stability of mix. However, it may affect stability at some extreme case. Therefore, a particular mention is warranted.

When mix is discharged from mixer to truck, segragation of coarse particles might be happened if there is no proper device to avoid it. In the continuous type mixer, a system of extended steel plates can correct such defects. Loading of mix to the truck is the last stage in asphaltic concrete plant operation.

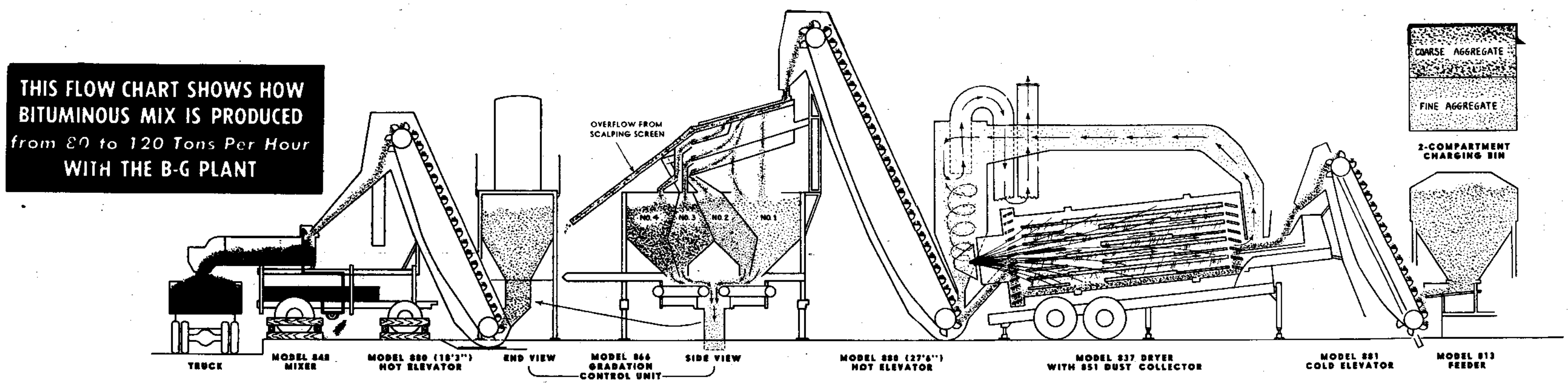

Figure 1. Flow Diagram of Hot-Mix Continuous Type Asphaltic Concrete Plant (Reproduced from Barber Greene Pamphlet).

Figure 2. General View of Continuous Asphaltic Concrete Plant.

Figure 3. Continuous Plant during Operation.

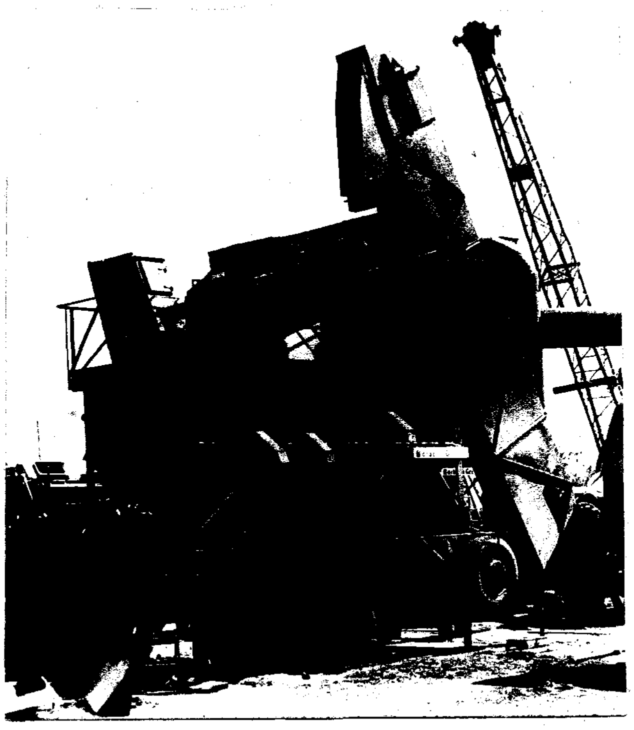

Figure 4. Gradation Unit.

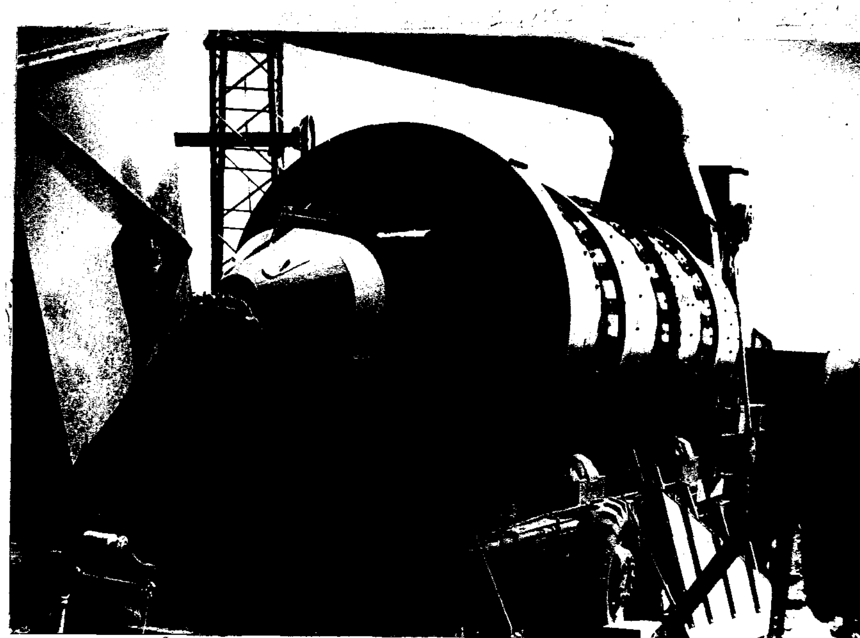

Figure 5. Dryer.

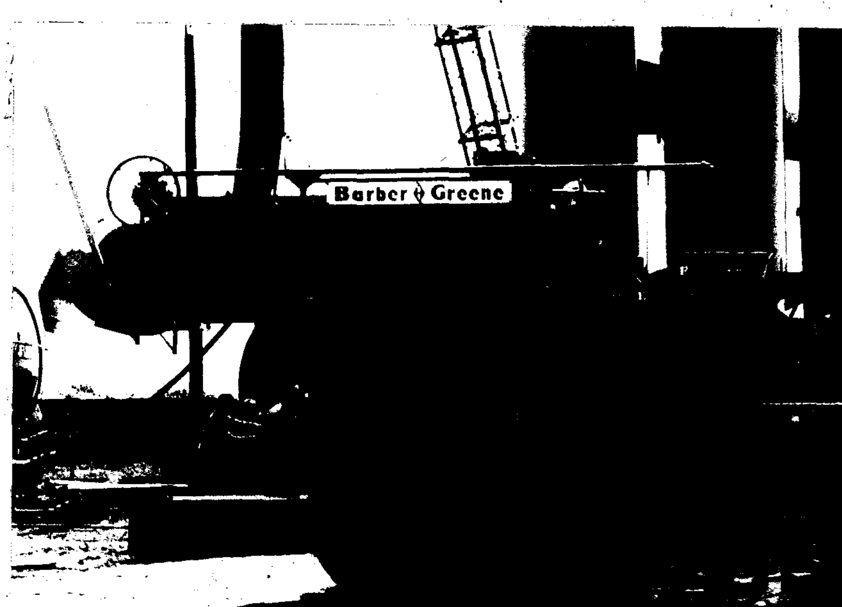

Figure 6. Mixer.

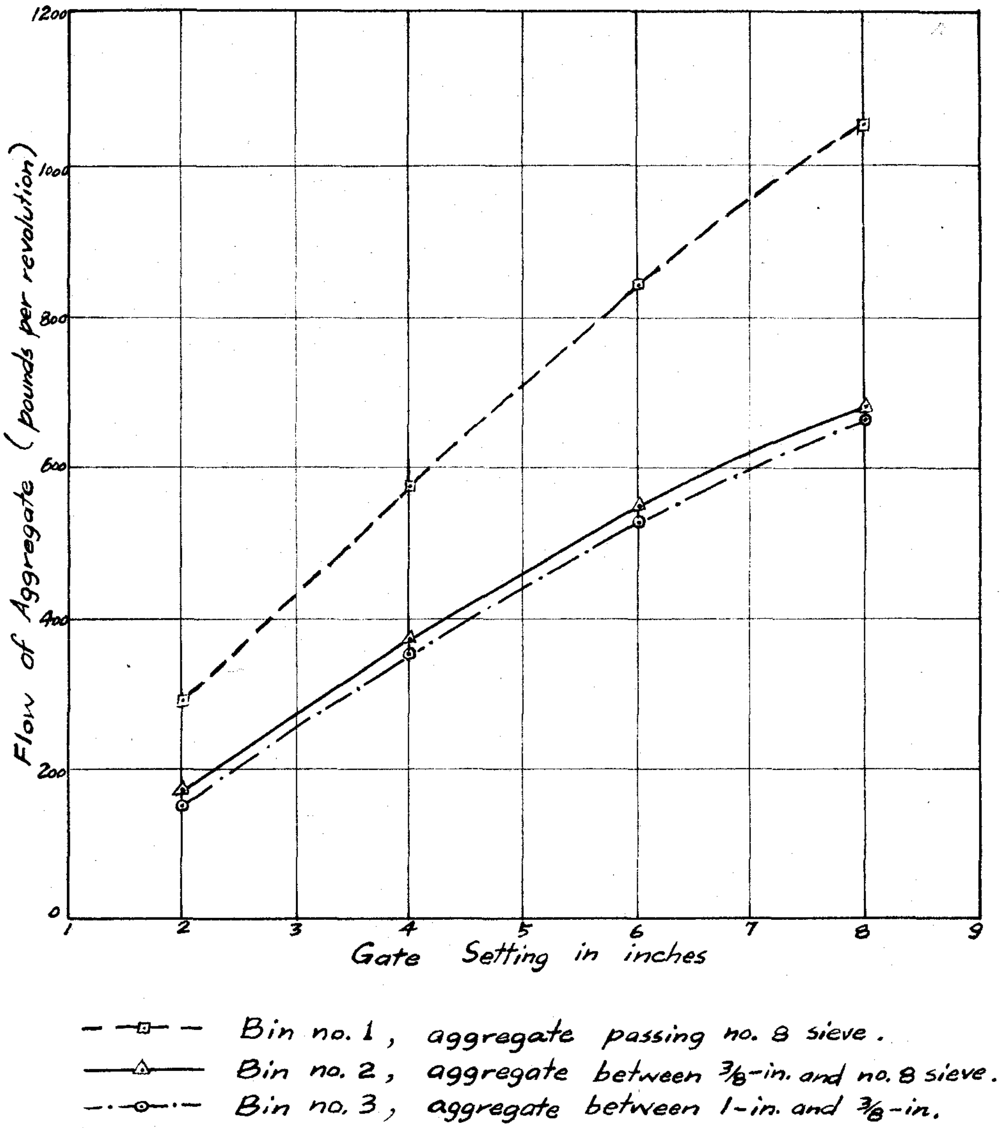

Figure 7. Calibration Curve for Flow of Aggregate in Hot-Bins.

ASPHALTIC CONCRETE PLANT INSPECTION

Control in the manufacturing of asphaltic concrete mix is executed by a plant inspector. Since contract system has been adopted in almost all highway paving jobs, plant inspection is considered as one of the most important means to avoid faulty manufacture and to protect interest of the general public.

Before any suggestions are made for the plant control of asphaltic concrete mixture, it seems necessary to have a general review of existing inspection practice. Descriptions as regards control tests will be listed under separate heading in order to present a clearer picture. It is not intended to give details about inspection practice or control tests because the primary purpose of this review is just to point out that no rapid plant stability test is available now. The urgent need for such a test has been discussed in the preceding part.

Survey of Prevailing Inspection Practice

In 1940, the Subcommittee on Inspection Requirement of the Association of Asphalt Paving Technologists made a report dealing with the general practice in bituminous plant inspection (5). Contained in that report is a fairly complete survey of inspection practices followed by most state and city organizations in this country. At that time, such a comprehensive survey must be very valuable. Due to continuous improvements in the technique of manufacturing and testing of road materials and mixtures, changes in inspection practices during the past decade warrant the repetition of similar investigation. Therefore, an up-to-date survey has been made.

At the end of 1948, sixty questionnaires asking about asphaltic concrete plant inspection were sent to highway commission or engineering department of all states and some big cities in this country. Their kind cooperation in furnishing all related information makes this nation-wide survey a success. The succeeding concise summary invludes answers from forty states and six cities.

It has been mentioned before that details regarding plant inspection are not going to be presented. Descriptions will be concentrated to means for plant control since they are more closely related to the main objective of this study. In view of the different character between military and civil service, practice for plant control adopted by the Corps of Engineers, U. S. Army, is not included in this survey.

Inspection in general

Among the 46 answers received in this survey, only two states mentioned that they had no asphaltic concrete or similar bituminous paving. As regards general regulation for asphaltic concrete plant inspection, analysis of the 44 answers reveals that there are still a great number of states and cities having no definite rules for plant inspection. Some states just mention that trained inspectors are stationed at the plant. Others have little asphaltic concrete paving so that no particular regulation is necessary. The summary of inspection practices is shown in Table 1.

Among 17 states and cities having their own regulation for plant inspection, some have very comprehensive rules to instruct what and how to do while others briefly point out a few important items. It is interesting to see that more states and cities follow the inspection practice suggested by the Asphalt Institute (6) but very few directly follows that recommended by A. S. T. M. (7). Of course, there are many similarities between these two recommendations.

Since the plant inspector is always kept busy during long working hours, it is considered as desirable to provide comprehensive inspection manual with simplified, tabulated information in order to help him for the effective control at asphaltic concrete plant.

Means for plant control

Under this heading, summary and description will be given to three subjects, namely, plant control tests, adjustment of mix formula by plant inspector, and laboratory stability tests related to plant control.

The survey reveals that there are different arrangements in different states as regards control tests performed by the plant inspector. Only the sieve analysis of heated aggregate and mineral filler is almost unanimously adopted as a plant control test. Asphalt content of the mix, specific gravity of compacted mix, and penetration test for asphalt cement are some common plant control tests specified by many states. One state requires the plant inspector to mold specimens for laboratory stability test.

To avoid the change in quality of mix due to reheating might be the main reason for such arrangement. In case of cities, it is only natural that central laboratory would perform more control tests because of the convenience in transportation.

In most states, plant inspector is authorized to make necessary adjustments, within specification limits, for composition of the mix. However, no direct field test is available to tell when such adjustments should be made. Visual inspection of the mix, when it leaves plant, and working condition during laying and rolling are, probably, the only means for immediate plant control. Since the inspection practice recommended by Asphalt Institute is the most popular one followed by states and cities, its suggestion related to adjustment of mix composition is cited as follows (6, p. 4):

> The Head Inspector should divide his time between plant and job. He is responsible for most of the visual inspection, for maintaining close cooperation between plant and job operations, and for the preparation of daily summary reports. Within specification limits, he should make such adjustments in composition of the mix, and temperature at which it leaves the plant, as he deems advisable to facilitate placement and compaction on the job.

Informations from visual inspection and actual working condition might be good enough for the inspector to know when and how to make temperature adjustments. When the mix composition is concerned, more definite means shall be provided in order to determine correctly when and how to make the proper modification. Conventional plant control tests such as gradation, extraction, density, and penetration are good references for the question "How to make the adjustment?". However, none of them gives a positive direct answer for the quality of final mix. Let us take, for example, the gradation of aggregates, usually certain constructional tolerances are specified by highway commissions or engineering departments. Then, the plant inspector runs sieve analysis, once or several times a day, for the heated aggregate and filler. He combines the results to get the gradation of aggregates in the mix or he can get the gradation directly from a composite sample. In either case, a comparison between actual and designed grading could be made. If the actual gradation is different from the designed one but still within specification limits, the plant inspector would not know whether adjustment for mix composition should be made or not. The same is true for other testing results such as penetration of asphalt cement and asphalt content in the mix. Even a combination of all these testing results cannot help very much either.

Some states have prepared charts to use surface area of aggregate as a reference for the adjustment of asphalt content. Particular constants are assigned to different kinds of aggregate in order to make further correction for the asphalt content found from charts. Penetration or specific gravity of asphalt has been taken into consideration too. The method using centrifuge kerosene equivalent (8) is another example of similar character. Certainly, these methods help the plant inspector to some extent. However, as the quality of mix can be affected by many factors other than those represented by surface area or centrifuge kerosene equivalent method, validity of above mentioned practices seems to be limited to certain conditions only. Furthermore, surface area computed from aggregate gradation may vary greatly from the actual value due to the discrepancy of arbitrary assigned surface constants. In the case of centrifuge kerosene equivalent method, it is assumed that coarse aggregate has the same character as aggregate passing No. 4 sieve. This assumption may not be true in many instances, especially when crushed stone and sand are used for coarse and intermediate aggregate respectively. In short, a mix might have high stability even if its actual asphalt content differs from that found by surface area or centrifuge kerosene equivalent charts. Therefore, the inspector cannot depend entirely upon such methods to answer the urgent question "When adjustment should be made?"

On the other hand, datum regarding specific gravity of compacted mix (sample taken from the pavement) gives better indication for quality of mix because percentage of voids can be computed. Nevertheless, this information is not available until next morning when the asphaltic concrete mat is cold and hardened. The disadvantage in waiting for this information is just the same as that in waiting for testing results from laboratory stability tests.

At this stage, it seems desirable to mention something about laboratory stability tests. The survey indicates a wide diversity as regards type of laboratory stability test used by states and cities. Since most answers in this survey did not indicate clearly whether the test is used for design, control, or both, only a general description will be made.

Hubbard-Field (9, 10), Marshall (11), and Hveem Stabilometer (12) are the most common tests adopted by states and cities. Other tests such as triaxial (13,14) and unconfined compression (15,16) are not so widely used. Almost all states specify that the plant inspector should send representative mix samples regularly to the central laboratory and stability test will be performed over there. Only one state requires plant inspector to mold the specimen before sending to laboratory for testing. Some discussions about various stability tests will be presented later.

Control Tests at Hot-Mix Plants

Plant control would be difficult unless substantial information regarding asphalt, aggregate (including filler), and final mix are available. For the purpose of getting information, all the tests should be run as often as possible. However, it is limited by the time available to the plant inspector. If two inspectors are stationed in the plant, one can specialize in running control tests, while the other would watch the whole plant and occasionally visit the job site in order to cooperate with the inspector over there. In case one inspector only is stationed in the plant, he can have very little time to run tests. Therefore, frequency of testing usually depends upon number of inspection personnel. Furthermore, conditions about raw material and plant operation would have some influence too. It is only natural that less tests will be required if raw materials are in good condition and the plant operations are proceeding uniformly and smoothly.

There are various arrangements as regards housing for plant laboratory. Some states specify that the contractor has to furnish a shed to be used for running field tests. Others provide their own. A good example of the latter case is shown in Fig. 8-9. The trailer, completely furnished with required equipments, can be moved very conveniently to any place.

Description about control tests will be limited to comparatively popular ones only. In some instance, sampling methods will also be discussed if they are particularly used at continuous hot-mix plants.

Gradation of heated aggregate and mineral filler

Sieve analysis for heated aggregate and mineral filler is standardized by A. A. S. H. O. (17) and designated as testing method T27-46 which is the same as A. S. T. M. (18) designation C136-46. The only difference lies in the method of sampling. At continuous plants, the sample can be taken by two ways, namely, the composite sample method and the bin sample method. In the former case, sample including mineral filler and aggregate of all sizes is taken from the chute directly connected to the mixer. This sample, if properly taken, should be more representative than the other because it is the actual dry mix feeded to the mixer. Another advantage of this method is the saving in time and labor. Only the sieve analysis of just one sample is sufficient to give required information. In case of bin sample, the testing process is tedious; the result indirect. Composite gradation of dry mix can be computed only when samples from each aggregate bin and mineral filler hopper are tested. However, bin sample method gives additional informations which would not be available had composite sample been taken. From the bin-sample data, it is possible to compute the asphalt content in final mix and measured rate of flow of heated aggregate and mineral filler. Rate of flow refers to the quantity passed through the gate opening per revolution of counter as shown in Fig. 7.

Testing and sampling of cold aggregates will not be described here because they are just ordinary material tests.

<u>Penetration of asphalt cement</u>

Standard method for penetration test is designated as T79-42 by A. A. S. H. O. and D5-52 by A. S. T. M. The purpose of making penetration test is not only for verifying grade of asphalt cement received but also to check the loss of penetration, if there is any, during storage. Since steam heat is usually applied continuously to the asphalt tanks, high temperature of asphalt cement might accelerate its oxidation so as to cause hardening. Therefore penetration test is desirable in order to assure the quality of asphalt cement.

<u>Asphalt content</u>

In most cases, adjustment for mix formula is usually effected by the change in asphalt content. Consequently, the determination of percentage of asphalt cement in the mix is of prime importance. Methods for getting this information can be classified into two general types, namely, the direct and the indirect method. In the direct method, test on the final mix has to be run and asphalt content can be found directly. In the indirect method, weight of aggregate, filler, and asphalt cement are determined separately and then the asphalt content is computed. Direct method reveals actual condition of the mix at a certain instant. However, special care should be taken in sampling the mix, otherwise the result would not be representative. Indirect method represents the average condition during a certain period. It gives only a rough idea about asphalt content. A brief description about both methods will be presented.

Several testing devices are available for getting the asphalt content by direct method. M. A. VerBrugge (19) suggested a rapid field test by using a Chapman flask to measure the displacements by composite aggregate and mix of equal weight respectively. Asphalt content can be computed by simple computation. Although this is a time-saving device, the question lies upon the degree of accuracy that can be attained by using this method. On the other hand, A. A. S. H. O. specifies the extraction of mix by centrifuge method which is designated as T58-37. Accuracy of this method depends largely upon the correction factor for ash. If character of mineral filler and aggregate are kept unchanged, the ash correction should remain constant. Therefore, a constant value can be applied to all similar samples and the time required for testing can be greatly reduced. Other extraction methods are more or less similar to the hot extraction test designated as A. S. T. M. D762-44T. Those extraction methods are usually adopted at central laboratories only. In either case, gradation of aggregates can be found from the extracted sample.

In regard to the indirect method, there are generally two ways in getting the asphalt content. It has been mentioned before that bin samples taken from continuous plant can be used to compute asphalt content in the mix. With one revolution of the counter as a base, the weight of aggregate, mineral filler, and asphalt cement fed to the mixer are determined. Asphalt content of mix can be computed accordingly. This computed asphalt content usually does not agree too well with that found by laboratory extraction test. The difference might be caused either by segregation of the mix taken for extraction test or by variations in the rate of flow of aggregate, filler, or asphalt cement.

Another indirect way in estimating average asphalt content in the mix is to check the total quantity of asphalt cement used for the manufacturing of certain truckloads of mix. Since truck scale is usually furnished to measure the weight of asphaltic concrete shipped from the plant and the quantity of asphalt cement used can be measured by inserting a calibrated rod to the asphalt tank below the mixer, the average asphalt content can be estimated with reasonable accuracy from the available data.

Specific gravity of compacted mix

This is deemed as a valuable information regarding quality of mix. Sample taken from the pavement is cut to suitable size and then tested for specific gravity by water displacement method. For fine textured specimens it is usually coated with paraffin before testing. But the paraffin coating device is not successful for mixtures containing coarse angular aggregates.

Plant stability tests

Among various stability tests, Marshall method (11) is the only one that can be performed either in the central laboratory or at the plant. If the testing procedure for Marshall test is studied, it seems that every step is exactly the same as that for ordinary laboratory stability tests except a portable machine is furnished and the compaction of specimen is effected by dropping of hammer. The use of constant temperature water bath in heating the specimen up to the specified temperature before testing is retained in Marshall method. Therefore, in the opinion of the author, Marshall test is not to be included in the category of rapid plant stability tests. Nevertheless, its testing procedure will be described briefly in order to facilitate the comparison between this and the suggested Plant Stability Test.

In the Marshall test, a representative mix weighing 1000 to 1250 grams is introduced to the mold. It is rodded 25 blows with the mixing trowel. After rodding, the surface of the mixture shall be leveled off approximately $\frac{1}{2}$ inch above the top of the forming mold. Then the specimen is compacted by a 10-pound hammer dropping from a height of 18 inches. Each side of specimen will receive 50 blows. Temperature of mix, immediately before compaction, shall not be less than 225^0 F. If height of specimen, after the first 50 blows, exceeds the required value, it has to be corrected by scrapping off the excess material before the second 50 blows are applied on the opposite end of the specimen. When compaction is completed, the mold, together with specimen, shall be cooled under water for approximately two minutes. Then the specimen is removed from the mold and its specific gravity determined by water displacement method. Before stability test, the specimen shall be immersed in water at 140^o F., plus or minus 1^o F., for a 20 minute period and not to exceed one hour. At last, the specimen is placed in the test mold and tested with a portable machine at the speed 2-inch per minute. The test mold consists of two segments of a 4-inch inside diameter ring from which a 3/4-inch strip has been removed from each side. The total load required to break the specimen is termed as stability and the deformation of specimen, expressed in hundredths of an inch, is called its flow value.

Besides Marshall test, there is an empirical method, known as "Pat Stain Test" (20), which has been used at sheet asphalt plants. Since it involves too much personal equation and its validity is limited to experienced inspectors only, "Pat Stain Test" is considered as obsolete at the present time.

Table 1. Summary of Inspection Practices at Asphaltic Concrete Plants

Inspection practice	Number of states and cities	Per cent of Total
Having their own inspection manual or instruction to plant inspectors	17	38.7
Following that recommended by Asphalt Institute	7	15.9
Following that recommended by A. S. T. M.	2	4.5
No definite regulations	18	40.9
Total	44	100.0

Figure 8. Plant Laboratory (Huxley Plant, Iowa State Highway Commission).

Figure 9. Inside View of Plant Laboratory.

LABORATORY INVESTIGATION OF SUGGESTED PLANT STABILITY TEST

From previous descriptions and discussions, it is obvious that there is an urgent need for a simple and rapid testing device designed primarily for the use at asphaltic concrete plants. The main objective of this research project is to develop such a testing method. This method will be named "Plant Stability Test". Before presenting the origination and investigation about the suggested test, a brief review of existing mechanical tests seems to be desirable.

Mechanical tests for bituminous mixtures can be classified in different ways. Where the character of their results are concerned, they can be divided into two groups, the analytical and the empirical. Triaxial compression (13, 14) is a typical analytical test, while most other tests are just empirical methods for indicating the quality of mix. If the principal property of mix being revealed by the test is considered, again all tests can be separated into two groups, namely, those involving plastic properties and others involving elastic properties. For the latter group, impact test and methods for the measuring of modulus of elasticity and rigidity modulus (21, 22) are typical examples. Since plastic properties are considered to be more important in regard to service behavior of bituminous paving, tests involving elastic properties receive less attention from asphalt paving technologists.

Tests involving plastic properties of mix can be further classified, according to their testing method, into several types. The following classification is suggested by the author. This classification is somewhat similar to that recommended by Lonsdale (23) in 1938. There are few modifications which are deemed necessary in view of the recent developments related to mechanical tests. The suggested classification is listed as follows:

Compression tests
Tensile tests
Direct shear tests
Extrusion tests
Beam tests
Bearing tests

For each type of testing, some popular methods will be listed. Descriptions regarding testing procedure are limited to those which will be compared with Plant Stability Test.

Compression tests are popularly used to reveal mechanical properties of bituminous mixes. They can be subdivided into three types, namely, the unconfined, the semi-confined, and the confined compression. For unconfined compression tests, the specimen is molded either in cylindrical or cubical shape. Vokac (15) made extensive investigations in connection with this test. On the other hand, Marshall method (11) can be considered as a type of semi-confined compression. In the case of confined compression, Hveem Stabilometer (12) and triaxial compression test shall be included.

Most recent developments in applying unconfined compression test for coarse bituminous mixtures were made by the Public Roads Administration Laboratory (16). According to their procedure, 4- by 4-inch cylinder is used as test specimen. The molding pressure is 3000 p.s.i. maintaining for 3 min. and temperature of mix just before molding should be 260° F. Test of specimen is performed with a constant rate of deformation (0.2-in. per min.) and the compressive strength of the specimen shall be taken as a measure for the quality of mix.

Procedure for Marshall test has been described under the heading "Plant stability tests".

Triaxial compression test is similar to that used in soil testing. For asphaltic concrete mixes, the specimen is usually 18-in. high and 6-in. in diameter. The other confined compression test, Hveem Stabilometer, has an entirely different arrangement in furnishing and recording side pressure. Specimens 2.5-in. high and 4-in. in diameter are used. Selection of this dimension is based upon ordinary loading condition of bituminous pavements. It is specified that the testing speed shall be 0.05 in. per minute. Formula for calculating the relative stability is cited as follows (24):

$$S = \frac{22.2}{\frac{R\,D}{400-R} + 0.222}$$

Where S = Relative stability

R = Stabilometer reading at 400 lbs. per sq. in. applied load.

D = turns of displacement on specimen.

In the case of tensile test, quantities measured are usually the breaking load and the elongation at break. Specimen may be either in beam shape (25) or in figure-of-eight type (20) similar to that used for Portland cement test. Cohesiometer designed by Hveem may be considered as another type of tensile test.

In order to avoid confusion, the term direct shear test is chosen for this group because action of shear is also involved, at a more or less extent, in other tests. For example, triaxial compression test can be considered as a shear test too. The most popular direct shear test was developed by Skidmore (26). Test specimen for ashpaltic concrete mix is 2.5- to 3-in. high and 4-in. in diameter. It is sheared across a diametral plane by cylindrical clamps and the breaking load is taken as a measure for the quality of mix. Lee and Markwick (25) suggested another shear test. According to their method, a slab 2.5-in. wide, 8-in. long, and 1-in. thick is used as the test specimen. It is cemented between two parallel steel plates and sheared by the relative motion of these plates.

There are several kinds of extrusion tests. The first one was developed by Emmons and Anderton (27). They designed a steel mold with openings on the sides and bottom. Maximum load for squeezing a specimen through the openings is recorded as the stability value. This test was abandoned afterwards due to the difficulty in preparing the rectangular shaped specimen. Emmons, then, deviced another type of extrusion test, known as roller stability machine (28). The most popular extrusion test is the Hubbard-Field method (9, 10). According to that method, specimen for coarse bituminous mix shall be 6-in. in diameter and approximately

2-in. in height. It is extruded through a concentric orifice, 5.75-in. in diameter, at the bottom of a cylindrical mold. The maximum pressure during extrusion is termed Hubbard-Field stability. Rate of extrusion has to be 0.04-in. per sec.

Beam tests were performed in different ways. Lee and Markwick (26) used beams in the size of 10-in. by 2-in. by 1-in. The beam is rested on roller supports and allowed to sag by its own weight. Rader (21,29) made similar experiments with beams 8-in. long tested at-70° F. According to his method, external load should be applied at the center. In either case, modulus of rupture and modulus of elasticity can be computed. Rader's method is really a test involving elastic properties of mix.

Bearing tests have been used by many technologists for verifying the quality of bituminous mixes. The most recent development was contributed by Campen and Smith (30). Their test is somewhat similar to the California Bearing Tests for soil. The load required to produce 0.15 in. settlement is termed the bearing index.

It is seen from previous descriptions that all mechanical tests, except Marshall method, are performed in the central laboratory. Marshall test can be run at the plant, but its principle testing procedure is just the same as that for ordinary laboratory mechanical tests. As properties of a mix will be greatly affected by the temperature during testing, the general practice is to use constant temperature oven or water-bath for keeping the specimen at specified temperature before testing. However, in the case of plant test, self-adjusted oven or water-bath would not only add a big item to the equipment list (which must be as simple as possible) but also delay the testing procedure to a great extent. Therefore, the elimination of oven or water-bath is considered as one of the most important features for the suggested Plant Stability Test. Another attempt in saving time and labor is the use of a single mold for both molding and testing of specimen. By such a device, the removal of specimen from mold can be avoided.

In developing the Plant Stability Test, efforts have been made to furnish all possible experimental backgrounds for every step in the testing procedure. Of course, there is no necessity to repeat certain experiments which have been performed by other investigators. In that case, result of the original experiment will be cited. For the purpose of clearness, laboratory investigations for test mold and test specimen are presented separately.

Test Mold

It seems logical that the first step in investigating the suggested stability test is to study the character of test mold. In order to avoid the confusion due to mixed influence of test specimen and test mold, specimens were prepared by following ordinary procedure which would be described later. Under this heading, the origination, sensitivity, and comparative study of test mold are to be included. As reproducibility of testing results can be affected by factors more than test mold alone, it will be described under another heading.

<u>Origination</u>

The purpose of a stability test is to predict service behavior of mix when it is compacted and subjected to normal traffic. Consequently, it is necessary to analyze the mechanical properties of a compacted mix before the type of test can be properly determined. Lee and Markwick made a clear analysis about such properties and classified them into three groups. Their classification (25, p. 146T) is quoted as follows:

> From the point of view of mechanical properties bituminous materials exhibit the characteristics of (1) plastic materials, which flow under a sustained load, (2) elastic materials, which show the pronounced hardness and elasticity characteristics of solids, (3) granular materials, which are characterized by (a) void content and porosity, (b) consolidation, (c) dilatancy when subjected to deformation.

Among the three items listed above, elastic properties of bituminous mix are generally believed to be less important under ordinary conditions. It is the plastic property which determines the resistance to deformation. A mix is termed "Stable" if its resistance to deformation is comparatively high. Lee and Markwick listed granular properties to illustrate the influence of weathering and disintegration. In the case of dense-graded bituminous surfacing with adequate amount of traffic, the influence of weathering and disintegration would be less important if aggregate and bituminous binder are properly selected.

From the above analysis, it is believed that a measure about the resistance to deformation would give enough information for the predication of service behavior. Of course, the measuring of specific gravity for test specimen is advisable too. At this stage, it seems desirable to know various elements causing resistance to deformation. Endersby (31, p. 206) classified these elements as follows:

(1) Interlock (mutual interference of the mineral particles with one another).

(2) Internal friction within the aggregate, between its surfaces.

(3) Cohesion due to asphalt.

(4) Apparent cohesion due to surface tension effects in asphalt, etc.

For the above four elements, no clear demarkation can be drawn because some of them are more or less linked together. Even if the most typical analytical mechanical test - triaxial compression is applied, the possible direct answer is cohesion and angle of internal friction as found by Mohr circle method. Since it is impractical to adopt complicated analytical tests at hot-mix plants, the only solution is to develop a simple empirical test which must be sensitive to various elements affecting resistance to deformation. The merit of the suggested empirical test will be verified with an indirect method. The four elements as listed before are affected by various factors such as gradation and type of aggregate, content and type of asphalt, density of mix, etc. Therefore, if the test is sensitive to all these factors, it is reasonable to believe that the test would be sensitive to all four elements too.

As mentioned before, the suggested test will be empirical in nature. Nevertheless, in the design of test mold, it is intended to simulate the actual loading condition as much as possible. Previous investigations regarding testing method and correlation of laboratory tests with service behavior are considered as valuable references. Of course, a cautious manner has to be maintained at any instant.

Probably the most complete comparative study of popular mechanical tests was made by Tulsa District, U. S. Engineer Office, in 1943. Since it is an unpublished report not available for distribution, no direct access has been made by the author. In a correlative study about Hubbard-Field, Skidmore shear, impact, and compression tests with service behavior, Vokac (32, p. 222) criticized most of the tests and finally drew the following conclusion (the term compression test refers to the unconfined type): " We, therefore, cannot help but attach great significance to the substantial agreement of the compression test data with service behavior."

Because of its simplicity and sensitiveness, unconfined compression test is also used by P. R. A. (16) for certain research work concerning bituminous mixes. In view of the above facts, the new test is decided to be some type of compression. The question, then, is what type should it be.

Considering a block of bituminous pavement under wheel load, it is obvious that this block is pressed by the vertical compression from wheel and reaction from base course. These two vertical forces are simulated in the unconfined compression test. In addition to these, there is certain side pressure exerted by adjoining blocks of pavement. If more close simulation is wanted, means should be provided to furnish similar side pressure. However, distribution of this side pressure is very uncertain. When the wheel is affected by acceleration, decerelation, or braking, distribution of side pressure will be influenced accordingly. Uniform distribution of side pressure might be true if the wheel was standstill.

This condition is simulated in the Hveem Stabilometer and triaxial compression test. Both of them are confined compression tests which are good for laboratory investigation but too complicated for field application. As simplicity is one of the most essential requirements for a plant test, a type of semi-confined compression is chosen as the basic feature for the test to be developed. In other words, non-uniform side pressure is furnished in addition to vertical pressure. This arrangement may not exactly agree with the actual loading condition, but it is considered as good enough for an empirical test.

Based upon the above consideration, a test mold was designed (Fig. 10-11). The test specimen shall be 4-in. in diameter and 4-in. high. It is exactly the same as that used by P. R. A. (16). The height diameter ratio of test specimen is always a subject of great controversy. In Hveem Stabilometer, a ratio of about 0.6 is used to simulate actual loading condition. Vokac (15) made extensive study about this ratio and suggested a maximum value for D/H as 1.33. It is equivalent to specify a minimum of 0.75 for the ratio H/D. On the other hand, Pfeiffer (33) criticised all tests using specimens with low H/D ratio. He pointed out that if such specimens were used there would be a disturbing effect caused by the friction between the steel bearing plate and the end of test specimen. His suggestion is to use the ratio 2 as a minimum. No compromise can be made between these adverse recommendations. For the suggested test, the ratio is decided to be 1 because it has been used by P. R. A. (16) without causing difficulty. However, this H/D ratio can stand further investigation to verify whether a higher H/D ratio would give even better results or not. When plant application is concerned, the difficulty in molding might be the practical limitation for increasing the height of specimen. More descriptions about test mold will be given under the heading "Equipments".

Another factor that should be considered in connection with size of specimen is the uniformity of testing results. As bituminous mixtures are heterogeneous in character, specimens should be of adequate size otherwise results might not be consistent. In the case of asphaltic concrete mixtures used for highway surfacing, the maximum size for aggregate is usually 1-in. Cylindrical 4-in. by 4-in. specimens are considered as satisfactory for testing 1-in. mix. More discussions about reproducibility of results are to be described later.

For unconfined compression tests, the stress-strain curve of a certain specimen is characterized by its modulus of elasticity, modulus of permanent deformation, compressive strength, and elastic limit (32). Since the stress-strain curve drawn for the suggested test is similar to that of unconfined compression test (described under the heading "Comparison with other mechanical tests"), it is possible to derive similar informations too. However, these four characteristics are interrelated to one another. In order to make the test as simple as possible, only the most critical one - compressive strength will be measured. Laboratory investigations indicate that compressive strength alone is sufficient to reflect variations in the quality of mix. Vokac (32, p. 221) made a similar statement as follows:

> Even if he should choose to limit himself to the measurement of compressive strength alone he would be able to predict with almost 100 per cent accuracy the service behavior of the mixture to be laid.

At this stage, it must be mentioned that the measured compressive strength (total load) shall be called "Stability" for the suggested test.

By making certain assumptions and approximations, it is possible to make some analytical study for the specimen tested by the suggested method. However, such studies are unlikely to be of much help because so many uncertainties are involved in assumptions and approximations. Therefore, no analytical study is to be presented. The dependability of Plant Stability Test will be verified by field applications and laboratory investigations which follow immediately.

<u>Sensitivity</u>

It has been mentioned before that a quality indicating mechanical test must be sensitive to all factors affecting the stability of bituminous mixes. Consequently, the first step in investigating the validity of a mechanical test is to study its sensitiveness as regards gradation and type of aggregate (including filler), content and type of asphalt, density of mix, etc.

In order to concentrate the attention to test mold alone, process in preparing test specimen has to be the same as that used for ordinary stability tests. The procedure, therefore, is to mold specimen at 250° F by a static load of 3000 pounds per sq. in. (double plunger method) maintained for three minutes. Molding pressure of 1000 lbs. per sq. in. is used only for one series of specimen used in studying the sensitivity of test to variation in density of specimen. The molding is done with ordinary molds as used in preparing specimens for P. R. A. unconfined compression test (16). Temperature of mold is also 250° F. After molding, the mold together with specimen is cooled by running water for few minutes and then the specimen is extruded from the mold and cured in air for 24 hours at room temperature. Hot mix used for testing is prepared by mechanical mixing at 300° F. It is realized that individual batch for each specimen would give more uniform results but, due to limitation of equipment and time, multi-batches are used with particular care to avoid segregation.

For each specimen, percentage of air voids and voids in mineral aggregate are computed from its specific gravity which is found by water displacement method. In the case of some rich mix, certain amount of asphalt will be absorbed by aggregate. Furthermore, loss of asphalt during mixing is almost unavoidable. Since the absorption and loss as described above are neglected in the conventional method for computing theoretical maximum density, it is possible that the computed density may be even lower than that found by water displacement method. If that happens, percentage of air voids appears to be less than zero. Of course, that is impossible. A blank space in the table will indicate such case.

Right before testing, specimens are immersed in hot water at 140° F (with a tolerance of 1° F) for one hour. The heated specimen is slipped into the test mold which is also at 140° F. A tappered ring can be used to facilitate this operation (Fig. 10). Then, a compression ram 3 31/32-

in. in diameter and 5-in. high is placed over the specimen to transmit the pressure from testing machine. The whole assembly is brought back to 140° F water bath for 3 min. in order to keep everything at right temperature. It is now ready for testing. Speed for deformation shall be 0.05-in. per min. per in. height of specimen. In other words, it has to be 0.2-in. per minute for specimens with a height of 4-in. This speed is chosen because it has been proved as satisfactory by P. R. A. (16) in unconfined compression test using 4-in. specimens.

Before the description about testing results for various experiments, it seems appropriate to list all materials used for such tests. Asphalt cement (penetration 73) is used as bituminous binder. Its properties are shown in Table 2. Crushed gravel and uncrushed gravel are used as coarse aggregate; sand as fine aggregate; limestone powder and refined fly ash as mineral filler. Properties of all mineral materials are shown in Table 3.

Furthermore, it should be mentioned that all tests are performed with a set of three identical specimens. In testing heterogeneous materials like asphaltic concrete mixes, it is desirable to have as many specimens as practicable, otherwise testing results might not be representative. Fortunately, fairly uniform results are found at all occasions so that 3-specimen system is considered as satisfactory. For all tests under this heading, the maximum size for coarse aggregate is 3/4 in.

In making any investigative tests, the general principle is to keep everything constant but vary one factor which is to be studied. This principle has been followed through all sensitivity studies.

In the investigation about the sensitivity of test towards gradation of aggregate (including filler), three different gradations, A, B, and C, are chosen (Table 4, Fig. 13). Testing results are shown in Table 5 and Fig. 14. It is seen that optimum stability is quite different for mixes of various aggregate gradings.

Table 6 and Fig. 15 show the effect on stability of mix due to variation in type of coarse aggregate. Grading A is used for both crushed gravel and uncrushed gravel mixes. The stability of the mix composed of crushed gravel is substantially higher than the other. This exactly agrees with the generally recognized fact that angular particles cause higher resistance to deformation.

Effects due to variation in type of filler are shown in Table 7 and Fig. 16. Grading B is used for both mixes. The difference in stability value found from the test indicates the sensitivity to quality of mineral filler. Since the test has been verified to be sensitive to coarse aggregate and mineral filler, it is reasonable to believe that the same would be true in the case of fine aggregate contained in asphaltic concrete mixes.

Since density of specimen varies with the molding pressure (assuming other factors constant), two different molding pressures, 3000 p. s. i. and 1000 p. s. i., are used in order to study the sensitivity of test towards density of mix. Testing data are shown in Table 8 and Fig. 17.

Sensitivity of test towards asphalt content has been included in all previous experiments. It is indicated in all stability curves that there is a definite optimum asphalt content for all types of mix (optimum asphalt content refers to that corresponding to highest stability). When 1000 p. s. i. molding pressure is used, the curve is not so sharp because the density of mix is well below normal condition. Due to material difficulties, the sensitivity as regards type of asphalt has not been tested. As the suggested test is sensitive to all other factors influencing stability of mix, it is unlikely that the test would not be sensitive to type of asphalt.

At this stage, it seems necessary to mention that all experiments described above are aimed at the investigation of sensitivity of test towards various factors affecting resistance to deformation. No attempt has been made to study the selection of material or the design of mix.

Comparison with other mechanical tests

The purpose in making this comparative study is to evaluate the standing of Plant Stability Test among all common mechanical tests. It has been mentioned before that the general principle in making a comparative study is to maintain other factors constant and concentrate upon one variable. Therefore, specimens for all mechanical tests are prepared in the same manner, regardless of their original methods. By such arrangement, it is possible to have a definite comparison regarding type of testing. Since speed of loading is closely incorporated with type of testing, it is kept unchanged from that specified in the original test.

Materials used in this series of tests are the same as that described before. Crushed gravel, sand, and limestone powder are combined according to grading A and mixed with 73-penetration asphalt cement. Method for preparing specimen follows that described under last heading. As regards size of specimen, it is 4-in. by 4-in. cylinders for both unconfined compression and Field Stability Test, 6-in. in diameter 2-in. high for Hubbard-Field test, and 4-in. in diameter, 2½-in. high for both Hveem and Marshall test.

Testing results are shown in Table 9 and Fig. 18. An optimum stability is indicated in all curves except that for the Hveem Stabilometer test. This is just one of the characteristics inherited in the Hveem test. In explaining the use of this test, Hveem (34, p. 6) stated: "Stabilometer tests are used primarily to determine the maximum amount of asphaltic binder which can be introduced in a given aggregate without developing instability." There is no remarkable difference in the asphalt content corresponding to optimum stability as found from various tests.

Some investigators have tried to correlate the stability values of various tests with one another. Their intention is to find an equation or a curve representing the relationship of any two tests. As most stability tests are empirical in nature and their sensitivity to various factors is substantially different, the suggested correlation has not been successful. In regard to relative merits of all tests, it is beyond the scope of this study to give any admiration or criticism. The objective of this comparative study is simply to indicate that the suggested test is as effective as any other test so far as the type of testing is concerned.

Since the Plant Stability Test is somewhat similar to unconfined compression test, it seems desirable to compare some of their common characteristics. In Fig. 18, stability curves for both tests are shown. The one representing Plant Stability Test magnifies the general character of the other. When plant application is concerned, this magnification is very advantageous. Since portable testing machines are usually far less accurate as compared with laboratory stationary machines, magnified stability readings give more accurate indication regarding the quality of mix. The stress-deformation curves for both tests are shown in Fig. 19. It is seen that the general character of these two curves are somewhat similar. As compressive strength is the only item to be recorded in Plant Stability Test, no further discussion will be devoted to stress-deformation diagram.

Test Specimen

Since the most particular feature of Plant Stability Test is the way in handling test specimen, it is necessary to investigate all factors related to such operation. The whole procedure of Plant Stability Test might be unreliable unless there are experimental backgrounds for each step involved in the preparation and testing of specimen. Again, no repetition will be made in case similar experiments have been performed by other investigators. In such occasions, the original results are cited.

Curing of specimen

Curing of specimen is absolutely necessary in the testing of cold mixes. When hot-mix asphaltic concrete is concerned, usually there will be no difference in testing results for specimens with or without curing. In some extreme case, curing of hot-mix specimen at room temperature might be desirable if the coarse aggregate had the property of extraordinary high absorption. Even in such case, the difference due to curing is probably so small that it cannot be measured by ordinary portable testing machine. The conclusion made by U. S. Waterways Experiment Station (35, p. 50) regarding curing of specimen is quoted as follows:

> It was found that the stability and flow of specimens were not affected by the curing period. Specimens which were tested with no curing period showed stability and flow equal to those which had been cured for a period of 24 hrs.

For the Plant Stability Test, no curing perios is allowed for the specimen.

Temperature of mold

There is no universal agreement in regard to temperature of mold used for preparing specimen. The purpose for using hot mold (same temperature as hot-mix) is to avoid sudden chilling of mix in contact with the mold. Usually specimens prepared with hot mold will have a more smooth surface. However, the formation of smooth surface might be the result of segregation in the mix. In other words, there is a concentration of asphalt mortar and free asphalt close to the mold and, consequently, a deficiency of mortar and asphalt in the nearby inside sphere of specimen. The effect of this segregation may be very small but, anyhow, it can be considered as an advantage for using cold mold (at room temperature).

In that case, since asphalt mortar and free asphalt are not concentrated at the portion close to the mold, the surface of specimen will not be so smooth as the other case. Fig. 20 shows the difference in surface texture for specimens prepared with hot and cold mold. Under the consideration of simplicity and shorter testing time, mold at room temperature is used for the suggested test.

Compactive effort

Almost every mechanical test has its own particular method for the compaction of specimen. The general principle in preparing specimen is to simulate the actual condition of bituminous pavement. Since orientation of particles is an important element related to efficiency of consolidation, density alone does not tell the whole story. For example, two specimens prepared by different type of compaction might have equal density but their resistance to deformation is likely to be unequal. In such case, difference in efficiency of consolidation is the main reason. This is verified by tests using asphaltic concrete mix (Table 10). It is seen from the table that specimens compacted by static load alone have the same specific gravity as the other but its stability value is substantially lower. The mix used for this experiment contains crushed limestone (maximum size 1-in.) limestone powder, and 80 penetration asphalt cement. Its asphalt content is 5.6 per cent.

Method for preparing specimen has been studied by many investigators. The British Road Research Board (36) tried the use of a roller for compacting the specimen. Texas Highway Department (37) added a gyratory motion to the mold besides static load for compaction. Dynamic load in the form of dropping hammer is adopted in the Marshall method and drop compaction with a cam-operated table has been investigated by Waterways Experiment Station (35). Another device for preparing specimen is the use of vibration before compressive load is applied. All these methods have their particular values. It is hard to say which one gives the most comparable result to field procedure. The general belief is that specimens prepared by static load alone cannot represent the actual condition of bituminous pavement. However, compaction by pure static load is still a popular method for the preparation of specimen. This is because of its simplicity and the elimination of personnel equations which are often involved in tamping, hammer dropping, and gyratory motion.

In choosing the type of compactive effort for the Plant Stability Test, considerations are given to two factors, namely, simulation to pavement condition and simplicity in operation. The final decision is to apply certain number of blows with a 10-lb. hammer dropping from a height of 18-in. followed by 1000 lbs. per sq. in. static load maintained for 1 min. The rate for hammer dropping shall be approximately once per second. If the operator lifts and drops the hammer too fast, it is likely to cause some uncertainties, and, consequently, to introduce personal equations. Details about the hammer are shown in Fig. 12. The 2.5-in. rod attachment at the bottom of hammer seat will be described under the heading "Temperature control".

It has been mentioned before that density alone cannot indicate everything about the condition of consolidation for bituminous pavements. Therefore, exact simulation to pavement condition is impossible unless extensive correlative studies are made with experimental roads involving all possible variations in regard to aggregate, binder, and the mix as a whole. A comparison between laboratory prepared specimens and cored samples from the road will give the answer for proper compactive effort. Since such constructional project exceeds possibility for college research, the next choice is to use "Density" as a reference.

As mentioned before, a combination of dynamic and static load shall be used for the preparation of specimen. By such a combined compactive effort, it is possible to have a more close simulation as regards efficiency of consolidation for bituminous pavements built with modern paver and roller. Had this objective been reached, there would be more sound background for the use of density as the only correlative factor.

Table 11 shows results of all correlative tests. Specific gravity for laboratory prepared specimens and samples taken from pavement are measured by water displacement method. Thickness of layer, from which samples are taken, is 2-in. The sample is dug out in the form of a slab (about one ft. square) one day after the pavement has been laid. It is then cut into smaller pieces and its specific gravity measured. This specific gravity cannot represent the pavement condition in the future because the density of asphaltic concrete pavement usually increases after it has been opened to traffic for a certain period. Again, this is a subject which deserves long time investigation. For the present purpose, it seems appropriate to adjust the specific gravity of laboratory prepared specimen to be equal or little higher than that of pavement sample. Under this consideration, the compactive effort is decided to be fifty blows by hammer followed by 1000 p. s. i. static load maintained for one min. It is seen in Table 11 that specific gravities of pavement samples are very close to or little lower than that of specimens prepared by the selected compactive effort. Tests made with three types of mix as indicated in the table cannot represent all varieties of asphaltic concrete paving. However, results from these tests are considered as good enough for the experimental application of Plant Stability Test.

Height of specimen

It is very difficult, if not impossible, to prepare specimens with a height exactly equal to 4-in. or other round numbers. The general practice is to specify certain tolerance. In order to determine the proper value for such tolerance, specimens of various height were prepared. Results listed in Table 12 reveal that the difference in stability value for specimens between 3.85-in. and 4.14-in. high is very small. Therefore, it is decided that the height of specimen for Plant Stability Test shall be 4-in. plus or minus 0.10-in.

In the suggested test, the height of specimen can be measured without extruding it out of the mold. In other words, a combined height of specimen, compression ram, and base plate shall be measured. It is advisable to make the thickness of base plate and compression ram a round number so that the height of specimen can be found very easily. The measurement for combined height can be done with a right angle ruler or a dial fixed at definite position on a solid stand. Dial with divisions representing 0.01-in. is good enough for this purpose.

Temperature control

Control of temperature is a very important step in developing Plant Stability Test. Operation for this test would be as slow as that for others unless the use of constant temperature oven or water bath is eliminated. First attempt in solving this problem was to use time as a reference for temperature control. This device has been considered as not accurate enough. It was then decided to use an armored thermometer inserted in the center of specimen in order to give a definite indication about temperature before and during testing. This thermometer method would not be reliable except that the temperature difference between the center and outside portion of specimen follows a definite pattern. In order to study this thermal character of specimens, a series of tests were performed.

Considering the assembly of specimen and test mold as shown in Fig. 11, the temperature difference between the center and outside portion of specimen may be influenced by two factors, namely, (a) thermal capacity of the specimen and mold (b) amount of heat transmitted within and without the assembly. In physics, the thermal capacity of a body is equal to cM. M is the mass of a body and c its specific heat. The mass can be considered as constant for either the specimen or the mold. Specific heat for mold is also a constant, while that for specimen will be influenced by condition of mix. When the transmission of heat is concerned, it seems appropriate to consider the case of conduction only. Heat transmitted in linear steady state conduction is determined by the formula:

$$H = \frac{k\,A\,(t_2 - t_1)}{d}\,T$$

Where H = Amount of heat transmitted by conduction.

k = Thermal conductivity of the substance.

A = Cross sectional area of the body.

$(t_2 - t_1)$ = Temperature difference between two cross sections.

d = Distance between the two cross sections.

T = The Time of flow.

In radial steady state flow, the formula is modified in geometrical factors, but considering small portions of the medium the above formula is still valid. In the case of non-steady state flows, specific heat of materials must be also considered in conduction formulas. In the equipment used for the Plant Stability Test, the thermal conductivity of the mold and all dimensional factors for both the mold and the specimen are always constant. In order to minimize the variation in amount of heat transmitted from the assembly to the air, a 1-in. insulating sleeve is used to cover the mold. This sleeve preserves heat of the whole assembly and eliminates influences caused by variation in wind velocity and air temperature.

From previous descriptions, it is seen that temperature difference between center and outside portion of specimen depends principally upon is attached at the bottom of hammer seat in order to reserve a hole for armored thermometer which is connected with the compression ram. This rod has exactly the same shape as that of the lower section of armored thermometer. The armor for protection the glass thermometer should be fairly strong. An alternate way is to use metal stem thermometer which is also available in the market. Its trade name is Weston All-Metal thermometer.

The armored thermometer is placed at the center of specimen after the compaction by hammer. It is kept there during compaction by static load and at the time of testing. When the specimen is tested under compressive load, the shortest distance from the plane of failure to the center of specimen is approximately one inch. At center portion of specimen, the condition during testing is somewhat similar to that during compaction by static load. Therefore, it is believed that no significant influence to stability value will be caused by the insertion of thermometer. This has been verified by tests to be described later.

Temperature for testing shall be 160° F as indicated by the inserted thermometer. This decision is based upon the fact that tests using thermometer controlled specimens at this temperature give approximately the same stability value as that found from tests using water heated specimen at 140° F (Table 15).

Density of specimen

Specific gravity of specimen is usually determined by water displacement method. For Plant Stability Test, this method cannot be used because specimen is not extruded from the mold after molding. As the height of specimen is measured to one-hundredth of an inch (refer to "Height of specimen") and its cross sectional area is constant, it is simple to compute the volume. Consequently, density of specimen can be found since its weight is known. This computed density is usually a little lower than the specific gravity found by water displacement method. At asphaltic concrete plants, what the inspector wants to know is the relative variation in density of specimen prepared at different times. Therefore, indication given by this computed density is as good as that given by the other.

Table 2. Properties of Asphalt Cement Used for Sensitivity Tests

Specific gravity at 77° F/77° F	1.0016
Flash point (open cup)	610° F
Loss on heating (5 hours at 325° F)	0.12%
Soft point (R and B method)	121° F
Penetration at 77° F	73
Soluble in $C\ Cl_4$	99.75%

Table 3. Properties of Mineral Materials Used for Sensitivity Tests

Material	Sp. Gr.	Size used in mix	Remarks
Crushed gravel	2.67	3/4-in. to No. 8	Absorption 1.7%, Wearing (L. A. abrasion, grading B) 27%
Sand	2.62	Passing No. 8	17.4% passing No. 200
Limestone powder	2.68	Passing No. 50	70.5% passing No. 200
Refined fly ash	2.46	Passing No. 50	69.0% passing No. 200

Table 4. Gradation Chart

Designation	Per cent Passing									
	3/4-in.	½-in.	3/8-in.	No.4	No.8	No.14	No.28	No.48	No.100	No.200
Grading A	100	88.4	77.1	56.1	43.8	37.1	28.4	19.1	12.3	7.8
Grading B	100	100	85.7	66.1	51.6	44.2	35.2	25.4	16.6	10.3
Grading C	100	79.8	66.9	47.4	36.3	29.4	20.9	12.1	6.6	3.7

Table 5. Testing Results Regarding Sensitivity to Gradation of Aggregate[1]

Per cent of A.C.	4			5			6			7		
Grad. of agg.	A	B	C	A	B	C	A	B	C	A	B	C
Stability in lbs	3340	4300	3340	4720	5660	3840	4340	5080	2230	1430	2660	1850
Per cent of air voids	5.8	8.1	7.6	2.3	5.0	4.2	-	1.5	1.4	-	-	-
V. M. A.[2]	15.2	17.6	16.9	14.3	17.1	16.0	14.5	16.2	15.8	16.5	16.7	17.4

[1] Crushed gravel is used for coarse aggregate, sand as fine aggregate, and limestone powder as mineral filler. All data are the average of testing results from three specimens.

[2] V. M. A. means percentage of voids in mineral aggregate.

Table 6. Testing Results Regarding Sensitivity to Type of Aggregate[1]

Type of agg.	Crushed gravel				Uncrushed gravel			
Per cent of A. C.	4	5	6	7	3	4	5	6
Stability in lbs.	3340	4720	4340	1430	2220	2280	2680	1560
Per cent of air voids	5.8	2.3	-	-	9.0	4.8	2.1	0.6
V. M. A.	15.2	14.3	14.5	16.5	15.0	13.4	13.0	14.0

[1] Sand is sued as fine aggregate, limestone powder as mineral filler. Grading A is adopted for all mixes. All data are the average of testing results taken from three specimens.

Table 7. Testing Results Regarding Sensitivity to Type of Mineral Filler[1]

Type of filler	Limestone powder				Refined fly ash			
Per cent of A. C.	4	5	6	7	4	5	6	7
Stability in lbs.	4300	5660	5080	2660	3390	3740	3660	760
Per cent of air voids	8.1	5.0	1.5	-	7.1	3.2	1.0	0.3
V. M. A.	17.6	17.1	16.2	16.7	16.3	15.1	15.2	16.8

[1] Crushed gravel is used as coarse aggregate, sand as fine aggregate. Grading B is adopted for all mixes. All data are the average of testing results taken from three specimens.

Table 8. Testing Results Regarding Sensitivity to Density of Mixture[1]

Molding pressure	3000 lbs. per sq. in.				1000 lbs. per sq. in.			
Per cent of A. C.	4	5	6	7	4	5	6	7
Stability in lbs.	3340	4720	4340	1430	1630	1950	1650	1600
Per cent of air voids	5.8	2.3	-	-	9.4	5.6	2.9	0.6
V. M. A.	15.2	14.3	14.6	16.5	18.4	17.2	17.0	17.2

[1] Crushed gravel is used as coarse aggregate, sand as fine aggregate, limestone powder as mineral filler. Grading A is adopted for all mixes. All data are the average of testing results taken from three specimens.

Table 9. Testing Results for Comparison of Various Mechanical Tests.[1]

Per cent of A. C.		4	5	6	7
Hveem	Gauge reading at 400 p.s.i.	46	41	42	159
Stabilo.	Relative stability	17.4	18.0	16.9	7.1
Hub.-Field stability in lbs.		5020	6770	5180	2700
Marshall stability in lbs.		1210	1990	1640	1020
Compressive strength (unconfined compression) in lbs.		1250	2640	2120	800
Stability by P. S. T.[2] in lbs.		3340	4720	4340	1430

1 Crushed gravel, sand, and limestone powder are combined according to grading A and mixed with 73-penetration asphalt cement. All data are the average of testing results taken from three specimens.

2 P. S. T. represents Plant Stability Test.

Table 10. Stability Value for Specimens Prepared in Different Ways.[1]

Method of compaction	Sp. Gr.	Stability in lbs.
2000 p. s. i. static load maintained for 3 min.	2.38	3570
75 blows by 10-lb. hammer dropped from a height of 18-in. followed by 1000 p.s.i. static load maintained for one minute.	2.38	4190

1 All data are the average of testing results taken from three specimens.

Table 11. Study of Compactive Effort for 4-in. by 4-in. Cylindrical Specimen[1]

Type of mix	Sp. Gr. of laboratory prepared specimen under respective compactive efforts: 75 blows followed by static load 1000 p. s. i.	50 blows followed by static load 1000 p. s. i.	25 blows followed by static load 1000 p.s.i.	Sample taken from pavement: Sp. Gr.	Per cent of air voids
A	2.32	2.30	2.28	2.30	5.0
B	2.38	2.35	2.32	2.34	5.5
C	2.37	2.34	2.31	2.33	6.5

[1] All data are the average of testing results taken from three specimens. Mix A contains crushed gravel (maximum size 1-in.) as coarse aggregate, sand and agricultural lime as fine aggregate and filler. Mix B and C contain crushed stone, sand, and limestone powder. Maximum size for aggregate is 1-in. for Mix B and 0.75-in. for Mix C.

Table 12. Relation Between Height and Stability of Test Specimens.[1]

Height of specimen in in.		3.05	3.56	3.85	4.00	4.14
Stability in lbs.	Individual Readings	4960	4530	3850	3750	3730
		4970	4490	3840	3790	3690
		5010	4470	3790	3770	3700
	Average	4980	4500	3830	3770	3710
Per cent of stability (Taking stability for 4-in. high specimen as 100 per cent)		132.1	119.4	101.6	100	98.4

[1] Maximum size of aggregate in mix is 3/4-in.

Table 13. Temperature of Specimen as Affected by Variations in Air Voids

Compactive effort	Per cent of air voids	Temperature (^{o}F) at outside portion of specimen when it is 160°F at center.
3000 p.s.i. static load for three minutes	2.3	132
50 blows followed by 1000 p.s.i. static load for one minute	4.7	134
25 blows only	11.7	135

Table 14. Temperature of Specimen as Affected by Variations in Asphalt Content, Initial Temperature of Mix, and Original Temperature of Mold

Variable factor		Temperature (°F) at outside portion of specimen when it is 160°F at center
Per cent of A. C.	3	136
	5	134
	7	134
Initial temp. of mix (°F)	240	131
	250	134
	260	136
Original temp. of mold (°F)	70	134
	110	139

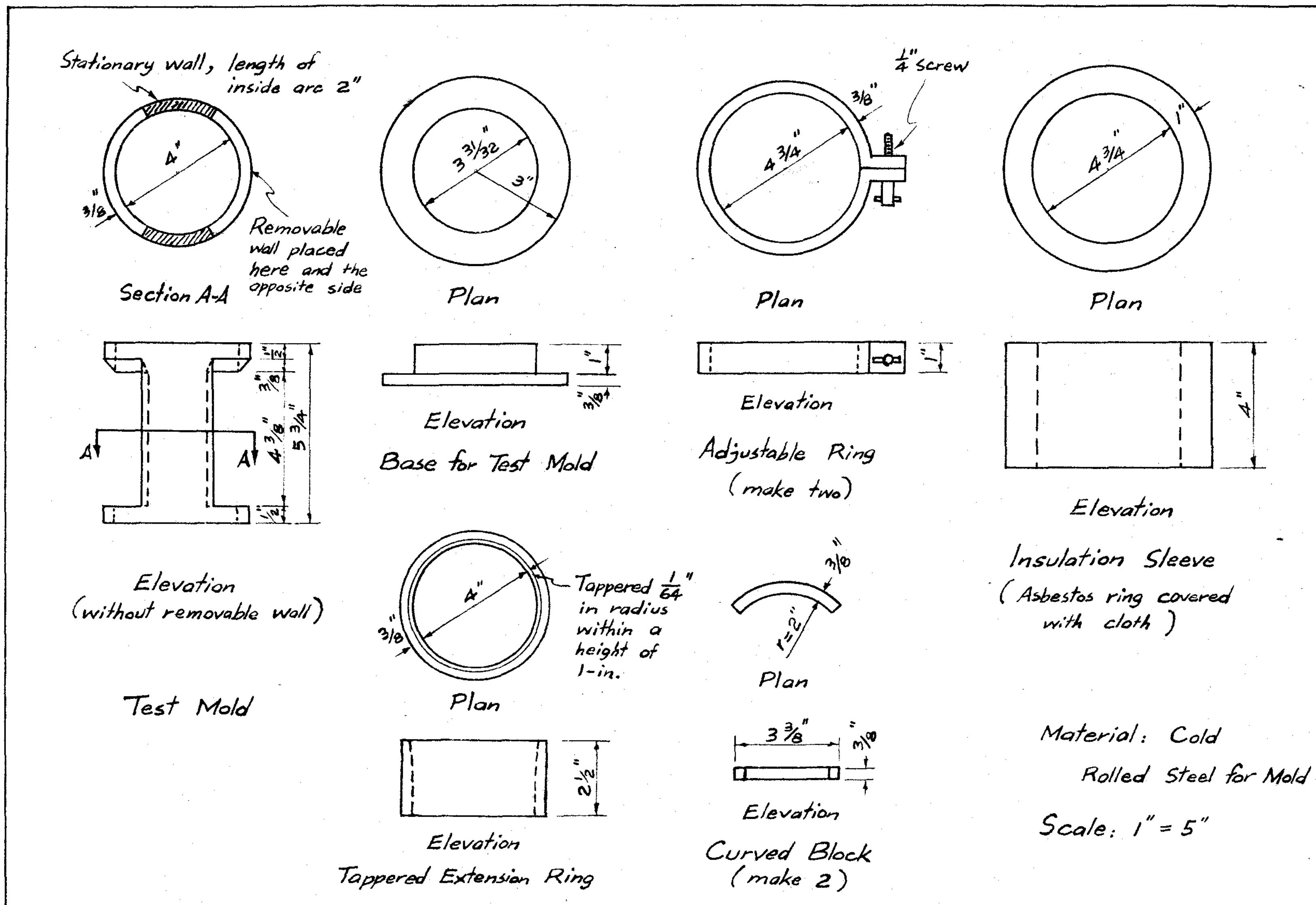

Figure 10. Test Mold and Accessories for Plant Stability Test.

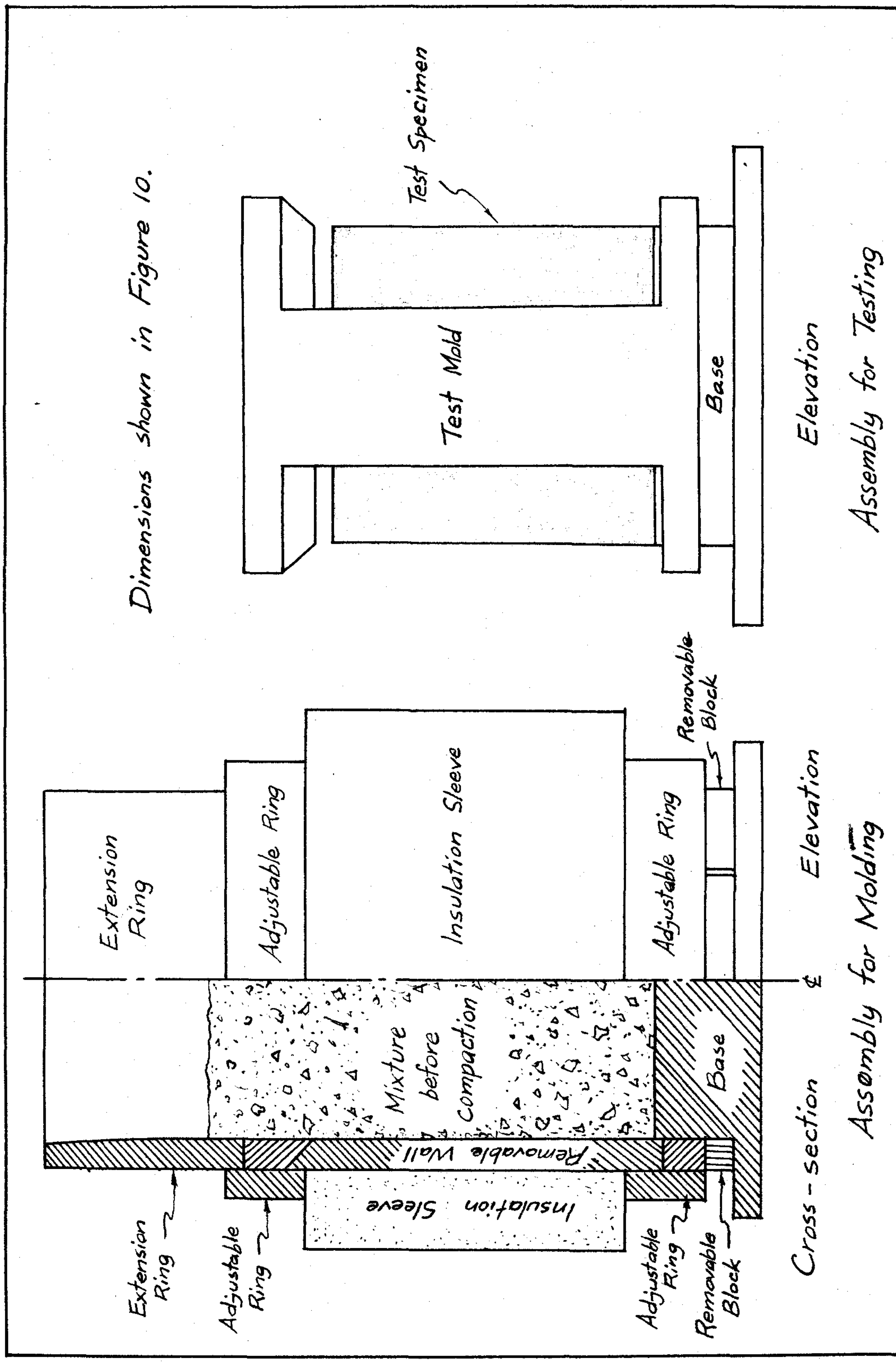

Figure 11. Assemblies for Test Mold

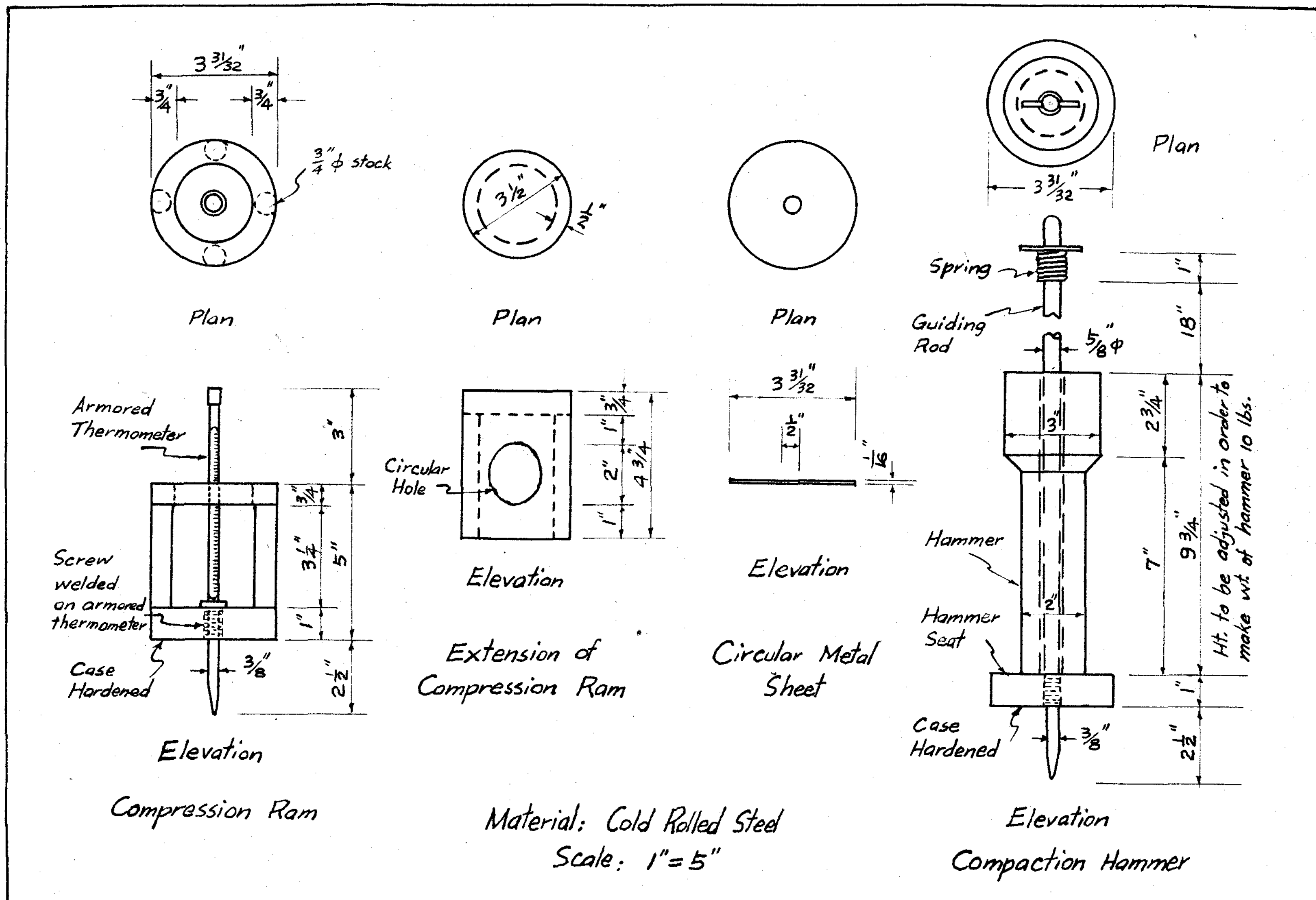

Figure 12. Compaction Hammer and Compression Ram for Plant Stability Test.

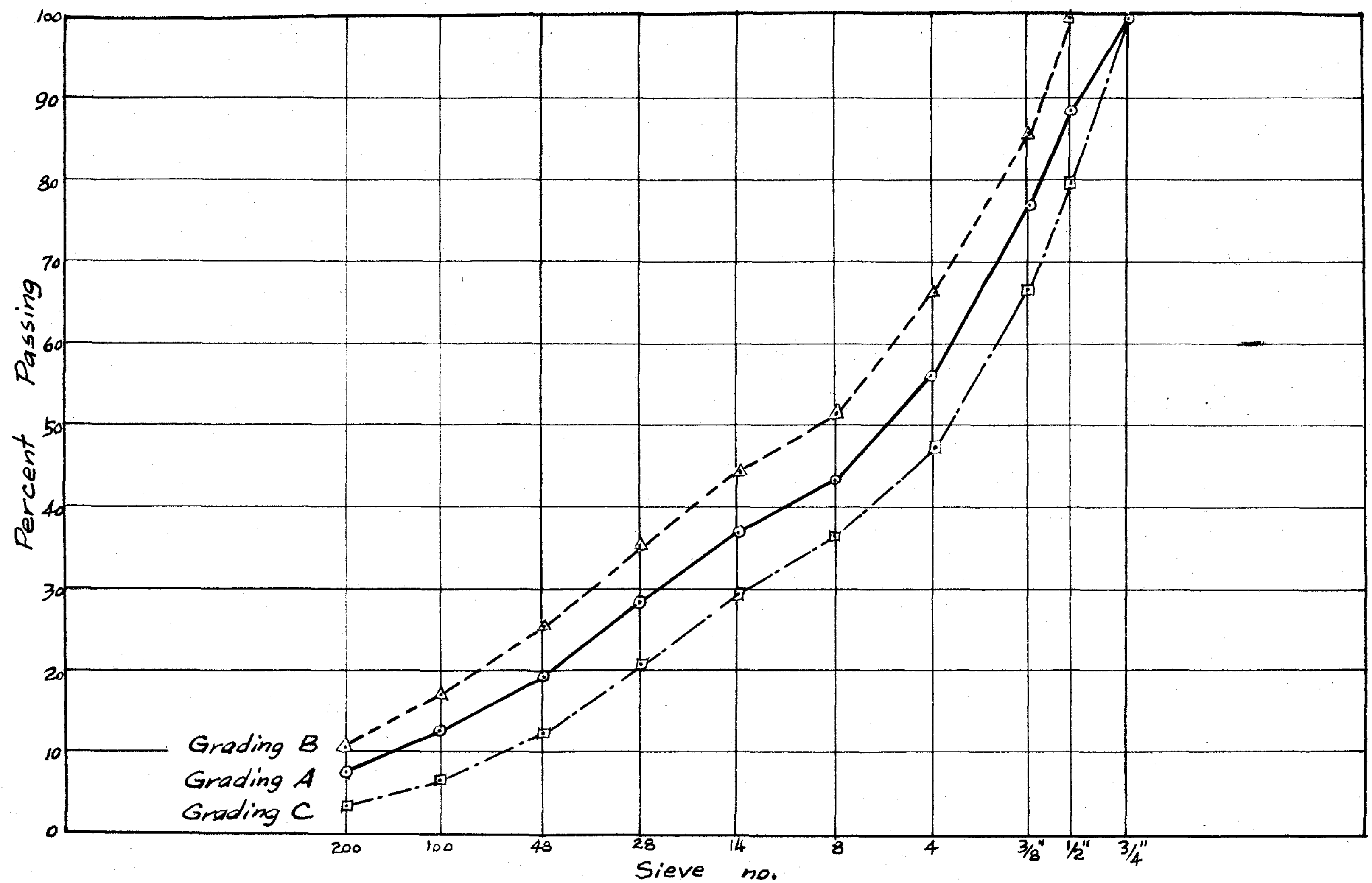

Figure 13. Gradation Curve for Aggregate in Various Mixtures.

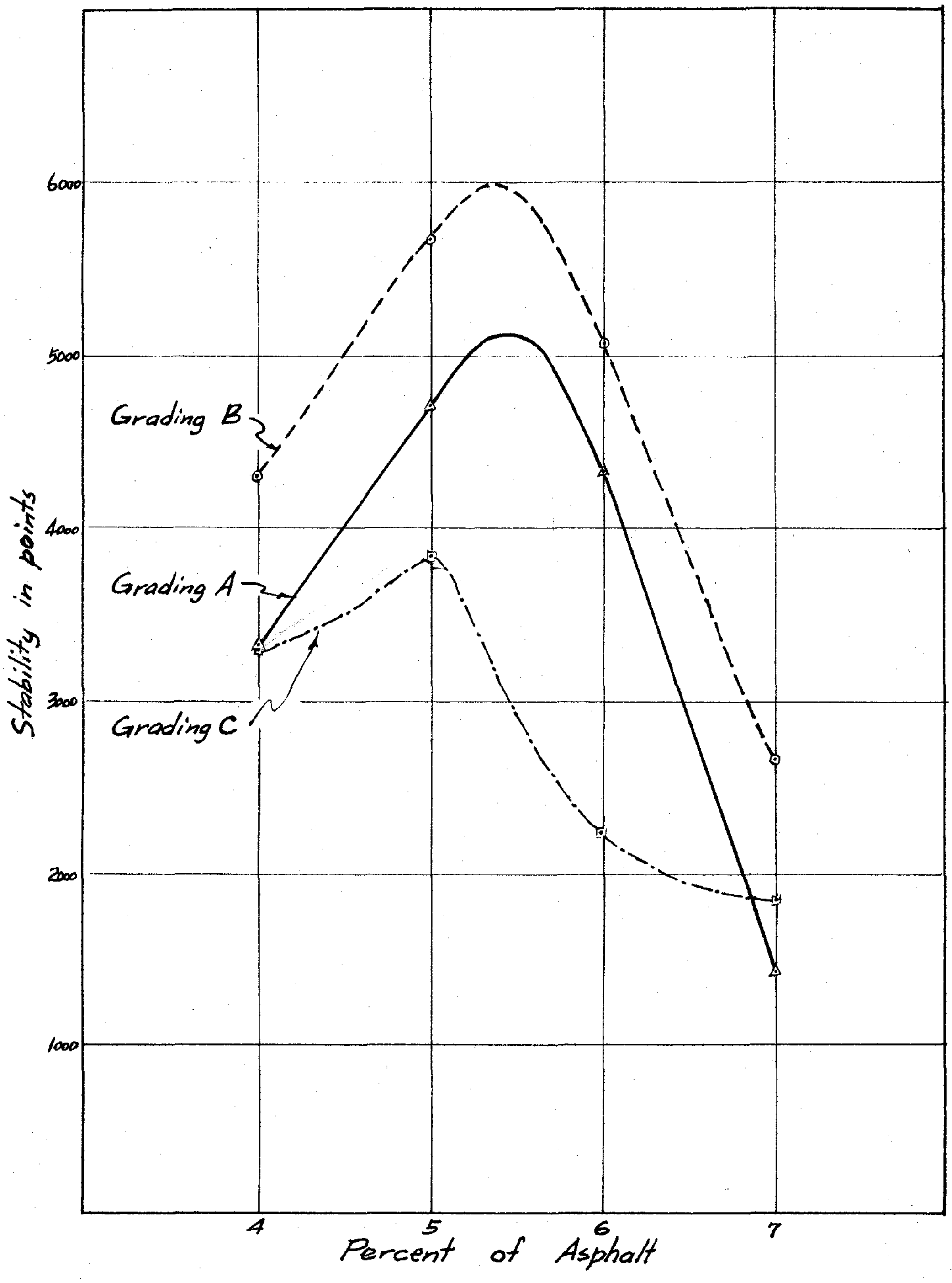

Figure 14. Stability Curve for Mixtures with Aggregate in Different Gradings (refer to Table 5 for details).

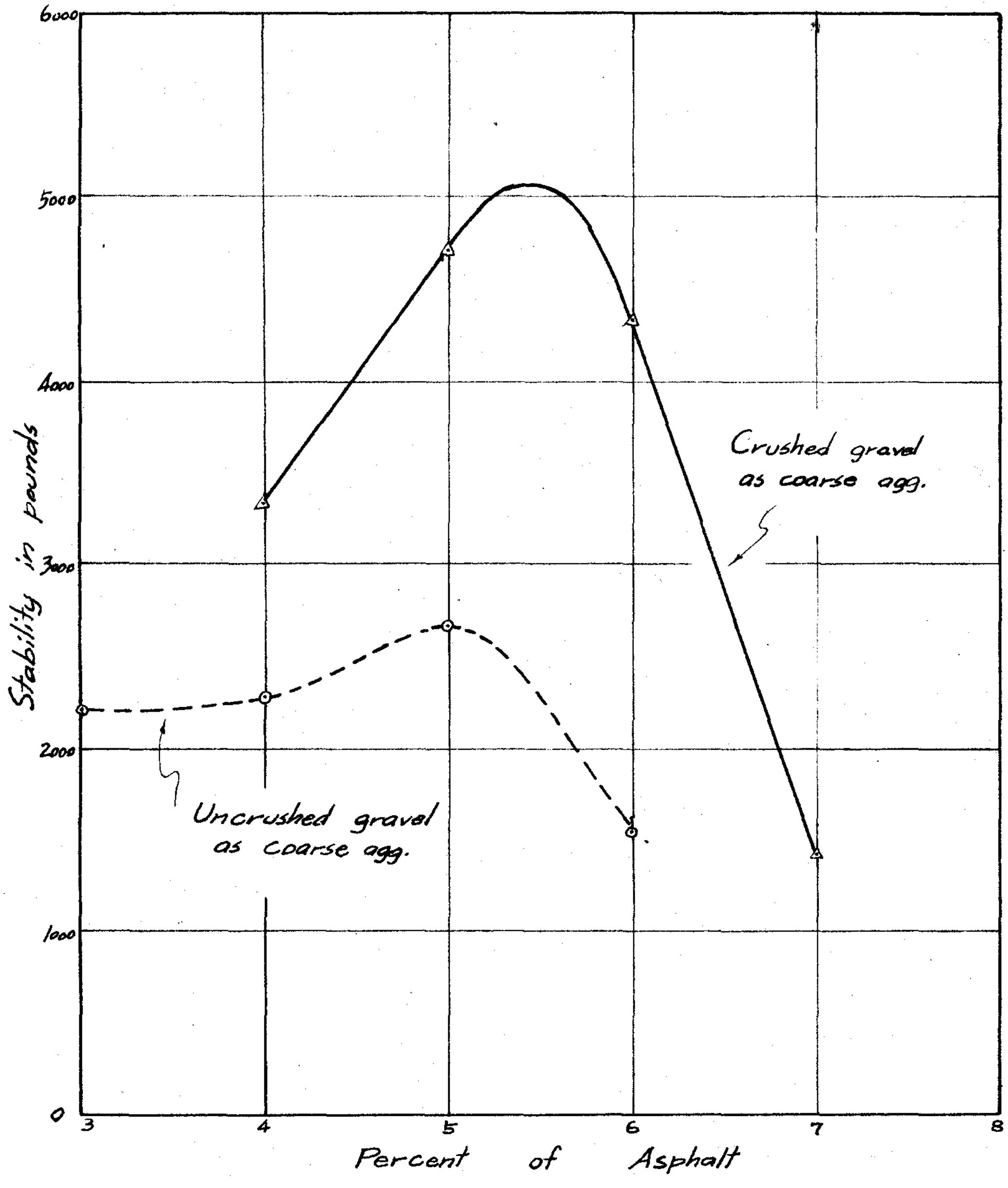

Figure 15. Stability Curve for Mixtures with Different Type of Coarse Aggregate (refer to Table 6 for details).

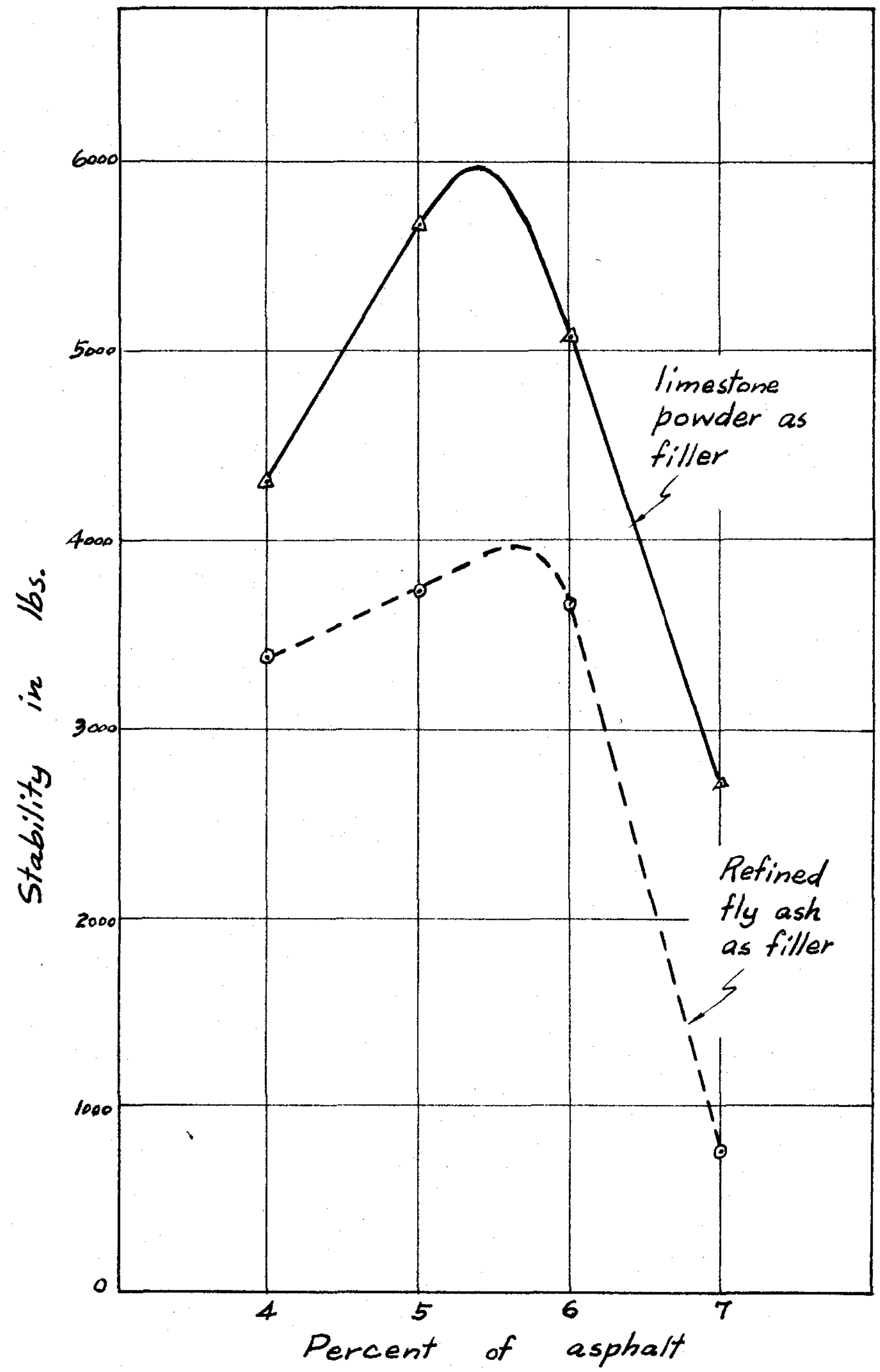

Figure 16. Stability Curve for Mixtures with Different type of Mineral Filler (refer to Table 7 for details).

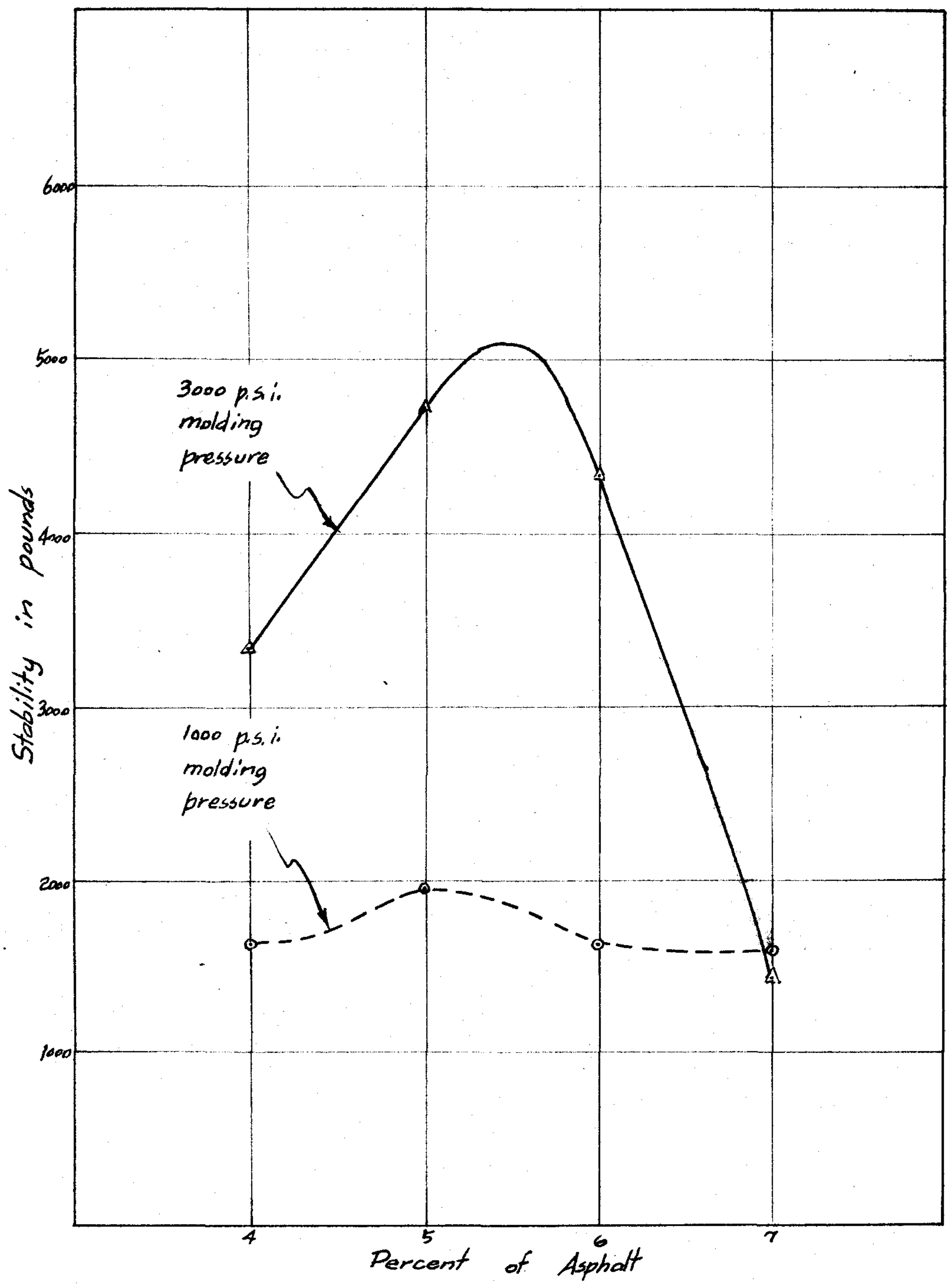

Figure 17. Stability Curve for Mixtures with Different Compactive Effort (refer to Table 8 for details).

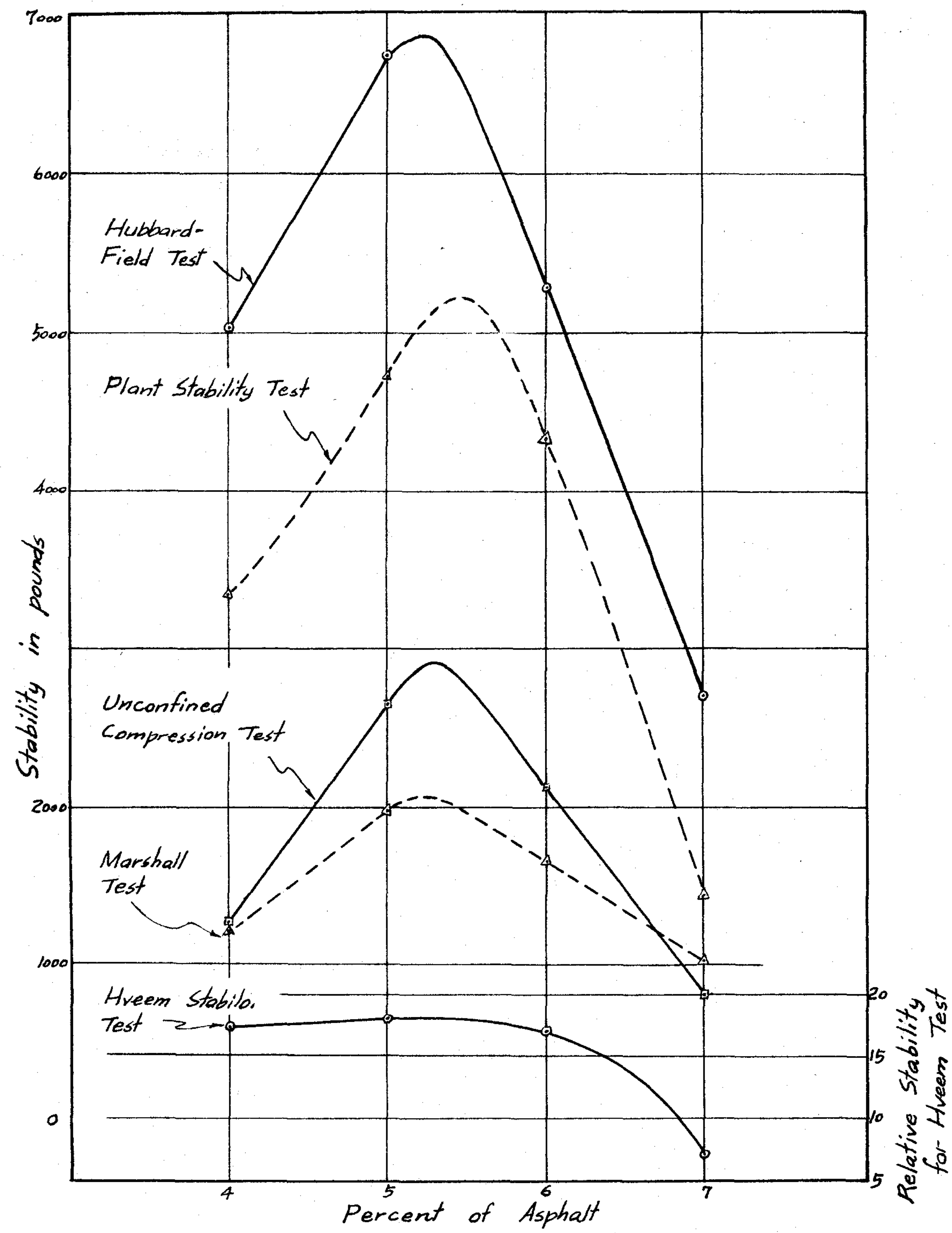

Figure 18. Stability Curve for Various Mechanical Tests (refer to Table 9 for details).

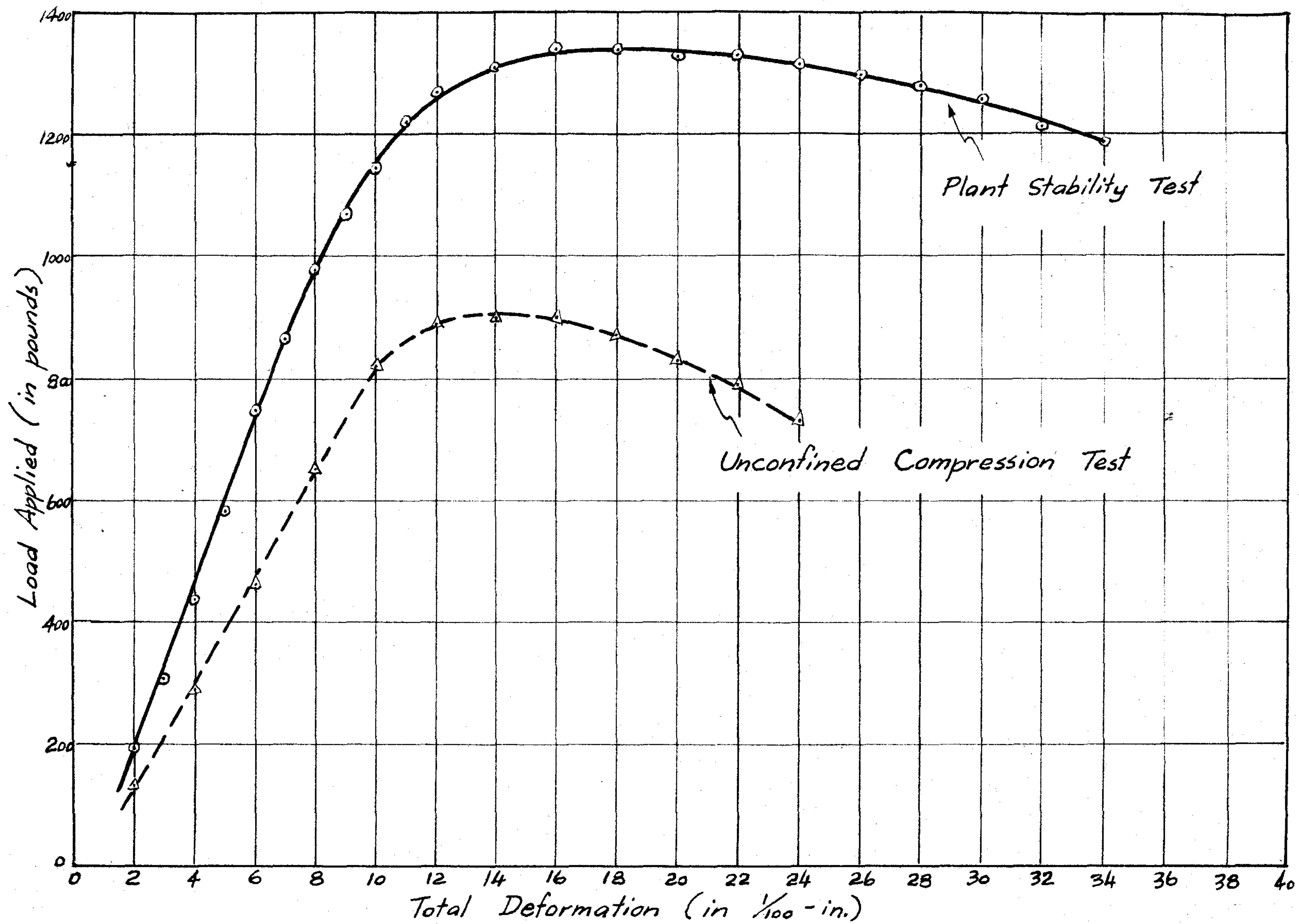

Figure 19. Load Deformation Diagram for Compressive Tests.

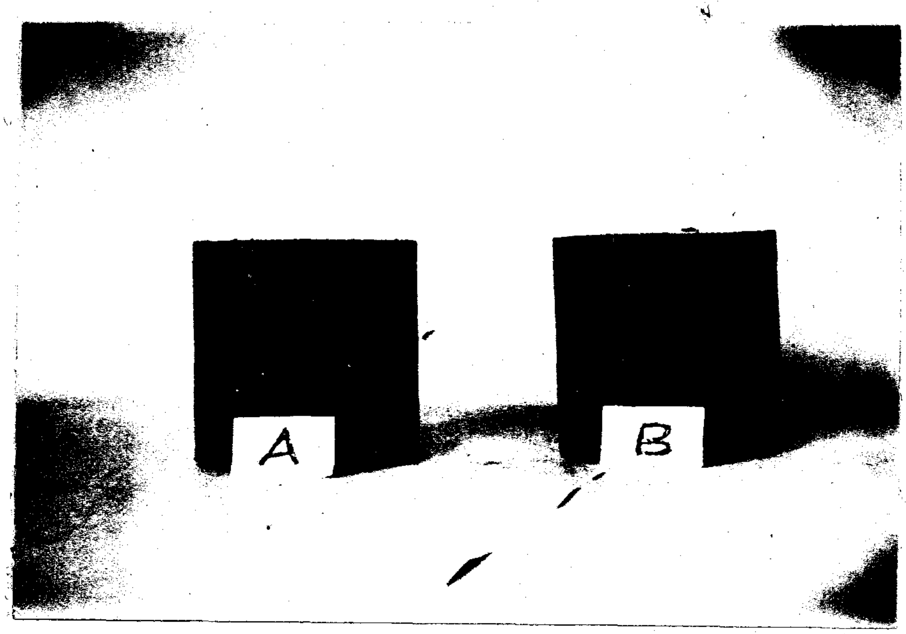

Figure 20. Comparison of Specimens Prepared with
Molds at Different Temperature.
Specimen A - - - - Cold Mold.
Specimen B - - - - Hot Mold.

EXPERIMENTAL APPLICATION OF PLANT STABILITY TEST

As Plant Stability Test is purposely designed for the use at hot-mix plants, laboratory investigation alone cannot verify its dependability and effectiveness. Therefore, experimental plant application is necessary in order to check the practical value of this test.

It must be mentioned here that the primary purpose for this study is to investigate the validity of testing method. Naturally, more correlative experiments related to service behavior of mix have to be made before this method can be considered as complete. Since years of observation are necessary for such correlative experiments, they cannot be covered under this study.

General Description

Under this heading, the equipments and testing procedure will be described. Some of the equipments are made just for the experimental plant application. They can stand further improvement when the test is to be used as means for routine control at asphaltic concrete plants. On the other hand, testing procedure which is to be described later has been proved as satisfactory at continuous plants. If this test is performed at batch plants, the only necessary modification would be the method for sampling mix.

<u>Equipments</u>

Equipments used for Plant Stability Test are listed as follows:

Portable testing machine
Complete set of test mold
Compression ram with thermometer
Compaction hammer and accessories
Insulated weighing pan and thermometer
Funnel
Spatula
Trowel
Ruler (or dial with stand)
Balance sensitive to grams
Two pails, one for sampling, the other filled with water.

All above items except the balance and pails are shown in Fig. 22-27. Descriptions about some of them have been included in previous descriptions. The portable machine and few other items are to be explained.

In designing the portable machine, the primary consideration is economy in cost. Since the machine will be used just for first trial, it is not justified to build an elaborate one. As shown in the picture, a medium-duty journal jack (capacity 15-ton) is used to furnish the required pressure for compaction and testing. The speed in raising the head is controlled by that in turning the level bar inserted in the ratchet system. A reference circle is provided to facilitate the control regarding turning speed of the bar. By such a device, it is possible to get a speed of 0.2-in. per min. for the testing of specimen. If more accurate control is desired, a system of transmission gear is necessary or the journal jack can be replaced by a complete gear box made specially for this machine. Furthermore, a small battery motor can be added to this unit in order to have a more accurate control for testing speed.

For the purpose of recording pressure, a proving ring is used. The ring shall be 8-in. outside diameter, 6-in. inside diameter, and 2-in. wide. If it is made with special high-strength steel, its capacity could be higher than 8-ton. With such a ring, the machine can be used either for compaction or for testing of specimen. Unfortunately, special steel was not available when the machine was made. The only possible way is to use structural steel. Therefore, capacity of proving ring is much lower than what is expected. In that case, the machine is good for testing only. Specimens must be compacted by another hydraulic portable machine which is not necessary if the desired proving ring is available.

The calibration curve for proving ring is shown in Fig. 21. There are ball bearings at top and bottom of the ring. In order to avoid the sidewise motion of the ring, it is advisable to add a horizontal plate between the ring and the compression ram. This plate, extended beyond the four vertical rods, is restricted to vertical motion only. The dial used for measuring the deformation of proving ring has divisions representing 0.0001 inch.

Fig. 10-11 show the details of test mold. Before molding, the extension ring and two removable walls are attached to the mold by two one inch wide adjustable steel rings. Between these two rings, an insulation sleeve is placed. There are two curved blocks which can be placed between the base plate and bottom of the mold. They shall be removed later in order to get a double plunger action during compaction. When compaction of specimen is finished, the extension ring, insulation sleeve, adjustable rings, and removable walls are detached from the mold and the system is ready for testing.

Details of compaction hammer and compression ram are shown in Fig. 12. The diameter at top of hammer is little larger so that it is easier to lift. Since there is a 2.5-in. rod attached at the bottom of hammer seat, a steel tube 3.5-in. in diameter and 4-in. high serves as a stand for the hammer (Fig. 22). A circular metal sheet is to be placed between the hammer seat and the mix in order to avoid the sticking of asphalt mortar to the hammer seat. This metal sheet is left there during testing. Compaction with hammer must be done on a concrete stand about 30-in. high.

Fig. 25 shows the weighing pan which is covered with a thick paper board and completely insulated on sides and bottom with asbestos paper. Temperature of mix can be measured with a thermometer inserted in the pan. The purpose for such arrangement is to keep the temperature of mix as uniform as possible.

Testing procedure

Procedure in making the Plant Stability Test has been discussed separately under previous headings. At this stage, it seems appropriate to give a systematic description for all steps from sampling of mix to the end of testing.

Before test is to be run, all equipments must be arranged in right order. In case the test mold is still warm after using or if the air temperature is above 80°F, it has to be cooled in water bath (temperature 70°-80°) for one minute, wiped until dry, and lightly oiled over its inside surface. Since most of the steps in making the test must be done at proper time, orderly arrangement for equipments is doubly important for Plant Stability Test.

At continuous plants, the mix shall be sampled right under the discharging end of the mixer. A pail is used to collect an integral stream of mix discharged through the gate so that the sample can be representative. Quantity of sample must be roughly as much as required to prepare one specimen. It is advisable to put the thermometer into the mix right after sampling because ordinary mercury thermometers are slow in action.

The mix is then taken to the plant laboratory and scraped into the weighing pan. It shall be covered instantly and the thermometer placed at the center. Weight of mix required to prepare the specimen can be estimated from results of previous tests. Usually it is more or less than 1850 gm. As the temperature of output at hot-mix plants is usually somewhere around 290° F, temperature of mix in the pan after weighing would not be much higher than 260° F. This temperature must be watched very carefully. When it drops to 260° F, molding operation shall be started. The mix is scraped from weighing pan through funnel to the mold. Loading and unloading of weighing pan must be done with extreme care in order to avoid segregation of aggregate particles.

After the mold is filled, a spatula shall be used to spade around inside surface of the mold so as to reduce the possibility for forming large surface voids. Then the mix has to be leveled off and a circular metal sheet placed on the top. The next step is to apply dynamic load with the hammer. When the specimen has received ten blows, curved blocks under the mold must be removed in order to get a double plunger action for the remaining forty blows. Hammering should be done steadily at the rate of one blow per second. The guiding rod for hammer must be always kept vertical without slant, otherwise the top of speciman would not be level.

Compression ram together with armored thermometer shall be placed over the specimen after it has received a total of fifty blows (Thermometer is inserted into the hole in the specimen). 1000 p. s. i. static load is then applied for further compaction. The preparation of specimen is finished when this load has maintained for one minute.

The combined height of specimen, compression ram, and base plate shall be measured to 0.01-in. with either a right angle ruler or a dial fixed at definite position on a stand. At this stage, the extension ring must be removed so that the reading on inserted thermometer can be seen. When the temperature of specimen drops to 170°F, the insulating sleeve and two one-inch rings are removed and the test mold together with the specimen shall be placed on the portable testing machine. Now the thermometer reading must be watched very carefully. When it is 160° F, the removable plates are detached and the specimen must be tested immediately. Testing speed shall be 0.2 in. per minute. The highest reading is recorded and its equivalent stability value in pounds can be found from the calibration curve (Fig. 21). The time from beginning of molding to this stage is usually ten minutes.

The specimen together with the mold shall be weighed to grams and density of mix can be computed. Since temperature of specimen at this time is still high, there will be no difficulty in removing the specimen from the mold. The last thing to do is general cleaning.

Comparative Tests

The dependability of Plant Stability Test has been verified by laboratory experiments. However, there are two more questions concerning the effectiveness of this test. (a) Is the testing results reproducible? (b) It has been shown that the test is sensitive to various factors if specimens heated by constant-temperature water bath are used. Would the test still be sensitive if temperature of specimen is indicated by inserted thermometer? The above questions will be answered under the next two headings.

Reproducibility of results

Reproducibility of results can be seen in Table 12 and 19. In Table 12, specimen were made with 3/4 in. mix; while in Table 19, one inch mix was tested. As asphaltic concrete mixtures are heterogeneous in character, test results can not be as uniform as those for homogeneous materials such as steel, aluminium, etc. Therefore, variations as shown in both tables are considered as within allowable limits. In other words, Plant Stabillty Test can be used for testing mixes with maximum size of aggregate equal to or smaller than one inch.

<u>Sensitivity</u>

The most direct way to verify the sensitivity of Plant Stability Test towards various factors is to repeat the sensitivity tests as described before. The only modification to be made is the method for preparing and controlling test specimen. On the other hand, such extensive experiments would not be necessary if it is possible to indicate that the sensitivity of test is not influenced by the difference as described in regard to conditions of specimen. In order to get such an indication, a series of correlative tests should be performed.

A mix composed of crushed gravel (maximum size 3/4 in.), sand, limestone powder, and 65 penetration asphalt cement is used for this experiment. Again, no description about gradation and properties of materials is deemed necessary. Three set of specimens are prepared from the same mix; each set includes three specimens. Set A is prepared according to the ordinary procedure which has been used in the laboratory investigation of test mold. Compaction of Set B and C follows the particular method for Plant Stability Test as described in the previous article. Curing period of 24 hours is allowed for Set A and B; of course, none for Set C. As regards method for temperature control, 140° F water bath is used for Set A and B and inserted thermometer method for Set C. Testing speed is 0.2-in. per min. in each case.

Table 15 and Fig. 28 show all testing results. It is seen that stability values for Set C are almost the same as that for Set B. In other words, thermometer controlled specimens give the same result as that given by specimens heated in constant temperature water bath for one hour. This definitely indicates that temperature control with inserted thermometer is as effective as the control by using water bath.

On the other hand, Fig. 28 reveals that sensitivity of test is nearly the same for Set A and C. For more clear description, it can be stated that there would be no great influence upon sensitivity of test if specimens prepared and tested according to ordinary laboratory method are substituted by those treated with procedures involved in Plant Stability Test. Therefore, all sensitivity studies described under the heading "Test Mold" are valid for Plant Stability Test as a whole.

Application for Plant Control

The best way to study the application of Plant Stability Test for plant control is to correlate test results with service behavior. If there are experimental roads built for investigative purposes, a trial application of the suggested test would be desirable. Due to limitations regarding authority, equipment, and time, neither of the above experiments can be covered under this study. Plant experiments described under the next heading were made just for verifying testing method. Before this method can be applied for routine plant control, it is necessary to establish certain minimum stability values. A discussion for such minimum requirements will be given later.

Experiments performed

Experimental application of Plant Stability Test was made at an asphaltic concrete hot-mix plant of the continuous type. The maximum size of coarse aggregate is one inch and the asphalt content 5.25 per cent. Properties of asphalt cement and mineral materials are shown in Table 16-17. Gradation of mix is listed in Table 18.

It was found from several days' trial at the plant that the suggested test could be very conveniently applied for plant testing. Time from beginning of molding to the end of testing is about ten minutes. Table 19 shows results of testing performed in one day. Time interval between consecutive tests is generally one hour. It is seen from the table that stability values for all tests are fairly uniform in that day. Exception to this is the stability value for Test no. 4. When mix for Test no. 4 was sampled, the plant had been shutdown and just started again. Probably, the higher stability value for Test no. 4 is due to higher percentage of fines in the mix. At continuous plants, it is not unusual that when plant has been shutdown and starts again there is always a little higher content of fines in the mix mostly due to the action of dust collector.

In the same day, four specimens were molded at the plant and brought back to the central laboratory. The next day, they were heated to 140° F by submerging in water bath for one hour and, then, tested on stationary machine. Data for these four specimens are shown in Table 20. Their stability values are very close to those found from plant tests and their specific gravities are nearly the same as the one for pavement sample (refer to note below table).

The author realizes that plant experiments as described above are certainly not sufficient to indicate any minimum requirements in regard to stability value for mix. No further experiments can be made because the plant is running at fixed mix formula under the authority of Iowa State Highway Commission. The purpose of these plant tests is just to check whether the suggested testing method can be conveniently applied at the plant to give same results as found from laboratory tests. When this objective has been attained, there must be more correlative experiments which will be described in the next paragraph.

Investigations to be made

Minimum requirement regarding stability value of an asphaltic concrete mix may be specified in two ways. One way is to require a minimum stability value in pounds, regardless of the characters of bituminous and mineral material. Although such a definite and simple requirement can be very clearly included in the specification, one might criticize that the effects due to asphalt and aggregate would outweigh that due to mix composition and plant operation. For example, 3000 pounds has been specified as minimum stability value. When 120-penetration asphalt cement and soft crushed stone are included in the mix, everything must be under strict control in order to meet the specified requirement. However, if 60-penetration asphalt cement and hard crushed stone are used, 3000 lbs. stability can be very easily reached even if the mix composition is not the ideal one or if the manufacturing of mix is not under proper control. For the purpose of eliminating effects due to individual constituents, the other way for specifying minimum requirement of mix is to require the stability value of plant mix to be not lower than a certain percentage of the stability value found from laboratory prepared ideal mix. In either case, correlative experiments are necessary in order to specify the minimum stability value or the minimum percentage of ideal stability value.

The most ideal case for such correlative experiments is to cooperate with a series of experimental roads including all possible variations in regard to type of constituents, mix composition, method of laying and compaction, type and volume of traffic, etc. It has been mentioned before that correlative tests are also necessary in determining the proper comparation of test specimen. Since such constructional projects are beyond the possibility of college research and no similar projects operated by highway commissions or engineering departments are available in the near vicinity, these necessary investigations have to be made in the future. Up to the present moment, only the testing method of Plant Stability Test has been found as dependable and satisfactory. More correlative experiments are necessary before the suggested test can be formly applied for routine plant control.

In the Plant Stability Test, compressive strength alone has been considered as sufficient to indicate quality of mix. However, it might be advantageous to study the character in regard to deformation of specimen during testing as a further investigation for the suggested test. Again, such investigation should be correlated with experimental roads in order to check the practical value for this additional information.

Table 15. Correlative Tests by Using Specimens Prepared and Controlled by Various Methods[1]

Specimen			Stability in lbs. Per cent of asphalt as indicated			
Designation	Compaction	Temperature control	4	5	6	7
A	3000 p.s.i. static load	Water bath at 140° F	3270	3980	4100	1870
B	50 blows followed by 1000 p.s.i.	Water bath at 140° F	2960	3450	3380	1600
C	50 blows followed by 1000 p.s.i.	Inserted thermometer at 160° F	2920	3430	3410	1620

[1] All data are the average of testing results taken from three specimens.

Table 16. Properties of Asphalt Cement Used at Hot-Mix Plant

Specific gravity at 77° F/77° F - - - - - - - - - - - - - - - 1.0024

Flash point (open cup) - 500

Loss on heating (five hours at 325° F) - - - - - - - - - - - 0.12%

Soft point (R and B method) - - - - - - - - - - - - - - - - - 120° F

Penetration at 77° F - 82

Soluble in $C\ Cl_4$ - 99.81%

Table 17. Properties of Mineral Materials Used at Hot-Mix Plant

Material	Sp. Gr.	Predominate size in mix	Remarks
Crushed limestone	2.50	1 in. to No. 4	Absorption 4.5% Wearing (L. A. abrasion, grading B) 41.3%
Sand	2.62	No. 8 to No. 100	4.1% passing No. 200
Limestone powder	2.68	Passing No. 200	89% passing No. 200

Table 18. Gradation Chart for Asphaltic Concrete Mix

Sieve opening	1-in.	3/4-in.	½-in.	3/8-in.	No.4	No.8	No.30	No.50	No.100	No.200
Per cent passing	100	93	81	70	52	42	19	15	9	4.8

Table 19. Experimental Control Tests at Hot-Mix Plant

Test no.	1	2	3	4	5	6	7	8
Height of specimen (in.)	4.09	4.02	3.95	4.01	4.02	3.97	4.05	4.03
Density (gm./c.c.)	2.16	2.18	2.18	2.19	2.17	2.17	2.16	2.17
Stability (lbs.) by F.S.T. method	2380	2440	2440	2660	2440	2380	2300	2440
Remark	-	-	-	First truckload after shutdown	-	-	-	-

Table 20. Laboratory Testing Results for Specimens Prepared at Hot-Mix Plants

Specimen no.	1	2	3	4
Height of specimen (in.)	4.02	4.05	4.03	4.05
Density (gm./c.c.)	2.19	2.17	2.16	2.17
Sp. Gr.	2.30	2.29	2.28	2.29
Stability (lbs.) by P.S.T. method using 140° F water bath	2480	2350	2300	2420

Note: Testing results for samples taken from two inch binder course,

Sp. Gr. - - - - - 2.29

Air Voids - - - - 2.8 per cent

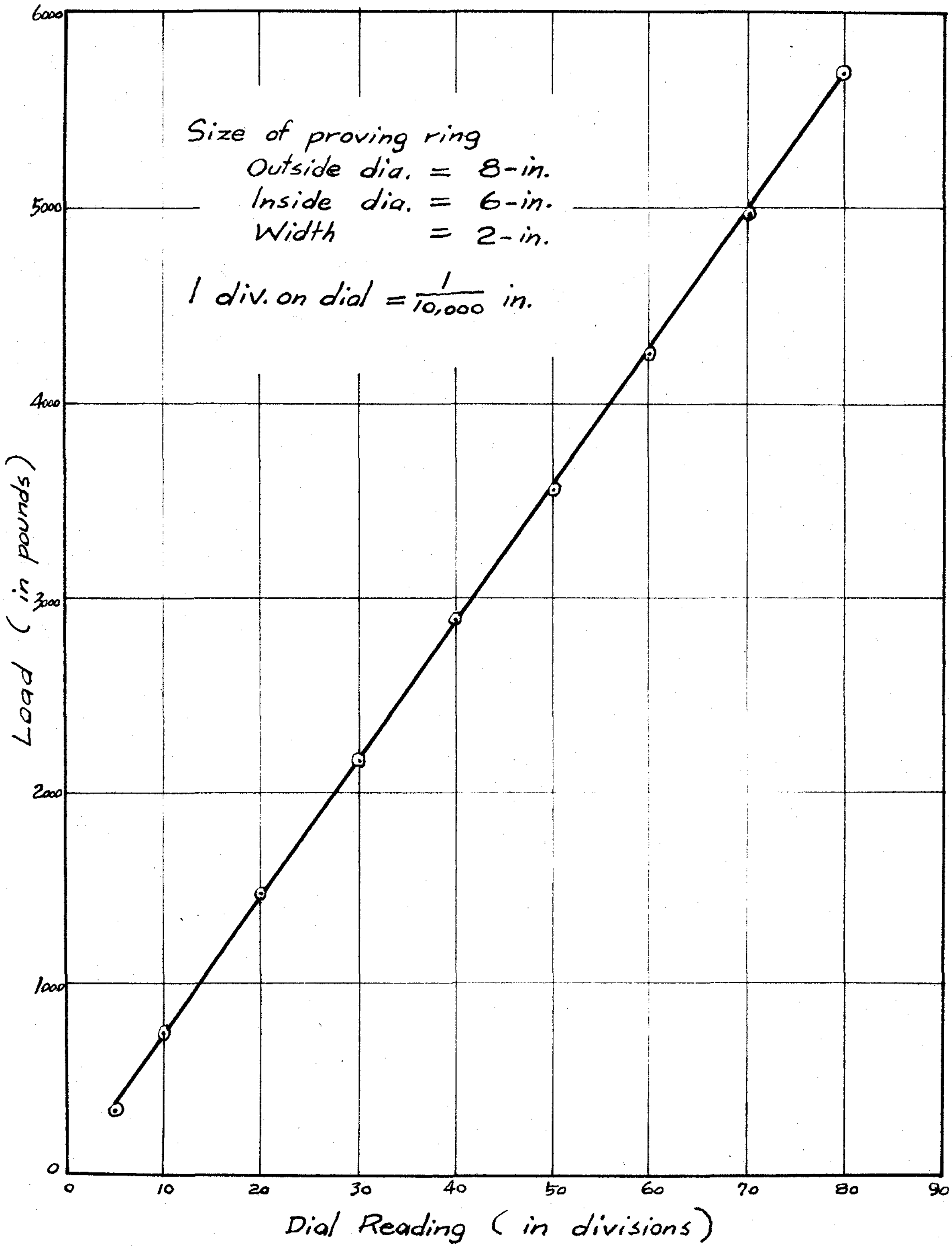

Figure 21. Calibration Curve for Proving Ring

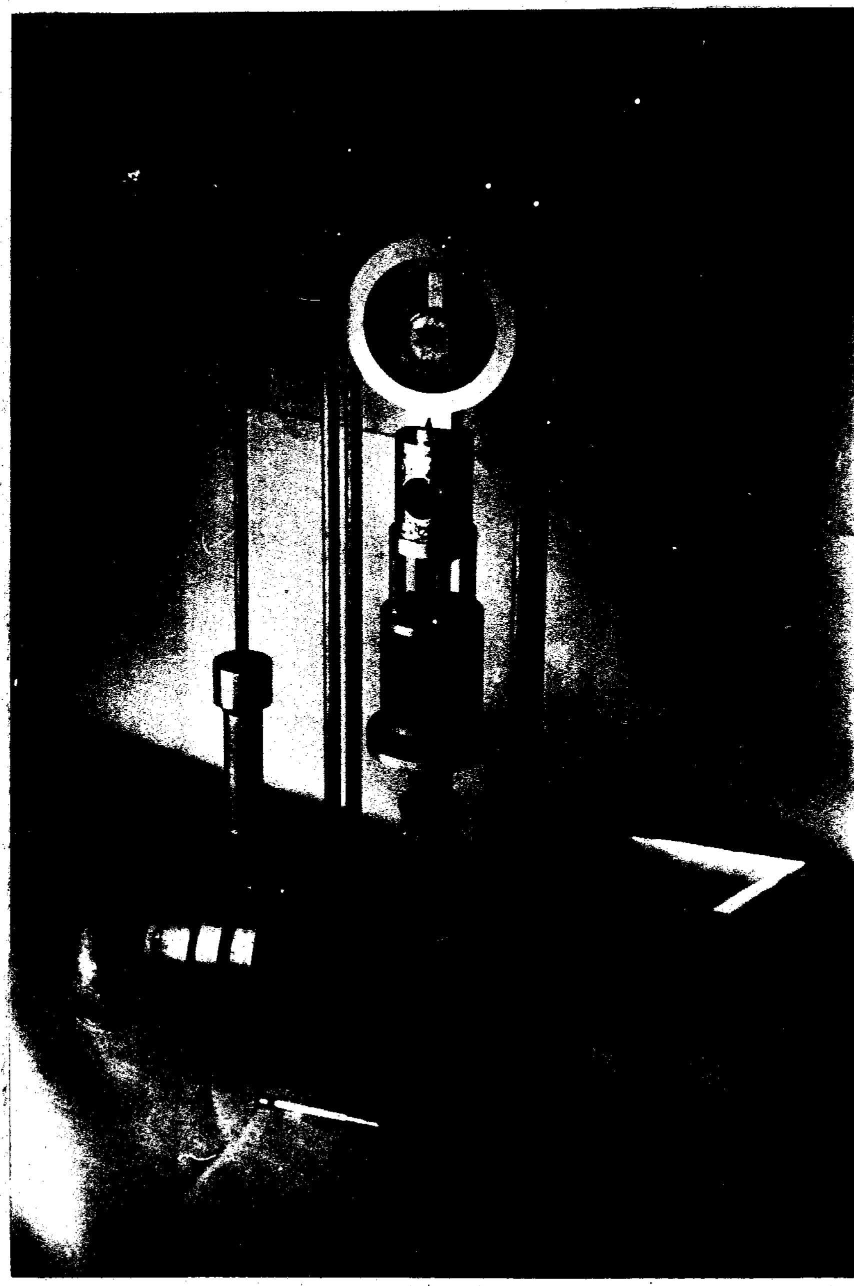

Figure 22. Complete Set of Equipments for Plant Stability Test.

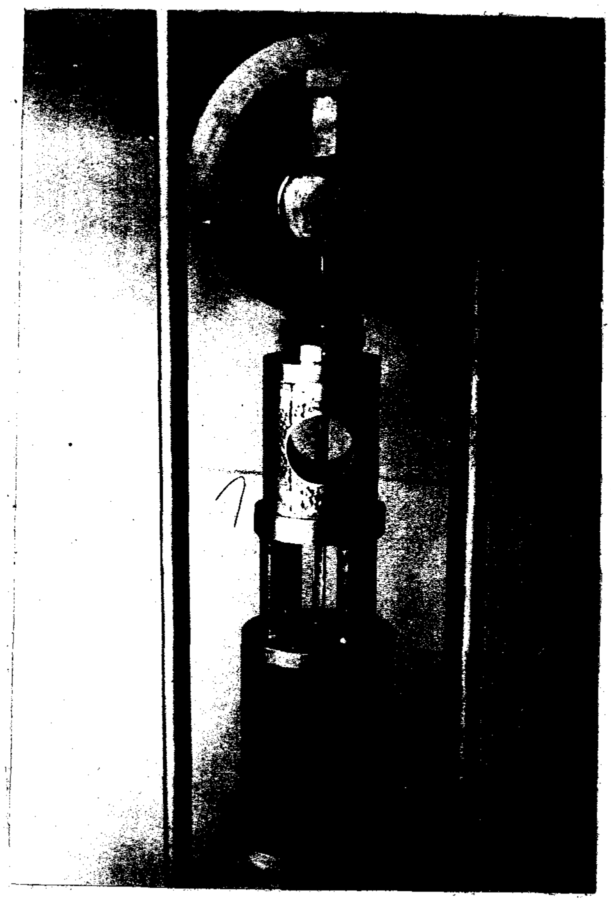

Figure 23. Close View for Center Portion of Portable Machine.

Figure 24. Disassembled Test Mold.

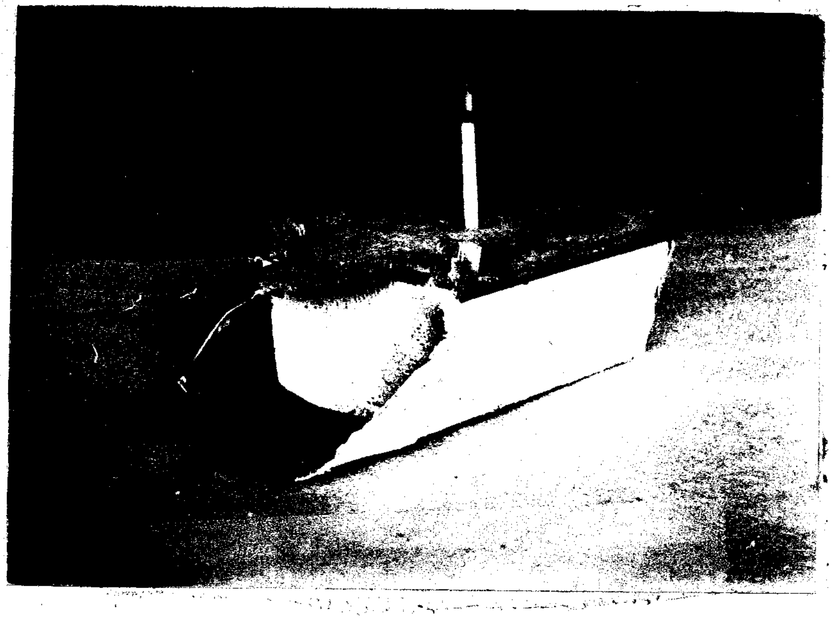

Figure 25. Insulated Weighing Pan.

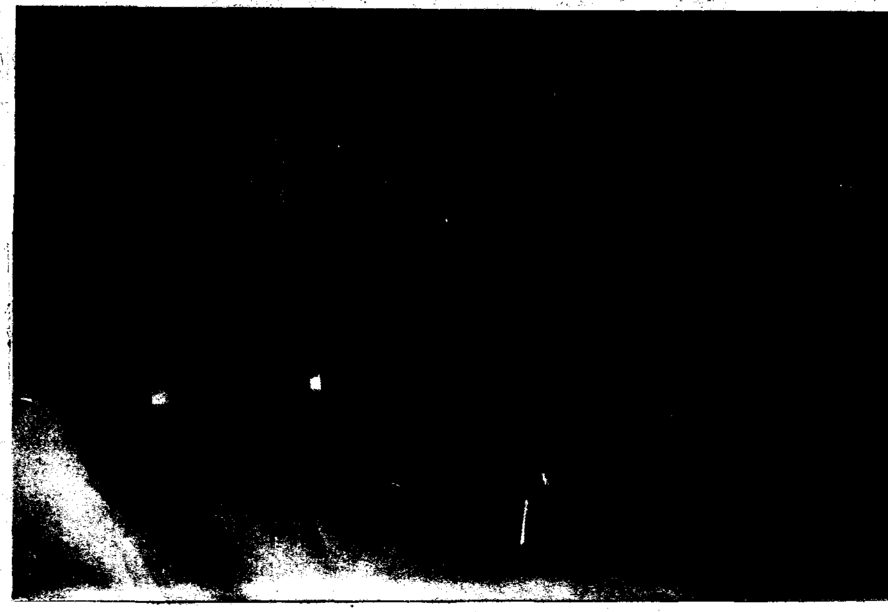

Figure 26. Arrangement of Equipments Before Molding.

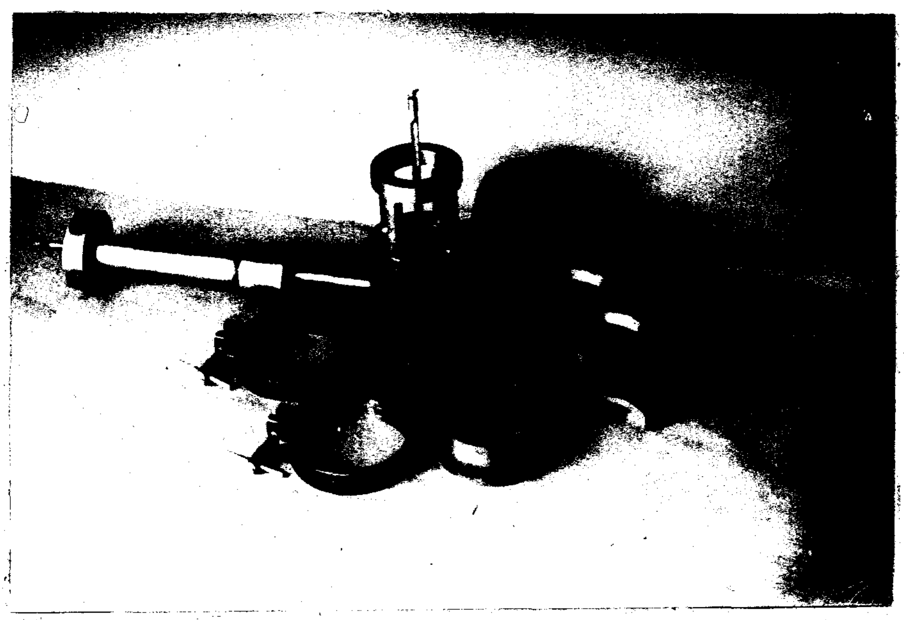

Figure 27. Specimen Ready for Testing.

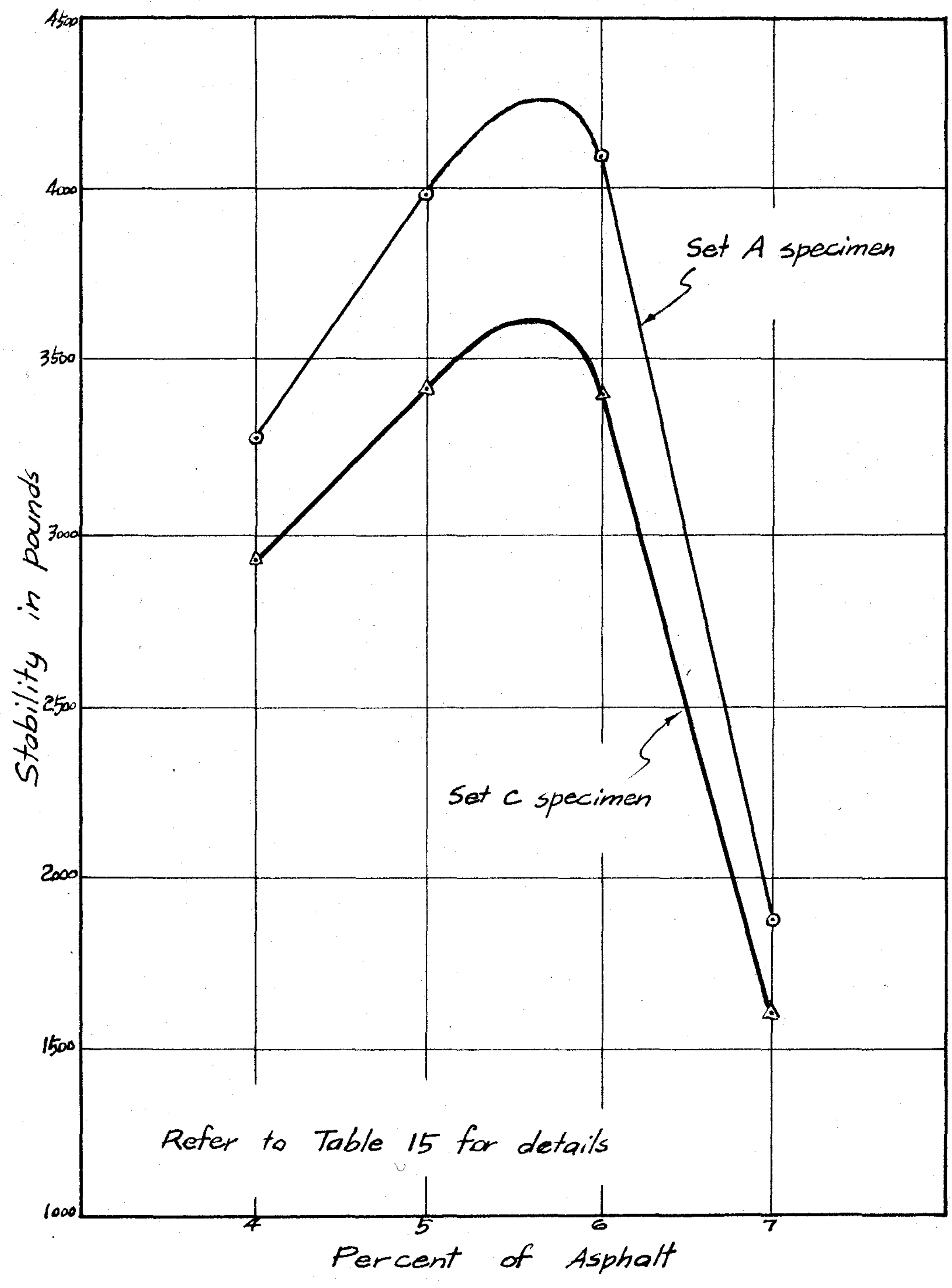

Figure 28. Comparison of Stability Values for Specimens Prepared and Controlled by Different Methods.

SUMMARY

Asphaltic concrete pavements have been extensively used for primary roads during recent years. Most of them belong to the hot-mix, hot-laid type. Since the knowledge about asphaltic concrete mixtures is not so complete as that regarding other common engineering materials, there are still many uncertainties involved in the design, manufacturing, and laying of such mixtures. Consequently, every step in asphaltic concrete paving deserves great attention. This study covers the control at hot-mix plants.

By reviewing the process in manufacturing asphaltic concrete mixtures, it is seen that so many hard to control factors would affect the quality of output. If there is no rapid plant test to indicate quality of mixture, the plant inspector cannot assure that the output is always satisfactory.

A survey of prevailing inspection practices reveals that the desired rapid quality indicating test is not available now. Many states depend too much upon personal experience of engineers or inspectors. In order to make asphaltic concrete paving a physical science rather than an art, it is necessary to have a complete and handy field manual together with a rapid quality indicating test which can be conveniently applied at the plant.

The main objective of this research project is to develop the desired rapid quality indicating test. The term "Plant Stability Test" is used for this test device. Although this test involves plastic properties of asphaltic concrete mixtures, only the compressive strength of

specimen is recorded. Compressive strength is considered as a measure of resistance to deformation. For any bituminous mixtures, resistance to deformation is affected by type and gradation of aggregate (including filler), type and content of bituminous binder, density of mixture, etc. Therefore, the first step for investigating the effectiveness of this test is to verify its sensitivity to all these factors. Experiments indicate that the suggested test has a desirable character of high sensitivity.

In order to have some idea about the standing of this test among common mechanical tests, a comparative study has been made. Specimens prepared with similar compactive effort are used for Hveem Stabilometer, Hubbard-Field, Marshall, unconfined compression, and the suggested test. Results disclose that the suggested test is as effective as any other tests so far as the type of testing is concerned.

The most particular feature for Plant Stability Test is the elimination of constant temperature oven or water bath used for heating the specimen before testing. Since it is absolutely necessary to test specimens at a definite temperature, an armored thermometer inserted in the specimen serves for this purpose. Various experiments have been performed to verify the dependability of this device. By controlling the temperature for both the mold and mixture just before molding, it is possible to get a positive temperature control for the specimen during testing.

Another feature of the suggested test is the use of the same cylindrical mold for both molding and testing. By such a device, time and labor for the extrusion of specimen from the mold can be saved. Other laboratory investigations in regard to test specimen include compactive effort, temperature of mold, height of specimen, etc. All laboratory tests act as experimental background for the development of the suggested test.

As Plant Stability Test was designed for the use of hot-mix plants, it must be actually applied at the plant in order to verify its practical value. A portable testing machine and other equipment were built for this purpose. Results indicate that this test can be very conveniently applied for plant control. Time from the beginning of molding to the end of testing is usually ten minutes. With such a rapid control test, plant inspector knows the quality of mix. He can make any necessary adjustment if the stability value found from this test is below the minimum requirement. By applying the suggested test at hot-mix plants, effective control of asphaltic concrete mixtures would not be difficult.

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