PROGRESS REPORT
TREATING LOESS, FINE SANDS AND SOFT LIMESTONES WITH LIQUID BINDERS

Project No. HR 20

Iowa Highway Research Board

Project No. 295 S

Iowa Engineering Experiment Station

Iowa State College

Ames, Iowa

May, 1954

A Progress Report

on

Treating Loess, Fine Sands and

Soft Limestones with Liquid Binders

Project H.R. 20	Iowa Highway Research Board
Project 295-S	Iowa Engr. Exp. Station

By

Ladis H. Csanyi
Professor in Charge
Bituminous Research Laboratory
Engineering Experiment Station
Iowa State College
Ames, Iowa

May 1954

TABLE OF CONTENTS

	Page
Introduction	1
Authorization	1
Purpose of the Study	1
Bituminous Research Laboratory	1
Approach to the Problem	2
Factors Affecting the Formation of Thin Films of Bituminous Binders on Aggregates and Dusts	4
Measurement of the Thickness of Bituminous Films on Aggregates	4
Methods of Producing Thin Films of Bituminous Binder on Aggregates	5
Selection of Method of Forming Thin Films for Study	5
Application of Thin Films by the Atomization Method	6
Asphalt Cement and Atomization	7
Study of Atomizing Nozzles	8
Formation of a Bituminous Mortar with Mineral Fillers	9
Processing Loess	9
Formation of a Bituminous Mortar with Loess	11
Materials Used in Tests of Bituminous Paving Mixtures	11
Tests Conducted on Mixtures	12
Test and Evaluation of Bituminous Mortars	13
Test and Evaluation of Sand Asphalt Mixes	14
Test and Evaluation of Agricultural Limestone Mixture	15
Test and Evaluation of Sand-Mortar Mixes	15
Test Pavements	16
Preparation of Mixes for the Test Road	17
Laying of Test Pavements	18
Behavior of the Pavements under Traffic	19
Conclusions	19
Further Work	19
Acknowledgements	20
References	21
Appendix I	22

Plates

	Page
I. Fundamental and Theoretical Section of the Bituminous Research Lab	24
II. Practical Research Section of the Bituminous Research Laboratory	24
III. Laboratory Mixer adapted to atomization method	24
IV. Laboratory Mixer showing nozzle, mixer cover and grid paddle tips	24
V. Atomized asphalt spray	25
VI. High speed photographs of nozzle emanation	25
VII. Microphotograph of active mortar	25
VIII. Microphotograph of inactive mortar	25
IX. Atomization spray system used on B-G Mixall	26
X. Operation of B-G Mixall	26

Tables

	Page
1. Code Designation of Materials	27
2. Gradation of Fine Aggregates	27
3. Characteristics of Bituminous Materials	27
4. Results of Stability and Void Tests Mortar 8.100; 9.20-25	28
5. Results of Stability and Void Tests Mortar 8.100; 9.18-25W	28
6. Result of Freezing and Thawing Test, Volume Change, Mortar 8.100; 9.14-25	29
7. Result of Freezing and Thawing Test, Moisture Content, Mortar 8.100; 9.14-25	29
8. Result of Freezing and Thawing Test, Volume Change, Mortar 8.100; 9.18-25W	30

Tables (Cont'd.)

Page

9. Result of Freezing and Thawing Test, Moisture Content, Mortar 8.100; 9.18-25W 30

10. Results of Stability and Void Tests, Mortar 7.100; 9.10-15W. 31

11. Result of Freezing and Thawing Test, Vol. Change, Mortar 7.100; 9.10-15W . 31

12. Result of Freezing and Thawing Test, Moisture Content, Mortar 7.100; 9.10-15W 32

13. Results of Stability and Void Tests, Sand Asphalt Mix 0.0; 2.100; 1.4-8½W . 32

14. Results of Stability and Void Tests, Sand Asphalt Mix 0.0; 2.100; 2.5-10W . 32

15. Results of Stability and Void Tests, Sand Asphalt Mix 0.0; 1.100; 1.4-10W . 33

16. Results of Stability and Void Tests, Sand Asphalt Mix 0.0; 1.100; 2.5-10W . 33

17. Results of Stability and Void Tests, Sand Asphalt Mix 0.0; 3.100; 3.5-10W . 33

18. Results of Stability and Void Tests, Sand Asphalt Mix 0.0; 4.100; 3.4-10W . 34

Page

19. Results of Stability and Void Tests, Sand Asphalt Mix 0.0; 5.100; 3.5-10W . 34

20. Result of Freezing and Thawing Tests on Sand Asphalt Mixes 35

21. Results of Stability and Void Tests, Ag Lime Mix 0.0; 6.100; 3.5-11W. . . 35

22. Results of Freezing and Thawing Tests on Ag Lime Mix 36

23. Results of Stability and Void Tests on Sand and Limestone Dust Mortar Mixes . 36

24. Results of Stability and Void Tests on Sand and Limestone Dust Mortar Mixes . 37

25. Results of Stability and Void Tests on Sand and Limestone Dust Mortar Mixes . 37

26. Results of Freezing and Thawing Tests on Sand and Limestone Dust Mortar Mixes . 38

27. Results of Freezing and Thawing Tests on Sand and Limestone Dust Mortar Mixes . 38

28. Results of Stability and Void Tests on Sand and Loess Mortar Mixes 39

29. Results of Freezing and Thawing Tests on Sand and Loess Mortar Mixes 39

Figures

Page

1. Cross Section of mat designed by conventional practice 40

2. Cross Section of mat designed by mortar principle 40

3. Temperature - viscosity relations of asphalt cements 41

4. Temperature - surface tension relations of asphalt cements 41

5. Gradation Chart of Sands. 42

6. Characteristics of extruded portion of Hubbard-Field Stability Test Specimen. 42

7. Stability and Voids Curves of Mortar 8.100; 9.20-25S and W 43

8. Freezing and Thawing Test Chart, Volume Change, Mortar 8.100; 9.20-25S . . . 43

9. Freezing and Thawing Test Chart, Moisture Content, Mortar 8.100; 9.20-25S . 44

10. Freezing and Thawing Test Chart, Volume Change, Mortar 8.100; 9.20-25W . . . 44

11. Freezing and Thawing Test Chart, Moisture Content, Mortar 8.100; 9.20-25W . 45

Page

12. Stability and Voids Curves of Mortar 7.100; 9.10-15W 45

13. Freezing and Thawing Test Chart, Volume Change, Mortar 7.100; 9.10-15W . . . 45

14. Freezing and Thawing Test Chart, Moisture Content, Mortar 7.100; 9.10-15W . 46

15. Stability and Voids Curves of Sand Asphalt Mix 0.0; 2.100; 1.5-9W; 2.5-10W. 46

16. Stability and Voids Curves of Sand Asphalt Mix 0.0; 1.100; 1.4-10W; 2.4-10W. 47

17. Stability and Voids Curves of Sand Asphalt Mix 0.0; 3.100; 3.5-10W, 0.0; 4.100; 3.4-10W, 0.0; 5.100; 3.5-10W . 47

18. Stability and Voids Curves of Ag Lime Mix 0.0; 6.100; 3.5-11W 48

19. Stability and Voids Curves of Sand Limestone Dust Mortar Mixes Sand No. 1. . 48

20. Stability and Voids Curves of Sand Limestone Dust Mortar Mixes Sand No. 1. . 49

21. Stability and Voids Curves of Sand Limestone Dust Mortar Mixes Sand No. 2. . 49

Figures Cont'd.

Page

22. Stability and Voids Curves Sand Limestone Dust Mortar Mixes Sand No. 2. . 50

23. Stability and Voids Curves Sand Limestone Dust Mortar Mixes Sand No. 3. . 50

24. Stability and Voids Curves Sand Limestone Dust Mortar Mixes Sand No. 3. . 51

25. Stability and Voids Curves Sand Limestone Dust Mortar Mixes Sand No. 4. . 51

26. Stability and Voids Curves Sand Limestone Dust Mortar Mixes Sand No. 4. . 52

27. Stability and Voids Curves Sand Limestone Dust Mortar Mixes Sand No. 5. . 52

28. Stability and Voids Curves Sand Limestone Dust Mortar Mixes Sand No. 5. . 53

Page

29. Stability and Voids Curves Sand Loess Mortar Mixes Sand No. 1 53

30. Stability and Voids Curves Sand Loess Mortar Mixes Sand No. 1 54

31. Stability and Voids Curves Sand Loess Mortar Mixes Sand No. 2 54

32. Stability and Voids Curves Sand Loess Mortar Mixes Sand No. 2 55

33. Test Road, Location of mixes on Marston Court 56

34. Test Road, Location of mixes around Bldg. B. 57

35. Device developed for splittling coarse aggregate 58

A Progress Report

on

Treating Loess, Fine Sands and Soft Limestones with Liquid Binders

Ladis H. Csanyi, Professor in Charge
Bituminous Research Laboratory
Engineering Experiment Station
Iowa State College
Ames, Iowa

Man's ability to utilize the materials and resources nature has provided on earth has improved his lot through the ages and has fostered the building of his civilization. If civilization is to continue to prosper and his living conditions to improve, man must apply this ability and his ingenuity to an even higher degree than ever before in every field of human endeavor. This is particularly true in the field of transportation in the United States.

Motor transportation in the United States has expanded tremendously in the last decade; and if the portents are correct, it will expand to an even greater extent in the future. The expansion has been so rapid that it has outstripped our capacity to build the roads over which it must travel. This has created many problems of considerable magnitude. Among these is that of extending in rural areas the all-weather roads needed to meet the demands of commerce and recreation. Where funds and suitable materials are available, this problem is not serious. In other places where funds are limited and suitable materials for road construction are scarce, this problem is quite serious and acute. Iowa and many other states are confronted by the latter condition. Yet in these areas, there exist tremendous quantities of other materials such as loess, fine sands, soft limestones, which under present practices are considered unsuitable for good all-weather road construction. If good all-weather roads are to be extended in these areas within the funds available, some means must be found and developed for using these cheap and readily available local materials.

The Iowa Highway Research Board, recognizing the need for all-weather rural roads for the welfare and continued prosperity of the State of Iowa, and cognizant of the depletion and absence of suitable materials needed for the construction of such roads under present practices, has undertaken an intensive research program to seek and develop means for using local materials for this purpose. The project reported here is one of several undertaken by the Board to investigate the development of such means.

AUTHORIZATION

The Iowa Highway Research Board on December 28, 1951 approved Project HR-20 entitled "Treating Loess, Fine Sands and Soft Limestones with Liquid Binders" and recommended to the Iowa Highway Commission the appropriation of $48,900 for the prosecution of this project. Upon approval of the Iowa Highway Commission and allocation of funds, a contract for the execution of the work on the project was awarded to the Engineering Experiment Station of Iowa State College with the date for completion of the work set for December 31, 1953. This study under the same title is designated Project 295-S of the Engineering Experiment Station.

Based upon the progress made in the investigation upon the completion date of the project, the Iowa Highway Research Board approved an extension of the project for an additional eighteen months to June 30, 1955 and recommended an additional appropriation of $65,850 for its continuance. The work of the extended project was somewhat modified, expanded and intensified.

This progress report covers the work completed during the initial portion of the project up to December 31, 1953.

PURPOSE OF THE STUDY

Certain areas of Iowa abound in loess, others contain soft limestones that are readily and cheaply available, and a large portion of the state is underlaid with sand. None of these materials is considered suitable in present practices for use in all-weather road construction. The loess is too fine and too difficult to handle; the limestones are considered too soft, and some of the harder ones unsound for this use; the sands are not naturally of the desired gradation and do not lend themselves to blending into satisfactory gradations.

The purpose of this project is, therefore, to study and develop means and to determine the feasibility of using these materials, loess, fine sand, and soft limestones, either separately or in combinations in conjunction with liquid binders to produce paving mixtures applicable for all-weather road construction. Also included in the project was the development of methods of processing any of these materials, if necessary, to make them suitable for the desired purpose.

BITUMINOUS RESEARCH LABORATORY

When the scope, magnitude and complexity of this project is considered, it becomes apparent that special facilities are necessary if a comprehensive investigation is to be made. In recognition of this and also to provide for future studies in the bituminous field, the Engineering Experiment Station and the Iowa Highway Research Board collaborated in the establishment of a modern bituminous research laboratory at Iowa State College. In this venture, the Engineering Experiment Station furnished the space needed, furnishings and utilities necessary to conduct this project and such equipment as is normally found in a modern bituminous research laboratory. The Iowa Highway Research Board provided the special equipment necessary to conduct the work of this particular project.

The location selected for this laboratory is in Building B on the Campus of Iowa State College. A small building separate from other buildings, it contains four rooms, each about 40 feet by 15 feet. At first, two of these rooms were assigned to the laboratory. Upon the extension of the project, the laboratory was expanded to three rooms. One room, designed and equipped for fundamental and theoretical research, is devoted to special and routine physical and chemical analyses of bituminous binders and paving mixtures. Special equipment is also provided in this room for the study of atomizing bituminous binders. The second room, designed for practical research, is devoted to the storage, physical analyses and processing of aggregates, the storage of bituminous binders and the mixing and testing of paving mixtures. The third room, divided into three parts, contains the laboratory office and record files in one part, a dark room for ultraviolet light work and time-motion study of high speed photography in another part, and a microscope, electrophoresis and radio active tracer work area in the third part.

The fundamental and theoretical room, Plate 1, contains such usual equipment as ovens, stills, penetrometer, Saybolt Furol viscosimeter and others necessary to conduct the normal chemical and physical tests of bituminous binders. In addition to these, it also contains such added equipment as a Kopper Viscometer, a De Nouye surface tensiometer, constituent extractors, a low speed centrifuge, two high speed centrifuges capable of developing 28,000 g, and freezing and humidity cabinets. This section also contains the equipment used to study the atomizing characteristics of nozzles by high speed photography. A Fastax Camera with its various accessories, capable of taking 7,000 pictures per second, is part of this equipment.

The practical research section of the laboratory, Plate II, contains storage bins for aggregates and equipment such as a Los Angeles rattler tester, a Ro Tap, a Gyratory and a Gilson Vibrating Screen and other devices used in determining the various physical characteristics of aggregates. For processing of aggregates and mixing of paving mixtures, this section has a laboratory scale pilot plant consisting of a small crusher, a hammermill pulverizer, a Miskella infra red vibratory drier and a Hetherington-Berner laboratory pug mill mixer of 50 pound batch capacity. Paving mixtures prepared in the laboratory or field are tested in this section by the Marshall and Hubbard-Field Stability methods. The equipment necessary to conduct these tests is available, including both forming and testing molds, two Marshall Mechanical Compactors and a Marshall Testing Machine. A Kneading Compactor is on order and will arrive in time for comparative tests on coarse aggregate paving mixtures. Bituminous binders used in the preparation of paving mixtures are stored in electrically heated, thermostatically controlled storage tanks[1] in this section.

One part of the third room, devoted to miscellaneous aspects of research on aggregates, binders and paving mixtures, contains various types of equipment. Microscopes used for the visual examination of aggregates, bituminous films, and paving mixtures include a Leitz ortholux microscope fitted with photographic attachments, a standard microscope fitted with a micrometer vernier measuring eye piece, and a standard binocular low magnification microscope. A Gieger-Muller counter with binary scaler is available for radio active tracer and film stripping tests. Other equipment for electrophoresis and paper chromatography are available for other studies of the chemical characteristics of asphalt.

Another part of the third room is a dark room in which macrophotography of paving mixtures, ultraviolet ray work and time-motion study of high speed films may be conducted. The equipment available here includes a Bell and Howell 16 mm. time-motion projector, various ultraviolet ray tubes and a Leitz Foca slide camera. Study of references related to the project filed on microfilm may also be studied in this area.

The laboratory is also fitted with a dressing room in a corridor between the sections of the laboratory where workers may change clothes. It may be of interest to note here that all of the employees of the laboratory are either graduate or undergraduate students of the college with the exception of two women laboratory assistants who are student wives. All employees on the project are under the direction of the author.

APPROACH TO THE PROBLEM

In seeking an approach to this problem, it must be conceded that the current practices used in designing and mixing bituminous paving mixtures in the United States are not suited to the use of local materials such as the ones under consideration in this project for the construction of bituminous roads. If this were not true, such materials would be used today and there would be no reason for this study. Consequently, some modification of these practices or even an entirely new concept of design or mixing or both must be sought if these materials are to be used in bituminous pavements.

So, although present practices are thereby removed from consideration in this study, they must be critically examined to secure the leads that may point to modifications or set the direction for the development of a new principle.

The generally accepted basis for design of a bituminous mix is predicated upon the production of a dense, stable and durable mixture that may be compacted into a pavement. The density of such a mixture is usually attained through the gradation of the combined aggregates used to provide the least voids compatible with other requirements. The density, therefore, may be secured by the blending of coarse and fine aggregates and a mineral filler in proper proportions to yield a smooth gradation curve. The bituminous binder is added in a quantity which is sufficient to coat each particle of aggregate and to fill a prescribed percentage of the voids contained in the aggregates.

The stability of the mixture is attained through the interlock or friction developed between the aggregate particles. The bituminous binder in the mixture acts primarily to hold the aggregate particles in position once the binder has set or hardened. Experience has shown that anything that reduces the interlock or friction between aggregate particles such as a thick coating of binder on the aggregate particles or excessive binder in the voids of the aggregate will adversely affect the stability of the mixture.

The durability of the mixture, as a pavement in service, may be said to depend on many factors such as the toughness of the aggregates, the affinity between the aggregates and the binder, the weathering behavior of the binder, the design of the mixture, proper mixing and laying of the mixture into a pavement among many others. It is extremely difficult to measure durability in terms other than time itself in service.

If one were to take a cross section of a bituminous mixture compacted into a pavement under these principles, one would see an intermeshing of coated particles of coarse aggregate, the voids of which are filled with coated particles of fine aggregate. The remaining voids are filled with mineral dust and binder. (See figure 1.) Thus the bituminous binder permeates the entire mass and forms a semi-solid plastic cement holding the aggregates in place.

Let us now see how the natural materials, with which this study is concerned, fit into present practices. In considering soft limestones, it is obvious that even though this stone is properly graded, it does not possess the toughness or the strength needed for the desired stability because it crushes and breaks up under traffic loads. Such degradation of the stone creates uncoated and uncemented particles which destroy the cohesiveness of the mix needed to resist the action of traffic. And so the pavement fails. How may this be avoided if such stones are to be used? One way would be to design a mix in which the strength needed is transferred to another aggregate and the stone is used merely to give bulk to the mixture. Natural ungraded sands, which cannot be blended readily into the desired gradation, usually contain a large quantity of voids. To attain the density believed essential, these voids would have to be filled with either mineral dust or binder or a combination of both. Filling the voids with binder is not desirable because the stability would be adversely effected and the pavement would tend to bleed. On the other hand, the use of a large quantity of mineral dust for this purpose is not considered practical because conventional mixers cannot form coatings on the individual particles of the dust and large quantities of dust tend to ball up during mixing, substantially affecting the durability of the pavement in service. So if ungraded sands are to be used, some method must be found that can form coatings of binder on the individual particles of the dust or by which the binder itself may be strengthened.

Loess is a rather peculiar material. It may be used in two forms that necessitate processing of the material found in the natural state. As the loess is dried, it becomes exceedingly hard. So, one form of application may be in pellet form. Another form would be a mineral dust secured by pulverizing the hard, dried loess. Since the pellet form is comparatively soft, it may be considered similar to soft limestone with its attending problems. As a dust, it may be used as a filler, but since so little of this material is used in conventional mixes, it would hardly be worthwhile processing for this purpose. If a method of coating individual particles of dust with a binder is found, loess in combination with ungraded sands would find wide use.

From the foregoing discussion, it can be seen that several approaches in developing means of utilizing the materials with which this work is concerned may be explored.

One approach is that of toughening and strengthening the binder. A means by which this can be achieved is already in operation in Germany. The product produced by this method is called Gussasphalt[2]. In this method, a large quantity of mineral dust can be incorporated into the bituminous binder in colloidal suspension, resulting in the hardening and toughening of the binder. (Anyone familiar with natural Trinidad asphalt, which contains a large quantity of dust, is aware of the toughness of this binder although the asphalt itself is very soft.) By the Gussasphalt method, large quantities of loess or any other fine mineral matter might be incorporated into a soft asphalt to produce a tough binder to give strength and density to mixes made of ungraded sands. Although the method is successful, it is much too cumbersome and time-consuming for American production demands.

The other approach revolves around the development of a method of mixing wherein every particle of mineral dust could be coated by a very thin film of binder. If this can be attained, a mortar of mineral dust and bituminous binder can then be produced; and, if this mortar possesses the required body and cementing properties, it could be used in cementing ungraded sands and coarse particles together into a bituminous pavement. (See figure 2.) The stability of the mix would depend upon the strength of this mortar augmented by the interlock of the ungraded sand particles. If the strength of such a mix can be developed to a sufficiently high degree, coarser particles need not interlock and can be used mainly to provide bulk to the mixture.

The idea of developing and utilizing a bituminous mortar is not entirely new. A modification of this concept is used in designing a stone filled sheet asphalt mix used extensively in the United States. The mortar is a stable sheet asphalt mix in which small stones are included. This basic idea has been applied to the design of asphaltic concrete mixes by some designers who use a sheet asphalt mix to cement the coarse aggregate together. In Germany a similar method is used in which coarse aggregate particles are embedded in a sand asphalt mortar. Such a mix has been descriptively dubbed a "raisin cake" mix and is used quite extensively. Thus, the mortar theory of design would be developed in this project to the fullest degree by the use of a mineral filler and binder as the basic mortar.

Here, then, are two definite and distinct approaches by which the natural materials with which we are concerned may be utilized. A decision as to which road to follow must be made. It has already been mentioned that the production of a material such as Gussasphalt under present practice is much too cumbersome, requires special equipment for mixing and transporting, and the output capacity of the operations are too low for American demands. Attention in this project, therefore, has been directed toward the seeking of a means of producing very thin films of binder upon individual particles of mineral dust. It is hoped that methods developed can be used in conjunction with existing plants of high production capacity. The methods developed will also be applied to the study of the feasibility of using a mortar so created as a means of cementing ungraded aggregates together into a stable and durable pavement.

FACTORS AFFECTING THE FORMATION OF FILMS ON MINERAL AGGREGATES

In the study and evaluation of a method now in use or the development of a new method of producing thin films on mineral particles, some of the factors that influence the formation of the films and their behavior in producing films on such particles must be recognized and understood.

The factors that affect the formation of bituminous films upon mineral aggregates are many, varied, and complex. They involve some extremely complicated theories of physical and surface chemistry. Although all of these theories and their effects upon the formation of films must be considered in this study, only a few of the more important ones will be discussed here. Such factors as the viscosity and surface tension of the binder at the instant of contact with the aggregate, the quantity of the binder present at that time, the surface character of the aggregate, the temperature of both the binder and aggregate, the affinity between the binder and the aggregate, the manner of introduction of the binder into the mixer and some other conditions prevalent during mixing will be included. Although these factors are enumerated separately here, they act in concert, each in its own fashion, as prevalent conditions dictate in developing the films on the mineral particles.

Viscosity, surface tension, and internal cohesion of a bituminous binder are probably the most important factors that effect the formation of thin films on aggregates. Generally, it may be said that the viscosity, surface tension and cohesion of a binder are interrelated. When the viscosity increases, the others increase also; and when the viscosity decreases, they also decrease. Since the viscosity of a bituminous binder is a function of temperature, the temperatures of the binder and the aggregate at the instant of contact between the two becomes of material significance in the formation of a thin film. A binder having a low viscosity, surface tension, and cohesion will flow and spread rapidly over the surface of a heated aggregate. The same binder coming into contact with a cool aggregate is cooled, its viscosity is increased, its flow and spread are retarded. A thicker film is the result. This behavior is of especial importance when the binder is an asphalt cement or heavy cut-back which must be heated to an elevated temperature to obtain the desired viscosity. Viscosity and surface tension measurements indicate that asphalt cements generally, regardless of penetration, possess about the same viscosity and the same surface tension at a temperature of 325°F. or slightly higher. (See figures 3 and 4.) So heating of a binder or aggregate to a mixing temperature in excess of 325°F. serves no useful purpose and may injure the binder. But temperatures below this will have a material effect on the formation of thin films, because as the viscosity increases cohesion increases also, the spread of the binder is retarded, and thicker films are formed. Emulsified asphalts and the lighter cut-backs, whose viscosities are not so susceptible to temperature, will form thin films at much lower temperatures.

The thickness of films is also influenced by the quantity of binder present. While the elevated temperature is maintained, this has little effect because a thin film compatible with the existent forces will remain the same. As the mixture cools, the excess binder is drawn up and films thicken progressively as the temperature decreases. Therefore, thin films may be retained when the quantity of binder is adjusted for high temperature conditions rather than for lower temperature conditions.

Under some conditions, as discussed previously, aggregates of a rough surface texture will tend to acquire thicker films than aggregates with smooth surfaces. As the binder cools, the crevices of the rough surface tend to fill up, producing a film of varied thickness.

Thinner films tend to form on aggregates when the binder is more widely distributed during its introduction into the mixer[3].

Other factors, such as the temperature inside the mixer, the mixing action, time of mixing, and quantity of material in the mixer, also have their effects upon the thickness of the films formed on the mineral particles.

The surface tensions of both the binder and the aggregate also affect film thickness, since affinity between binder and aggregate is dependent to some degree upon the relation between these surface tensions, among other factors. A thin film of binder on an aggregate appears to possess greater adhesion to the aggregate than a thicker film.

Thus, to successfully produce thin films of bituminous binder on aggregates, particularly on mineral dust particles, the method used must control many factors.

MEASUREMENT OF THE THICKNESS OF BITUMINOUS FILMS ON AGGREGATES

Whenever thin films of binder on an aggregate is mentioned, the question of how thin or how thick immediately arises. In the previous section, it was mentioned that the quantity of binder present during mixing influences the thickness of the films formed. The question of what is a desirable film thickness must be answered. It is obvious before the quantity of binder to be used on the mix can be determined, that there must be some means of measuring the thickness of the films.

The need of a means for measuring such film thicknesses resulted in a project entitled "Measurement of Bituminous Film Thicknesses on Aggregates", Project No. 272, which was begun by the Engineering Experiment Station in 1949. The work was carried forward and a means of measuring the thickness of such films on coarse aggregates was developed. (See Appendix I.) Measurement of such films on fine aggregates and mineral dusts proved much more difficult, and work on this phase was still in progress when this present project was authorized. Since measuring film thickness on these aggregates is important, work on the development of means of measuring the thickness of such films is being carried forward under this project. Two methods for measurement of film thickness on aggregates smaller than 1/8 inch in size are under study.

The method under consideration for measurement of film thickness on fine aggregates having particle sizes between passing a No. 8 sieve and retained upon the No. 100 sieve involves the method used for measuring the grooves in long playing phonograph records. The coated particles in this size range are lightly molded into a specimen of convenient shape. This specimen is then placed in a freezer at 30°F. below zero for several hours so that the films of binder are frozen hard. Upon removal from the freezer, a groove in the films coating the particles is cut by a razor edged blade. The specimen is returned to the freezer to set the groove. After the groove has set, the specimen is removed from the freezer and the dimensions of the groove measured microscopically. From these dimensions the depth of the film may be calculated. Work on determination of the feasibility, accuracy and reliability of this method is in progress.

The measurement of film thickness on particles passing the No. 100 screen is exceedingly difficult. The method being tried on fine aggregates will be tried on this size also to see if it will work. Since it is known that asphalt films less than 5 microns in thickness are amber in color rather than black, this line of demarkation is being used in this project until a better method is developed. Where the film is almost transparent, a depth focusing microscope, such as the Leitz ortholux which can measure depth to 1 or 2 microns, is used.

METHODS OF PRODUCING THIN FILMS OF BITUMINOUS BINDER ON AGGREGATES

Several methods have been devised which form bituminous films that are usually much thinner than those formed by the conventional method. These methods utilize such factors which affect film thickness as low viscosity binder, quantity of binder available, method of application of binder and modified mixing action. All of these methods are adaptable with some minor modifications to the twin shaft pug mills used in conventional mixing operations.

The method which requires no adjustment, modification or change in mixing procedure and is most commonly used is that in which low viscosity emulsified asphalts are utilized. It is generally recognized that low viscosity, emulsified asphalts and light cut-backs will produce comparatively thin films of binder on aggregates. The low viscosity and surface tension of these binders promotes spreading of the binder over the surface of the aggregate. Since lower cohesion accompanies the lower viscosity, thin films will form. If no excess of binder is present, these thin films will persist as the binder sets and hardens.

Another method, known as the "Steam Mix", has been used quite extensively in the North Atlantic States. In this patented method, the viscosity of an asphalt cement is temporarily lowered by the introduction of steam which produces a temporary asphalt emulsion. The lowered viscosity permits a wider distribution of the binder as it enters the mixer than would normally be possible. Fine spray nozzles may be used in this method for this purpose, and since no emulsifying agent is used, the temporary emulsion breaks rapidly after forming the thin film on the aggregate. Relatively hard asphalt cements have been used in this process.

Another method which forms thin films on aggregates is the Impact Process. This process, also patented, is used extensively in Europe. It is also used in some of the North Atlantic States, where a number of asphalt plants have been adjusted and fitted with the necessary equipment. Thin films are formed in this method by the combined effects of a number of factors. Low viscosity of the binder is achieved by heating the asphalt cement to 330°F. Wide distribution of the binder in entering the mixer is attained by pressure pumping the liquid binder through certain atomizing nozzles which create a cloud of minute droplets of binder in the mixer. The operating speed of the mixer is increased above normal operating speed to toss the aggregate particles up into the cloud of binder. Since the droplets of binder are ejected from the nozzles with some velocity and the particles are cast up with some speed, the impact between the droplet of binder and aggregate particle causes the droplet to splash over the surface of the aggregate, providing a wider spread of the binder which improves the formation of thin films. By limiting the quantity of binder introduced in this atomized form into the mixer during mixing, exceedingly thin films can be obtained on all sizes and shapes of aggregate. Since no kneading action is utilized in mixing, the thin films formed will persist.

SELECTION OF A METHOD OF FORMING THIN FILMS FOR STUDY

It has been noted that there are several methods by which thin films of bituminous binder may be produced on aggregates. There are also several other methods proposed, and still others which suggest themselves for this purpose. That the basic concept of this study, namely the use of a bituminous mortar composed of coated particles of mineral dust as a bonding agent for ungraded coarser particles in a pavement, might be tested as quickly and conclusively as possible. The method found, after careful study, to be best suited to the materials involved in this project was selected.

In the study of existing methods, the use of emulsified asphalt as a binder was considered first. Since fine dust particles tend to prematurely break the usual asphalt emulsions, it was realized that a special emulsion which could resist this action must be used. Presuming that such an emulsion was readily available, the next question that arose was what effect would the 35 to 40 percent of water contained in a direct emulsion have upon pulverized loess which may contain up to 50 percent clay. A quick check indicated that balling of the clay would prove troublesome. The other alternative then was the use of an inverted asphalt emulsion which normally contains up to 7 percent water. Since such an emulsion is not readily available locally in Iowa, the use of emulsions for this purpose was tabled.

The "Steam Mix" was studied next. The water vapor contained in the asphalt cement for temporary emulsification was not considered sufficient to create a serious problem with loess. Although the binder in this process is introduced into the mixer in fine streams, experience indicates that mixtures containing a very high percentage of dust would encounter some balling of the dust during mixing. Therefore, since there was no definite assurance that a uniform homogeneous mortar of fines and binder could be consistently produced by this method, attention was turned to the third method.

It has been demonstrated that the atomization method can produce thin films on individual particles of mineral dust and can produce a bituminous mortar in several ways[4]. Mortars of limestone dust, fly ash and other mineral dusts have been produced by this method. It only remained, therefore, to determine whether or not a similar mortar of pulverized loess could be produced by this method. A quick check proved that a suitable mortar of an asphalt cement and loess could be readily and efficiently produced.

Consequently, the atomization method was selected as the means of preparing further specimens and mixes by which the basic concept of this study could be evaluated.

APPLICATION OF THIN FILMS BY THE ATOMIZATION METHOD

This method, patented by Dr. Albert Sommer of Switzerland and commonly called the "Impact Process", depends primarily upon the introduction of the binder into the mixer in an atomized form and passing the aggregate through the cloud of atomized binder. The equipment necessary includes a pressure pumping system by which the liquid binder is pumped through suitable atomizing nozzles situated in the mixer and increasing the speed of the mixer so that the aggregate is cast up through the atomized binder. In Germany, a special mixer has been designed which tosses the aggregates through the atomized binder most effectively and reduces the kneading action in the mixer to a minimum. A standard batch type asphalt plant can readily be converted to this operation by the addition of a nozzle and pressure pump system and by slightly increasing the mixer speed. A number of plants have been so converted in the North Atlantic States.

In this method, the asphalt cement, most commonly used as the binder, is heated to about 330°F. to reduce its viscosity to a point where it may be pumped readily through the atomizing nozzles at pressures less than 300 pounds. By proper placement of the atomizing nozzles inside the mixer, a wide uniform distribution of the binder can be secured. Either by increasing mixer speed or by using a specially designed mixer, the aggregates can be cast up through the atomized asphalt. This modification not only raises the aggregates up into the binder but also fluffs them so that each particle may secure its own film of binder as it passes through the atomized cloud. By the action of the mixer blades, the particles are rotated in flight so that a uniform film is formed over its entire surface. As previously indicated, the formation of the film is improved by the impact created between the moving particle and the droplet of binder. The thickness of the films formed in this operation depends largely upon the temperature and operating conditions of the mixer, the temperature and size of the droplet of binder, the temperature of the aggregate and the quantity of binder introduced into the mixture. Since the aggregates secure their films of binder by passing through the atomized cloud of binder, no kneading action of the mixer is required to coat aggregate particles. Consequently, the mixer can be discharged as soon as the proper quantity of binder has been introduced. In this connection, converted mixers that were designed for kneading must be discharged immediately upon completion of the introduction of the binder or the kneading action will tend to agglomerate the coated dust particles.

The mixer must be tightly enclosed, particularly when a large amount of mineral dust is used. By the action of the mixer, the dust usually forms a cloud in the top of the mixer around the atomizing nozzles. When the atomized fog of binder is introduced, the individual particles of dust pick up their films and drop back down into the body of the mixer where they are uniformly distributed through the aggregate.

When this method is in operation, it quickly becomes apparent that the quantity of binder used in a mixture is quite critical. Insufficient binder makes a mix which is very dry, brownish in color and in which uncoated aggregate particles are quite noticeable; an excess of binder makes the mix exceedingly fat and wet. Even a slight excess of binder will noticeably effect the consistency of the mixture. Thus, the method appears to possess an inherent binder control for the mixture.

Since this method was selected as a means of testing the validity of the basic concept of this study, it became necessary that a laboratory mixer that would operate under this method be available. Since a twin shaft pug mill mixer is essential to this process, a small Hetherington-Berner laboratory twin shaft pug mill mixer of 50 pound batch capacity was purchased, modified and equipped to operate under this method. The mixer was equipped with a pressure pumping system and a binder measuring tank, a high pressure rotary asphalt pump and all necessary appurtenances such as pressure relief valve, pressure gage, control valve and high pressure piping to carry the binder to a suitable atomizing nozzle in the mixer. The speed of the pump driven by an electric motor was adjusted to the capacity, operating pressure and atomizing characteristics of the nozzle used. The entire system is electrically heated by calrods. (See plate III.) Since the initial purpose of the mixer was the preparation of bituminous mortars, the mixer was enclosed and its speed was increased. The mixer was enclosed by a plexiglass cover so that the operation of the nozzle and mixing action could be observed. (See plate IV.) The speed was increased to 100 RPM, which gives the paddle tips a peripheral speed of 300 feet per second. To further improve fluffing of the dust during mixing action, the mixer arms were fitted with wire mesh paddle tips. (See plate IV.)

The mixing procedure for preparation of a bituminous mortar is as follows: The proper quantity of mineral dust, dried and heated to 320°F., is weighed out and placed into the mixer. The supply measuring tank for the bitumen is filled with binder at 330°F. The cover on the mixer is closed and the mixer started. The asphalt pump is started and the binder is circulated through the system. As soon as the mineral dust in the mixer is fluffed up into a cloud of dust, which takes a few seconds, the control valve on the atomizing system is opened and the binder is introduced into the mixer in an atomized fog. As soon as the proper quantity of binder, measured either volumetrically from the measuring tank or timed through the constant displacement pump has been introduced, the control valve is closed and the mixture is discharged. Pump pressures from 90 to 250 pounds are used, depending upon viscosity of the binder and back pressure characteristics of the atomizing nozzle used. The time required to introduce the binder needed to prepare a mortar, of course, depends upon the quantity of asphalt used and will vary between 12 and 20 seconds per 20 pound batch of mortar. It was mentioned that it is essential to empty the mixer as soon as the binder is introduced, since the kneading action destroys the life in the mix and causes the mortar to ball up.

In producing mixes in this manner, several important questions arise. Does atomization of the binder have any adverse effects upon its physical or chemical characteristics? What are the desired characteristics of the nozzle emanations and how are these effected by temperature, pressure, etc.?

ASPHALT CEMENT AND ATOMIZATION

Since oxidation of an asphalt cement will alter its physical and chemical properties, one wonders while watching the atomization of the binder how much oxidation is occurring. One also wonders if atomization has any other detrimental effects upon the binder. These are extremely important questions that must be studied and answered.

Ordinarily with such a large area of binder exposed to air during atomization, it would be expected that a high degree of oxidation would take place. Yet if the conditions that prevail during the atomization of the binder are closely examined and studied, it will be found that the opportunities for oxidation are reduced rather than increased beyond those present in conventional mixing operations. In this process, the asphalt cement is heated to 325°F. to lower its viscosity to a point required by the nozzle to atomize it. The liquid asphalt pumped under pressure goes into the nozzle and is spun and ejected in a hollow conical film. The asphalt remains a film until it has cooled sufficiently to increase its surface tension to the point where the film breaks up into minute droplets. (See plate V.) The measurement of the actual temperature of the droplets created by atomization is extremely difficult but the temperature of the binder is considerably below 320°F when the film breaks. This is proved by the fact that, when individual droplets of binder strike the skin of an operator, they do not burn. In fact, they are not even noticed as attested by the fact that one day after a series of studies on atomization characteristics of nozzles, the back of an operator's ear was entirely coated with asphalt without him noticing it until later in the day. So, even though a large area of asphalt is exposed to the air, its relatively lower temperature tends to reduce oxidation. When the droplet strikes the hot aggregate, it splashes and rapidly regains its temperature from the aggregate which assists it in forming a very thin film. Further, since the mix is discharged from the mixer immediately after the binder has been introduced, less oxidation will occur than occurs during the wet mix period of the conventional operation during which the mix is fluffed while the binder is in contact with the hot aggregate. It may be concluded then that very little if any oxidation occurs during atomization. Theoretical conjecture, however, proves nothing and the question of oxidation must be settled by test.

The usual tests of penetration, softening point, loss on heat, etc. were made on the asphalt cement both before and after atomization. The results of these tests indicated that no change in physical properties of the binder occurred from atomization.

During these tests, it was noted that they were not sufficiently sensitive to indicate the small changes in these properties. It was, therefore, decided that other special tests more sensitive to small changes of properties of particular significance in the formation of thin films should be made. The tests selected were for the measurement of viscosity and surface tension over a wide range of temperatures.

Viscosity measurements were run over a range of temperature from 80°F to 400°F. The Brookfield viscometer was used from 150°F to 400°F and temperatures were read by a calibrated thermocouple pyrometer placed in the asphalt. Measurements were made every 10°F. For temperatures below 150°F., the Koppers viscosimeter was used. The viscosity measurements in centipoise were plotted and comparisons of before and after atomization were made. No change of any significance was found.

Surface tension measurements were made with the De Nouye surface tensiometer over a temperature range of 180°F. to 400°F. These measurements were also plotted and a comparison of the asphalt before and after atomization was made. No change of any significance was found.

These special tests, which are highly sensitive to any hardening caused by oxidation, were repeated. The results secured indicated that no change occurred in the properties of the asphalt from atomization.

It is known that oxidation of an asphalt will materially increase its so-called "asphaltene content". To determine whether or not any change of chemical constituents of the asphalt occurred during atomization, chemical tests for the so-called "asphaltene", "resin" and "petrolene" contents were run before and after atomization. Several tests were tried, including the AASHO method[5], the Minnesota Method[6], and the Abraham Method[7], and were found to be time consuming and frequently unreliable. Since a large number of these determinations had to be made to check various nozzles and atomizing conditions, it was necessary to develop a more rapid and reliable test for the asphaltenes. This was done, and these tests were made by this modified method[8]. The results of these determinations indicate that no significant change in the asphaltene content occurs in asphalt cement from atomization.

Up to this time, only asphalt cement has been used in the atomization method for preparing bituminous mixes. Emulsified asphalts and cutbacks, when used in the future, will be similarly tested to determine the effect of atomization upon their physical and chemical properties.

STUDY OF ATOMIZING NOZZLES

In reviewing the development of the atomization method, it was found that many various types of atomizing nozzles had been tried and tested and only a few found that produced the desired results. From this it is obvious that the characteristics of the emanation from a nozzle are of considerable importance. Variations in operating conditions of a nozzle, such as pump pressure, viscosity of binder, pump discharge and capacity can alter the emanation characteristics of a nozzle. Therefore, a study was undertaken as part of this project to ascertain the critical characteristics of the nozzle emanation and the effects of varying nozzle operating conditions upon these characteristics.

Considering the fundamental idea of the atomization method as previously discussed, it may be deduced that the size, velocity and path of the droplets produced by a nozzle are the critical characteristics of its emanation. After trying several methods, high speed motion picture photography was selected as the method that could give the desired information concerning size, velocity and path of a droplet of binder after it left the nozzle.

A Fastax 16 mm. high speed motion picture camera was purchased. This camera is capable of taking 7,000 pictures per second. It is equipped with a film speed timer and a 50 mm. f.2 lens and is provided with its "Goose" control unit and a heavy adjustable tripod. Other accessories such as lens extenders for close work, a light meter, and high intensity lights with their controls were also provided.

Since this study had to be conducted along with other phases of the project, it was necessary that a separate atomizing system be constructed. This was done and the unit was mounted on a movable carriage so that pictures of the operation of the nozzle could be taken from any angle. The pump of this system was driven by a vari-speed motor to provide a wide flexible range of operating conditions of the nozzle. The output capacity and the pumping pressure of the pump could be varied when working with binders of various viscosity. In this way, the effects upon the nozzle emanation could be studied and the data gained could be applied to operation of the system in practice.

Since no work had been done along these specific lines, the techniques required to photograph the nozzle emanations had to be developed the hard way. Because the droplets of the atomized asphalt are very minute, when they lose their velocity after ejection from the nozzle they become airborne and are subject to even the slightest draft. The greatest difficulty in this development was the containment of the asphalt spray. Many methods of containment were tried, but the final solution devised uses no contairment at all. The nozzle operates in the open, and is directed into a shallow container, the bottom of which is covered with sand. The container is placed at such a height that the droplets of asphalt still retain some of their velocity and all of the droplets are caught by the sand in the bottom of the container.

The next problem was to determine the camera speed so that a droplet in space could be stopped on successive frames of the film. It was found that a speed of 7,000 frames per second was required. From the speed of the film, the exposure time of each frame could be determined. At 7,000 frames per second, each frame is exposed for about 3/100,000 of a second. One hundred feet of film passes through the camera in 0.9 second at this speed. This, of course, requires extremely intense lighting to obtain an actual image of the droplet. A characteristic of the asphalt came to our assistance in this regard. Since the asphalt is highly reflective of light, it was found that by proper placement of the lights, a reflected image of each droplet could be readily photographed. Even under these conditions, an intensity of 40,000 to 50,000 foot candles of illumination, 4 to 5 times that of noon-day sunlight, had to be used.

Still another problem that had to be solved was the positioning of the camera to secure a picture of a droplet large enough to be measured when enlarged or projected. By the use of lens extenders, the camera can be placed within 28 inches of the subject, and this distance proved satisfactory in securing a good reflected picture of the droplet. Since the emanation from the nozzle is a hollow cone, the axis of the lens must be placed perpendicular to the side of this cone if the trajectory of the droplet is to be determined. Focusing the camera is relatively easy because it possesses a focusing arrangement directly through the lens, and with a lens that has a good depth of focus, a good clear picture can be secured.

Upon completion of the development of techniques of photography, arrangement of lights and containment of asphalt spray, (see plate VI), many pictures of the emanation of various nozzles operating under various conditions were taken.

A Bell and Howell 16 mm. time-motion motion picture projector was secured for measuring the size and velocity of the droplets, plotting their trajectories and analyzing their general behavior. This projector is set at a fixed distance from a grid screen. Measuring the distance from projector to screen, a magnification ratio can be calculated. By this method, the diameter of a droplet projected on the screen may be measured. To facilitate plotting of the trajectory of a droplet, successive frames of the film are projected upon cross section paper on which each successive position of the droplet is marked. From this plot, the path and the speed of the droplet may be calculated from the film speed, magnification ratio, and measured distance between plotted positions of the droplet.

This analysis of the size and behavior of droplets and nozzle emanations is in progress. It is hoped that the splash effect of the contact between droplet and aggregate may also be photographed and analyzed.

FORMATION OF A BITUMINOUS MORTAR WITH MINERAL FILLERS BY THE ATOMIZATION METHOD

The atomization method can combine an atomized binder and a mineral dust into a bituminous mortar in several ways. The physical form of the mortar depends largely on the temperature of the dust when placed into the mixer and the conditions in the mixer during mixing.

When the body of the mixer is heated by steam jacketing or other means and the mineral dust placed into the mixer is hot, about 350°F., the binder will form very thin films around individual particles of dust during mixing. If sufficient atomized binder is present, all the particles of the dust will be coated. The high temperature of the dust is essential in this case. It will be recalled from the discussion on oxidation that the droplet of binder is relatively cool when it comes into contact with the aggregate, and that it depends upon absorbing heat from the aggregate to liquefy sufficiently to form the film. Since the particles of mineral dust are very small, they must be heated to a temperature of 350°F. to carry sufficient heat to effect the formation of the film of binder. Under these conditions, a bituminous mortar is produced directly. (See plate VII.) This type of mortar may be designated as an active mortar because it may be molded into shapes, which it will retain, by relatively low pressure.

When the mixer is cooled by a cold water jacket or other means, and the dust placed into the mixer is at atmospheric temperature, an entirely different combination of atomized binder and the dust takes place during mixing. The dust does not possess sufficient heat to liquefy the droplet of binder and permit it to form a film around the dust particle. Therefore, since the droplet is soft and sticky, the fine particles of dust that come into contact with it stick and coat its surface with dust. (See plate VIII.) This is unique because the asphalt droplets are coated with dust. This type of mortar may be considered inactive because it remains loose and powdery and looks very much like the original mineral dust. Tests indicate that as much as 20% binder by weight may be included in a mineral dust in this manner.

The inactive mortar may be activated in several ways. In the activation, the droplets of binder are so liquefied that they move out from under the dust particles and form thin films around each particle of dust. This activated mortar is the same as the active mortar produced directly. Since activation involves liquefication of the binder, any means that can accomplish this will activate an inactive mortar. One way is to heat an inactive mortar to about 350°F. Addition of a solvent such as gasoline, carbon tetrachloride or any other will accomplish the same result at atmospheric temperature. Activation may also be accomplished by the use of high pressure to liquefy and squeeze the binder out around the dust particles.

This project is concerned only with the active type of bituminous mortar. Therefore, though the inactive mortar has several applications in highway work, this phase will not be pursued further. It is reported here as a part of the record.

Microscopic examination of an active mortar shows that when sufficient binder is present, each individual particle of dust has its own thin film of binder and when insufficient binder is present, some of the particles remain bare. Excess binder gives the mortar a liquid consistency. Visual examination of a mortar will clearly indicate the proper quantity of binder, for the lines of demarkation between insufficiency and excess are quite sharp and clear. Microscopic examination shows that the films coating the particles are almost transparent and appear light brown rather than black in color. It will be recalled from a previous discussion on film thickness that films of this color are extremely thin, probably under 2 microns in thickness.

The preceding discussion shows that the atomization method can produce a bituminous mortar of binder and dust in several forms which cannot be produced by conventional mixing operations.

PROCESSING LOESS

If loess, as found in its natural state generally, is to be used by the atomization process for the formation of a bituminous binder, it must somehow be converted into a mineral dust. To convert it easily and economically, information concerning its characteristics and composition is necessary. We were quite fortunate in this regard because Dr. D. T. Davidson, a colleague in the Engineering Experiment Station, is conducting an exhaustive study of the classification and physical and chemical properties of loess found in Iowa[9,10] as a companion project under the sponsorship of the Iowa Highway Research Board. From this work, it was learned that loess found in Iowa is composed predominately of silt and clay, with the clay content varying from very small amounts up to as much as 50%, and that the moisture content in its natural state varies from zero up to 30 percent. This information is pertinent because it shows that loess is composed of mineral particles of a size that would make an excellent mineral dust if the particles can be separated.

A high moisture content makes the loess very liquid. As the moisture is gradually removed, the loess becomes plastic, then very hard and brittle. When all the moisture is removed, it becomes dusty having separated into its primary particles. There are, then, two methods of separating the loess into its primary particles, the wet and the dry. Since the mineral dust used in the atomization method must be dry, the wet method was not considered, and attention was directed toward the development of a dry method of separation.

Preliminary tests conducted on the drying of loess indicated that some rather unusual changes took place during drying. The drying was conducted in the laboratory in a Miskella Vibro Veyor Dryer. This type of dryer was selected for laboratory use because it uses infra-red lamps as the heating source and a vibrating pan for conveying the material through the dryer. In this type of a dryer, the loss of fines during drying is reduced to a minimum. The dryer was modified by installing electrical strip heaters on the vibrating pan to increase its drying capacity. The dryer as modified can readily dry and heat material up to 325°F.

When moist loess containing about 25 percent moisture is put through this dryer, a large quantity of moisture is given off rapidly and the loess changes from a plastic form into a material which is quite lumpy, hard and dusty. The lumps of loess were found to be extremely hard. When struck with a hammer, they would shatter. The shattered lumps appeared quite dry inside. The moisture content of the material, after passing through the dryer, was about 12 percent. Additional drying reduced the moisture content very little and seemed only to make the lumps harder.

These observations led to the next step in the laboratory processing of the loess. The material discharged from the dryer on the first pass contained a considerable quantity of dust and other particles that would pass the No. 10 sieve. This material was screened out. The material retained on the No. 10 sieve was then passed through a small laboratory jaw crusher whose jaws were set at 1/8 inch opening, which reduced the loess lumps to 1/8 inch or smaller. All of the screened and crushed material was then passed through a small laboratory hammermill pulverizer fitted with a 1/16 inch screen. Although the material contained about 12 percent moisture, it passed through the pulverizer easily. The material discharged from the pulverizer was a fine mineral dust, all of which passed through the No. 200 sieve and had a moisture content of less than one percent. Most of the moisture contained in the loess immediately prior to pulverization was removed during pulverization.

This laboratory procedure processed loess into a mineral dust suitable for use for the formation of a bituminous mortar by the atomization method, and it bears promise of economical commercial operation.

Since the initial drying produced a quantity of fine material, a commercial rotary drum dryer was believed to be unsuitable because most of these fines would be blown out the stack of the dryer by the high draft required for its oil or gas fired burner. A laboratory pilot model of a vibratory enclosed spiral dryer externally heated was developed, built, and tested, and was found to have considerable economic possibilities.

Further work on this type of a dryer was discontinued when a Mixall was loaned by the Barber-Greene Company for tests on the drying of loess and for larger scale adaptation of the atomization method.

The dryer on the Mixall is a short, large diameter, rotary type, drum dryer fired by an oil burner. Tests on the drying of loess in this machine gave excellent results as to the character of the dried loess and the extremely low loss of fines during drying. The procedure used in drying the loess in this machine was as follows. The drier was warmed up and then charged with 300 pounds of loess containing about 30 percent moisture. The oil fired burners were turned on full and the drum was rotated for about 1 1/2 to 2 minutes at a speed of about 7 RPM. During the drying period great clouds of steam were emitted from the dryer, and the steam materially decreased when the dust began to appear. The drying time was determined by watching the exhaust stack of the dryer. The moment dust began to appear, the dryer was discharged and very little dust was lost during the drying period. By the arrangement of this machine, the loess discharged from the dryer had to pass momentarily through its mixer before it was collected in barrels. The loess secured from this operation contained about 10 to 12 percent moisture and was well broken up by the tumbling action of the dryer. Most of it passed the No. 8 sieve and a considerable portion of it was dust, therefore, no crushing was required prior to pulverization.

After the loess was dried, it was passed through the pulverizer. To show how well the loess was broken up in this drying operation, 21 tons of loess dried in this manner was pulverized in an eight inch laboratory hammermill pulverizer. This pulverized loess contained about 1 percent of moisture and all particles passed the 200 mesh sieve.

The pulverized loess was used for the preparation of loess bituminous mortars in the laboratory and for the preparation by the atomization method of ungraded sand loess mortar bituminous mixes laid in the test roads described later.

These tests proved quite conclusively that loess as found in nature could be easily and economically processed commercially into a mineral dust suitable for a bituminous mortar made by the atomization method. The estimated cost of processing loess in this manner is about 20 to 25 cents per ton, making a mineral dust of loess available for use in bituminous mixtures at a cost of 70 to 75 cents per ton at the source of the material.

FORMATION OF A BITUMINOUS MORTAR WITH LOESS

A bituminous mortar of a binder and mineral dust can be produced by the atomization method. Though several types of dust, such as limestone dust, fly ash, marble dust, and sands passing the 200 mesh sieve, have been used for this purpose, pulverized loess had never been tried. Indications were that it could be used successfully, but these indications had to be confirmed.

To check the use of loess for a bituminous mortar, the following experiment was conducted. Fifteen pounds of pulverized loess at atmospheric temperature was placed in the adapted laboratory mixer. The body of the mixer was cooled by circulating cold water through a water jacket surrounding the mixer body. Fifteen percent by weight of 150-200 penetration asphalt cement at 320°F. was introduced in an atomized form during mixing. The result was an inactive bituminous mortar of binder and loess. In the next test, the body of the mixer was heated by calrods. The fifteen pounds of pulverized loess was heated to 325°F. before being placed into the mixer, and fifteen percent of the same binder at 320°F. was introduced into the mixer in a similar manner during mixing. The result was an active bituminous mortar of the binder and loess.

This experiment proved conclusively that both an active and an inactive form of bituminous mortar can be produced when pulverized loess is used as the mineral dust.

MATERIALS USED IN TESTS OF BITUMINOUS PAVING MIXTURES

Work so far had shown that thin films of binder can be applied to individual particles of a mineral dust, and that such particles so coated by a binder will produce a bituminous mortar. The basic concept underlying this entire project, namely that of utilizing such bituminous mortars as the bonding agent for ungraded aggregates in the preparation of a satisfactory bituminous paving mixture, however, still remained to be verified.

To check this basic concept over the wide range of materials that may be used in the construction of bituminous pavements, many local materials were tested. Materials tested as binders in these experiments included asphalt cements of 150 to 200 penetration and 200 to 300 penetration. Tested as mineral dusts were limestone dust, fly ash and loess, and tested as fine aggregates were numerous sands, having a wide range of gradations, found locally. Since these materials had to be combined in a number of different proportions, it was thought desirable to devise some sort of simple coding for the identification of the materials and their combinations in the various mixes.

In the code devised, the various materials are numbered, each group being numbered consecutively from 1. (See table 1.) In designating the combination of the materials in a mixture, a sequence of these numbers separated by a semicolon is used. The sequence in the table is mineral dust, fine aggregate, coarse aggregate, and binder. To indicate the proportion of each material used in the mixture, its designation number is followed by a period or decimal point followed by its percentage in the mixture. As an example; suppose we have a mixture which contains 25% of Page County Loess. (no. 8), 75% of Blow Sand, (no. 1), and 6% of 150-200 penetration asphalt cement, this mix would be designated 8.25; 2.75; 0.0; 2.6. In this coding the combinations of the aggregates are indicated as their percentages of total aggregate and not as percentages of mixture, while that of the binder is percent of total mixture. In the example, the coarse aggregate designation was included and shows that no coarse aggregate was used in the mix. Since no coarse aggregates were tested in this phase of the project, the coarse aggregate designation was dropped and the designation, as used here for the example, would be 8.25; 2.75; 2.6. Special conditions during mixing such as use of a different nozzle are shown by a letter at the end, that is, this mix made with the Wibau nozzle would read 8.25; 2.75; 2.6W. Where no letter is given, the standard nozzle was used.

MINERAL FILLERS

Loess.

The dictionary describes loess as a pale, yellowish clay or loam forming deposits along river valleys. A geological definition is much more complicated. For the purpose of this work, it is sufficient to know that loess will vary widely in composition even in areas relatively close together and that it is composed primarily of silt and clay[9].

Since it was believed that the clay content of the loess would have a decided bearing upon its use in a paving mixture, a number of materials of this nature having a wide range of clay content and secured from various locations were included. The following are the physical characteristics of these materials:

No. 1. Loess from Dunlap, Iowa.
- Clay content, 21%
- Gradation of pulverized loess
  - 99.8% passing no. 100 sieve
  - 98.5% passing no. 200 sieve
- Specific gravity, 2.50

No. 2. Loess from Missouri Valley, Iowa.
- Clay content, 13%
- Gradation of pulverized loess
  - 99.4% passing no. 100 sieve
  - 98.2% passing no. 200 sieve
- Specific gravity, 2.75

No. 3. Loess from Shenandoah, Iowa.
- Clay content, 30%
- Gradation of pulverized loess
  - 97.4% passing no. 100 sieve
  - 92.0% passing no. 200 sieve
- Specific gravity, 2.53

No. 8. Loess from Page County, Iowa.
Clay content, 38%
Gradation of pulverized loess
100% passing no. 200 sieve
Specific gravity, 2.70

Fly Ash.

The fly ash received was tested primarily for its ability to form a mortar and not for use in a bituminous mix. It was found that a bituminous mortar of this material could be produced. No. 5 fly ash was secured from Louisville, Ky. through the courtesy of Mr. Walter Handy.

No. 5. Fly Ash from Louisville, Ky.
Gradation: 97.1% passing no. 200 sieve
Specific gravity, 2.60
No check was made for chemical contents

Limestone Dust.

Although two sources of limestone dust were available, only the limestone dust from Buffalo, Iowa, was used in these tests. That from Milwaukee, Wisconsin, was used only for mortars for check purposes. The Buffalo limestone dust used in both the laboratory and road tests was furnished through the courtesy of the Linwood-Stone Products Co. of Buffalo, Iowa.

No. 7. Limestone Dust from Buffalo, Iowa.
Specific gravity, 2.72
Gradation: passing no. 60, 97.5%
passing no. 80, 92.8%
passing no. 100, 89.6%
passing no. 200, 64.9%

FINE AGGREGATES

Sands.

To check the effect of various gradations of natural sands in relation to the preparation of bituminous paving mixtures by the atomization method, sands having a wide range of gradation were selected. The gradations are that of the material as found in nature or readily available at sand pits. No blending for adjustment of gradation was made.

No. 1. Blow sand from Muscatine County.
Specific gravity, 2.70
Gradation: See figure 5 and table 2.

No. 2. Fine sand from Muscatine County.
Specific gravity, 2.63
Gradation: See figure 5 and table 2.

No. 3. Concrete sand from Hallett, Boone, Iowa.
Specific gravity, 2.62
Gradation: See figure 5 and table 2.

No. 4. Concrete sand from Roberson, Ames, Iowa.
Specific gravity, 2.65
Gradation: See figure 5 and table 2.

No. 5. Plaster sand from Roberson, Ames, Iowa.
Specific gravity, 2.65
Gradation: See figure 5 and table 2.

Agricultural Limestone.

No. 6. Ag Lime from Cook's Quarry, Ames, Iowa.
Specific gravity, 2.65
Gradation: See figure 5 and table 2.

BITUMINOUS MATERIALS

For the physical and chemical characteristics of the bituminous binders used, see table 3.

TESTS CONDUCTED ON MIXTURES

In an effort to determine their stability under load at various temperatures and moisture conditions, their reaction to simulated weather conditions such as freezing and thawing and to ascertain the void content of laboratory specimens various physical tests were made of the many mortar and paving mixtures prepared. The binder was extracted from the mixtures to check the binder content and to determine whether or not any changes occurred in the chemical constituents of the binder. Visual and microscopic examinations were made to note the consistency of the mix, the formation of films on aggregates, the characteristics of these films and the uniformity of the mixtures and binder films.

Since none of the experimental mixtures made in this phase of the work contained coarse aggregates, the Hubbard-Field Stability Test was selected as the test for stability of the mixture because it was believed that its results could best be correlated to service behavior. Test specimens 2 inches in diameter and about 1 inch in height were prepared in strict accordance with the requirements of this test[11]. The specimens were tested in the prescribed test mold in a Marshall Testing Machine whose rate of load application is almost the same as that required by the Hubbard-Field Test[11].

Twenty five specimens of each batch of bituminous mortar or paving mixture were prepared for test. Stability tests were made after the specimens had been cured at room temperature, about 75°F., for 3 days. Five of the specimens were tested for stability at room temperature; an another five were tested after heating for one hour in a constant temperature oven at 140°F.; and still another five after one hour of immersion in a constant temperature bath at 140°F. Upon completion of the stability test, the specimens were removed from the test mold and the quantity of material extruded was ascertained by measuring the height of the specimen. (See figure 6.) The character of the extruded section was carefully examined, and notes were made concerning its condition, shape and cracking. (See figure 6.) Such an examination of the extruded section yields excellent comparative information concerning the flow and cohesive character of the mixture.

Four of the remaining ten specimens were subjected to the freezing and thawing test recommended by A.S.T.M. D560-44. Twelve cycles of freezing and thawing were run in this test, since it was found that most specimens subject to failure failed within this range, though several tests were run for as many as 100 cycles. In addition to this test and as a part of it volume change and moisture absorption measurements were made after each freezing and each thawing phase. The volume change was determined by measuring the diameter of the specimen at four designated points and the height at two designated points. The volume change was designated as a percentage of the molded volume. The change in moisture content was found by weighing each specimen after each phase of the cycle and recording the change as a percentage of the original dry weight.

The void content of the laboratory compacted specimen was determined in accordance with the procedure specified by the test[11]. Five specimens were used for this purpose. The specific gravity was checked by the method suggested by Mr. Paul J. Serafin[12].

TEST AND EVALUATION OF BITUMINOUS MORTARS

The ability to produce bituminous mortars using various mineral dusts does not mean that such mortars are necessarily suitable for highway purposes. So each of these mortars was tested and studied to ascertain the best combination of mineral dust and bituminous binder to provide a mortar that can satisfactorily bond ungraded aggregates together in a highway pavement.

Since this phase of the project was to verify the basic concept of a mortar theory, no effort was made to develop design criteria for these mortars or mixes. Efforts were directed to the development of mortars that can serve as a bond for ungraded aggregates in a mix suitable for highway purposes.

Many preliminary tests were run on different combinations of materials under various conditions to ascertain their mixing behavior, the general limiting proportions of the materials, and in the case of loess the effects of clay content on mixing procedure. The clay content was found to have no effect on mixing procedure. The information gained from these preliminary tests served as guides for the selection of various combinations and proportions of materials to be subjected to more detailed test.

The materials selected for detailed test were the Page County loess, no. 8, because it has a very high clay content, and the Buffalo limestone dust, no. 7, and a 150-200 penetration asphalt cement, no. 2. (See tables 1 and 3 for details of physical characteristics of these materials.) From the information gained from the preliminary tests, the binder content was varied from 20 to 25% in the loess mortars and between 10 and 15% for the limestone dust mortars. Tests were made also of the same combination of mortars prepared by two different nozzles used for atomization of the binder.

Several series of tests were run. One series was made to determine the optimum binder content for the loess mortars. A second series was run to determine the optimum binder content for limestone dust mortars. Both of these series of tests included stability, freezing and thawing tests, and determinations of void contents. A third series was run to determine the efficacy of the two different nozzles. These nozzles differ in capacity and probably in their emanation characteristics. The Wibau nozzle, which is made in Germany, has a much higher capacity at the same pump pressure than the standard nozzle made in the United States, therefore, the mixing time of the mortar made with the Wibau nozzle is much shorter than that made with the standard nozzle.

These series of tests were coded as 8.100; 9.20-25 indicating the use of 100% of no. 8 loess combined with 20 to 25 percent of no. 9 binder introduced by the standard nozzle. The addition of the letter W indicates the same proportion of materials with the binder introduced by the Wibau nozzle. The same coding was used with the limestone dust. It should be remembered here that the dust proportion indicates the percent of total aggregate and the binder proportion indicates percent of total mix.

The results of the various tests conducted upon the various mortars are tabulated and charted as follows:

Mortar 8.100; 9.20-25.

Stability	Table 4	Figure 7
Voids	Table 4	Figure 7
Freeze-Thaw		
Volume Change	Table 6	Figure 8
Moisture Content	Table 7	Figure 9

Mortar 8.100; 9.20-25W.

Stability	Table 5	Figure 7
Voids	Table 5	Figure 7
Freeze-Thaw		
Volume Change	Table 8	Figure 10
Moisture Content	Table 9	Figure 11

Mortar 7.100; 9.10-15W

Stability	Table 10	Figure 12	
Voids	Table 10	Figure 12	
Freeze-Thaw			
Volume Change		Table 11	Figure 13
Moisture Content		Table 12	Figure 14

Although all of the mortars tested in these series were subjected to the same tests, it should be noted from the test results that some tests are more critical than others. The results of the tests taken collectively serve for a reasonable comparison of the various mortars and the effect of the various nozzles. But in evaluating a mortar itself, each test must be studied independently.

Analyzing first the results of the tests on loess mortars, it may be said that the stability decreases in all cases with increase in binder content. A rather unusual character of these curves is noted (see figure 7) in that they all flatten between 23 and 24 percent of binder. Comparison of the stability curves for mortars produced by the two different nozzles shows that the standard nozzle yields higher stability at the lower binder content than the Wibau but from 23 percent binder upward, the results of the two are practically the same.

With regard to voids in compacted specimens of loess mortars in all cases, regardless of nozzle, the void content decreased as binder content increased.

Analysis of the freezing and thawing tests definitely indicates that this is the critical test for loess mortars. This is to be expected because this test is highly sensitive to any uncoated particles of clay contained in the mix. Table 6 clearly shows the excessive volume changes that occur at the lower binder contents which may be considered indicative of the effect of moisture on exposed clay particles. This was further confirmed by microscopic examination of these mixes which showed that insufficient binder was present to coat all the particles of dust in the mix. Some question may arise whether or not the void content might not be a contributing factor. A comparison between table 6 and table 11 clearly proves that void content alone does not cause this extreme result because the voids in the loess mortar in this range are considerably lower than those in the limestone dust mortar. From this test, the optimum binder content of a mortar containing loess may be taken at 23 to 24 percent binder. Comparison between the two nozzles indicates that the standard nozzle causes less reaction at lower binder contents but at optimum binder content, the results are the same for both nozzles.

In evaluating the tests, generally a rather unusual relationship becomes apparent. The optimum binder content taken from the freeze-thaw test seems to have a marked effect upon the stability because at 23 to 24 percent of binder, the stability curve suddenly flattens. Since this loess contains 38 percent clay, it is probable that the optimum binder content for a loess containing less clay will be somewhat lower.

Taking 23 to 24 percent of binder as the optimum for this mortar, the corresponding stabilities are about 2000 pounds at 77°F., 1000 pounds at 140°F. dry and 800 pounds at 140°F. wet. According to the design criteria suggested for this test[11], the minimum low stability limit for intensive mixed traffic is 1200 pounds with 2000 pounds desired. For light traffic, a stability below 1200 pounds is permitted. Therefore, if this mortar containing 23 to 24 percent of binder were used alone as the paving mixture in a highway pavement, it could serve light traffic. From table 5, it is noted that curing of the mortar for an additional 25 days increased its stability.

Analysis of the limestone dust mortar shows that shrinkage, rather than expansion, occurs during the freeze-thaw test. (See figure 13.) The extent of this, however, is negligible. The stability curves conform more nearly to the usual shape expected in that a peak is reached at the optimum binder content. Thus, in this case, the stability test is the critical test. From the various tests, 13 percent of binder emerges as the optimum binder content for this mortar. The stabilities for this mortar at 13% binder content are 6900 pounds at 77°F., 1850 pounds at 140°F. dry and 2850 pounds at 140°F. wet. Based on the design criteria suggested for this test, this mortar could be used alone as the paving mixture for a highway carrying intensive mixed traffic.

One thing noted in mixing this mortar and confirmed by test results is that the mixes tend to be erratic because the dust is very sensitive to the binder content. A slight increase of binder, as little as 1/4 percent, may make the mix very wet. More study is needed to ascertain the causes of this sensitivity.

Comparison between the loess and limestone mortars shows that the loess requires considerably more binder. This is no doubt due to the much finer gradation of the loess. The limestone mortar is also considerably stronger than the loess. This may be attributed to gradation. Both can resist freezing and thawing equally well when the proper quantity of binder is used. In mixing, the loess yields a smooth workable consistent mixture while the limestone dust is somewhat harsher and somewhat erratic.

From the results of these tests, it appears that these mortars possess considerable promise in their ability to verify the basic concepts of the mortar theory, and that they hold some promise of serving as suitable paving mixtures for light traffic in themselves.

TEST AND EVALUATION OF SAND ASPHALT MIXES

Considerable attention has been given in the United States to the development of a sand asphalt paving mixture. The results of these studies indicate that local ungraded sands do not readily lend themselves to treatment because the resultant mixes contain a very high percentage of voids. Promising results have been secured wherever the sands are well graded and possess or have added about 10 to 15 percent of fines passing the 200 mesh sieve.

To check the atomization method in the production of a sand asphalt mix, five different locally available sands were tested. (See figure 5.) In these tests two asphalt cements, one having a penetration of 150-200 and another of 200-300 were used. The tests were the same as those made on the bituminous mortars. The results of these tests are shown in tables 13, 14, 15, 16, 17, 18, 19, and figures 15, 16, 17.

The analysis of these test results show that these sands do not lend themselves directly to the preparation of a suitable paving mixture by the atomization method. In all cases voids in the compacted specimens are high and stabilities are very low. Sands that have some gradation are a little better than those which have no gradation.

TEST AND EVALUATION OF
AGRICULTURAL LIMESTONE MIX

Agricultural limestone made from a very soft limestone is generally available in most of Iowa. This material is produced for the farmers who use it to sweeten the soil in their fields. Since this material is abundant and is relatively inexpensive, its applicability as an aggregate for a bituminous pavement was studied. Presently it is used in conjunction with asphaltic concrete mixes as a blend material to adjust gradations in sands and also as the mineral dust. The purpose of this study is to test this as produced as a single aggregate for a bituminous mixture. The gradation of the material of this type used in these tests is shown in figure 5 and table 2.

The tests conducted on this material are the same as those conducted on the bituminous mortar and sand asphalt mixes. The test results are shown in figure 18 and in tables 21 and 22.

The stability tests indicate that the optimum binder content lies between $8\frac{1}{2}$ and $9\frac{1}{2}$ percent. These are confirmed by the freeze-thaw tests. Although stability tests were not made at 140°F. wet in this series, preliminary tests indicate that these are above the 140°F. dry results. From this it may be concluded that this material can be used as a single aggregate in a bituminous pavement for intensive mixed traffic when mixtures are made by the atomization method. This was confirmed by test road tests.

TEST AND EVALUATION OF
SAND MORTAR MIXES

The results of tests conducted upon sand asphalt mixes using ungraded sands show that these materials alone are not adaptable to the production of a satisfactory paving mixture. The validity of the basic concept of this project can now be tested. Will the use of a suitable bituminous mortar in conjunction with such sands make them available in the production of a satisfactory paving mixture.

It was learned from the tests performed on limestone dust and loess mortars that they possessed considerable promise in fulfilling the objective of the project. Although some of these mortars could in themselves serve as paving mixtures, the amount of binder required makes these mixes comparatively expensive. If ungraded sands could be added to these mortars primarily as bulk without adversely affecting or perhaps improving the characteristics of the mortar, the binder content of such a mixture would probably be considerably lower than that of the mortar, and a sand bituminous mortar mixture could be produced inexpensively. Ungraded aggregates would then be suitable for highway purposes.

A complete series of laboratory tests were planned. To gain as much information as possible from these tests, numerous combinations of various proportions of sands, mineral dust, and binder were used in preparing the mixes. The five different sands, limestone dust and loess, and both 150-200 penetration and 200-300 penetration asphalt cements were included.

The first tests conducted used limestone dust as the mineral filler, the five sands as fine aggregates and both asphalt cements. Mixes were prepared of each sand in which the limestone dust content was varied from 10 to 40 percent for each percentage of binder content. The binder content of these mixes was varied between 5 and 9 percent at one percent intervals. Stability at various temperatures and void content tests were made on all mixes. Since freezing and thawing tests are time-consuming, they were run only on selected mixes.

The results of these tests are shown in tables 23, 24, 25, 26, 27, and in figures 19, 20, 21, 22, 23, 24, 25, 26, 27, 28.

Evaluation of the results of these tests on the individual sands are as follows:

No. 1 sand.

The optimum quantity of dust lies between 30 and 40 percent, and the optimum binder content is 8 percent. A mix using this sand with the optimum quantity of dust and binder possesses a stability of over 1200 pounds, making it suitable for intensive mixed traffic.

No. 2 sand.

The optimum quantity of dust is 30 percent with an optimum binder content of 6 percent. The stability of such a mix is about 1350 pounds, making it suitable for intensive mixed traffic.

No. 3 sand.

The optimum dust content in this case is 30 percent with an optimum binder content of 6 percent. The stability of such a mix is about 1800 pounds, making it suitable for intensive mixed traffic.

No. 4 sand.

The optimum dust content in this case is between 30 and 40 percent with an optimum binder content of 6 percent. The stability of such a mix is about 2100 pounds, making it suitable for intensive mixed traffic.

No. 5 sand.

The optimum dust content in this case is 30 percent with an optimum binder content of 7 percent. The stability of such a mix is about 1600 pounds, making it suitable for intensive mixed traffic.

The freezing and thawing tests conducted show that none of the selected mixes were adversely effected.

The evaluation of this series of tests shows that a bituminous paving mixture suitable for a pavement carrying intensive mixed traffic can be prepared with the use of ungraded sands in conjunction with a bituminous mortar. The binder contents in all these mixtures are about 6 percent, which is about one-half of the binder required in a mortar alone. The conclusion is that a relatively inexpensive mix can be prepared of these materials.

This series of laboratory tests verifies the validity of the basic concept of this project that ungraded sands can be bonded together by a bituminous mortar to produce a paving mixture satisfactory for secondary road use.

After laboratory proof of the validity of the basic mortar theory was obtained, it was decided to confirm the laboratory results by subjecting these mixes to actual traffic in a test road. To expedite the construction of this test road, the series of tests planned for the loess mortars was limited to those necessary to furnish the information needed for the design of mixes using loess in the test road.

Since sands no. 1 and no. 2 had the least amount of gradation of the group of sands tested, and since they possessed gradations which set boundary limits within which most local sands in Iowa would fall, they were selected for use in the test roads. The laboratory tests on loess mortars was limited to these two sands, and the mixes used followed very closely the various combinations of materials used in the limestone dust series.

The results of these tests are shown in tables 28 and 29 and on figures 29, 30, 31, and 32.

An evaluation of these tests on the basis of the sand used is as follows:

Sand no. 1.

The optimum loess content of this sand is 30 percent with an optimum binder content between 8 and 9 percent. The stability of such a mix is about 1300 pounds, which makes it suitable for intensive mixed traffic. It was noted that the voids of such a mixture was about 9%, and that all mixes containing 40 percent loess with 9% binder disintegrated in the 140°F. water bath.

Sand no. 2.

The optimum loess content in this case is between 20 and 30 percent with an optimum binder content of about 6 percent. Voids in this case were much lower than those for no. 1 sand. The stability for this mix is about 900 pounds, making it suitable for light traffic pavements.

General evaluation of these mixes indicates that a loess mortar can bond sands with almost a single size particle, regardless of size, into a paving mixture satisfactory for light traffic. It should be noted that this mixture lowered the binder content of the mortar alone from 23 percent to about 6 to 7 percent. Freezing and thawing tests show no adverse effect upon such a mixture.

TEST PAVEMENTS

The laboratory work on this project had progressed so rapidly and the results were so encouraging that it was decided to lay several small test pavements of the more promising mixes. Although this work was not contemplated in the original authorization, it was decided to lay such test roads during the summer of 1953. By laying the pavements at that time, one full year would be saved in ascertaining the behavior of these mixes under traffic over a complete cycle of seasons. One purpose of this test was to verify the laboratory results under actual traffic and weather conditions, and the other was to determine whether or not these mixes required any special construction practices.

Two locations were selected for the test pavements. The same mixes were used in both test areas. One area on Marston Court extending from Bissell Road to Riggs Court (see figure 33) carries about 3300 vehicles per day. Although this traffic is made up mostly of passenger cars, many service trucks use this road. Marston Court forms a T intersection with Bissell Road, a main campus artery, and vehicles entering Marston Court must make a sharp turn. These turns are usually made at about 20 miles an hour. Vehicles leaving Marston Court must slow down and frequently stop at the intersection. A pavement laid in this area is subjected to severe turning movements and starting and stopping of vehicles. The other area selected was around the Bituminous Research Laboratory in Building B. (See figure 34.) This area carries about 75 to 125 cars per day, primarily passenger cars, and a few heavy service trucks. This volume of traffic is about the same as that found on many secondary roads in Iowa. In these two locations are volumes of traffic, one of which will give accelerated results of paving behavior and the other will compare with secondary road traffic.

The mixes used in these tests included fine sand and loess, blow sand and loess, fine sand and limestone dust, and blow sand and dust and agricultural limestone. The fine and blow sands are the no. 1 and no. 2 sands of the laboratory tests. The binder used in all mixes was the no. 9, a 150 to 200 penetration asphalt cement. The extent and location of these various mixes together with thickness and type of base are shown on figures 33 and 34. Sections of penetration macadam sealed using 85-100 penetration and no. 9 asphalt cement were laid in these areas to test the use of soft, unit size, crushed limestone in this type of construction.

Observation of these test sections under these conditions over a full cycle of seasons it was believed would give a good test of the behavior of these mixes in actual service and indicate whether or not they could be used in secondary road pavement construction.

PREPARATION OF MIXES FOR THE TEST ROAD

The mixes used for the test pavements were prepared in actual small-size construction equipment modified to operate under the atomization method, and the mixes were laid in conformance with usual construction methods and techniques. It may also be of interest to note that these mixes were made and laid by students of the College hired for this work. With the exception of the author, who supervised the work, no one engaged in mixing or laying these mixes in the test road had any previous experience in the laying of a bituminous pavement. This is mentioned only to point out that no special skills are required in preparing or laying the mixes so long as they are properly controlled and the work adequately supervised.

A Barber-Greene Mixall, having a batch capacity of 300 pounds, was modified to operate under the atomization method. The modifications included providing a cover over the mixer, replacing normal paddle tips with heavy wire mesh tips, increasing the speed of the mixer and providing the pressure pumping system. The mixer was fitted with a single Wibau nozzle of 9 litre per minute capacity. (See plate IX.)

The mixing procedure used was as follows: The desired quantity of sand was volumetrically measured in a wheelbarrow, which was then dumped into the skip hoist of the Mixall. The material was dumped by the skip into the dryer of the machine where it was dried and heated to about 350°F. The heated material was then discharged from the dryer directly into the mixer. As soon as this material entered the mixer, the mineral dust, also measured volumetrically, was put into the mixer through a special opening in its cover. (See plate X.) Since the mineral dust was at atmospheric temperature, a dry mix period of 10 to 15 seconds was allowed for it to heat up to aggregate temperature. The binder was then introduced through the atomizing nozzle. The proper quantity of binder was measured volumetrically from a float gauged supply tank. After each mix, this supply tank was replenished with binder at 320°F. from a 180-gallon kettle used to heat the binder. As soon as the proper quantity of binder was added, the mixer was discharged into a wheelbarrow and the mix was taken to the paving operations. The temperature of the mix discharged from the mixer was generally about 340°F.

Once the mixing crew was well broken in, a 300-pound batch could be mixed in 75 to 90 seconds. During full day operations between 4 and 5 tons of mix were produced per hour. This output could probably be increased by using a larger capacity nozzle or two smaller capacity nozzles in the mixer. The nozzle used required 60 seconds to introduce the desired quantity of binder. Since dryer and mixing operations are conducted simultaneously, a slightly larger capacity nozzle could reduce the mix cycle time to 60 seconds.

Since accurate design criteria for the various mixes at this time had not been developed, the mixes were controlled by observation based upon data secured from the laboratory tests and the experience of the author. A basic mix containing 75 percent sand and 25 percent mineral dust as total aggregate was used. The binder was added in a quantity required to provide the mix with a consistency that was not too "fat" and possessed considerable "life". Life in a mix may be described as a tendency to creep slightly when the mix is dumped in a pile. Such life makes the mix smoother and easier to handle during paving operations. Since these mixes are rather sensitive to binder content, this form of control is not difficult. One or two trial batches will readily yield the proper binder content. However, the mixes must be watched carefully because an increase in temperature of the aggregate tends to flush the mixture. If the plant is thoroughly warmed up and the operator watches the moisture content in his aggregate and has acquired experience with the characteristics of the dryer, consistent mixes can be produced easily. Pump pressure and binder temperature must also be watched because these also may affect the consistency of the mix. By using the Wibau nozzle, a working pressure of 130 to 150 pounds with a temperature from 320°F. to 350°F. of the 150-200 penetration asphalt cement was found to function very satisfactorily.

As previously mentioned, the no. 1 and no. 2 sands were selected for this work because they had the poorest gradations of the sands tested in the laboratory. The no. 8 Page County loess was selected because it had a high clay content. It was felt that if these materials could be used to prepare a good mix and if this mix stood up under traffic, almost any local material could be made to work in a paving mixture.

The specific compositions of the mixes laid in the test road are as follows:

Blow sand and loess mixture contained 75% sand and 25% loess as total mineral aggregate and 6% of 150-200 pen. A.C. by weight. This combination made an excellent mixture.

Fine sand and loess mixture contained 75% sand, 25% loess as aggregate and 6% 150-200 pen. A.C. This, too, made an excellent mix but was somewhat fatter than the blow sand loess mixture.

The sand-limestone dust mixes were quite critical on binder content. The blow sand, limestone dust mixture containing 75% blow sand with 25% limestone dust in trial batches required 6% of 150-200 pen. A.C. As the equipment warmed up or the aggregate became a little too hot, this mix became quite fat and the binder content had to be reduced to 5½ percent. Therefore, the binder content in this mix varied between 5½ and 6 percent in the pavement.

The fine sand, limestone dust mix was even more critical than the blow sand mix. Trial batches of 75% sand with 25% limestone dust and 6% 150-200 pen. A.C. were practically liquid. To secure the desired consistency the binder content had to be reduced to 5%, but this gave a harsh mixture. Therefore, the fine sand, limestone dust mixture was arbitrarily readjusted to 67% fine sand, 33% limestone dust and 5½% binder. This gave an excellent mix and was used as the base on sections D. For surface courses the binder content was raised to six percent.

Practically no dust nuisance was created in drying and heating the sands in the Mixall. When attempts were made to dry and heat the agricultural limestone, the dust was very bad. The addition of 10 to 15 percent fine sand to the agricultural limestone, prior to drying, materially reduced the dust, and the ag lime mix as used contained 15% fine sand, 85% ag lime and 6 to 6¼% 150-200 pen. A.C. This mix also was quite critical on binder content, which may be attributed to the variation in gradation noted in the ag lime. Other mixes using fly ash as the mineral dust were tried and laid in small patches behind Building B. The experience gained from these operations clearly shows that these mixes can be made readily in regular construction equipment modified to the atomization method. The test mixes showed that more laboratory work is needed with limestone dust mixes to overcome their erratic behavior.

LAYING OF TEST PAVEMENTS

It has been mentioned before that these test pavements were laid primarily to determine whether or not any special construction methods or techniques are required and to determine the behavior of these pavements under various traffic conditions.

Section A of the pavement laid in the test road on Marston Court (see figure 33) was a conventional bituminous penetration macadam. The purpose of this section was to determine the applicability of soft Iowa limestones to this type of construction. This pavement was laid to a depth of 8 inches in three lifts of a soft Iowa limestone crushed to a gradation of between 1 and 3/4 inch. No particles were over 1 inch in size nor any below 3/4 inch in size. Each lift was rolled with a 3 to 5 ton steel tandem roller. The upper layer of top lift of stone showed marked degradation through crushing and splitting under this roller. This base was penetrated with a 85-100 penetration asphalt cement at the rate of 1 gallon per square yard. A layer of choke stone graded between ½ and 1/8 inch was then spread upon the penetrated surface at the rate of 30 pounds per square yard. This was broomed and rolled with the 3 to 5 ton steel tandem roller. During rolling it was noticed that extreme degradation of the choke stone was occurring, and a pneumatic tired roller was substituted for the steel tandem roller. The choke stone was then penetrated with the 85-100 pen. A.C. at the rate of 0.8 gallon per square yard. Considerable difficulty was encountered in getting this second application of the binder to penetrate into the choke stone due to the degradation caused by steel rolling. The application of the binder in all instances was made by hand through a no. 2 Littleford nozzle. A 180-gallon Littleford heater kettle with spray pump was used to heat and pump the binder. A light layer of coarse sand was then spread upon the penetrated choke stone at the rate of 10 to 15 pounds per square yard as a seal coat. This layer was broomed and rolled with a pneumatic roller.

Section B was constructed in the same manner and differed from section A only that it was 6 inches in depth and 150-200 penetration asphalt cement was used as the binder.

To determine the behavior of a relatively thin layer of the several paving mixtures, a penetration macadam base 5 inches in thickness was laid in section C. This base differed from the bituminous penetration macadam pavement in that the seal, choke stone and second application of binder was omitted in this case. The mixed materials were laid directly upon the penetrated base stone.

In section C, a mixture of fine sand and loess mixed as previously described was spread by hand, raked to a loose depth of 1½ inches and compacted with the 3 to 5 ton steel tandem roller to a compacted thickness of 1 inch. This mixture at a temperature of about 300°F. was raked and spread easily and smoothly. The mix was allowed to cool to about 110°F. before rolling. At this temperature it rolled nicely. If rolled at a higher temperature, it had a tendency to shove and push and develop hair cracks in its surface.

Sections C_2, C_3, C_4, and C_5 made of mixes as designated in figure 33 were laid in a similar manner. In some places where one section lapped over another during construction, the very thin layer of material overlapping the previously rolled section tended to tear badly under the steering wheel of the roller. This occurred, regardless of the temperature of the mixture during rolling. These tears were completely healed later by the action of traffic. From this experience it was learned that very thin layers of these materials cannot be rolled by a steel roller and a pneumatic roller should be used.

The various mixes laid in section D were laid directly upon the sub-grade to a depth of 6 to 7 inches to determine their behavior as both a base and a pavement. It was originally intended to lay these mixes in three two-inch lifts, but during construction this was changed to two three-inch lifts due to the limited space in which to maneuver the roller. The first lift was spread to a loose depth of 5 inches and rolled at 110°F. mix temperature to a compacted depth of slightly over 3 inches. On the second lift it was noticed that the mixes, when warm, tended to push and shove and tear under the roller, so further rolling was discontinued and the mix allowed to cool overnight. That night the temperature dropped to 41°F. Rolling was again attempted the next morning when the temperature was 54°F, and very little compaction was attained. Rolling was again stopped and resumed later in the day when the temperature rose to 70°F. Some additional compaction was secured. The total amount of compaction secured in this 5 inches of loose mix was about 1 inch which left the surface of this pavement above final grade. The day following this rolling the test road was opened to traffic. The weather during the next two weeks was very hot, up to 95°F. during the day. During this period, the traffic compacted this area of the pavement down to final grade.

In section H, used as a parking area, the pavement is a 2-inch penetration macadam surfaced with ½ inch of compacted mixture. The mixes in this area were spread to a loose depth of 3/4 inch. With the tandem roller, the surfacing pushed, shoved and tore, so rolling was completed with a pneumatic roller.

In section J, used as a sidewalk for pedestrians, an attempt was made to lay a ½ inch compacted depth of ag lime mix directly on dirt. When this area was rolled with the tandem roller, the mix actually shoved ahead in large sections indicating no bond between surfacing and subgrade. When rolled with the pneumatic roller, this did not occur.

Similar mixes were laid in the area behind Building B as shown in figure 34. Here full base and surface of mixes was laid in two lifts to produce a compacted depth of pavement of 3½ inches.

Several distinct characteristics of these mixes became apparent during these paving operations. These mixes could not be rolled hot, the best rolling temperature being around 110°F. Second, it was found that the mixes could be rolled cold or at warm atmospheric temperatures when laid in 2-inch lifts. Third, that these mixes could not be rolled by a steel tandem roller when the depth was less than one inch and that pneumatic rollers, which did an excellent job, had to be used. Fourth, mixes containing the proper binder content could be handled easily and smoothly. And fifth, the limestone mixes were extremely critical of binder content; excess binder makes the mix ball up and very difficult to spread evenly.

BEHAVIOR OF THE PAVEMENTS UNDER TRAFFIC

Immediately upon opening the test roads to traffic, the weather turned very hot. During this period, the pavements were quite soft. A pebble could be pressed into the pavement by merely standing upon it and when cars stopped and parked on the pavement for a while, they left shallow tire prints. However moving traffic did not rut or shove the pavement nor did pedestrians leave heel prints. Tire prints made by parked cars were ironed out by moving traffic. It was also noticed that hair cracks made during construction healed during this period. Strangely enough, during this two weeks of extremely hot weather, with the temperature up to 95°F. during the day, this pavement was highly skid resistant and cars starting and stopping upon it did not mar its surface. After several weeks under traffic, the pavement became considerably firmer and the softness was materially reduced.

The pavements hardened materially in cold weather, and when the temperature went down to freezing, the pavement became so hard that a pebble dropped upon it, actually bounced and sounded as though it were striking a stone. Cinders carried upon the pavement from an adjacent road were pulverized by traffic. Temperatures were as low as ten degrees below zero Fahrenheit during this winter. During this period, the pavement was kept under daily observation for the development of cracks, abrasion wear and injury from tire chains and snow plowing. No cracks developed, tire chains or snow plows did not mar the surface, no abrasion wear from the use of cinders spread for ice control was noted. The pavement stood up perfectly during the winter of 1953-54.

During the spring thaws the pavement was kept under constant observation. Some alligator cracks occurred over small areas of subgrade failure due to complete absence of subgrade drainage under the pavement, but most of the settlement areas appeared in the bituminous penetration macadam area. In one or two places, the mixed pavements subsided slightly due to subgrade settlement. As warmer weather came, the pavement softened slightly.

Remembering that the mixes used in these pavements were literally designed by observation and experience and information gained from laboratory test results, it may be said that these mixes have considerable promise and give further proof of the validity of the basic concept of the mortar theory. It may also be said that ungraded aggregates can be made available for bituminous pavements on secondary roads by this method of mixing.

CONCLUSIONS

Based upon information gained from the preparation of mortars and sand mortar mixes, both in the laboratory and in small construction equipment and based upon results of laboratory tests and the behavior of such mortars and sand-mortar mixes, the following conclusions may be drawn:

1. That minute particles of mineral dust can be individually coated with very thin films of bituminous binder by the atomization method.

2. That loess suitably processed into a mineral dust can also be so coated with thin films of binder.

3. That a bituminous mortar can be produced from individual dust particles coated with a bituminous binder.

4. That loess can be easily and economically processed into a mineral dust.

5. That the normal behavior of clay in loess with relation to moisture can be neutralized by coating each particle of clay with a very thin film of bituminous binder.

6. That mixes of ungraded sands bound by a bituminous mortar possess considerable promise for use as a low-cost bituminous pavements for secondary roads.

7. That the validity of the concept of binding ungraded aggregates together by a bituminous mortar as a mixture for paving purposes has been verified.

FURTHER WORK

It has been stated that based upon the progress made during this phase of the project, the project has been extended for an additional eighteen months to June 30, 1955, to carry the work forward along the following lines:

1. Investigation of the use of a wide range of asphaltic binders, including cut-backs, direct and inverted emulsified asphalts and other liquid binders deemed advisable. Examination of the use of admixtures such as rubber and other agents which may improve desirable characteristics of the binders.

2. Development of design criteria for bituminous mixes prepared under the mortar theory, this to include mixes containing a wide range of sands together with a wide range of fine materials and of other mixes made of locally available materials.

3. Investigation of other means of applying thin films of binder in the preparation of the desired bituminous mortar, any such means that may be found promising to be developed as far as possible.

4. Application of the mortar theory to bituminous concrete mixes containing coarser aggregates readily available locally and cheaply such as small stones, soft crushed rock, gravel, and others.

5. Development of simple tests for the control and proper formation of the bituminous binder in the mixes.

6. Laying of small test pavement sections to determine construction characteristics, traffic, and weathering behavior of mixes developed in the laboratory.

ACKNOWLEDGMENTS

The execution of a project of such magnitude and scope is beyond the efforts of a single individual. It requires the team work of many persons to carry the work forward rapidly. Therefore, the author of this report takes this opportunity to extend his appreciation to those who assisted him in carrying out this work.

To Messers. Robert M. Nady and Hon Pong Fung, Research Assistants in the Engineering Experiment Station who assisted in the work of this project, I wish to extend my deepest appreciation for their diligence and assistance. Without their help, this work would not have been done as rapidly as it was. I wish also to extend my appreciation to those students who worked hard at tasks which were at times disagreeable and dirty.

My deep appreciation is extended also to Dr. G. R. Town, Associate Director of the Engineering Experiment Station, for his assistance and encouragement in making the work of this project easier and more agreeable.

I wish also to thank Mr. Mark Morris, Director of the Iowa Highway Research Board, and the members of the Board for their assistance, interest, and encouragement and for making this study possible.

My special thanks to Mr. J. R. Daugherty, County Engineer of Muscatine County, and Mr. L. Hoppock, County Engineer of Page County, for their interest, courtesy and cooperation in furnishing the sand and loess needed for the construction of the test road.

My thanks also goes to the Standard Oil Company of Indiana for furnishing the binder for these research purposes, to the Linwood Limestone Products Company of Buffalo, Iowa, for the limestone dust furnished for this work, to the Barber-Greene Company for the opportunity to test their Mixall in these operations, to the Galeon Iron Works for their courtesy and cooperation of the loan of the 3-5 ton steel tandem roller, to the Electric Vibrator Corporation for their cooperative loan of a Jackson Vibrator, to the Littleford Company for the loan of one of their 180-gallon heater kettles, to the Iowa Highway Department for the use of a pneumatic roller and to others who cooperated in this study.

With the combined help and cooperation of all these people, companies, and machines, the development of this work was possible.

REFERENCES

1. Storage of Asphalt in Laboratories, L. H. Csanyi, Proceedings Association Asphalt Paving Technologists, 1953.

2. Gussasphalt, Teer und Asphaltstrassenbau, Dr. J. Oberbach, pp. 425. Strassenbau, Chemie and Technik Verlagsgesellschafts, 1950. Heidelberg.

3. The Effect of Mixing on Asphalt Content of Paving Mixtures, L. H. Csanyi, Technical Bulletin No. 152, 1948. American Road Builder's Assoc.

4. The Effects of Asphalt Film Thickness on Paving Mixtures, L. H. Csanyi, Proceedings Association of Asphalt Paving Technologists, 1948.

5. Highway Materials, Part II Tests Sixth Ed. 1950. American Association State Highway Officials, pp. 155.

6. Laboratory Studies of Asphalt Cements, F. C. Lang and T. W. Thomas, Bulletin 15, University of Minnesota, 1939, Appendix A3c, pp. 76-79.

7. Asphalts Allied Substances, H. Abraham. Fifth Ed. 1945, D. Van Nostrand, pp. 1228-1229.

8. A Rapid Means of Determining the Constituents of Asphalts, L. H Csanyi and H. P. Fung, Proceedings Association of Asphalt Paving Technologists, 1954.

9. Papers on Wisconsin Loess of Southwestern Iowa, D. T. Davidson and Associates, Iowa State College Bulletin, Engineering Report No. 16.

10. A Bibliography of the Loess, D. T. Davidson, T. Y. Chu, J. B. Sheeler, Iowa State College Bulletin, Engineering Report No. 8.

11. The Rational Design of Asphalt Paving Mixtures, Research Series Number 1, Asphalt Institute, 1935.

12. Measurement of Maximum Theoretical Specific Gravity of a Bituminous Mixture by Solvent Immersion, P. J. Serafin, Proceedings Association Asphalt Paving Technologists, 1954.

Appendix I

Measurement of Film Thickness of Bituminous Binders on Coarse Aggregate

Knowledge of the thickness and character of the film of a bituminous binder formed on an aggregate particle can be of material importance. The thickness and character of such a film can provide information concerning some of the physical characteristics of both the binder and the aggregate, the conditions prevalent during mixing, and the uniformity of the distribution of the binder. In recognition of the value of such information, a study was undertaken to develop means by which the thickness of such films may be determined and their characteristics studied.

As the study progressed, it became apparent that a single method which is relatively simple, rapid and dependable and uses comparatively inexpensive equipment, and by which the film thickness on coarse and fine aggregates and mineral dust could be measured was practically impossible. Therefore, the study was directed first toward the development of a means of measuring the thickness of bituminous films on coarse aggregate.

The simplest way of measuring the thickness of such a film would be by direct measurement. This would require that the aggregate be split in a manner which would not affect the thickness of the film. The method developed is based on this principle.

To split the aggregate without disturbing the film, the film must be set or frozen hard and brittle. This may be achieved by placing a coated particle of aggregate in an ordinary deep freeze cabinet set to operate at 20 to 30 degrees Fahrenheit below zero. Exposure of the film to this temperature for about 1 hour will set it very hard and make it brittle. The temperature selected must give sufficient time to split the aggregate and its film before the film begins to creep.

Since a clean sharp split of the aggregate and film is necessary, many types of splitting devices were tested. The one shown in figure 35 of this appendix gave the best results. The splitting edges made of tool steel may be mounted as shown in any hydraulic press having a capacity of at least 1 ton. In mounting the splitting edges in the press, care must be exercised to assure their proper alignment or a clean break may not result. The collar shown in figure 35 prevents scatter of the particle. Tests made by splitting the hardest aggregates indicated that these could be cleanly split with less than 500 pounds of pressure by this device.

Having split the aggregate and its coating, the film thickness may now be measured directly by any microscope fitted with a measuring scale. Since a number of measurements must be made of the thickness of the film around the circumference of the split particle, it is essential that some means of supporting the particle in proper position be devised and the most rapid means of measuring the film thickness selected. Many ways of supporting the split particle were investigated. The simplest way which was completely satisfactory was to embed the particle in a shallow container filled with sand. The particle should be embedded in this support so that its split face is parallel to the flat bottom of the container, and is perpendicular to the axis of the microscope during measurements. This may be done by adjusting the plane of the split face by a steel straight edge placed across the rim of the container at several points.

The measurement of the film thickness may be made in several ways. One way is by the use of a calibrated eyepiece micrometer. Another more rapid and accurate way is by the use of a calibrated microscope screw micrometer eyepiece in conjunction with a mechanical stage. A large number of readings of film thicknesses around the periphery of the particle may be made rapidly. The microscope lights used to illuminate the specimen during these operations should be fitted with some form of heat absorbing filters or the time available for measurements will be material reduced.

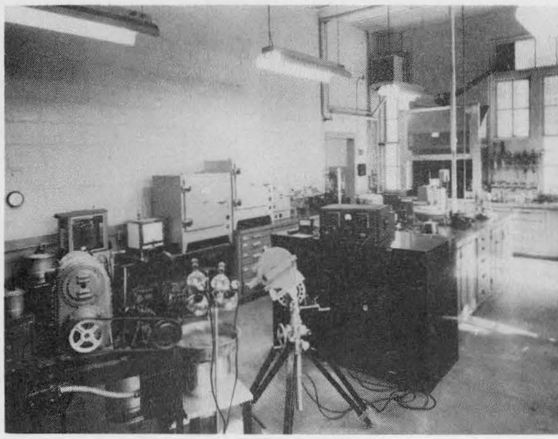
The procedure of measuring film thickness is as follows. A particle of aggregate coated with a bituminous binder, either by dipping or taken from a paving mixture, is placed in the freezer. After one hour it is removed from the freezer by a pair of long nose tweezers or tongs and is placed in the splitter and split in two. The two parts are removed carefully from the splitter with the tongs so as to not mar the film at the split edge and are placed in the sand container with split face upward. The container containing the specimens is put back into the freezer. After about 20 minutes in the freezer, the container with the specimens is removed from the freezer and the specimens are levelled. The container with the specimens is again returned to the freezer. Again after 20 minutes in the freezer, the specimens are taken out and placed on the microscope where 10 to 15 readings of film thickness are rapidly made. Readings at sections of the film disturbed by splitting edges should be avoided. If readings are taken at a time when the air is very humid, ice crystals will form on the surface of the aggregate. These may be brushed off with a fine camel hair brush. If readings are made rapidly, this need only be done once. The edge of the film must also be watched for creep. Should creep occur, further readings will be inaccurate. It may be found necessary to return the specimen to the freezer to avoid creep in making a complete series of readings.

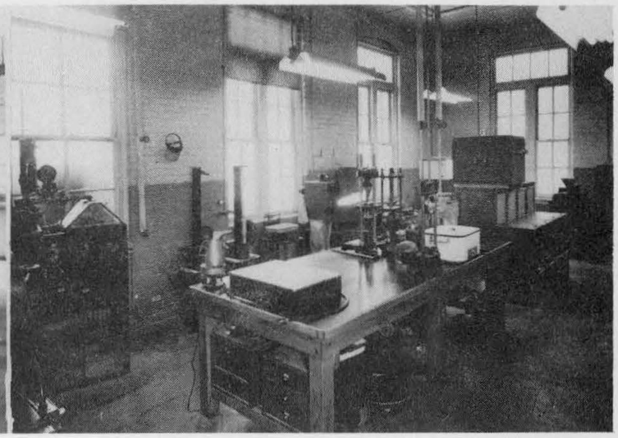
Measurement of films on smooth surface aggregates are easy because the surface of both the aggregate and film are clearly defined. Measurement of films on rough surface aggregates are more difficult. Although the surface of the film is clearly defined, the surface of the aggregate is not because the roughness is greatly magnified. In such a case, readings of thickness at ridges and in valleys of the surface should be made and averaged. Measurement of film thickness on absorbent aggregates is very difficult. This requires experience and proper adjustment of lights to define the actual film on the surface of the aggregate. In this case, however, the depth of absorption may also be measured.

After having made a series of readings of film thickness on an aggregate, these may be studied for variations, and if these are found small, the readings may be averaged.

During the study of this development, some unusual and interesting conditions were noted. When a damp or wet aggregate was coated by dipping and after draining of excess binder and subjected to measurement of film thickness by this method, it was noticed that a very thin layer of ice had formed upon the surface of the aggregate under the film. This quite clearly indicates the lack of adhesion between binder and aggregate. It was also noticed in measuring film thickness on various sizes of aggregates, that larger aggregates seemed to possess thicker films than smaller aggregates when adequate binder was present during coating.

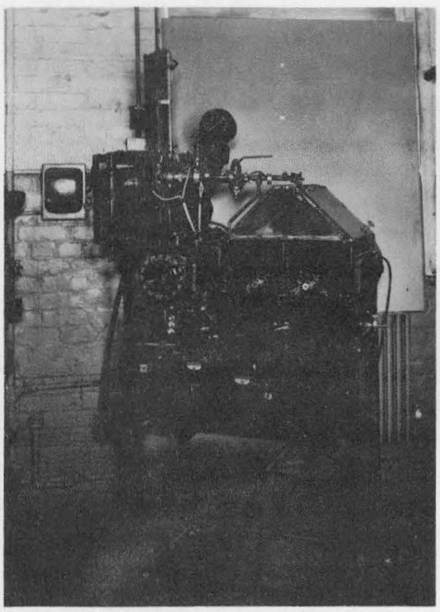
The accuracy of measuring the exact thickness of a film by this method is somewhat limited particularly on rough surfaced aggregates. The method, however, does possess an accuracy which is satisfactory for comparisons to determine the presence of excess binder, some characteristics of binder and aggregates in relation to each other, thickness of films formed by various methods of mixing and general conditions prevalent during mixing, such as cold binder or aggregate, insufficient mixing among others. The method also gives a clear index of the absorption characteristics of an aggregate with relation to various binders.



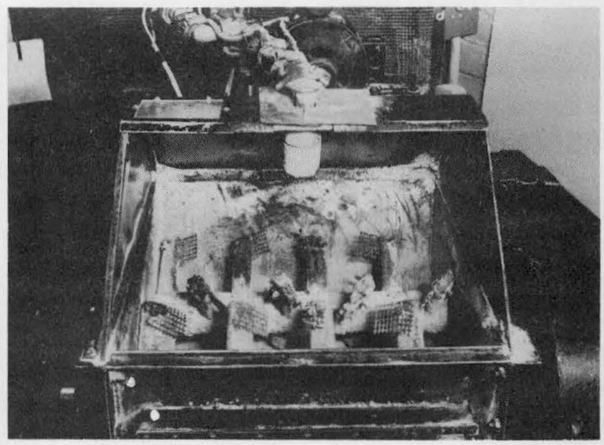


I. Fundamental and Theoretical Section of the Bituminous Research Lab.

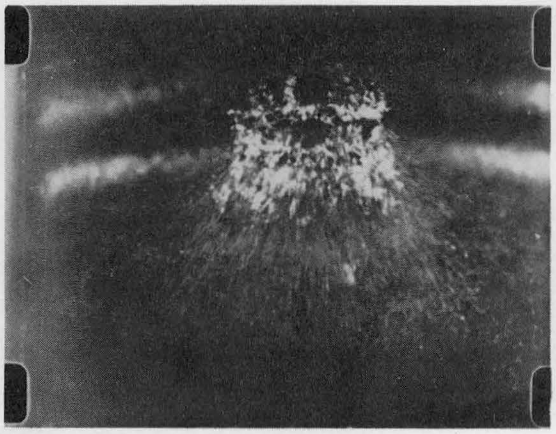
II. Practical Research Section of the Bituminous Research Laboratory.



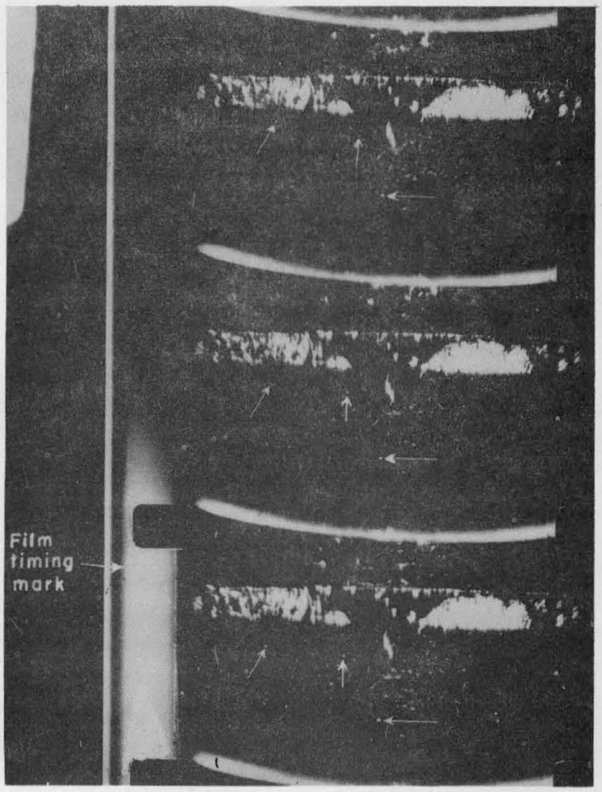
III. Laboratory Mixer adapted to atomization method.



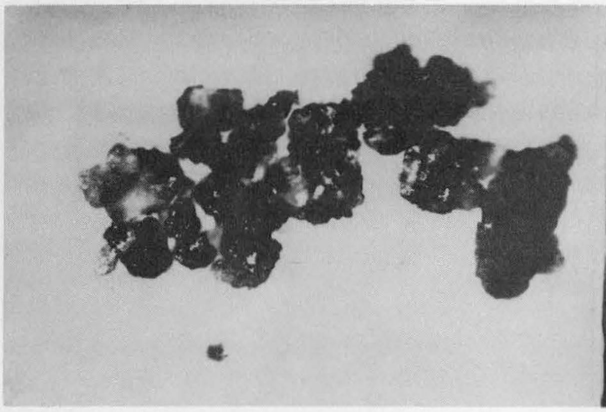
IV. Laboratory Mixer showing nozzle, mixer cover and grid paddle tips.



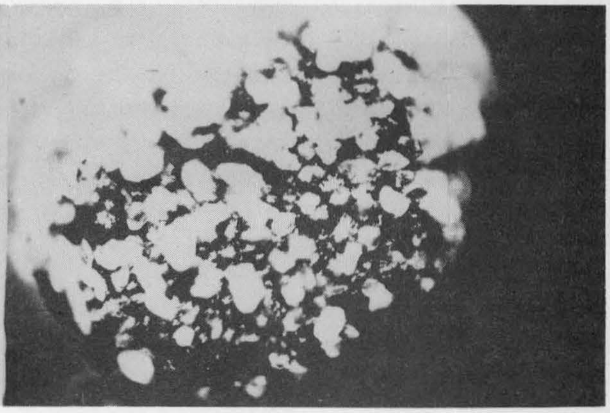
V. Atomized asphalt spray.



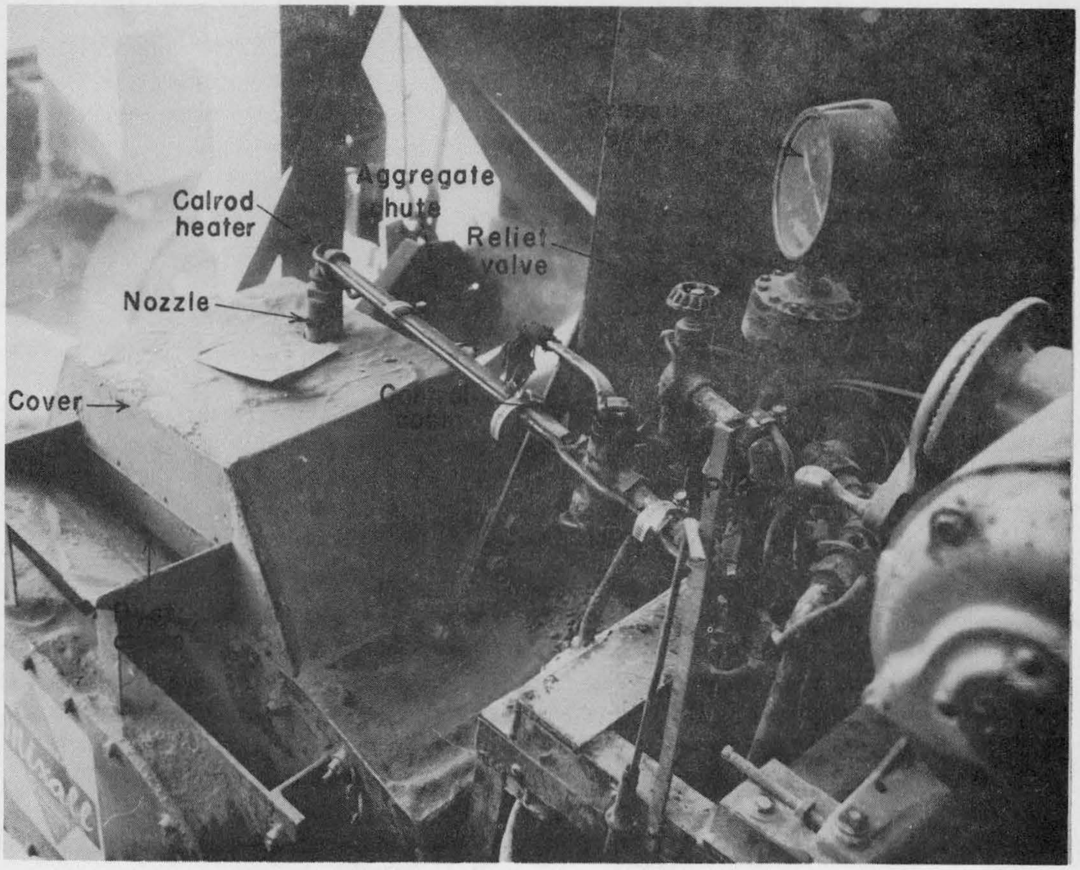
VI. High speed photographs of nozzle emanation.



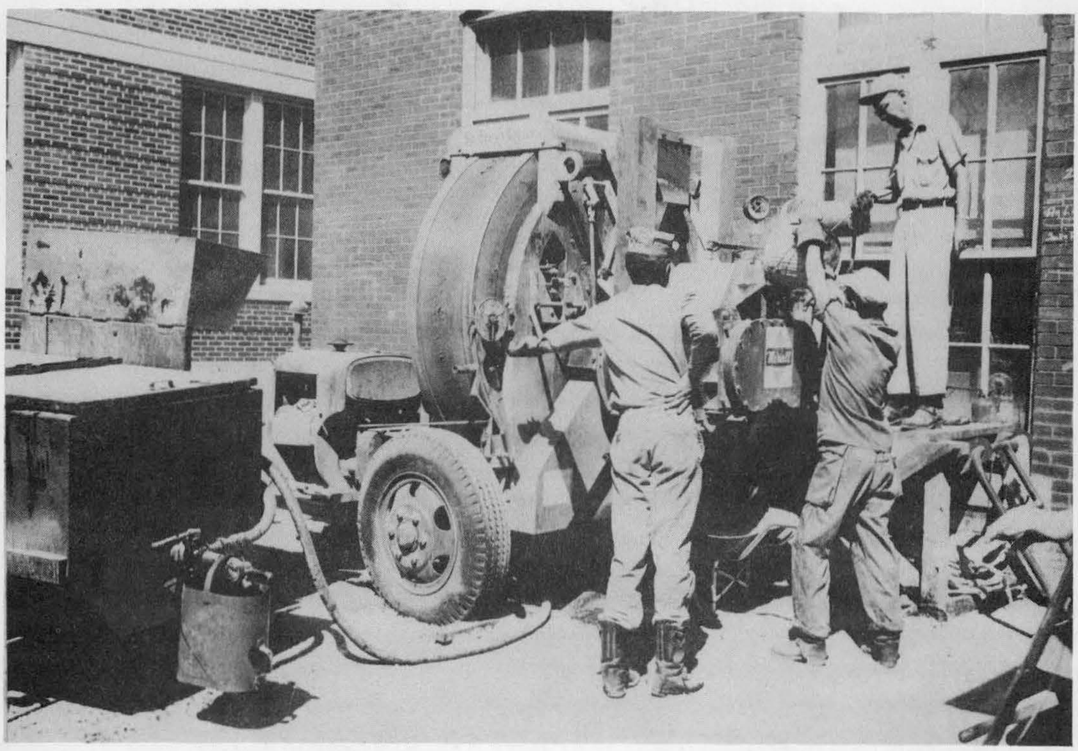
VII. Microphotograph of active mortar.



VIII. Microphotograph of inactive mortar.



IX. Atomization spray system used on B-G Mixall.



X. Operation of B-G Mixall.

Table 1. Code Designation of Materials.

Mineral Dust		Fine Aggregate		Binder	
Code No.	Description	Code No.	Description	Code No.	Description
1	Loess, Dunlap, Iowa	1	Blow Sand, Muscatine Co.	1	A.C. 200-300 pen Sugar Creek, Mo.
2	Loess, Mo. Valley, Iowa	2	Fine Sand, Muscatine Co.	2	A.C. 150-200 pen Sugar Creek, Mo.
3	Loess, Shenandoah, Iowa	3	Concrete Sand Hallett, Boone, Iowa	3	A.C. 200-300 pen Port Neches, Texas
4	Limestone Dust Milwaukee, Wisconsin	4	Concrete Sand Roberson, Ames, Iowa	9	A.C. 150-200 pen Sugar Creek, Mo.
5	Fly Ash, Louisville, Ky.	5	Plaster Sand Roberson, Ames, Iowa		
6	Hydrate Lime Buffalo, Iowa	6	Ag Lime Cooks Quarry, Ames, Ia.		
7	Limestone Dust, Buffalo, Ia.				
8	Loess, Page County, Iowa				

Table 2. Gradation Table for Fine Aggregates

No.	1	2	3	4	5	6
Description	Blow	Fine	Concrete	Concrete	Plaster	Ag Lime
% Passing #4	100.0	99.4	100.0	97.7	99.9	99.9
% Passing #10	100.0	94.0	88.8	84.9	99.4	90.0
% Passing #40	96.3	19.8	18.4	23.6	36.7	43.2
% Passing #80	14.7	2.6	3.0	2.0	3.6	28.7
% Passing #200	0.5	0.6	0.8	0.4	0.5	22.8

Table 3. Characteristics of Bituminous Materials.

Code No.	No. 1	No. 2	No. 3	No. 9	Test
Source	Standard Oil Indiana Sugar Creek, Mo.	Same as No. 1	Texaco Pt. Neches Texas	Same as No. 1	
Penetration	210	177	207	155	A.S.T.M. D5-47T
Loss on Heat %	0.04	0.02	0.01	—	A.S.T.M. D6-39T
Sp. Gr. at 77°F.	1.004	1.013	1.013	1.007	A.S.T.M. D70-27
Solubility in CCl_4 %	99.3	99.5	99.9	99.4	A.S.T.M. D165-42
Flash Point °F.	590	600	549	605	A.S.T.M. D96-46
Fire Point °F.	660	680	613	685	A.S.T.M. D96-46
Softening Point R&B °C.	40	43.5	40.5	42.5	A.S.T.M. D36-26
Viscosity at 180°F.	8000 cp	8400 cp	53,000 cp	3600 cp	Brookfield
Viscosity at 280°F.	276 cp	248 cp	540 cp	190 cp	Viscometer
Viscosity at 140°F.	—	—	—	81,880 cp	Koppers
Viscosity at 100°F.	—	—	—	3,168,800 cp	Viscometer
Asphaltene Content %	16.6	15.2	17.5	15.1	(8)
Surface Tension at 300°F.	28 dyne/cm	—	—	28.4 dyne/cm	De Nouye Surface
at 200°F.	33 "	—	—	34.9 "	Tensiometer
at 150°F.	—	—	—	50.0 "	

Table 4. Hubbard-Field Stability and Voids in Laboratory Compacted Specimens. Mortar 8.100, 9.20-25.

Asphalt Cement Content

	20%	21%	22%	23%	24%	25%
Voids %	5.5	2.1	3.8	2.3	2.2	1.3
Stability 77°F. Dry lbs.	5800	4000	2500	2000	2000	1400
Flow in.	1/4	5/16	5/16	11/32	13/32	13/32
Cracks	none	few hair	few hair	few hair	open & hair	open & hair
Separation	none	none	none	none	none	none
Swelling	none	none	none	none	none	none
Rounding	none	moderate	moderate	pronounced	pronounced	pronounced
Stability 140°F. Dry lbs.	3800	2050	1450	1100	970	540
Flow in.	1/4	1/4	1/4	5/16	11/32	3/8
Cracks	none	none	open	few hair	open & hair	open
Separation	complete	complete	complete	partial	partial	partial
Swelling	none	none	none	none	none	none
Rounding	slight	slight	slight	slight	moderate	moderate
Stability at 140°F. Wet	1900	1550	1050	780	750	500
Flow in.	5/32	7/32	7/32	9/32	9/32	5/16
Cracks	none	none	none	none	none	few open
Separation	complete	partial	complete	partial	partial	none
Swelling	slight	none	none	none	none	none
Rounding	slight	slight	slight	moderate	moderate	pronounced

Table 5. Hubbard-Field Stability and Voids in Laboratory Compacted Specimens. Mortar 8.100, 9.18-25W.

Asphalt Cement Content

	18%	20%	21%	22%	23%	24%	25%	23%*
Voids %	7.7	8.5	5.8	2.2	2.2	4.7	1.9	2.2
Stability 77°F. Dry	3800	3700	2500	2400	2200	2000	1500	2500
Flow in.	9/32	5/16	5/16	11/32	7/16	5/16	13/32	5/16
Cracks	few hair	few hair	few hair	none	hair & open	few open	open	open
Separation	none	none	none	none	none	none	none	none
Swelling	none	none	none	none	none	none	none	none
Rounding	slight	moderate	moderate	moderate	pronounced	moderate	pronounced	moderate
Stability 140°F. Dry	2600	1700	1300	1400	1000	950	750	1250
Flow in.	7/32	7/32	1/4	1/4	9/32	9/32	5/16	9/32
Cracks	hair	hair	hair	few open	hair & open	hair & open	open	open
Separation	partial	partial	complete	partial	partial	partial	partial	partial
Swelling	none	none	none	none	none	none	none	none
Rounding	slight	slight	moderate	slight	moderate	slight	slight	moderate
Stability 140°F. Wet	1600	1750	1000	1200	800	750	650	900
Flow in.	5/32	3/16	3/16	7/32	9/32	1/4	11/32	9/32
Cracks	none	none	none	none	open	few open	open	none
Separation	partial	partial	complete	partial	partial	none	none	partial
Swelling	slight	none	none	none	none	none	none	none
Rounding	slight	slight	slight	slight	moderate	moderate	slight	slight

* Cured for 28 days at room temperature.

Table 6. Freezing and Thawing Test. Loess Mortar 8.100, 9.14-25.

Volume Change % of Molded Volume

Asphalt content %	14		20		21		22		23		24		25	
Frozen or thawed	F	T	F	T	F	T	F	T	F	T	F	T	F	T
Cycle 1	6.3*	8.7°	4.7	5.5	4.2	1.6	0.4	0.4	-0.2	0.0	1.2	0.0	2.4	1.2
2	8.3		4.7	7.1*	0.7	1.6	-0.4	0.4	0.0	0.0	0.0	0.0	0.8	1.2
3			7.1°	6.3	1.2	0.8	0.0	-0.4	-0.8	-0.8	1.2	0.0	1.2	0.8
4			5.9	7.1	1.6	1.6	0.4	0.0	-0.2	-0.8	0.0	0.4	1.2	1.2
5			7.1	8.0	2.0	2.0	0.4	0.4	0.0	-0.4	0.0	0.0	2.4	1.6
6			7.6	8.4	2.0	2.8	1.2	0.4	-0.4	0.0	0.0	0.4	1.6	1.6
7			8.4	8.4	1.8	1.5	0.4	0.4	-0.4	+0.4	0.4	0.4	1.6	2.4
8			8.4	9.2	2.4	2.7	1.9	1.6	+0.8	0.4	0.8	1.2	2.4	2.4
9			9.2	10.0	2.7	2.7	1.2	1.6	0.4	0.4	0.8	1.6	2.0	2.8
10			9.2	10.0	3.2	3.2	1.9	1.9	1.2	0.8	1.6	1.2	2.8	2.8
11			9.6	10.4	3.2	3.2	1.9	1.9	0.4	0.8	1.6	0.8	2.4	2.8
12			10.4	11.2	3.2	4.0	2.0	2.0	1.2	0.0	1.2	0.8	2.8	3.2

* Surface crack.
° Edge broken.

Table 7. Freezing and Thawing Test. Loess Mortar 8.100, 9.14-25.

Moisture Content - Percent of Original Dry Weight

Asphalt content %	14		20		21		22		23		24		25	
Frozen or thawed	F	T	F	T	F	T	F	T	F	T	F	T	F	T
Cycle 1	2.5*	3.4°	1.2	1.8	0.6	0.9	0.6	0.8	0.4	0.6	0.4	0.6	0.4	0.7
2	3.4	4.3*	1.7	2.3*	0.9	1.1	0.8	1.1	0.6	0.8	0.6	0.8	0.7	0.9
3	4.3:	3.8	1.4°	1.4	1.1	1.2	1.1	1.1	0.8	0.9	0.8	0.8	0.9	1.0
4	2.8	3.1	1.3	1.7	1.1	1.4	1.1	1.3	0.9	1.0	0.8	1.0	1.0	1.1
5	2.7	2.9	1.9	1.9	1.4	1.6	1.3	1.5	1.0	1.2	1.0	1.1	1.1	1.4
6	2.9	3.2	1.8	2.2	1.6	1.8	1.5	1.7	1.2	1.3	1.1	1.2	1.4	1.5
7	2.7	2.7	2.2	2.7	1.8	2.0	1.7	1.9	1.3	1.4	1.2	1.4	1.5	1.7
8	3.0	3.3+	2.6	2.8	2.0	2.1	1.8	2.0	1.4	1.6	1.4	1.5	1.7	1.8
9	1.7	1.9	2.9	3.1	2.1	2.3	1.9	2.1	1.6	1.7	1.5	1.6	1.8	2.0
10	1.9	2.2	3.1	3.4	2.3	2.4	2.1	2.2	1.7	1.8	1.6	1.7	2.0	2.2
11	1.9	2.3	3.4	3.5	2.4	2.6	2.2	2.3	1.8	1.9	1.7	1.8	2.2	2.3
12	1.9	2.4	3.7	3.8	2.6	2.8	2.3	2.5	1.9	2.0	1.8	1.9	2.3	2.4

* Surface cracked
° Edge loosened
: Surface and sides badly cracked
+ Crumpling

Table 8. Freezing and Thawing Test. Loess Mortar 8.100, 9.18-25W.

Volume Change - Percent of Molded Volume

Asphalt content %	18		20		21		22		23		24		25	
Frozen or thawed	F	T	F	T	F	T	F	T	F	T	F	T	F	T
Cycle 1	0.7	1.4			-0.8	-0.4	-0.4	0.0	0.8	0.0	0.0	0.4	0.0	0.0
2	1.4	1.6			-0.4	0.4	0.0	0.8	0.0	-0.4	0.4	0.4	0.6	0.4
3	2.0*	2.3			2.0*	2.8	1.6	1.6	0.4	0.0	1.2	1.6	0.8	1.6
4	2.3	2.3			2.0	3.2	1.6	1.6	0.0	0.4	2.4	1.6	1.6	1.6
5	2.3	4.3			3.2	4.4	1.6*	2.3	0.4	0.0	1.2	2.4	1.2	1.6
6	4.3	4.7			4.8	4.8	1.9	1.9	0.0	0.4	2.4	2.4	2.0	2.0
7	5.1	5.9			5.2°	6.0	2.3	3.1	0.4	1.2	2.4	2.8	2.0	2.4
8	5.5	6.3			6.0+	6.7	2.7	2.7	-0.4	0.4	2.8	2.8	2.0	2.0
9	5.9°	6.7			6.8	8.8	3.5	3.5°	0.4	0.4	2.8	3.6	2.4	3.3
10	7.5	6.7			8.0	8.8	3.5	3.5	0.4	0.4	3.7	4.0	2.9	3.3
11	6.3	8.3			8.4	9.6	3.5	3.5	-0.1	-0.1	3.2	4.0	2.9	4.1
12	8.3	8.8			9.6	10.5	3.5	4.3	0.4	0.7	4.0°	4.4	3.7*	4.1

* Checked on side
° Crack on bottom
\+ Crack on top and bottom

Table 9. Freezing and Thawing Test. Loess Mortar 8.100, 9.18-25W.

Moisture Content - Percent of Original Dry Weight

Asphalt content %	18		20		21		22		23		24		25	
Frozen or thawed	F	T	F	T	F	T	F	T	F	T	F	T	F	T
Cycle 1	0.0	0.5			0.5	0.5	0.0	0.4	0.0	0.2	0.0	0.3	0.0	0.3
2	0.5	0.8			0.6	0.9	0.4	0.6	0.2	0.3	0.3	0.5	0.3	0.5
3	1.5*	1.7			1.6*	1.8	1.0	1.2	0.6	0.7	0.9	1.0	0.9	1.1
4	1.6	1.8			1.7	2.0	1.2	1.3	0.7	0.8	1.0	1.1	1.0	1.2
5	1.9	2.3			1.9	2.5	1.3*	1.6	0.8	1.0	1.1	1.4	1.2	1.5
6	2.3	2.5			2.5	2.7	1.6	1.8	1.0	1.1	1.4	1.6	1.4	1.6
7	2.6	2.8			2.8°	3.0	1.8	1.9	1.1	1.2	1.6	1.7	1.6	1.7
8	2.8	2.8			3.0+	4.2	1.9	2.0	1.2	1.4	1.7	2.0	1.7	1.9
9	3.3°	3.6			3.6	3.9	2.2	2.4°	1.4	1.5	2.0	2.1	1.9	2.1
10	3.6	3.8			3.9	4.1	2.3	2.5	1.5	1.6	2.1	2.2	2.1	2.2
11	4.0	4.4			4.2	4.7	2.5	2.8	1.5	1.7	2.2	2.5	2.2	2.5
12	4.5	4.8			4.8	5.0	2.9	3.1	1.7	1.8	2.5*	2.7	2.5*	2.6

Table 10. Hubbard-Field Stability and Voids in Laboratory Compacted Specimens. Mortar 7.100, 9.10-15W.

Asphalt Cement Content

	10%	11%	12%	13%	14%	15%
Voids %	12.3	10.5	8.2		1.6	4.4
Stability 77°F. Dry	6200	6800	7400	6900	4550	3100
Flow in.	--	9/32	9/32	1/4	9/32	5/16
Cracks	none	none	none	Hair	Few Hair	Hair
Separation	none	Complete	Complete	Partial	none	none
Swelling	none	none	none	none	none	none
Rounding	Slight	Slight	Slight	Slight	Slight	Moderate
Stability 140°F. Dry	1820	1600	2550	1850	1750	720
Flow in.	3/16	3/16	7/32	7/32	1/4	9/32
Cracks	Open	--	Open	none	Few Open	Many Open
Separation	Complete	--	Complete	Complete	Partial	Partial
Swelling	none	--	none	none	none	none
Rounding	Slight	--	Slight	Slight	Slight	Slight
Stability 140°F. Wet	2500	--	2400	2850	1750	1100
Flow in.	3/16	--	7/32	7/32	1/4	1/4
Cracks	Open	--	Few Open	none	Few Open	Open
Separation	Complete	--	Complete	Partial	Partial	none
Swelling	Slight	--	none	none	none	none
Rounding	Slight	--	Slight	Slight	Slight	Moderate

Table 11. Freezing and Thawing Test. Limestone Dust Mortar 7.100, 9.10-15W.

Volume Change - % of Molded Volume

Asphalt content %	10		11		12		13		14		15	
Frozen or thawed	F	T	F	T	F	T	F	T	F	T	F	T
Cycle 1	-0.4	-0.4	0.4	0.0	0.0	0.0	0.0	0.0	0.8	0.8	0.8	0.0
2	-0.4	-0.4	0.0	0.0	0.0	0.0	0.0	-0.4	0.8	0.8	0.4	-0.4
3	-0.8	-0.4	0.0	0.1	0.0	0.0	0.0	-0.4	0.8	0.0	0.0	0.4
4	-0.0	-0.8	0.4	-0.4	0.0	0.0	0.0	-0.4	-0.2	0.0	0.4	0.4
5	-0.8	-0.8	-0.4	-0.4	-0.4	-0.4	-0.8	-0.8	-0.4	-0.4	0.4	-0.4
6	-0.4	-0.8	-0.4	-0.4	-0.4	-0.4	-0.8	0.0	-0.4	-0.2	0.0	-0.8
7	-0.8	-0.8	-0.4	-0.4	-0.4	-0.4	-0.8	-0.8	-0.4	-0.4	-0.4	0.4
8	-0.4	-0.8	-0.8	-0.4	-0.4	-0.4	-0.8	-0.8	0.0	-0.4	0.4	0.4
9	-0.8	-0.8	-0.4	-0.0	-0.4	-0.4	-0.8	-0.4	-0.4	-0.4	0.4	0.8
10	-0.8	-1.2	-1.2	-0.8	0.0	-0.4	-0.4	0.0	-0.2	-0.4	0.4	-0.8
11	-0.8	-0.8	0.0	-0.4	-0.4	-0.4	-0.8	-1.2	-0.8	-0.4	0.4	-0.8
12	-0.8	-0.4	0.0	-0.8	-0.8	-0.8	-0.8	-1.2	-0.4	-0.8	0.8	0.8

Table 12. Freezing and Thawing Test. Limestone Dust Mortar 7.100. 9.10-15W.

Moisture Content - Percent of Original Dry Weight

Asphalt content %	10		11		12		13		14		15	
Frozen or thawed	F	T	F	T	F	T	F	T	F	T	F	T
Cycle 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.3	0.0	0.0	0.0	0.1	0.1	0.2	0.0	0.0	0.0	0.0
3	0.9	1.1	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0
4	1.1	1.3	0.2	0.3	0.1	0.2	0.1	0.1	0.1	0.1	0.0	0.0
5	1.4	1.7	0.2	0.4	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1
6	1.7	1.8	0.4	0.5	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
7	1.9	2.0	0.5	0.5	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
8	1.9	2.2	0.5	0.6	0.2	0.3	0.1	0.2	0.1	0.1	0.1	0.1
9	2.2	2.3	0.6	0.7	0.2	0.3	0.1	0.2	0.1	0.1	0.1	0.1
10	2.2	2.4	0.7	0.8	0.3	0.3	0.2	0.2	0.1	0.1	0.1	0.1
11	2.2	2.5	0.7	0.9	0.2	0.4	0.1	0.2	0.1	0.2	0.1	0.1
12	2.5	2.6	0.9	1.0	0.3	0.4	0.2	0.2	0.2	0.2	0.1	0.1

Table 13. Hubbard-Field Stability and Voids in Laboratory Compacted Specimens.
Sand Asphalt 0.0, 2.100, 1.4-8 1/2W.

Muscatine Fine Sand and 200-300 pen. A.C.

Asphalt Cement %	4	5	6	7	7 1/2	8	8 1/2
Voids %	22.2	20.7	19.0	16.2	15.8	15.0	13.6
Stability at 77°F. Dry	1350	1500	1550	1900	2250	2250	2350
Stability at 140° Dry	160	200	180	240	200	240	100

Table 14. Hubbard-Field Stability and Voids in Laboratory Compacted Specimens.
Sand Asphalt 0.0, 2.100, 2.5-10W.

Muscatine Fine Sand and 150-200 pen. A.C.

Asphalt Cement %	5	6 1/2	7	7 1/2	8 1/2	9	9 1/2	10
Voids %	21.6	19.7	17.6	18.0	14.1	13.7	11.5	10.3
Stability at 77°F.. Dry	1550	1650	1700	1700	2100	2200	2250	2300
Stability at 140°F. Dry	160	160	140	140	160	160	260	200

Table 15. Hubbard-Field Stability and Voids in Laboratory Compacted Specimens.
Sand Asphalt 0.0, 1.100, 1.4-10W.

Muscatine Blow Sand and 200-300 pen A.C.

Asphalt Cement %	4	5	6	7	8	8 1/2	9	9 1/2
Voids %	28	26	24.0	22	20	20	20	19
Stability at 77°F. Dry	1050	1150	1550	1650	1800	2200	2300	2500
Stability at 140°F. Dry	60	140	140	160	180	180	220	160

Table 16. Hubbard-Field Stability and Voids in Laboratory Compacted Specimens.
Sand Asphalt 0.0, 1.100, 2.5-10W.

Muscatine Blow Sand and 150-200 pen A.C.

Asphalt Cement %	4	5	6	7	8	8 1/2	9 1/2	10
Voids %	28.8	25.7	24.3	21.7	20.0	20.1	17.1	10.7
Stability at 77°F. Dry	1150	1550	1700	1900	2000	2050	2350	1400
Stability at 140°F. Dry	60	140	140	160	180	180	220	160

Table 17. Hubbard-Field Stability and Voids in Laboratory Compacted Specimens.
Sand Asphalt 0.0, 3.100, 3.5-10W.

Concrete Sand and 200-300 pen A.C.

Asphalt Cement %	5	6 1/2	7 1/2	8 1/2	9 1/2	10
Voids %	15.7	13.4	12.6	11.1	7.2	4.1
Stability at 77°F. Dry	2300	2450	2800	2550	2600	2900
Stability at 140°F. Dry	560	620	540	560	750	940

Table 18. Hubbard-Field Stability and Voids in Laboratory Compacted Specimens. Sand Asphalt 0.0, 4.100, 3.4-10W.

Concrete Sand and 200-300 pen A.C.

Asphalt Cement %	4 1/2	5 1/2	6 1/2	7	8	9	10
Voids %	20.5	18.1	15.7	12.8	11.2	8.8	5.2
Stability at 77°F. Dry	1950	2150	2300	2500	2650	2650	2850
Stability at 140°F. Dry	320	380	420	440	520	580	740

Table 19. Hubbard-Field Stability and Voids in Laboratory Compacted Specimens. Sand Asphalt 0.0, 5.100, 3.5-10.

Plaster Sand and 200-300 pen A.C.

Asphalt Cement %	5 1/2	6 1/2	7 1/2	8 1/2	9 1/2	10 1/2
Voids %	22.2	19.8	17.0	15.3	12.6	10.7
Stability at 77°F. Dry	1200	1250	1550	1650	1950	1900
Stability at 140°F. Dry	180	180	200	260	240	240

Table 20. Freezing and Thawing Test. Sand Asphalt Mix.

Mix.	Volume Change		Moisture Content		Remarks
	Max %	Range %	Max %	Range %	
0.0; 2.100; 3.5	- 9.8	6.6	0.7	0.5	No Failure
0.0; 2.100; 3.6	2.0	2.7	0.4	0.3	" "
0.0; 2.100; 3.7	± 0.8	1.6	0.4	0.3	" "
0.0; 2.100; 3.7	- 6.7	9.8	0.4	0.3	" "
0.0; 3.100; 3.5	- 7.3	8.9	1.5	1.3	" "
0.0; 3.100; 3.6	1.8	2.2	1.0	0.7	" "
0.0; 3.100; 3.7	- 0.8	1.2	0.7	0.5	" "
0.0; 3.100; 3.8	- 9.0	5.8	0.9	0.4	" "
0.0; 3.100; 3.9	- 0.9	1.3	0.5	0.4	" "
0.0; 3.100; 3.10	- 0.8	0.9	0.4	0.3	" "
0.0; 4.100; 3.4	- 0.4	0.8	0.6	0.3	Spalling at 6 Cycle
0.0; 4.100; 3.5	- 8.3	6.5	0.8	0.5	Cracks at 6 Cycle
0.0; 4.100; 3.6	- 1.1	1.9	0.7	0.4	Spalling at 6 Cycle
0.0; 4.100; 3.7	0.8	1.6	0.6	0.4	No Failure
0.0; 4.100; 3.8	-11.5	8.2	0.6	0.5	" "
0.0; 4.100; 3.9	1.2	1.2	0.4	0.3	" "
0.0; 4.100; 3.10	- 2.3	1.9	0.3	0.2	" "
0.0; 5.100; 1.5	- 2.7	2.7	1.1	1.0	No Failure
0.0; 5.100; 1.6	2.4	2.0	1.1	0.7	" "
0.0; 5.100; 1.7	3.1	2.3	0.8	0.7	" "
0.0; 5.100; 3.5	7.8	10.5	0.8	0.5	Cracks on Surface 1 Cycle
0.0; 5.100; 3.6	1.2	2.0	0.8	0.5	No Failure
0.0; 5.100; 3.7	2.0	1.2	0.7	0.4	" "
0.0; 5.100; 3.8	- 8.9	8.9	0.8	0.6	" "
0.0; 5.100; 3.9	1.6	2.4	0.7	0.6	" "
0.0; 5.100; 3.10	- 1.5	1.3	0.5	0.4	" "

Table 21. Ag Lime and Asphalt 0.0, 6.100, 3.5-11.

Asphalt Cement %	6	6 1/2	7	8 1/2	9 1/2	10	13
Voids %	14.8	14.3	10.9	7.9	5.4	4.0	1.2
Stability at 77°F. Dry	5600	5400	5000	5100	4750	4600	3800
Stability at 140°F. Dry		1100	1050	1450	1900	1450	1350

Table 22. Freezing and Thawing Test. Ag Lime-Asphalt Mix.

Mix.	Volume Change		Moisture Content		Remarks
	Max %	Range %	Max %	Range %	
0.0; 6.100; 3.5	-7.5	7.5	8.3	8.3	Complete Failure 4 Cycle
0.0; 6.100; 3.6	0.8	1.6	8.4	5.4	Edge Loose 7 Cy. Spalling 8 Cy. Edge
0.0; 6.100; 3.7	1.1	1.1	6.1	5.7	Spalling 9 Cy.
0.0; 6.100; 3.8	-7.8	7.8	4.5	3.4	No Failure
0.0; 6.100; 3.9	-1.5	2.3	1.4	1.1	Spalling 3 Cy.
0.0; 6.100; 3.10	5.2	2.0	2.1	1.9	No Failure
0.0; 6.100; 3.11	-2.8	2.6	0.6	0.5	" "

Table 23. Sand and Limestone Dust Mortar Mix.

Mix	Voids %	Hubbard-Field Stability lb,		Remarks
		77°F. Dry	140°F. wet	
7.10; 1.90; 2.6	20.0	1900	380	360 - 140° Dry
7.20; 1.80; 2.6	16.6	2350	580	520 - " "
7.30; 1.70; 2.6	16.2	2950	460	790 - " "
7.10; 1.90; 2.7	16.1	1800	500	
7.20; 1.80; 2.7	12.0	2500	860	
7.30; 1.70; 2.7	7.2	3000	1200	
7.10; 1.90; 2.8	14.3	1600	400	
7.20; 1.80; 2.8	8.2	2200	600	
7.30; 1.70; 2.8	4.6	3050	1700	
7.40; 1.70; 2.8	4.4	3600	1550	
7.20; 1.80; 2.9	8.7	3000	600	700 - 140°F. Dry
7.30; 1.70; 2.9	4.2	3600	1100	
7.40; 1.60; 2.9	3.7	3400	1250	1350 - " " "
7.10; 2.90; 3.5	12.7	1650	520	
7.20; 2.80; 3.5	5.4	2600	1100	
7.30; 2.70; 3.5	8.1	3000	1150	
7.10; 2.90; 3.6	11.9	1650	380	
7.20; 2.80; 3.6	5.6	2450	1000	
7.30; 2.70; 3.6	3.3	3200	1350	
7.40; 2.60; 3.6	7.2	3150	1150	
7.10; 2.90; 3.7	8.8	1800	400	
7.20; 2.80; 3.7	4.0	2000	620	
7.30; 2.70; 3.7	3.0	1650	620	High Flow Character
7.10; 2.90; 3.8	6.8	1650	54	
7.20; 2.80; 3.8	----			Mix Too Fat.
7.30; 2.70; 3.8	----			

Table 24. Sand and Limestone Dust Mortar Mix.

Mix	Voids %	Hubbard Field Stability lbs		
		77°F. Dry	140°F. Wet	
7.10; 3.90; 3.5	10.7	3400	1350	
7.20; 3.89; 3.5	8.7	4200	1650	
7.10; 3.90; 3.6	5.7	3550	1300	
7.20; 3.80; 3.6	4.8	4100	1700	
7.30; 3.70; 3.6	4.8	4300	1800	
7.10; 3.90; 3.7	6.2	3450	1350	
7.20; 3.80; 3.7	2.1	3250	1300	
7.30; 3.70; 3.7	1.3	3250	1200	
7.40; 3.60; 3.7	3.7	3850	1550	
7.10; 4.90; 3.5	6.8	3850	1400	Brittle
7.20; 4.80; 3.5	5.5	4150	1800	Brittle
7.30; 4.70; 3.5	---	----	----	Too dry to compact
7.10; 4.90; 3.6	10.7	4000	1600	
7.20; 4.80; 3.6	7.9	4700	1750	
7.30; 4.70; 3.6	3.9	4900	2100	
7.40; 4.60; 3.6	6.5	5000	2150	
7.10; 4.90; 3.7	6.1	4100	1250	
7.20; 4.80; 3.7	2.0	3550	1500	
7.30; 4.70; 3.7	2.3	3000	1200	
7.40; 4.60; 3.7	3.4	4500	1600	

Table 25. Sand and Limestone Dust Mortar Mix.

Mixes	Voids %	Hubbard-Field Stability lbs		Remarks
		77°F. Dry	140° F. Wet	
7.10; 5.90; 3.6	12.7	2650	920	
7.20; 5.80; 3.6	7.4	3400	1350	
7.30; 5.70; 3.6	7.0	3900	1600	
7.10; 5.90; 3.7	11.7	2800	700	
7.20; 5.80; 3.7	5.7	3700	1500	
7.30; 5.70; 3.7	2.7	3800	1650	
7.40; 5.60; 3.7	5.0	3850	1850	
7.10; 5.90; 3.8	6.0	2900	680	
7.20; 5.80; 3.8	2.6	2750	1050	
7.30; 5.70; 3.8	1.5	2850	1100	

Table 26. Freezing-Thawing. Sand, Limestone Dust Mortar Mix.

Mix	Volume Change		Moisture Content		Remarks
	Max %	Range %	Max %	Range %	
7.10; 1.90; 9.7	1.2	1.4	0.6	0.4	No Failure
7.20; 1.80; 9.7	1.2	1.2	0.5	0.3	" "
7.30; 1.70; 9.7	1.2	1.6	0.4	0.3	" "
7.10; 2.90; 9.5	3.8	7.6	0.4	0.3	" "
7.20; 2.80; 9.5	1.2	1.6	0.4	0.3	" "
7.30; 2.70; 9.5	0.8	1.2	0.5	0.4	Checks at 6 Cycle Porous
7.10; 2.90; 9.6	1.2	2.0	0.5	0.4	No Failure
7.20; 2.80; 9.6	1.2	2.0	0.4	0.3	" "
7.30; 2.70; 9.6	-2.7	3.1	0.3	0.2	" "
7.40; 2.60; 9.6	0.8	1.6	0.4	0.3	" "
7.10; 2.90; 9.7	1.2	2.0	0.4	0.3	Checks at 6 Cycle Porous
7.20; 2.80; 9.7	2.7	3.3	0.2	0.1	No Failure
7.30; 2.70; 9.7	2.8	2.0	0.1	0.1	" "
7.10; 2.90; 9.8	7.5	7.5	0.4	0.3	" "

Table 27. Freezing and Thawing. Sand, Limestone Dust Mortar Mix.

Mix	Volume Change		Moisture Content		Remarks
	Max %	Range %	Max %	Range %	
7.10; 2.90; 2.5W	0.8	0.8	0.6	0.4	O.K. 4 Cycles
7.20; 2.80; 2.5W	-0.8	0.8	0.3	0.2	O.K.
7.30; 2.70; 2.5W	0.8	0.8	1.7	1.6	O.K.
7.10; 2.90; 2.6W	0.8	1.2	0.3	0.2	O.K.
7.20; 2.80; 2.6W	0.4	0.4	0.2	0.2	O.K.
7.30; 2.70; 2.6W	0.4	0.4	0.3	0.2	O.K.
7.40; 2.60; 2.6W	0.4	0.4	0.9	0.8	O.K.
7.20; 2.80; 2.7W	0.9	0.4	0.1	0.1	O.K.

Table 28. Sand and Loess Mortar Mixes. 150-200 pen A.C.

Mix	Voids %	Hubbard-Field Stability lbs		Remarks
		77°F. Dry	140°F. Wet	
8.10; 1.90; 2.7	16.5	2700	500	
8.20; 1.80; 2.7	12.2	3600	850	
8.30; 1.70; 2.7	16.4	4200	Swelled	
8.10; 1.90; 2.8	17.4	2650	380	
8.20; 1.80; 2.8	13.1	3400	800	
8.30; 1.70; 2.8	12.7	4200	1100	
8.40; 1.60; 2.8	11.0	4500	Swelled	
8.10; 1.90; 2.9	13.8	3100	650	
8.20; 1.80; 2.9	10.6	3350	1100	
8.30; 1.70; 2.9	9.8	4350	1400	
8.40; 1.60; 2.9	8.4	4550	Swelled	
1.10; 2.90; 3.5	15.7	1800	480	
1.20; 2.80; 3.5	11.3	2200	840	
1.30; 2.70; 3.5	10.3	3300	720	
1.10; 2.90; 3.6	10.3	1800	580	
1.20; 2.80; 3.6	7.3	2700	920	
1.30; 2.70; 3.6	9.0	3150	800	
1.40; 2.60; 3.6	9.9	3500	Swelled	
1.10; 2.90; 3.7	6.7	2000	540	
1.20; 2.80; 3.7	3.6	2200	860	
1.30; 2.70; 3.7	4.6	2700	860	
1.40; 2.60; 3.7	8.9	3400	Swelled	

Table 29. Freezing and Thawing. Sand Loess Mortar Mix.

Mix	Volume Change		Moisture Content		Remarks
	Max %	Range %	Max %	Range %	
1.10; 2.90; 3.5	1.5	1.1	0.8	0.6	No Failure 4 Cycles
1.20; 2.80; 3.5	2.8	2.8	1.1	0.9	" " " "
1.30; 2.70; 3.5	5.6	5.2	1.6	1.4	Slight Crumbling 3rd Cycle
1.10; 2.90; 3.6	±0.4	0.8	0.7	0.6	O.K.
1.20; 2.80; 3.6	-2.8	4.0	0.8	0.7	O.K.
1.30; 2.70; 3.6	4.0	4.0	1.5	1.3	Slight Crumbling 3rd Cycle
1.10; 2.90; 3.7	-1.2	0.8	0.5	0.4	O.K.
1.20; 2.80; 3.7	0.8	0.8	0.5	0.4	O.K.
1.30; 2.80; 3.7					

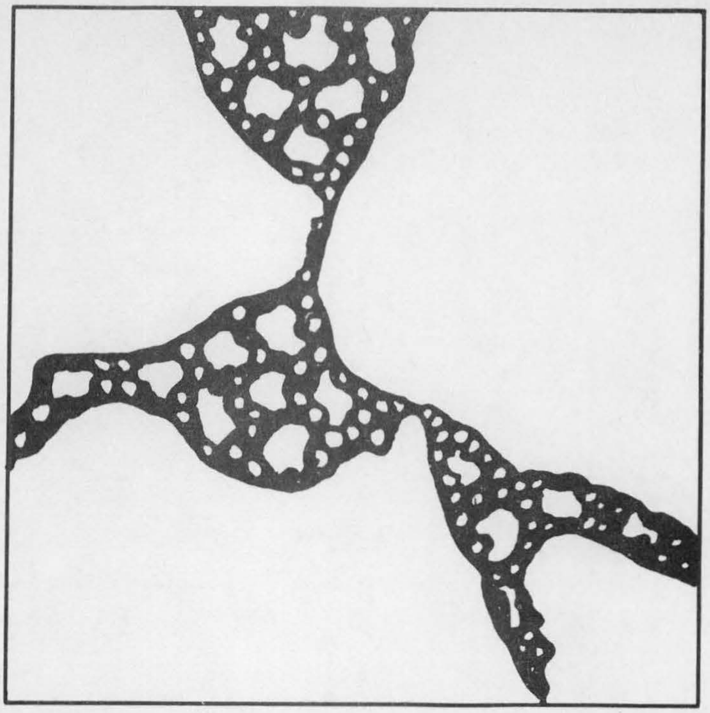


Fig. 1. Cross section of mat designed by conventional practice

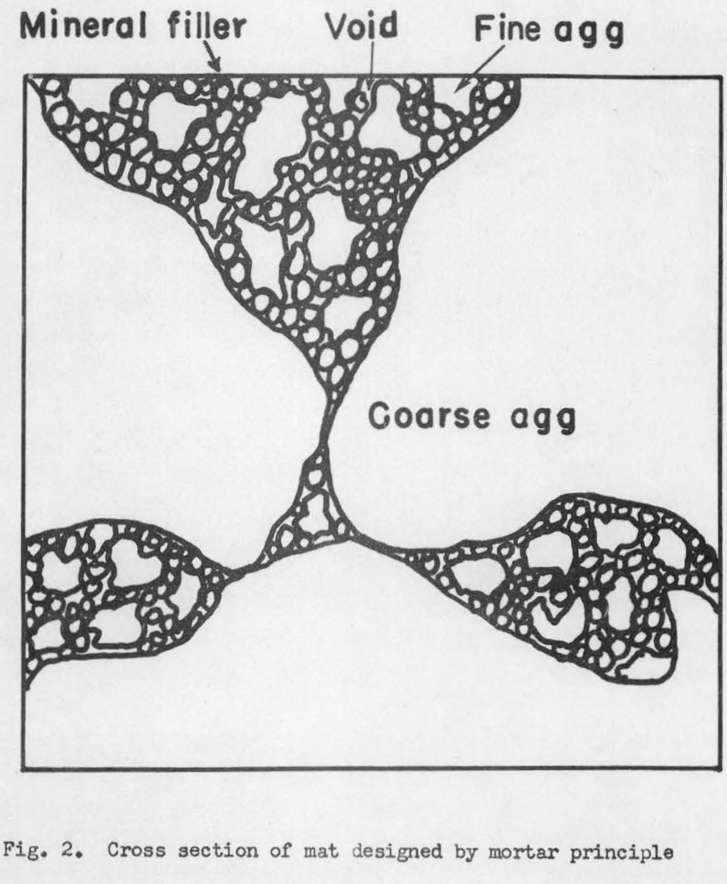


Fig. 2. Cross section of mat designed by mortar principle

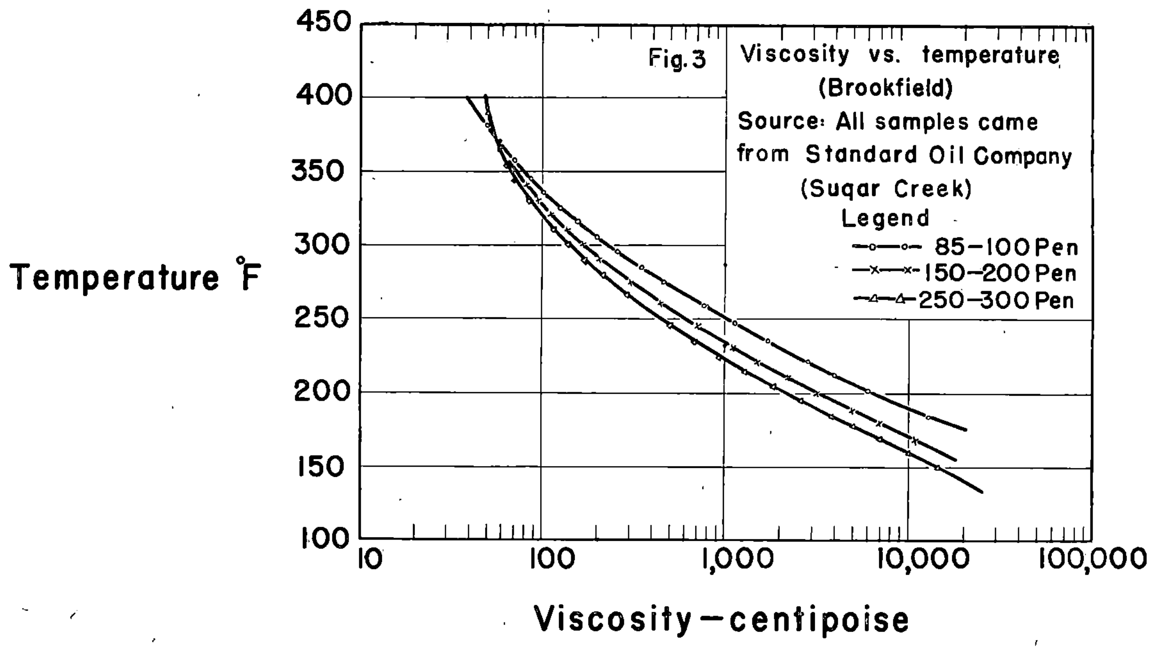


Fig. 3
Viscosity vs. temperature (Brookfield)
Source: All samples came from Standard Oil Company (Sugar Creek)
Legend
85–100 Pen
150–200 Pen
250–300 Pen
Temperature °F
450
400
350
300
250
200
150
100
10
100
1,000
10,000
100,000
Viscosity—centipoise

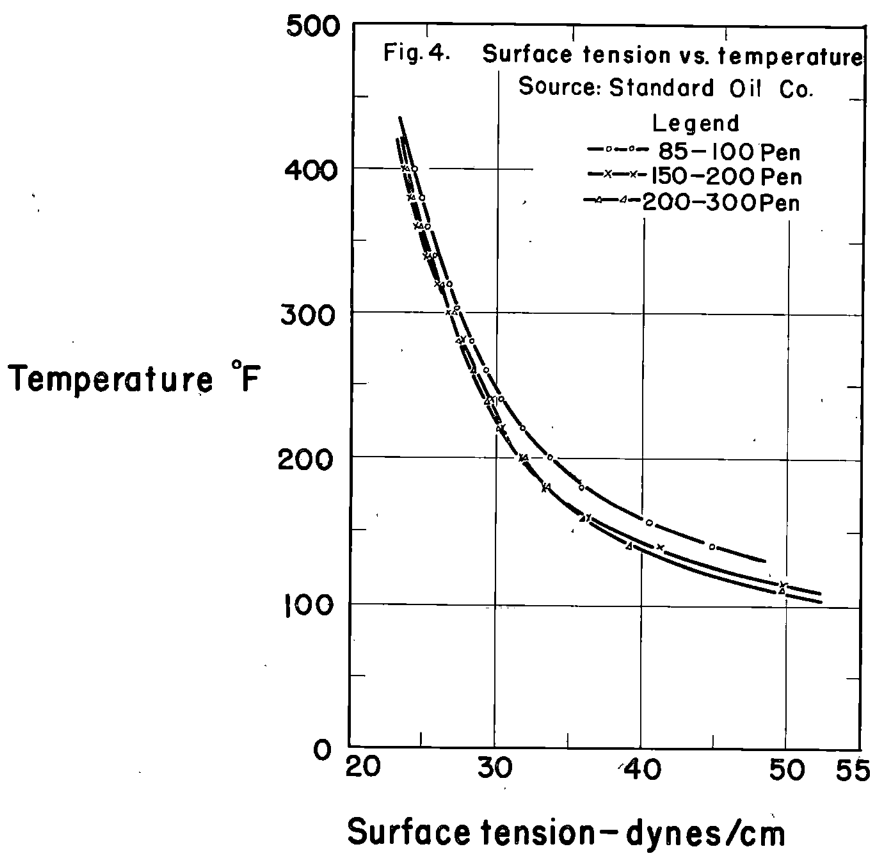


Fig. 4. Surface tension vs. temperature
Source: Standard Oil Co.
Legend
85–100 Pen
150–200 Pen
200–300 Pen
Temperature °F
500
400
300
200
100
0
20
30
40
50
55
Surface tension—dynes/cm

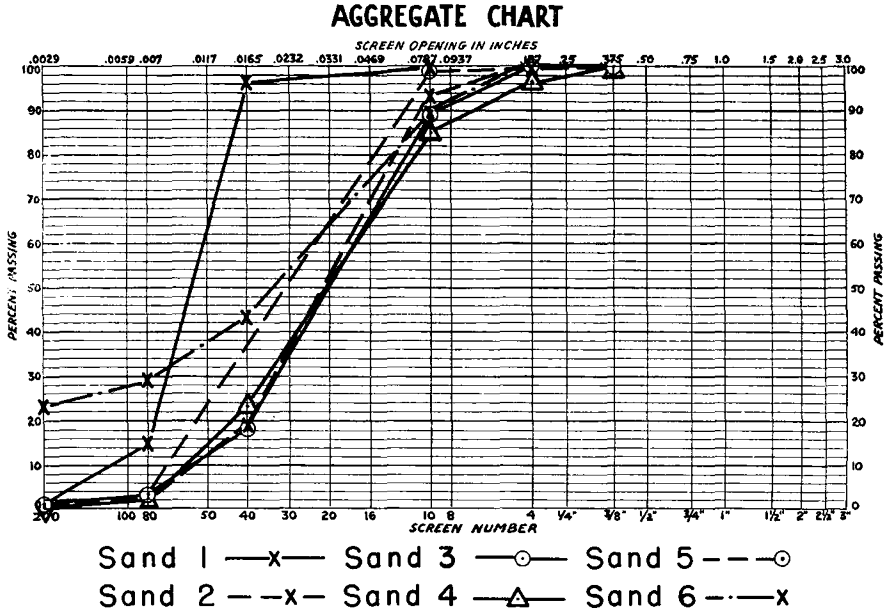


Fig. 5

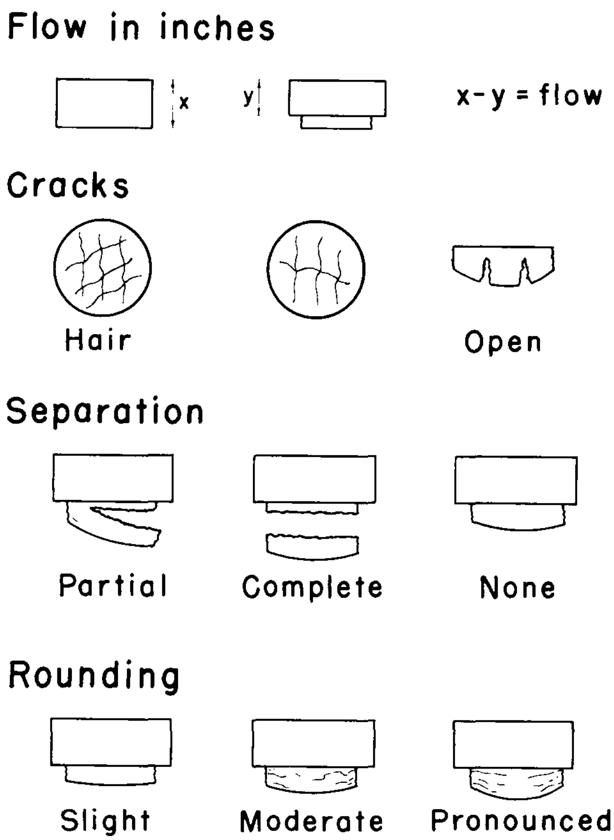


Fig. 6. Characteristics of extruded portion of specimen in Hubbard field stability test.

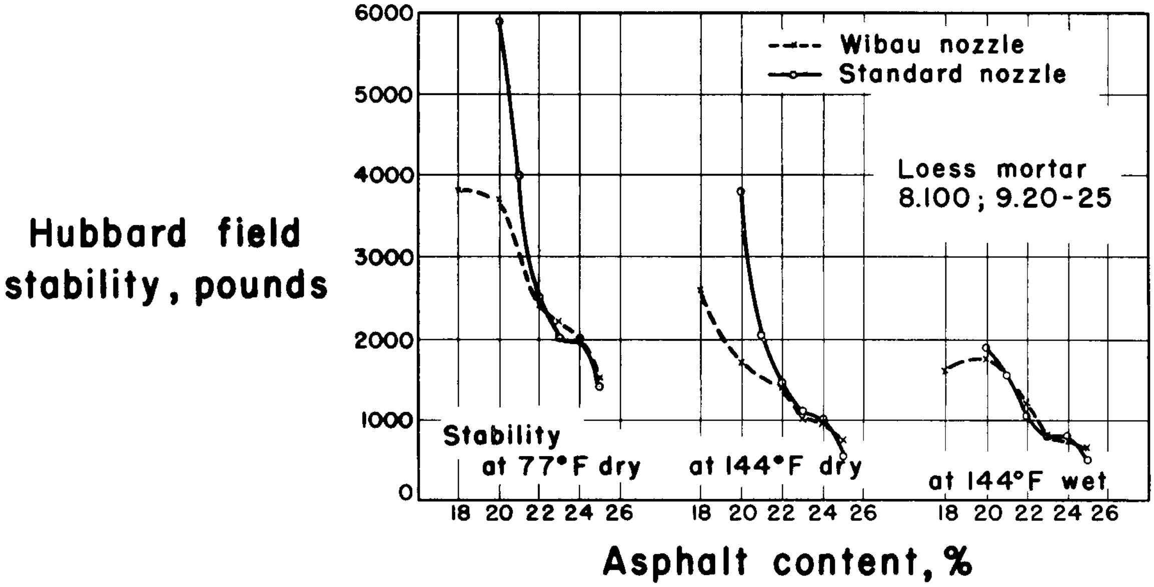

Hubbard field stability, pounds
6000
5000
4000
3000
2000
1000
0
Wibau nozzle
Standard nozzle
Loess mortar
8.100; 9.20-25
Stability
at 77°F dry
at 144°F dry
at 144°F wet
18 20 22 24 26
18 20 22 24 26
18 20 22 24 26
Asphalt content, %

Fig. 7

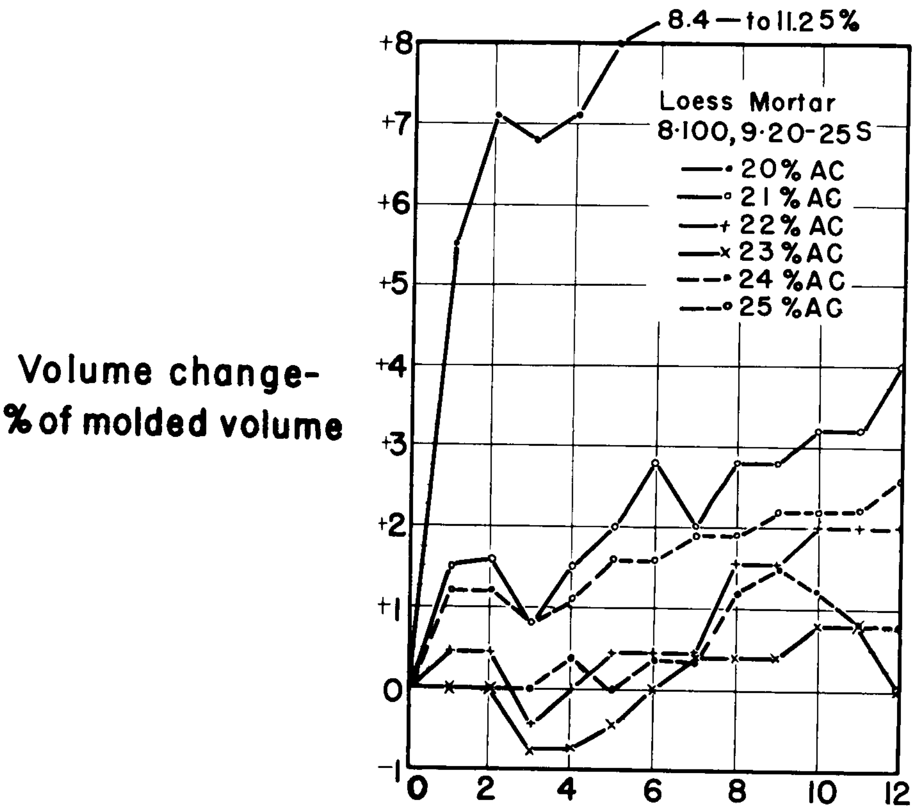

8.4—to 11.25%
Volume change-
% of molded volume
+8
+7
+6
+5
+4
+3
+2
+1
0
-1
Loess Mortar
8·100, 9·20-25S
20% AC
21 % AC
22% AC
23 %AC
24 %AC
25 %AC
0 2 4 6 8 10 12
Freeze-thaw cycles

Fig. 8

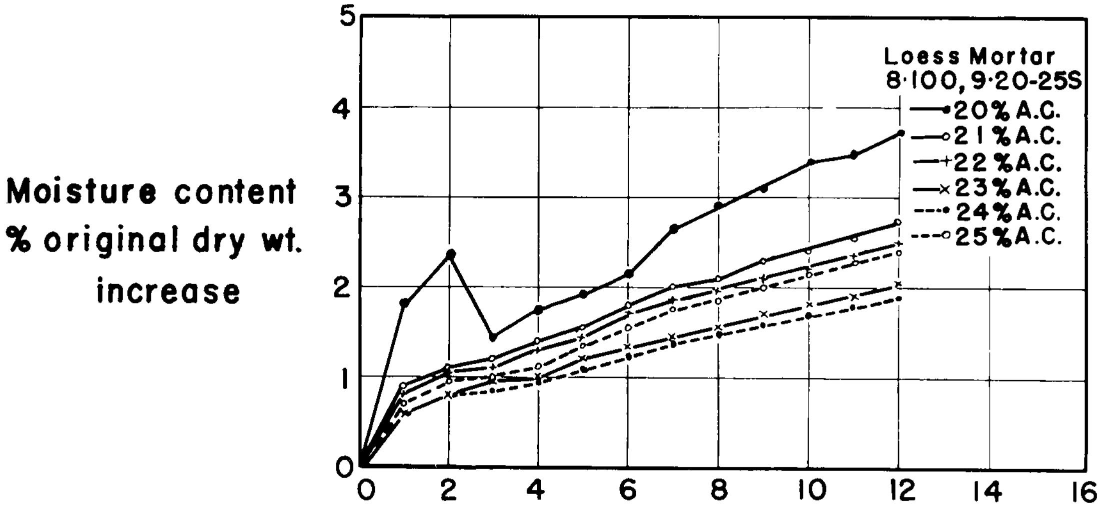

Loess Mortar
8·100, 9·20-25S
20% A.C.
21% A.C.
22% A.C.
23% A.C.
24% A.C.
25% A.C.
Moisture content
% original dry wt.
increase
Freeze-thaw cycles

Fig. 9

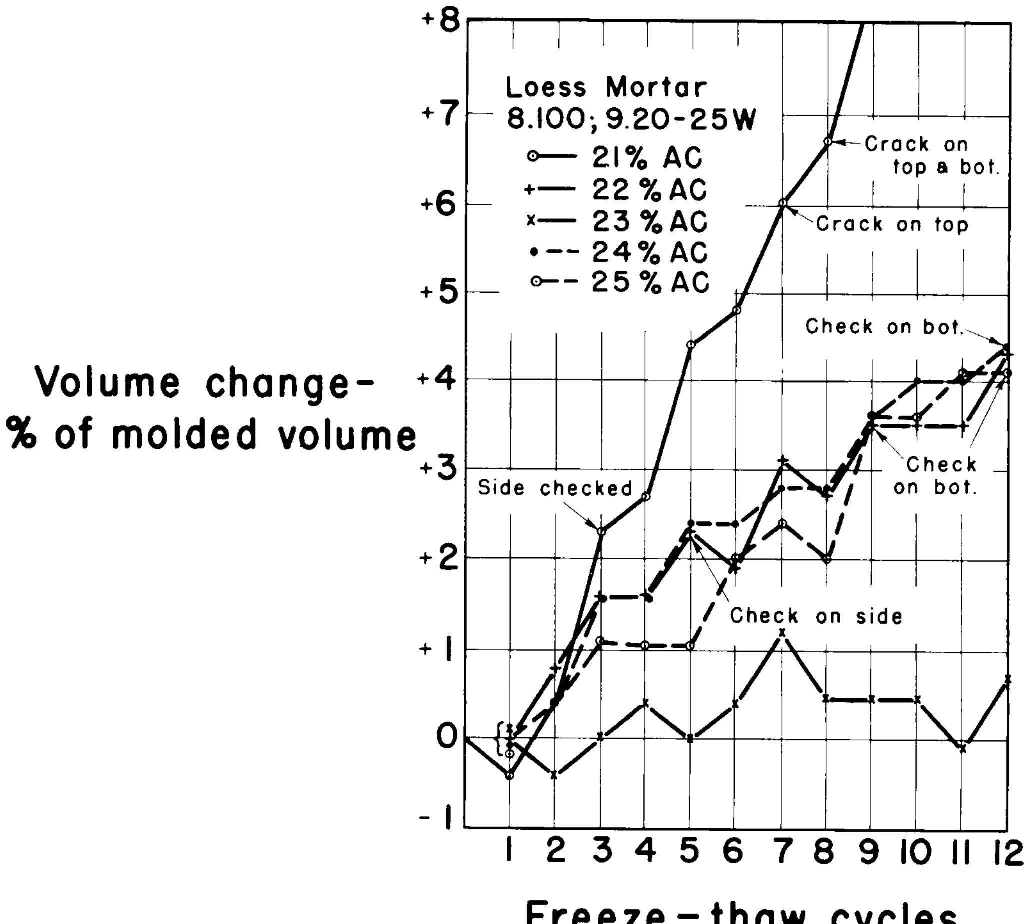

Loess Mortar
8.100; 9.20-25W
21% AC
22% AC
23% AC
24% AC
25% AC
Crack on top & bot.
Crack on top
Check on bot.
Check on bot.
Side checked
Check on side
Volume change-
% of molded volume
Freeze-thaw cycles

Fig. 10

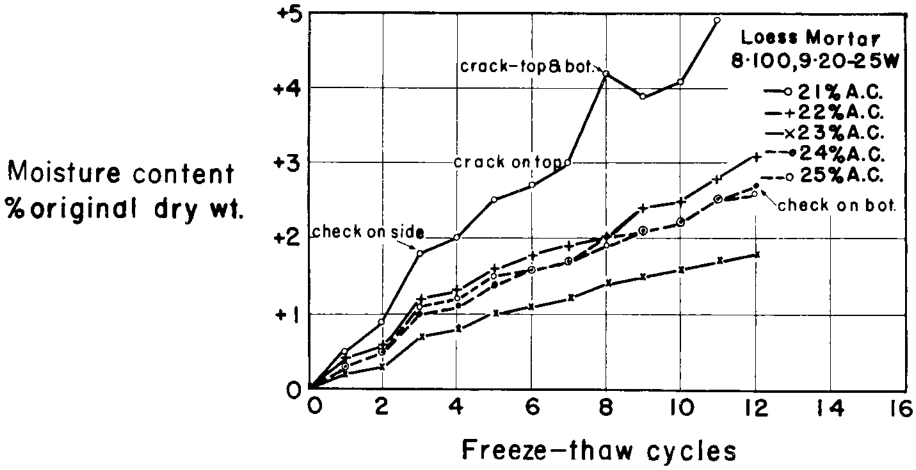


Fig.11.

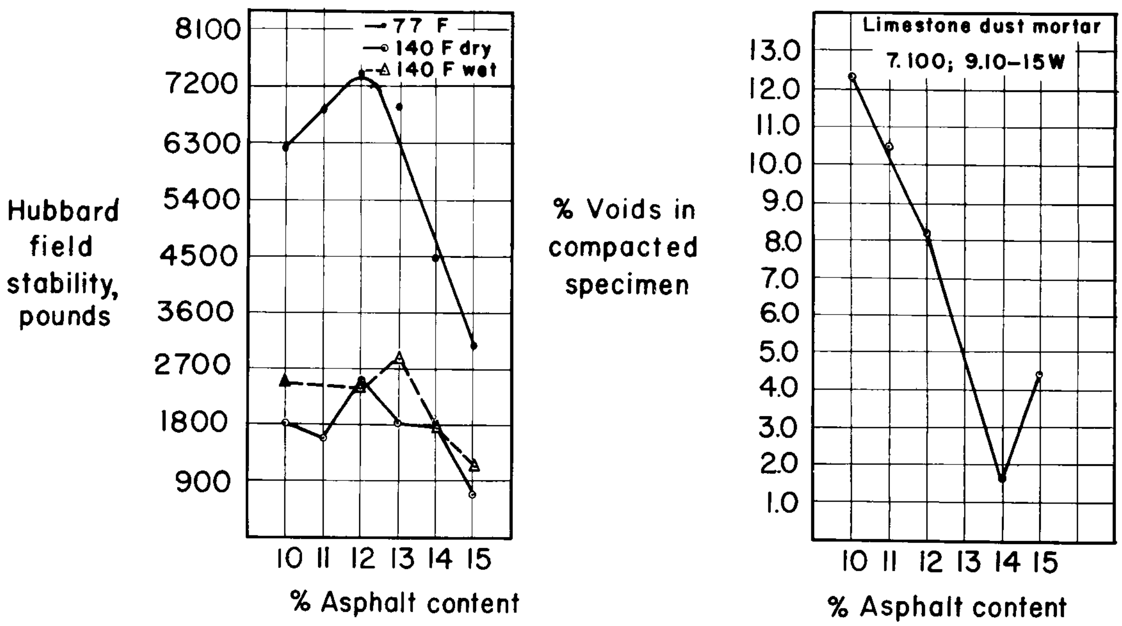


Fig.12

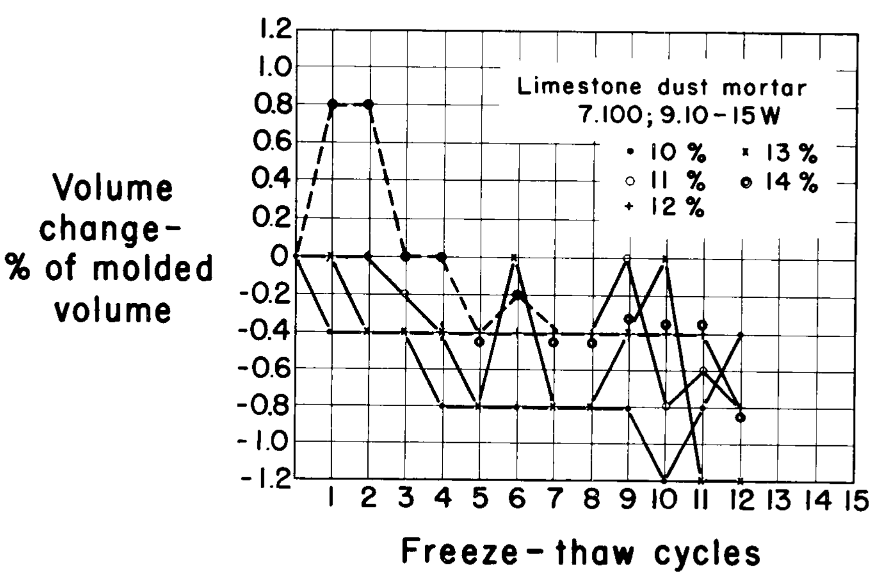


Fig. 13

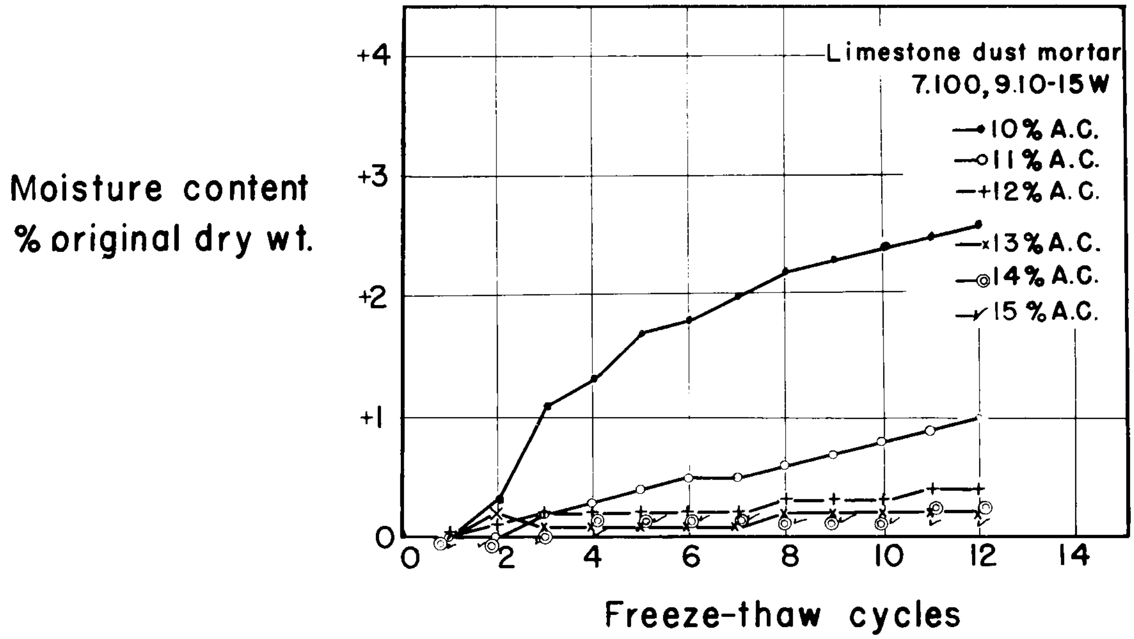

Moisture content
% original dry wt.
Limestone dust mortar
7.100, 9.10-15W
10% A.C.
11% A.C.
12% A.C.
13% A.C.
14% A.C.
15% A.C.
+4
+3
+2
+1
0
0
2
4
6
8
10
12
14
Freeze-thaw cycles

Fig. 14.

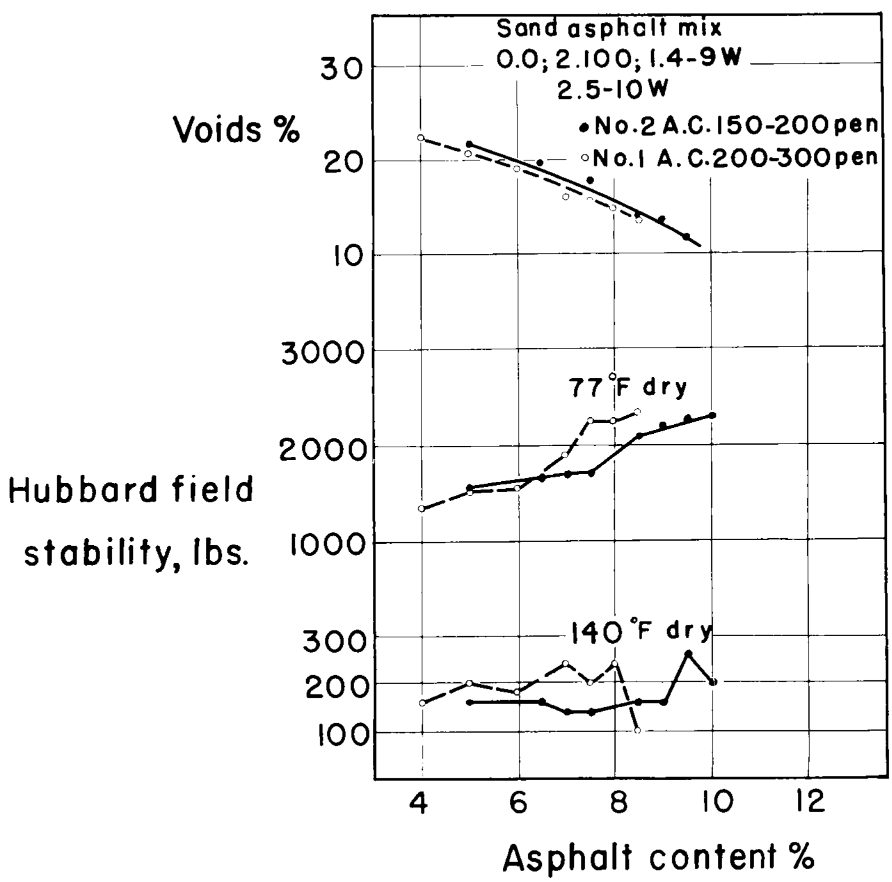

Sand asphalt mix
0.0; 2.100; 1.4-9W
2.5-10W
No.2 A.C. 150-200 pen
No.1 A.C. 200-300 pen
Voids %
30
20
10
Hubbard field
stability, lbs.
3000
2000
1000
77°F dry
140°F dry
300
200
100
4
6
8
10
12
Asphalt content %

Fig. 15.

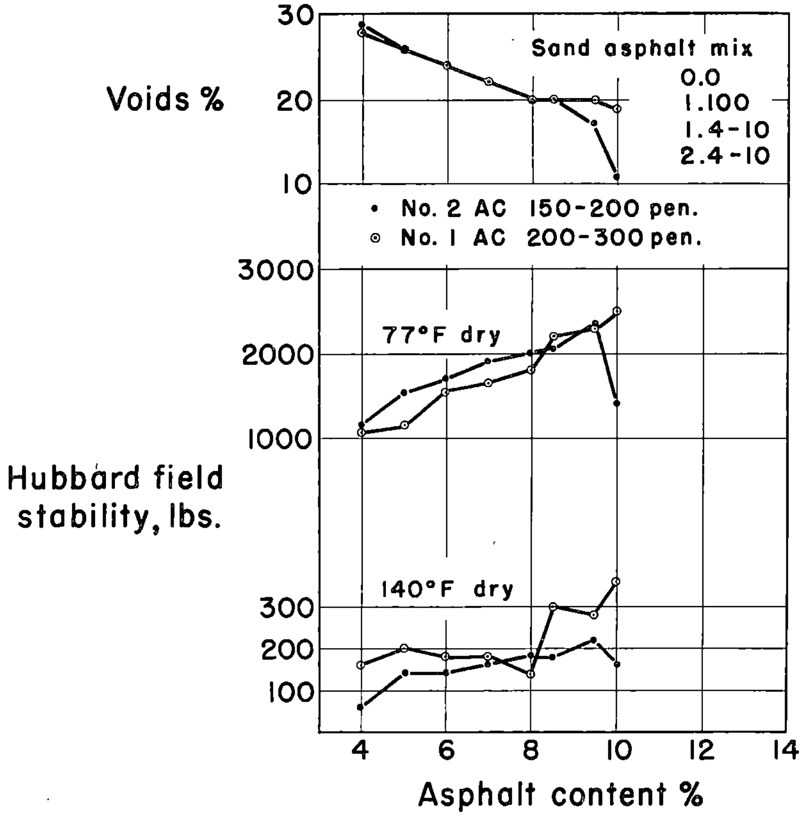

Voids %
30
20
10
Sand asphalt mix
0.0
1.100
1.4-10
2.4-10
• No. 2 AC 150-200 pen.
⊙ No. 1 AC 200-300 pen.
3000
2000
1000
77°F dry
Hubbard field stability, lbs.
140°F dry
300
200
100
4
6
8
10
12
14
Asphalt content %

Fig. 16

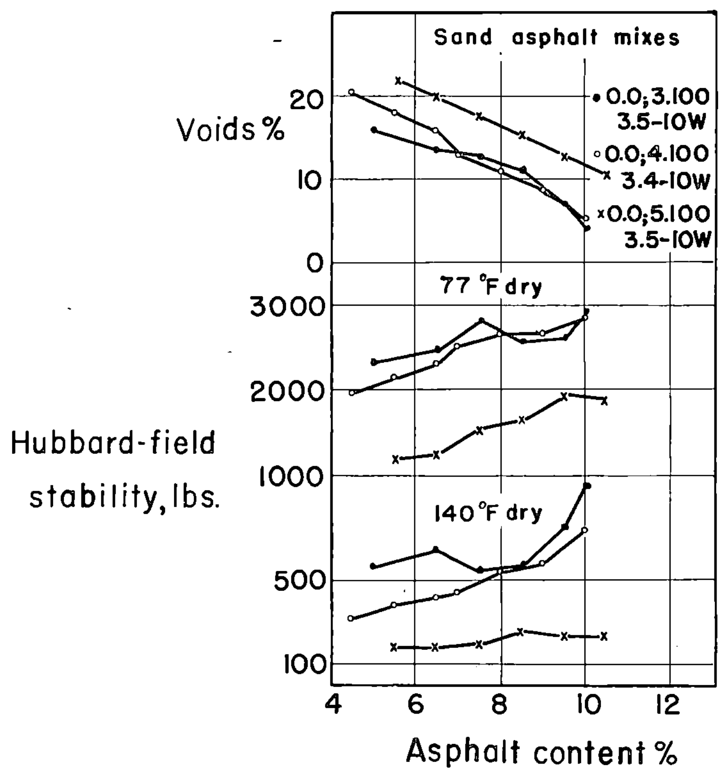

Sand asphalt mixes
Voids %
20
10
0
• 0.0;3.100 3.5-10W
◦ 0.0;4.100 3.4-10W
× 0.0;5.100 3.5-10W
77 °F dry
3000
2000
1000
Hubbard-field stability, lbs.
140 °F dry
500
100
4
6
8
10
12
Asphalt content %

Fig. 17

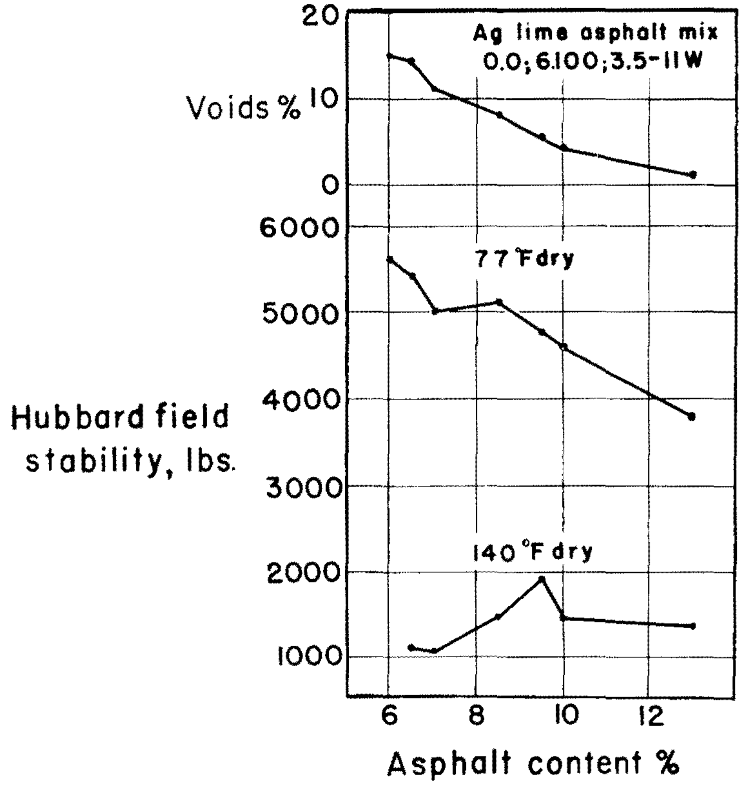

Ag lime asphalt mix
0.0; 6.100; 3.5-11W
Voids %
20
10
0
6000
5000
4000
3000
2000
1000
77°F dry
140°F dry
Hubbard field
stability, lbs.
6
8
10
12
Asphalt content %

Fig. 18

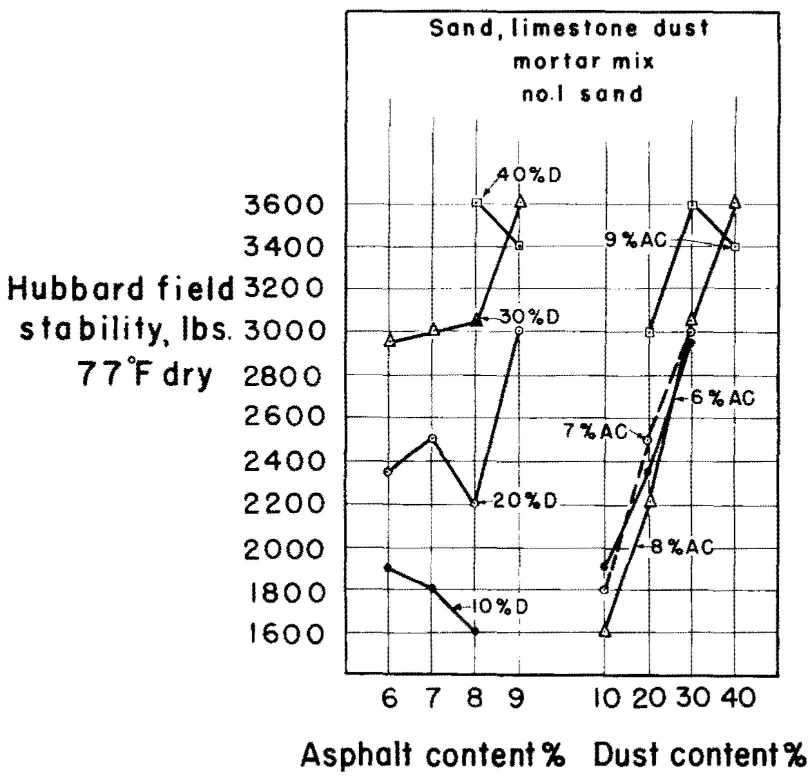

Sand, limestone dust
mortar mix
no.1 sand
Hubbard field
stability, lbs.
77°F dry
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
40%D
30%D
20%D
10%D
9%AC
6%AC
7%AC
8%AC
6 7 8 9
10 20 30 40
Asphalt content %
Dust content %

Fig.19.

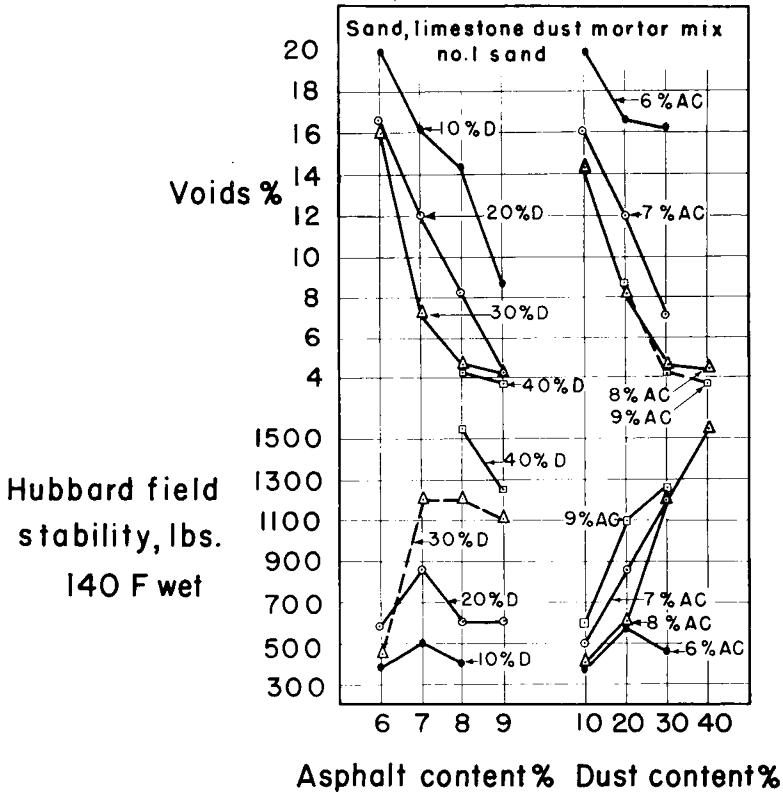

Sand, limestone dust mortar mix
no. I sand
Voids %
20
18
16
14
12
10
8
6
4
10 %D
20%D
30%D
40%D
6 %AC
7 %AC
8% AC
9% AC
Hubbard field
stability, lbs.
140 F wet
1500
1300
1100
900
700
500
300
40% D
30%D
20%D
10%D
9%AC
7 %AC
8 %AC
6%AC
6 7 8 9
10 20 30 40
Asphalt content% Dust content%

Fig.20.

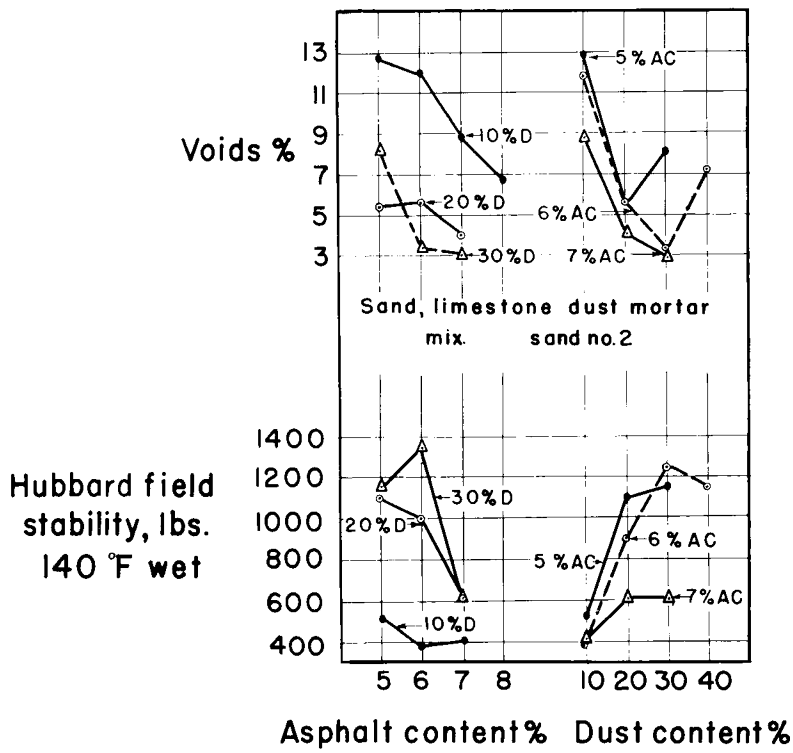

Voids %
13
11
9
7
5
3
10%D
20%D
30%D
5 %AC
6% AC
7%AC
Sand, limestone dust mortar
mix. sand no. 2
Hubbard field
stability, lbs.
140 °F wet
1400
1200
1000
800
600
400
30%D
20%D
10%D
5 %AC
6 %AC
7%AC
5 6 7 8
10 20 30 40
Asphalt content% Dust content%

Fig.21

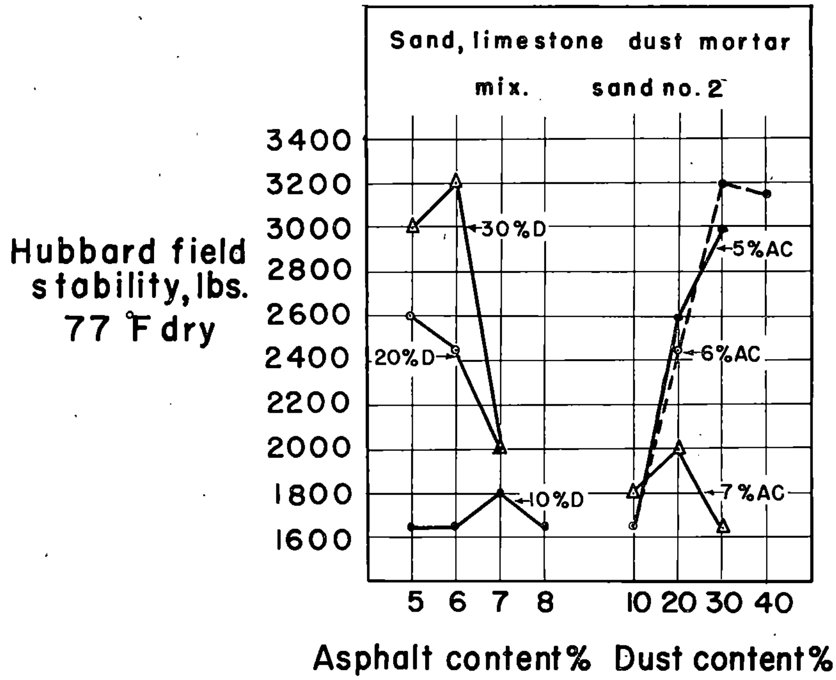

Sand, limestone dust mortar
mix. sand no. 2
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
Hubbard field stability, lbs. 77 °F dry
30%D
20%D
10%D
5%AC
6%AC
7%AC
5 6 7 8
10 20 30 40
Asphalt content% Dust content%

Fig. 22.

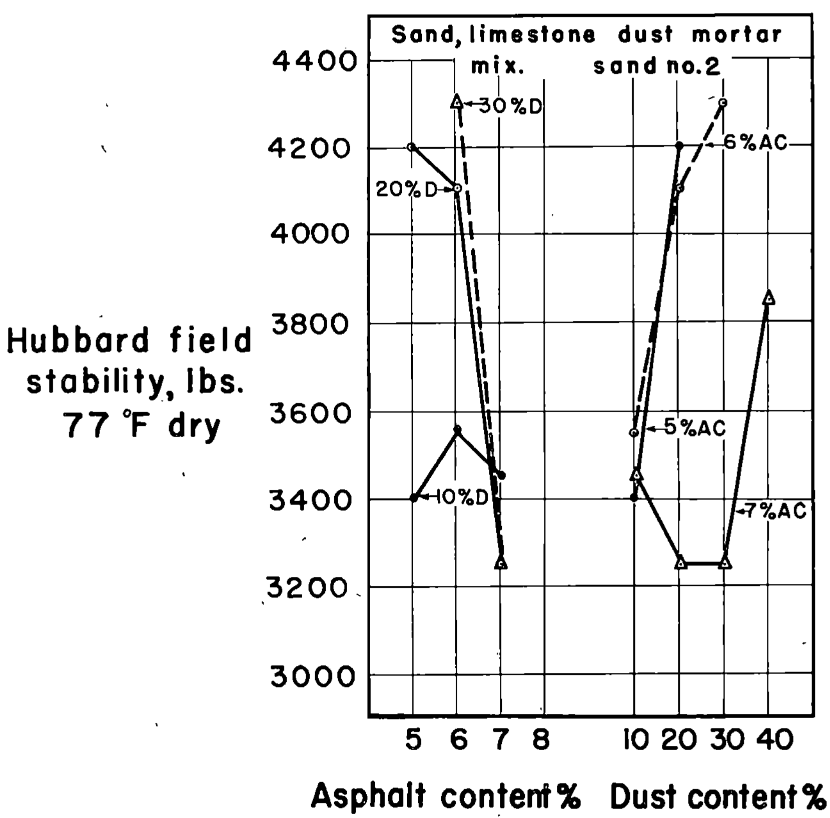

Sand, limestone dust mortar
mix. sand no. 2
4400
4200
4000
3800
3600
3400
3200
3000
Hubbard field stability, lbs. 77 °F dry
30%D
20%D
10%D
6%AC
5%AC
7%AC
5 6 7 8
10 20 30 40
Asphalt content% Dust content%

Fig. 23

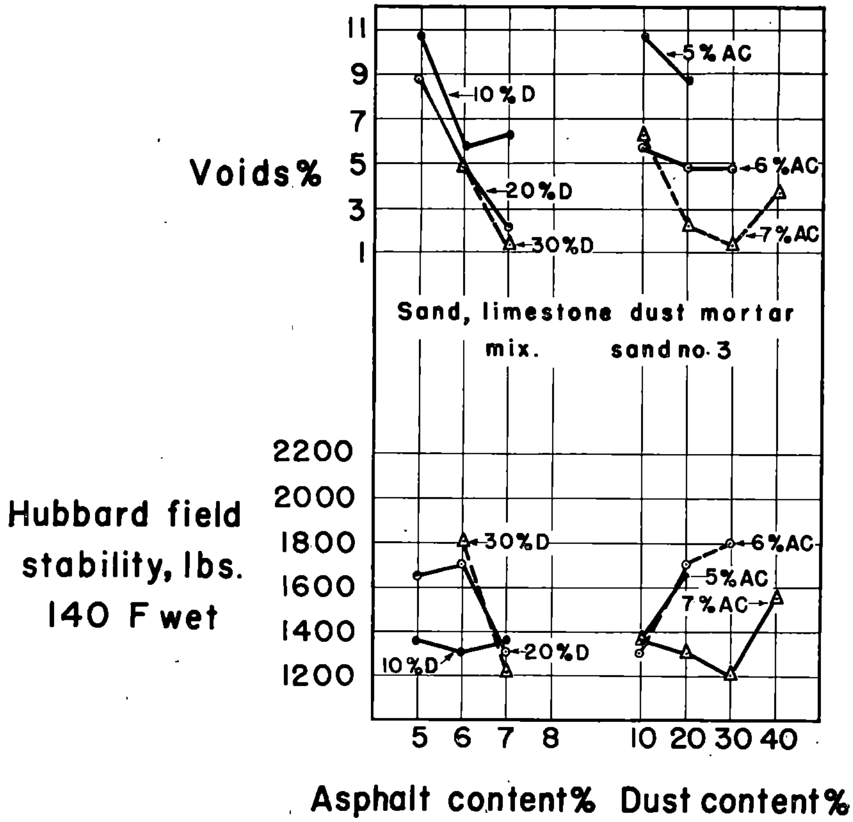

Voids%
11
9
7
5
3
1
10% D
20%D
30%D
5% AC
6 %AC
7%AC
Sand, limestone dust mortar mix. sand no. 3
Hubbard field stability, lbs. 140 F wet
2200
2000
1800
1600
1400
1200
30%D
10%D
20%D
6%AC
5%AC
7%AC
5 6 7 8
10 20 30 40
Asphalt content% Dust content%

Fig.24.

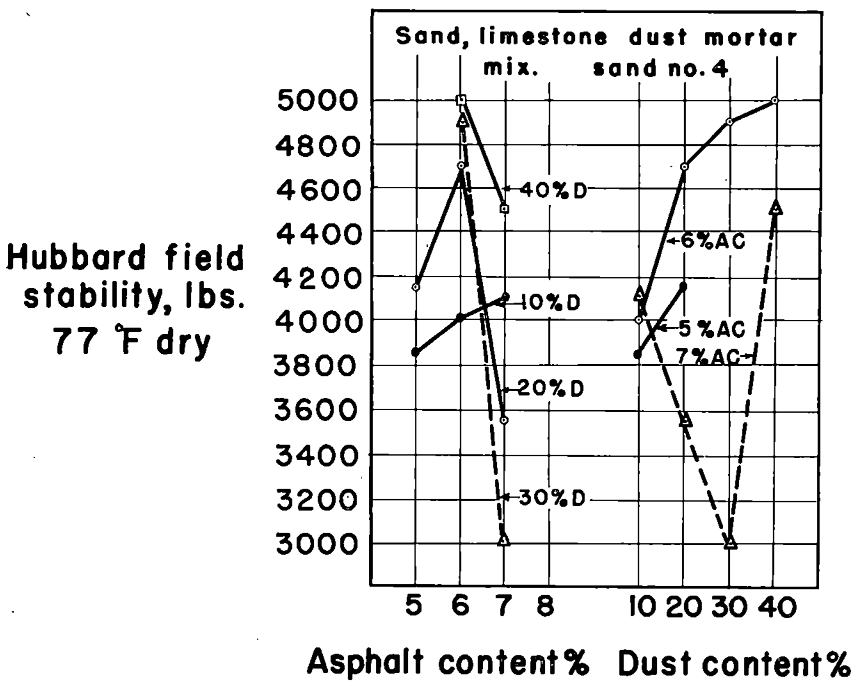
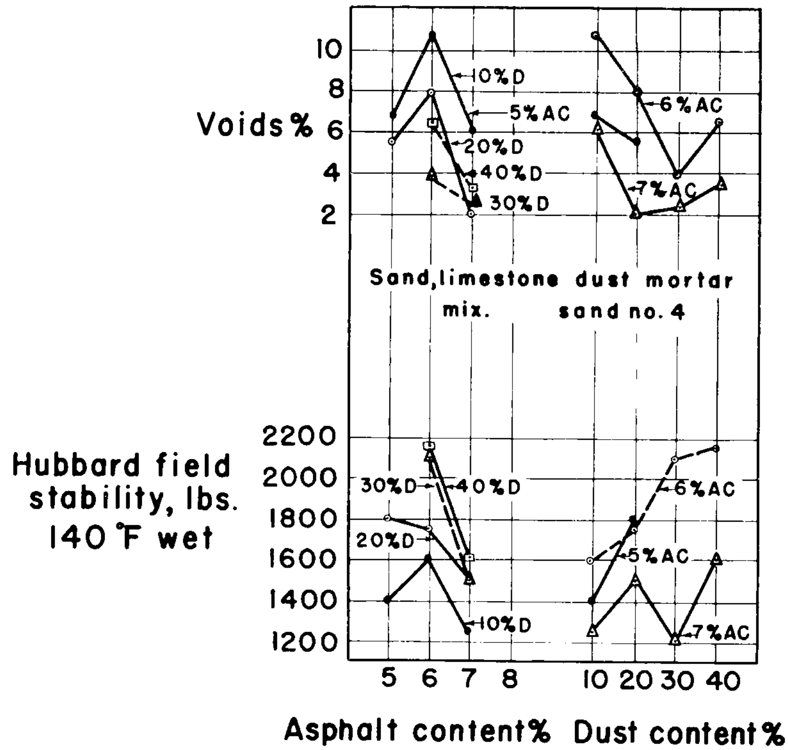
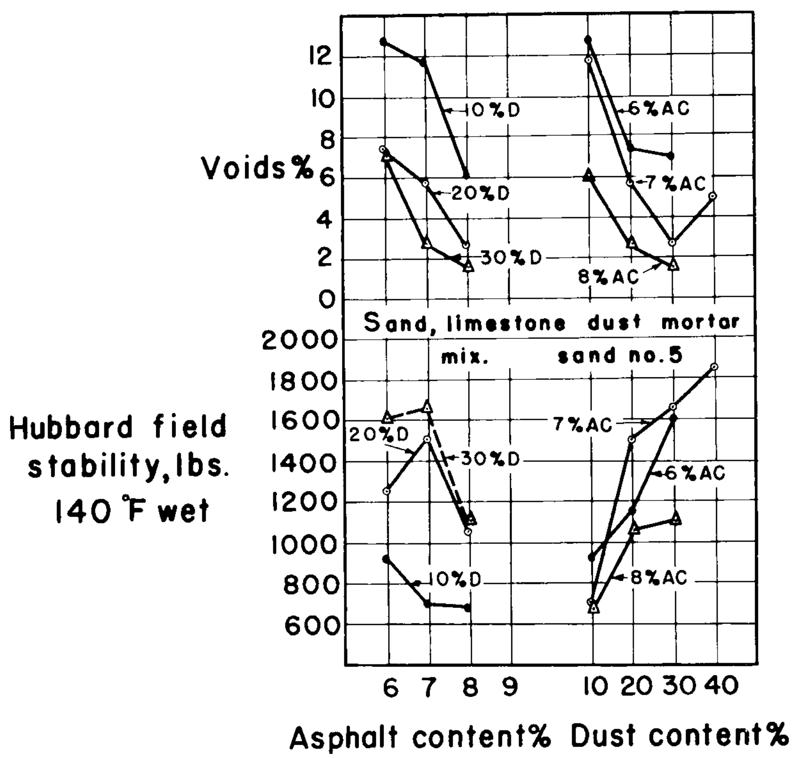

Sand, limestone dust mortar mix. sand no. 4
Hubbard field stability, lbs. 77 °F dry
5000
4800
4600
4400
4200
4000
3800
3600
3400
3200
3000
40%D
10%D
20%D
30%D
6%AC
5 %AC
7%AC
5 6 7 8
10 20 30 40
Asphalt content% Dust content%

Fig.25



Voids %
10
8
6
4
2
10%D
5%AC
20%D
40%D
30%D
6%AC
7%AC
Sand, limestone dust mortar mix. sand no. 4
Hubbard field stability, lbs. 140 °F wet
2200
2000
1800
1600
1400
1200
30%D
40%D
20%D
10%D
6%AC
5%AC
7%AC
5 6 7 8
10 20 30 40
Asphalt content%
Dust content%

Fig.26



Voids %
12
10
8
6
4
2
0
10%D
20%D
30%D
6%AC
7%AC
8%AC
Sand, limestone dust mortar mix. sand no. 5
Hubbard field stability, lbs. 140 °F wet
2000
1800
1600
1400
1200
1000
800
600
20%D
30%D
10%D
7%AC
6%AC
8%AC
6 7 8 9
10 20 30 40
Asphalt content%
Dust content%

Fig.27

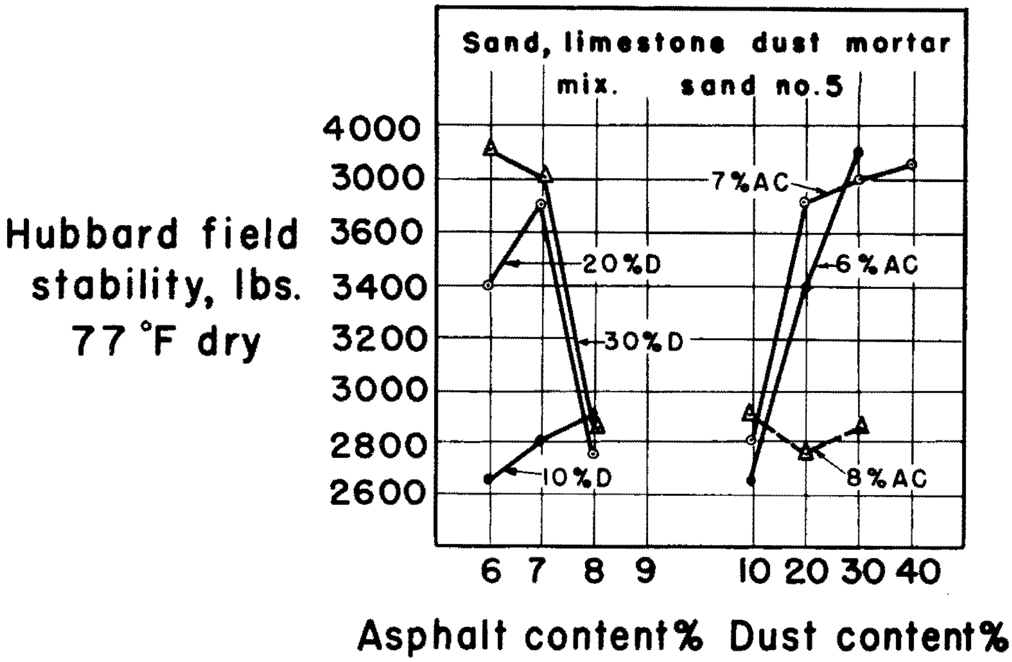

Sand, limestone dust mortar mix. sand no.5
Hubbard field stability, lbs. 77 °F dry
4000
3000
3600
3400
3200
3000
2800
2600
20%D
30%D
10%D
7%AC
6%AC
8%AC
6 7 8 9
10 20 30 40
Asphalt content% Dust content%

Fig.28

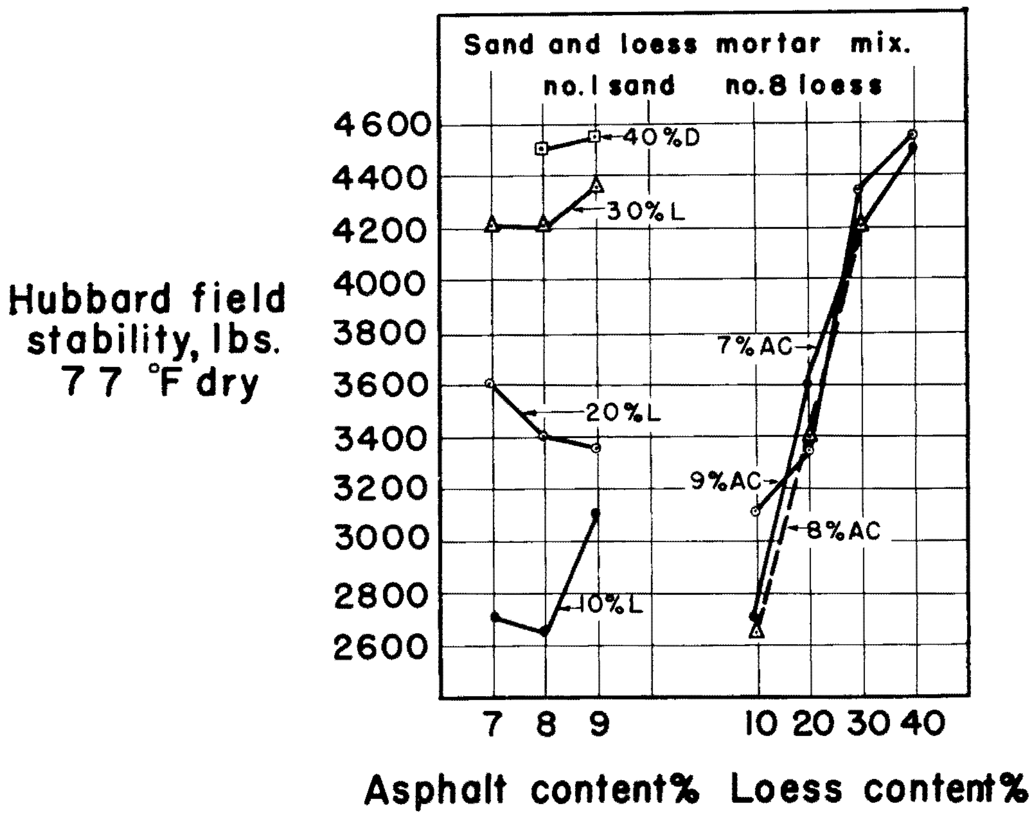

Sand and loess mortar mix. no.1 sand no.8 loess
Hubbard field stability, lbs. 77 °F dry
4600
4400
4200
4000
3800
3600
3400
3200
3000
2800
2600
40%D
30%L
20%L
10%L
7%AC
9%AC
8%AC
7 8 9
10 20 30 40
Asphalt content% Loess content%

Fig.29

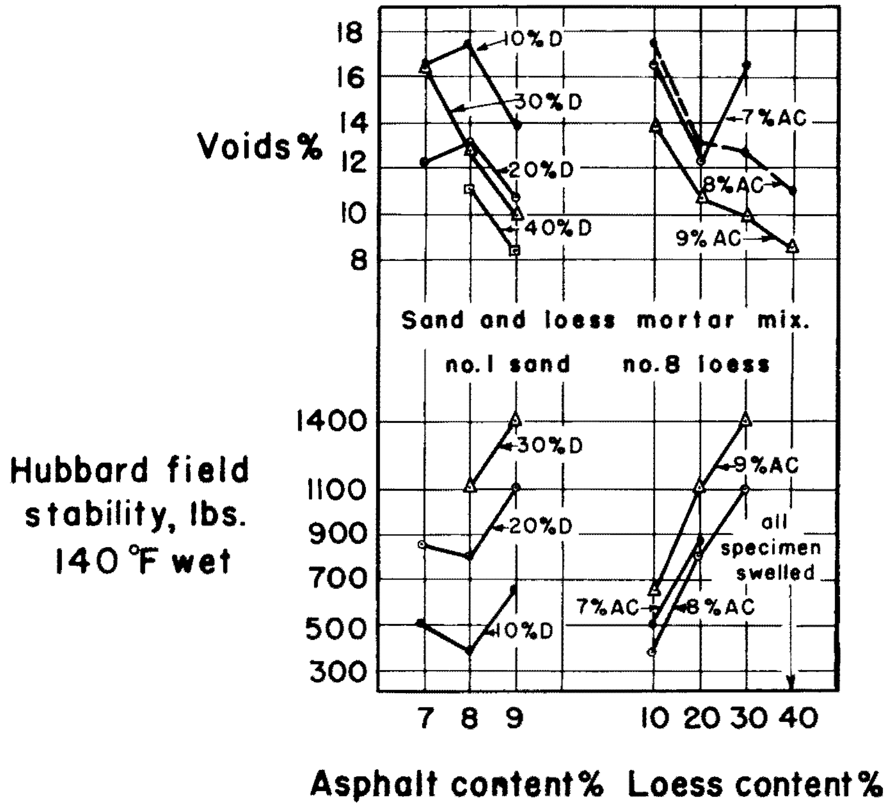

Voids %
18
16
14
12
10
8
10% D
30% D
20% D
40% D
7% AC
8% AC
9% AC
Sand and loess mortar mix.
no. 1 sand
no. 8 loess
Hubbard field stability, lbs. 140 °F wet
1400
1100
900
700
500
300
30% D
20% D
10% D
9% AC
all specimen swelled
7% AC
8% AC
7 8 9
10 20 30 40
Asphalt content %
Loess content %

Fig. 30

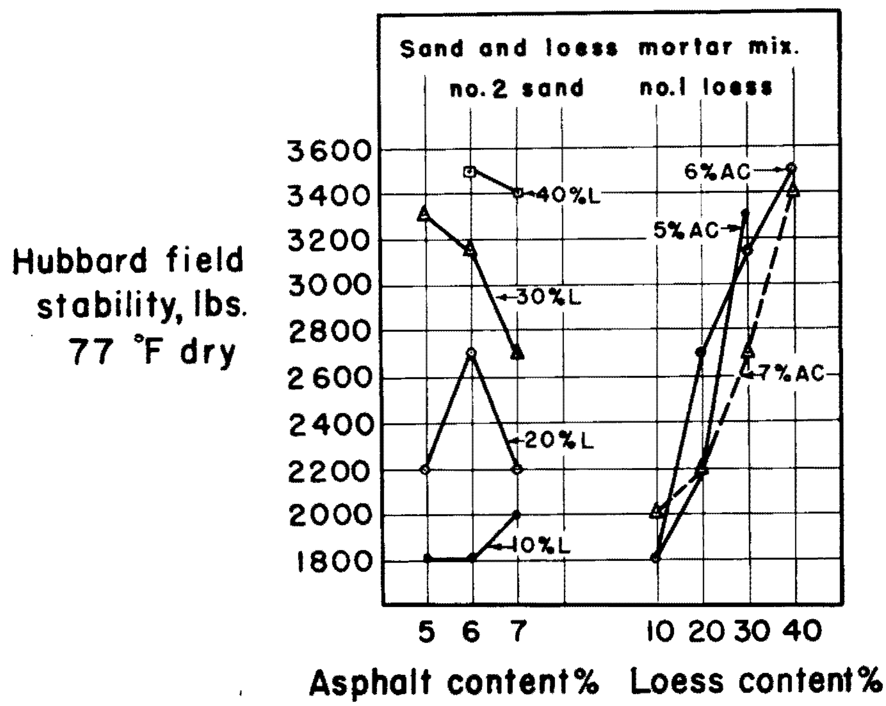

Sand and loess mortar mix.
no. 2 sand
no. 1 loess
Hubbard field stability, lbs. 77 °F dry
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
40% L
30% L
20% L
10% L
6% AC
5% AC
7% AC
5 6 7
10 20 30 40
Asphalt content %
Loess content %

Fig. 31

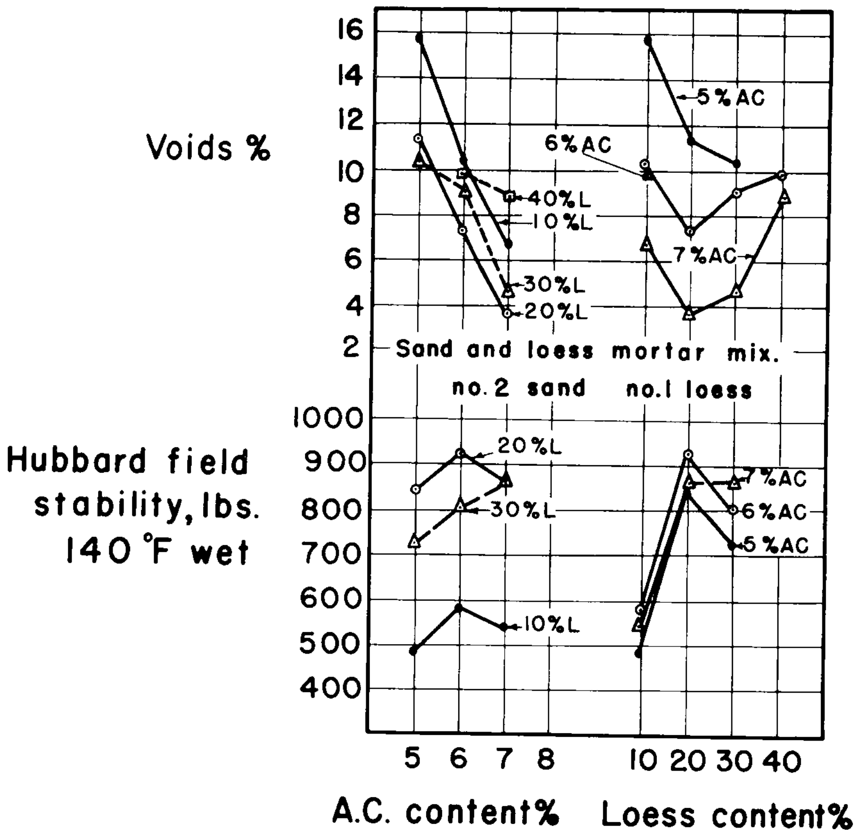

Voids %
16
14
12
10
8
6
4
2
6% AC
5% AC
7% AC
40%L
10%L
30%L
20%L
Sand and loess mortar mix.
no. 2 sand no. 1 loess
Hubbard field stability, lbs. 140 °F wet
1000
900
800
700
600
500
400
20%L
30%L
10%L
7% AC
6% AC
5% AC
5 6 7 8
10 20 30 40
A.C. content% Loess content%

Fig.32

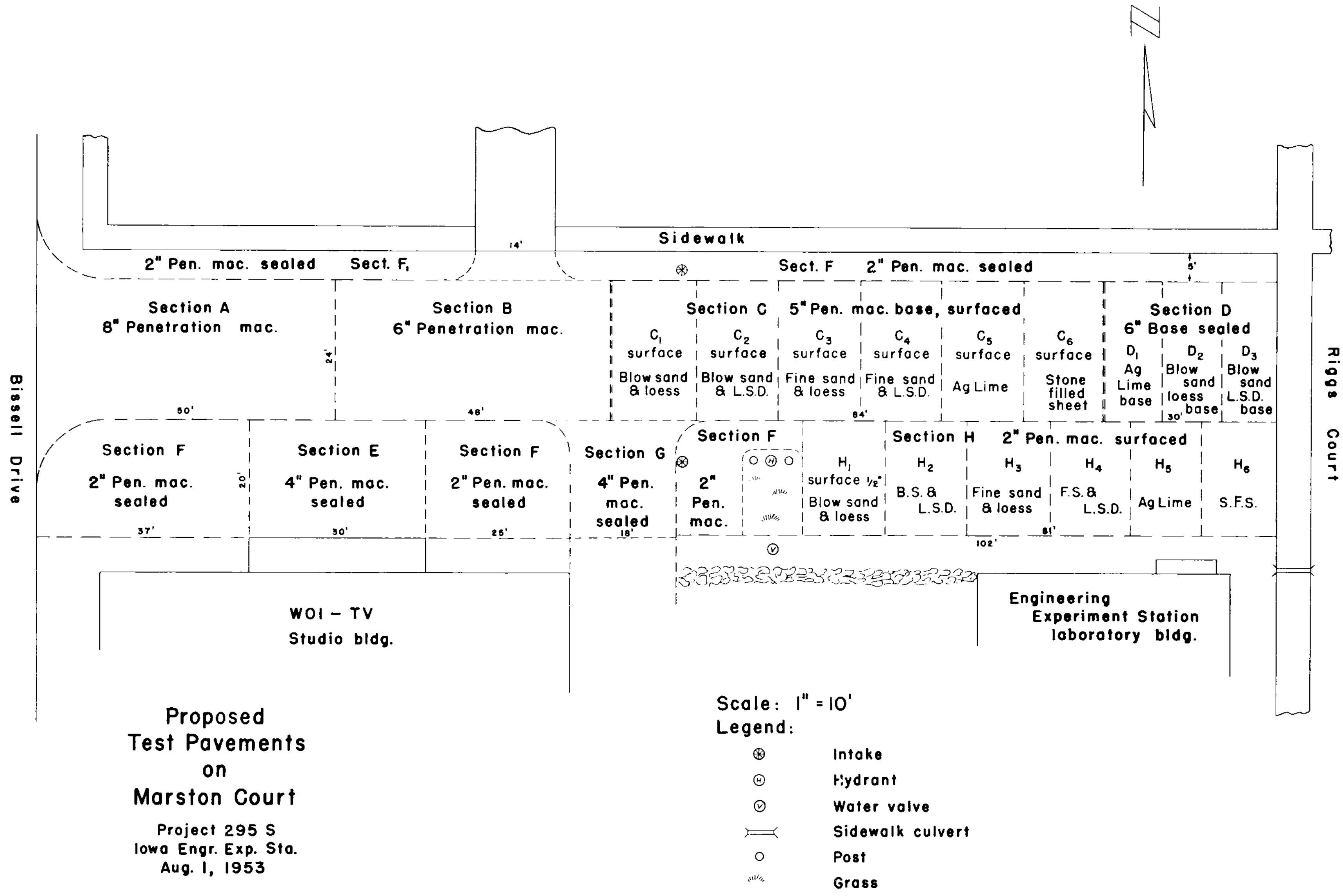


Fig. 33. Test road — location of mixes on Marston Court

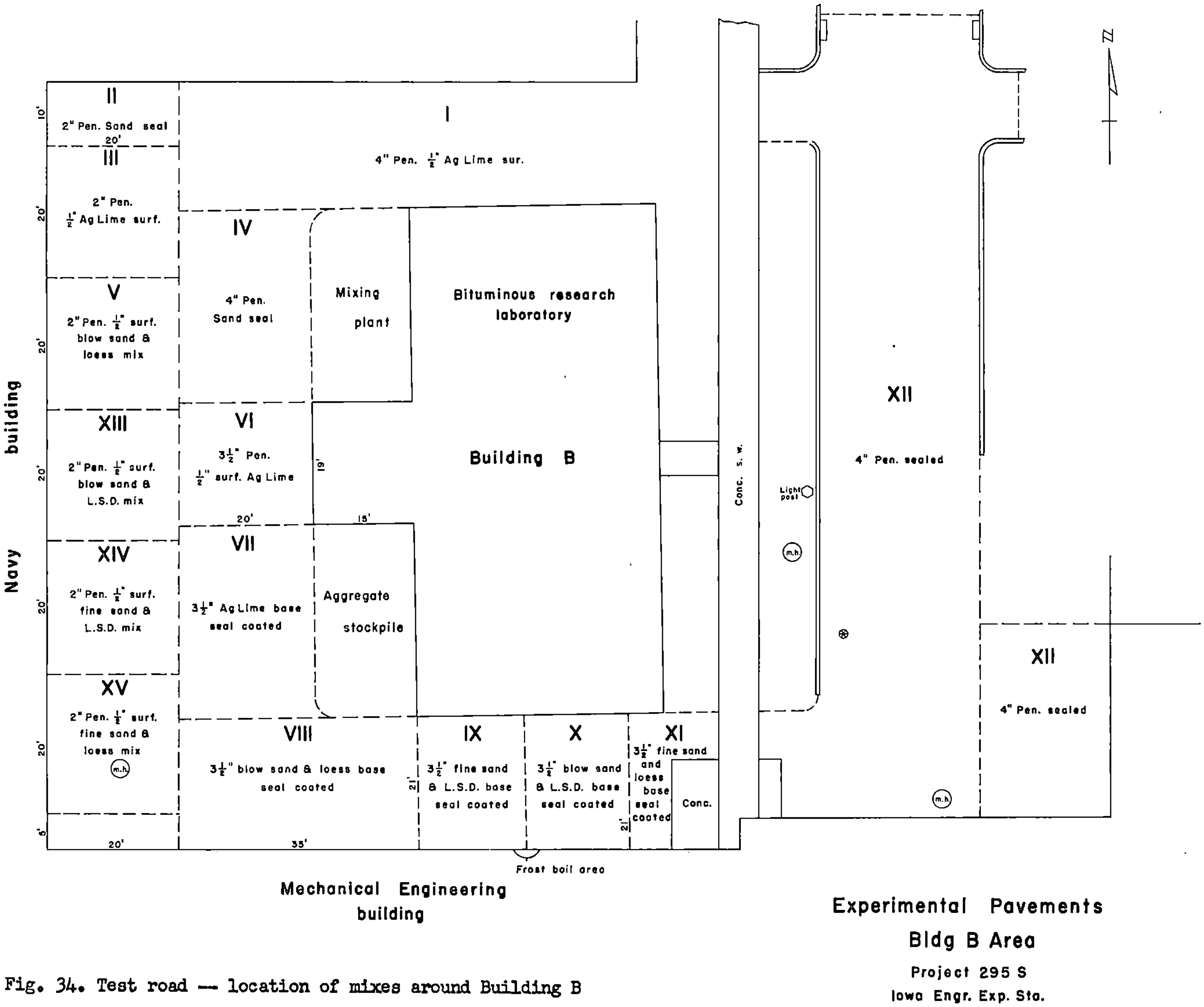


Fig. 34. Test road — location of mixes around Building B

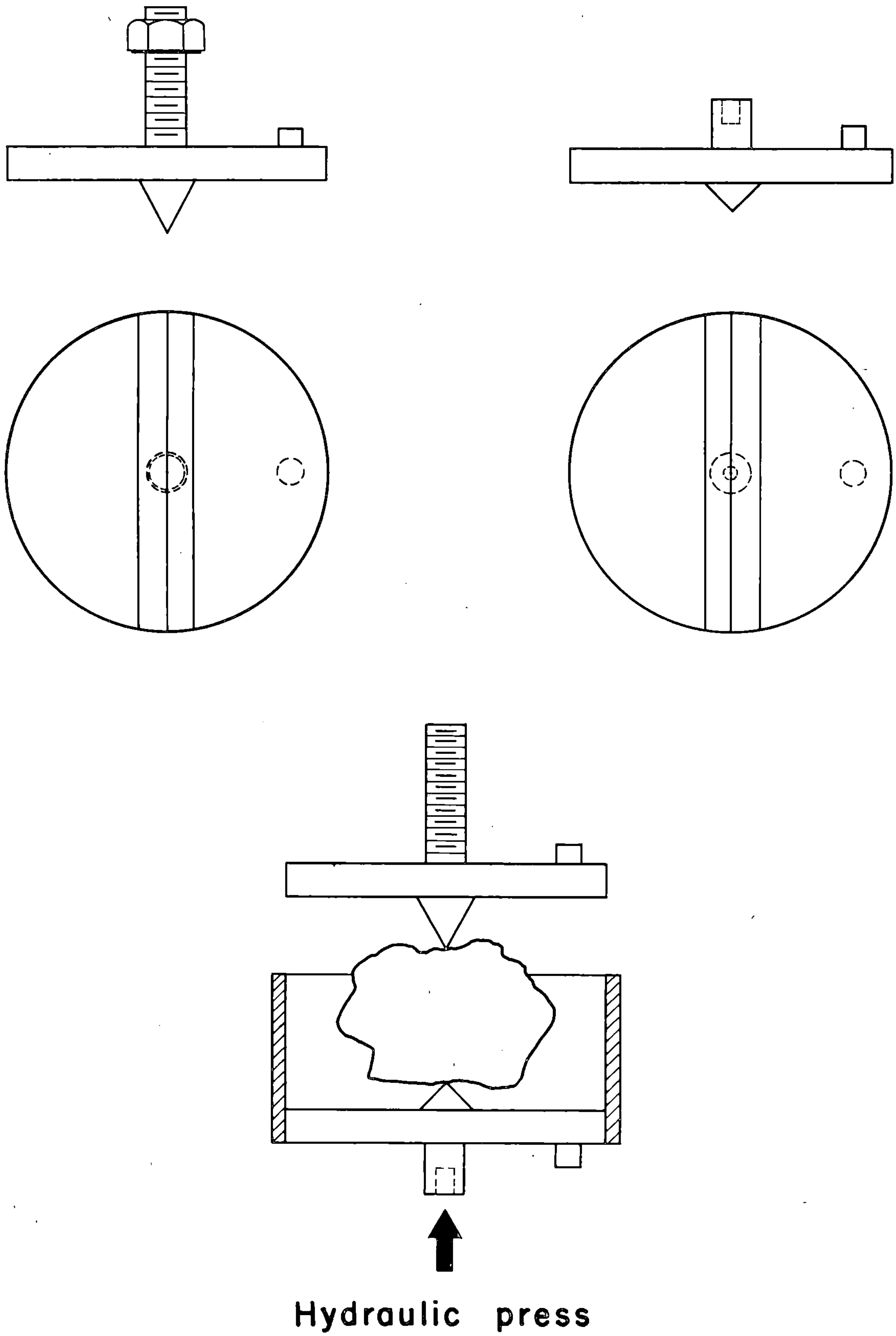


Fig. 35. Device developed for splitting coarse aggregate