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Final Report

A FIELD STUDY OF STRIPPING POTENTIAL OF ASPHALT CONCRETE MIXTURES

sponsored by

The State of Alabama Highway Department
Montgomery, Alabama

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ABSTRACT

An earlier laboratory study with representative Alabama materials illustrated the difficulties inherent in predicting field stripping performance with available laboratory testing procedures. A part of the problem appeared to be the inability to accurately model construction conditions in the laboratory. This study examined and modified laboratory conditions to better simulate construction conditions, particularly residual aggregate moisture.

Six asphalt-aggregate mixes were selected and a sampling and testing program conducted. Moisture content of aggregate and mix was measured during construction. Hot mix, aggregate and asphalt cement (without antistrip additives) were sampled during construction. Samples for wet-dry tensile and boil tests were prepared with field mix, mix prepared with standard laboratory procedures and mix prepared with controlled residual aggregate moisture content.

Cool and rainy construction conditions result in higher aggregate and mix moisture content. Larger aggregate particles have higher residual moisture than finer particles.

Residual aggregate moisture increased conditioned tensile strength and TSR for dolomitic limestone mixes, but decreased these parameters for siliceous sand-gravel mixes. Values for field mixes were generally higher than values for comparable laboratory mixes.

The wet-dry tensile test is a conservative method for designing and controlling mixes comprised primarily of dense dolomitic limestones. However, the unusual and, at this state, unexplained response of these mixes justifies a cautious and conservative approach.

The wet-dry tensile test does a reasonably good job of designing and controlling mixes comprised primarily of siliceous sand-gravel. However, additional testing should be conducted to further develop procedures for including residual aggregate moisture during mix design.

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INTRODUCTION

Although moisture susceptibility of asphalt concrete paving mixtures has been a recognized problem for several decades, the quantification of stripping potential during material selection and mix design has remained difficult. A completed laboratory study (1) with representative Alabama materials illustrated the difficulties inherent in predicting field stripping performance with available laboratory testing procedures. A part of the problem appears to be the inability to accurately model construction conditions in the laboratory, particularly incomplete drying and partial coating of aggregate. This study will examine laboratory tests for quantification of stripping potential with emphasis on the influence of residual moisture on and/or in the aggregate. When possible, test results from specimens of laboratory and field mixed materials will be compared.

Background

The process of stripping in asphalt concrete is most often thought of as a loss of adhesion between asphalt binder and aggregate. This was first considered to be an adhesion problem in 1932. (2). Researchers still consider adhesion to be the dominant failure mode; however, some have added that stripping may also be a result of a loss of cohesion (3). The Asphalt Institute defines stripping as "the breaking of the adhesive bond between the aggregate surface and the asphalt cement." The one factor common in all proposed stripping mechanisms is the presence of water.

Adhesion improving additives may be added to the asphalt or aggregate to overcome poor adhesion between the asphalt binder and aggregate surfaces. Many tests have been developed to evaluate the properties that affect stripping and to evaluate the effectiveness of adhesion improving additives. However, stripping is a complex phenomenon, influenced by many factors, and no test has been universally accepted as a predictor of stripping.

Failure caused by stripping occurs in two stages: loss of strength in the asphalt concrete followed by failure of the pavement under traffic (4). Many pavements experience stripping within the mix without subsequent structural failure of the pavement. Indications are that a stripped pavement's loss of strength will be minimized if the pavement structure has sufficient rigidity, or if the stripped material is located deep enough in the pavement structure so that applied stresses are small (4). Damage is usually minimal if only the coarse aggregate strips; however, if the fine particles strip, severe damage can result (5). Asphalt which is not bonded to aggregate may flush or bleed to the pavement surface and cause a loss of skid resistance (6).

Stripping may manifest itself in several forms before complete disintegration occurs. Excessive deformation may occur due to a loss of shear strength; it may appear as cracking, rutting, corrugations or shoving (7). If stripping becomes excessive, loss of strength and excessive deformation can lead to complete disintegration of the pavement, often in the form of pot holes (4).

Stripping Mechanisms

Adhesion, or the lack of it, can involve the interaction of many parameters and can be explained in terms of mechanical, chemical and thermodynamic phenomena. There are five different mechanisms, having wide acceptance, by which stripping can be explained: detachment, displacement, spontaneous emulsification, pore pressure and hydraulic scour (4). These mechanisms can act individually or together to cause stripping in asphalt concrete mixtures.

Detachment. Detachment is the separation of asphalt from aggregate surfaces with the asphalt coating remaining intact (8). Detachment is usually explained by the thermodynamic replacement of the asphalt by a thin film of water.

Displacement. Stripping by displacement occurs at the three phase interface between water, asphalt and aggregate, (i.e., at some point where water penetrates the asphalt film). It is a retraction of that asphalt-- water interface over the aggregate surface (8). There is a belief that displacement is a function of viscosity; that is, high viscosity binders show a higher resistance to displacement (9).

Spontaneous Emulsification. Spontaneous emulsification is the formation of an inverted emulsion with water and asphalt, where asphalt is the continuous phase and water the discontinuous phase (4). Emulsification may result in the loss of adhesion between the aggregate and asphalt binder and/or the loss of cohesion in the asphalt.

Hydraulic Scour and Pore Pressure. Hydraulic scour and pore pressure are mechanical phenomenon. They occur when the pavement is saturated; vehicle tires press water into the pavement in front of the tire and immediately suck it out behind the tires (10). This water movement and pore pressure cycling is believed to contribute to the stripping of asphalt films from aggregate.

Factors Which Influence Stripping

Stripping is affected by many factors. Some of the factors that have been identified are: material characteristics (asphalt and aggregate), mixture design, construction practices, traffic, and environment.

Asphalt Characteristics. The viscosity of an asphalt is the most common factor affecting an asphalt's stripping properties (4). High viscosity asphalts resist pulling along an air-- water interface and pulling of the asphalt film increases with decreased viscosity (3). A low viscosity asphalt has a higher "wetting power" and is therefore more desirable from the standpoint of coating (8).

There has been speculation that asphalt composition and compatibility between asphalt and aggregate may be a factor in the susceptibility of mixes to stripping. However, there are no definitive studies that demonstrate the nature or the magnitude of effect. Gharaybeh (11) concludes that there was no statistically significant ($\propto$ = 5%) difference between the two most widely used Alabama sources of AC-20 when combined with five typical aggregate combinations. Hazlett (12) tested a limestone mix with eight sources of asphalt cement and observed wide variations in stripping susceptibility as measured by retained tensile strength. Dukatz and Phillips (13) indicated differences in retained tensile strength of about 10% for two sources of AC-20, but this difference was overshadowed by the effects of aggregate source.

Aggregate Characteristics. Some aggregate properties that are suspected to affect the quality of the adhesive bond in an asphalt-aggregate mixture are: mineralogy (chemical composition), surface texture, absorption, surface age, surface coatings, and particle shape.

Mineraology (chemical composition) is generally recognized as the dominant factor affecting stripping (8). Aggregates are generally classified as hydrophilic, "water loving" or hydrophobic, "water hating." Hydrophilic aggregates usually have high silica content and an acidic surface. They have a greater affinity for water than asphalt and are considered to be more susceptible to stripping. Hydrophobic aggregates usually have high carbonate content and a basic surface. They have a greater affinity for asphalt than water and are generally considered more resistant to stripping. Contrary to these beliefs, some hydrophilic aggreates have been observed to be highly resistant to stripping, and some hydrophobic aggregates have stripped (4). This inconsistent response, as measured in laboratory tests, was observed in the completed study (1) for a siliceous gravel and a dolomitic limestone mix.

Surface texture affects how well asphalt will spread over a particle surface and how well that film holds onto the particle. Surface texture first affects the wettability of the aggregate. Liquid asphalt spreads easier over a smooth surface. Slick particles will, therefore, coat better initially. However, the smooth particle may not develop a good physical bond with the asphalt. Aggregates with rough microtexture can create stronger bonds with asphalt by providing a means for mechanical interlock between asphalt and aggregate. Asphalt which penetrates into pores and surface irregularities is resistant to displacement (8).

Aggregate absorption or porosity is related to surface texture. Absorptive aggregates can be good or bad depending on the presence of water. Highly absorptive aggregates when dry can create strong bonds by allowing asphalt to penetrate into particles. However, if absorbed moisture is present it may interfere with the formation of a good bond between asphalt and aggregate surface. Aggregate with large surface pores, such as limestone, exhibit stronger mechanical bonds than aggregates with smaller and fewer surface pores, such as quartz (4).

Another factor which may contribute to increased stripping susceptibility is the age of crushed surfaces. Some freshly crushed aggregates have shown poor stripping resistance (10, 14). Contamination of the fresh face by weathering can provide better stripping resistance (4). Stockpile age of a week, or more, usually provides sufficient time for exposure and reorientation of surface molecules (10).

Coatings on the surface of an aggregate can hasten or inhibit stripping. Coatings of clay, silt, dust from crushing, and water have been found detrimental to stripping resistance (10). Coatings of ferruginous materials, oil and fatty acids have been found beneficial to stripping resistance (4).

Particle shape affects how well the asphalt will coat the aggregate. Rounded particles are coated by asphalt with a more uniform film thickness than angular particles. Sharp corners on angular particles, where the asphalt film is usually thinnest, tend to be vulnerable to ruptures in the asphalt coating. The rupture then allows water to enter between the asphalt aggregate interface.

Mixture Design. Three mix parameters that lab tests indicate may influence stripping propensity are gradation, asphalt film thickness (asphalt content) and voids (1, 11, 13). Gradation alone is probably not that important, although well graded mixtures tend to show less tendacy to strip than mixes with basically one size material. Gradation, as it relates to asphalt film thickness and the voids in a mix, is important. Mixes with finer gradations (surface mixes) tend to have larger asphalt film thicknesses and lower stripping propensity. Coarser gradations (base/binder mixes) tend to have smaller asphalt film thicknesses and greater stripping propensity.

Gradation will also affect the nature of the voids in a compacted mix. Although voids are normally controlled at 6-8% for indirect tensile strength retention tests, coarser gradations will produce fewer but larger voids. Larger voids will permit easier access (greater permeability) to water and, thus, increase potential for stripping. The effect of void size on permeability is apparent during vacuum saturation. It is much easier to achieve 60-80% saturation for a coarse mix with 6-8% voids than for a fine mix with 6-8% voids.

Tensile strength ratio is a function of voids with higher voids resulting in lower retained strength (13). This influence is minimized in laboratory testing procedures where voids are controlled at 6-8%, but implications are that field performance will be affected by compaction.

Construction Practices. Compaction and weather conditions during construction influence the susceptibility of an asphalt pavement to stripping. Inadequate compaction will result in excessive and interconnecting air voids which allow penetration of water and, therefore, increase the potential for stripping (10). If rain immediately follows construction, stripping is more likely, since the asphalt viscosity remains low for several hours after construction (4).

One aspect of field construction that has received little attention in stripping research is the effect of residual aggregate moisture. It is often evident that aggregates are not completely dried. Steam rising from trucks hauling hot mix or water draining from truck beds is positive evidence of residual moisture in the aggregates. When excessive moisture is present in a mix, popping or snapping sounds can be heard as the steam escapes from the coated aggregate or the mix may slump and lack stability

(15).

The occurrence of residual moisture is obviously dependent on environmental conditions and production rate. In saturated aggregate stockpiles, the excess moisture in and on the aggregates will tax the drying system. Typically, when saturated aggregate passes through the dryer, the fine particles come out essentially dry throughout, however, the coarse particles may exit surface dry, but hold moisture in internal pores. According to Lottman (16), when saturated aggregate is heated by the hot gases, escaping water vapor consumes some of the heat energy and prevents the aggregate from reaching optimum drying temperature. Larger particles, which contain the greater percentage of total moisture, give off large amounts of vapor and are slower to reach a uniform temperature. However, the fine aggregates heat up and dry out faster due to their larger surface area to mass ratio. If the dryer retention time is too short, the internal temperature of large particles will remain relatively cool and the moisture in deep pores will not be vaporized.

In batch plants, aggregates leave the dryer and are segregated over screens into separate hot bins. This creates a temperature differential with hotter, drier fine aggregates in separate hot bins from the incompletely dried and cooler coarse aggregates. In the hot bin, the coarse aggregates may stop loosing water vapor. However, the absence of steam and dry particle surfaces does not mean that all internal moisture is gone. Vapor loss may, in fact, completely subside in the hot bin if internal aggregate temperatures remains low. However, as the segregated aggregates are batched into the pugmill and sprayed with hot asphalt cement, the heat, which is transferred to the coarse aggregate from the asphalt cement and hotter fines, elevates the temperature within the larger particles enough to resume the drying process. The release of steam from the deep pores of the aggregate in the pugmill is likely to initiate stripping damage. Three consequences result from the escaping steam.

1. Energy expended liberating the residual moisture will result in heat loss and a lower mixing temperature. At a lower mixing temperature the asphalt viscosity increases and reduces its wetting power or ability to coat the aggregate.
2. Escaping steam also impedes the asphalt from bonding with the aggregate particle. Some aggregates have a greater affinity for water than for asphalt. Moisture emerging from the internal pores displaces the asphalt film at the aggregate surface forming a water layer around the particle and preventing the asphalt from achieving intimate contact with particle surface. This leaves the asphalt coating unbound to the aggregate and vulnerable to stripping.
3. As the asphalt becomes more viscous as the mix cools, steam continuing to emerge from the internal pores will cause ruptures or blisters in the asphalt coating. The rupture in the asphalt film then provides an avenue for external water to enter between the asphalt film and aggregate surface.

In drum plants a similar situation can develop. Reynolds (17) explains that when the aggregates meet the asphalt spray in the drum all the particles are quickly coated. Aggregate temperature at this point is usually between 180° F and 200° F. The escape of vapor from aggregates causes the asphalt to foam slightly and increase in volume.

This foaming is considered to aid the coating process. However, when the mix is transferred to the surge or storage bin, the temperature of the mix is elevated. The remaining internal moisture driven out at this time may disrupt the asphalt-aggregate bond and initiate stripping.

Existing laboratory models do not account for the effect of residual moisture. Test procedures usually begin with heating of the aggregates in a convection oven overnight. This essentially assures that all moisture will be driven off. This modeling inconsistency may contribute to poor correlations with known field performance for some absorptive aggregate.

Traffic. The effects of loading on stripping susceptibility are not completely defined. Some theories include dynamic pore pressure and hydraulic scour (caused by traffic on wet pavements) as mechanisms which act to strip asphalt from aggregate surfaces. Some field investigations have shown that stripping appears to be more severe in areas of heaviest loading, i.e., wheel paths. This observation is primarily visual and the appearance of uncoated aggregate in wheel paths may be the evidence of stripping rather than the cause, i.e., cyclic hydraulic pressure may simply scour away the stripped and loosened asphalt coatings.

Jimenez (18) proposed a test procedure which conditions specimens by submerging and cycling the pore water pressure to simulate this condition. However, most procedures ignore the effects of traffic loading.

Environmental Factors. The primary environmental factor that affects stripping is water. Water can come from within the mix (in or on aggregate particles), it can enter the pavement from the environment (through precipitation or transpiration) or it can be trapped in the pavement when a layer is placed on a damp surface. In laboratory stripping models, water is introduced externally by saturation of samples.

Other climatic factors which occur in the field such as oxidation, temperature fluctuations, and freezing are sometimes simulated in the laboratory conditioning procedures.

Test Methods

Many tests have been developed to determine the susceptibility of asphalt concrete to moisture. The two basic types of tests are those run on loose mixtures and those run on compacted samples. None have, to date, received wide acceptance because of often highly variable results and lack of correlation with field performance.

Tests on Loose Mixture. Tests run on loose mixtures subject a coated sample to some moisture conditioning and evaluate the percent coating retained. Quantitative or qualitative means are used to determine the percent coating retained. The most widely used of these is the boil test. The boil test has been standardized as ASTM D3625. A similar procedure is the Texas Boil Test (12, 14) which was used in the previously completed study (1) and in this study.

In the boil test procedure, loose mix samples are immersed in boiling water and stirred for a set period of time. The sample is then evaluated based on the percentage of the asphalt coating that is retained on the aggregate.

The primary advantage of the boil test is its expedient nature. The methodology is relatively simple and requires no special equipment, making it an ideal field test.

The greatest pitfall of the boil test is the obvious differences between field and laboratory conditions.

1. Sample preparation does not resemble several aspects of field construction (aggregate drying, mixing, compaction)
2. Boiling water does not reflect field environmental conditions.

Another disadvantage of the boil test is the subjective qualitative nature of the sample rating, i.e., the determination of asphalt coating retention is a subjective visual rating.

Tests on Compacted Mixture. Tests on compacted samples are usually run to compare an engineering property, such as strength, before and after moisture conditioning. The immersion compression test is used to assess the loss of compressive strength due to the action of water. Currently the most widely used of this type test is the indirect tensile test. Variations of this type test are described in references 14 and 19-24. The procedure proposed by Tunnecliff and Root (22) was used in this study.

Lottman (19) developed a moisture conditioning procedure to evaluate the effects of stripping on tensile strength of asphalt mixtures using the indirect tensile test. Tunnicliff and Root (22) simplified the Lottman procedure by deleting the requirements for freeze-thaw cycles.

The basic wet-dry indirect tensile test procedure involves testing and comparing a group of conditioned (wet) specimens and a group of control (dry) specimens. The specimens are prepared by Marshall or Hveem procedures. The conditioned group is subject to accelerated moisture conditioning to promote stripping. Both conditioned and control groups are then loaded to determine tensile strength and/or modulus of elasticity. The ratio of the strengths or moduli from the conditioned and control groups provides an indication of stripping susceptibility.

The wet-dry indirect tensile test has become a popular stripping test partly because of the simulation of field conditions.

1. The laboratory procedure uses actual materials in true field proportions. Specimens made of field mix or cores can also be tested. With laboratory prepared specimens it is impossible to match the rapid and partial drying of aggregates or the vigorous mixing action of a pugmill or drum mixer.
2. The compacted specimens with controlled void content can model densified pavement. The 6-8% voids criteria is a midrange value between as constructed and after traffic compaction.
3. The critical environmental conditions which lead to stripping in the field (water saturation and realistic temperatures) can be simulated by moisture conditioning procedures.

Special conditions that may be variable from plant to plant or job to job, such as mixing of asphalt with partially dried aggregate in a drum mixer or storage at elevated temperatures in a silo, could be simulated on an individual basis but would be inappropriate for standard test methods.

The use of a basic engineering property (tensile strength) as a measure of stripping is a second reason for the appeal of the wet-dry indirect tensile test. It has a scientific basis and allows for a quantitative assessment of a mix. This attribute plus simulation of field conditions has led to increased popularity of the wet-dry indirect tensile test.

OBJECTIVES

The objectives of the research were as follows:

1. To examine the influence on stripping test results of differences between laboratory specimen preparation conditions and field conditions, with emphasis on the effects of aggregate residual moisture.
2. To develop modifications to existing laboratory test procedures in order to better simulate field conditions and improve their reliability as predictors of stripping propensity of asphalt-aggregate mixtures.
3. To examine criteria for separating stripping from nonstripping mixes with emphasis on consideration of aggregate material type (siliceous or carbonate) as a factor in the criteria.

An auxiliary objective added during the research was to investigate methods for measuring moisture content of asphalt-aggregate mixtures.

SCOPE

Test methods examined will be limited to wet-dry indirect tensile and boil test. For the wet-dry indirect tensile test, only the moisture conditioning procedures proposed by Tunnecliff and Root (22) was considered.

Six mixes comprised of four siliceous gravel and two dolomitic limestone mixes were tested. Two of the gravel mixes had base/binder gradations and two had surface gradations. The dolomitic limestone mixes had base/binder gradations. Mix designs were used for actual mixes sampled during production; except for one limestone mix where no field sampling was conducted. Although asphalt cements being used with the gravel mixes contained liquid antistripping additives, provisions were made to sample mix and asphalt without antistrip additives. Therefore, all mixes tested contained no antistrip additives.

Tests were conducted on mix sampled during actual production and on laboratory prepared mix. For laboratory prepared mixes, standard techniques and a technique developed to incorporate controlled residual moisture were used. Testing of cores, as contained in the initial plan of study, was discontinued after the initial project was sampled and tested. This decision was made because inconsistencies in the voids of cores and laboratory prepared specimens (6-8%) made comparisons of strength retention values rather meaningless. In addition coring with water may adversly affect core strength and placement of thin lifts (surface mix) precluded samples of adequate thickness for indirect tensile testing.

Moisture content tests were determined with microwave oven, distillation and conventional oven procedures. The moisture contents used in comparing and analyzing test results were those determined with the microwave oven.

PLAN OF STUDY

To accomplish project objectives six asphalt-aggregate mixes were selected and a program of sampling and testing conducted. Tests were conducted on aggregate constituents and on asphalt-aggregate mixtures.

Selection of Materials

In a completed study of stripping of Alabama mixes (1), the wet-dry indirect tensile and boil tests indicated potential for stripping opposite from observed field performance for two mixes. A gravel mix from the northwest part of the state gave high retained tensile strength and coating, although this and similar mixes have a reputation for severe stripping. A dolomitic limestone mix gave low retained tensile strength and coating, although this and similar mixes apparently have no history of stripping problems in Alabama.

Speculation was that the inconsistent behavior was caused by a failure of test procedures to duplicate field conditions. For the gravel mix, which contained porous gravel, the most likely specific cause seemed to be residual moisture in the aggregate. For the dolomitic limestone mix no specific causes were apparent, although inconsistent results for similar materials has been observed by others.

To study the influence of construction conditions on the predictability of the test procedures, materials with characteristics similar to those that exhibited inconsistent behavior in the completed study were chosen. The same dolomitic limestone was sampled, but it was not possible to test the same porous gravel. Table 1 describes the six mixes sampled and tested.

The initial plan was to sample only base/binder mixes, since the completed study

Table 1. Mix Characterizations

Mix A - Binder/Base "A" Gradation

Crushed stone (#57 & #78), dolomitic limestone (S1)		60%
Screenings (#810), dolomitic limestone (S1)		30%
Natural coarse sand, washed, siliceous (S2)		10%
AC-20		4.3%

Maximum mix sp. gr. (Rice) = 2.601

	Coarse Agg.	Fine Agg.
Apparent sp. gr.	2.834	2.686
Bulk sp. gr.	2.721	2.602
Bulk sp. gr. (SSD)	2.761	2.633
Absorption	1.47%	1.19%

Mix F - Binder Gradation

3/4" crushed gravel, siliceous (S3)		45%
Pit-run sand-gravel, siliceous (S3)		35%
Natural coarse sand, siliceous (S3)		15%
Natural fine sand (S4)		5%
AC-20		4.75%

Maximum mix sp. gr. (Rice) = 2.334

	Coarse Agg.	Fine Agg.
Apparent sp. gr.	2.556	--
Bulk sp. gr.	2.257	--
Bulk sp. gr. (SSD)	--	--
Absorption	5.18%	--

Mix G - Base "A" Gradation

Gravel (#57), siliceous (S5)		50%
Pea gravel, siliceous (S5)		10%
Pit run sand-gravel, siliceous (S6)		30%
Natural fine sand (S7)		10%
AC-20		4.5%

Maximum mix sp. gr. (Rice) = 2.452

	Coarse Agg.	Fine Agg.
Apparent sp. gr.	2.648	2.516
Bulk sp. gr.	2.546	2.341
Bulk sp. gr. (SSD)	2.584	2.410
Absorption	1.52%	2.98%

(Table 1 continued)

Mix H - Surface "B" Gradation

Crushed gravel (#6 & #78), siliceous (S8)	45%
Natural coarse sand, washed, siliceous (S8)	47%
Agricultural lime, dolomitic limestone (S1)	8%
AC-20	5.5%

Maximum mix sp. gr. (Rice) = 2.332

	Coarse Agg.	Fine Agg.
Apparent sp. gr.	2.593	2.579
Bulk sp. gr.	2.428	2.427
Bulk sp. gr. (SSD)	2.492	2.487
Absorption	2.63%	2.44%

Mix I - Surface "B" Gradation

Crushed gravel, siliceous (S9)	35%
Crushed gravel (#78), siliceous (S8)	25%
Natural coarse sand, siliceous (S9)	30%
Sump lime, limestone (S10)	10%
AC-20	5.45%

Maximum mix sp. gr. (Rice) = 2.332

	Coarse Agg.	Fine Agg.
Apparent sp. gr.	2.611	2.603
Bulk sp. gr.	2.405	2.420
Bulk sp. gr. (SSD)	2.484	2.490
Absorption	3.29%	2.90%

Mix J - Binder/Base "A" Gradation

Crushed stone (#57), dolomitic limestone (S11)	45%
Screenings (#810), dolomitic limestone (S11)	45%
Natural coarse sand, siliceous (S12)	10%
AC-20	3.85%

Maximum mix sp. gr. (Rice) = 2.614

	Coarse Agg.	Fine Agg.
Apparent sp. gr.	2.852	2.685
Bulk sp. gr.	2.816	2.627
Bulk sp. gr. (SSD)	2.829	2.649
Absorption	0.45%	0.82%

S1 - S12 indicate source (quarry or pit) of aggregate.

indicated they were more susceptible to stripping (lower retained coating and TSR) than surface mixes. However, because of difficulties in identifying suitable jobs with base/binder mix for sampling, two surface mixes with porous gravel were sampled. These surface mixes may indicate lower propensity for stripping than comparable base/binder mixes because of the larger asphalt film thickness and finer voids structure, but differences between laboratory and field conditions should be consistent with base/binder mixes.

Mix A is essentially the same as the base/binder Mix A in the completed study (1). The source of the dolomitic limestone is the same, but 10% natural coarse siliceous sand was used in lieu of 100% dolomitic limestone. Mix J is a similar base/binder mix with dense dolomitic limestone from the Birmingham area. The dolomitic limestone for mixes A and J are from the same geologic formation. Similar mixes have no history of stripping problems.

Mixes F, H and I contain porous siliceous gravel from the northwestern part of the state and have a history of stripping problems. The materials are similar to Mix D from the completed study which produced high coating and tensile strength retention. Mix F is a binder and H and I are surface mixes.

Mix G contains siliceous gravel from the southwestern part of the state. This material tends to be less porous than the gravel for Mixes F, H and I and does not have the reputation for severe stripping. Stripping and raveling are occasionally observed for this and similar materials which leads to the classification as a moderate stripper.

Field Sampling

In order to compare field and laboratory conditions, a field sampling and testing program was conducted. Hot mix was sampled and specimens prepared for wet-dry indirect tensile and boil tests. Mix constituents (aggregate and asphalt cement) were sampled during production for laboratory specimen fabrication. Mositure content of aggregate and of mix was measured during production to provide a picture of the drying process.

Indirect Tensile Specimens. Hot mix was sampled at the exit of the pugmill for fabrication of indirect tensile specimens. Approximately fifty pounds of hot mix was obtained and placed in a closed insulated box to minimize heat and moisture loss. The initial temperature of the sample varied from plant to plant between 275° F and 325° F. The hot mix was immediately taken into the field lab where samples were quickly measured into heated molds and compacted to between six and eight percent voids by automatic Marshall hammers. The number of blows required to achieve the proper void content was determined by a trial and error process for each mix. Typically, six to twelve specimens could be compacted before the mix cooled below an acceptable level (a drop of 30° F or greater from initial temperature was considered unacceptable). When the molds could be handled, specimens were extracted and sealed individually in plastic wrap to prevent loss of moisture. At least two sets of specimens were compacted for each mix, except Mix J which was not sampled during construction. All specimens were transported to the laboratory where conditioning and testing were completed within two days.

Boil Test Samples. Field boil test samples were obtained from the pugmill and sealed immediately in air-tight containers to avoid moisture loss. The samples were transported to the laboratory where the mix was divided into test size portions and tested within one week.

Moisture Content Samples. Samples were taken at several locations to provide an indication of the moisture content in the aggregate and hot mix throughout the drying, mixing and placement processes. Aggregate samples were typically taken from the cold feed belt and hot bins. Mix samples were taken at the pugmill and at the spreader. Samples were placed in sealed containers and moisture contents determined occasionally in the field, but normally transported to the laboratory for testing.

Laboratory Testing

Wet-dry indirect tensile and boil tests were the basic tests utilized for evaluating mix stripping propensity. Moisture content measurements were also an integral part of the laboratory testing program since the influence of residual aggregate moisture was a major consideration.

Moisture Content Measurement. Moisture content measurements conducted in this study utilized a microwave oven to dry samples. This procedure provides quick and consistent results without the cumbersome apparatus and hazardous solvents used in the distillation procedure: Moisture or Volatile Distillates in Bituminous Mixtures (ASTM D1461). The microwave procedure used for this research is similar to ASTM D4643, a recently adopted procedure for determining moisture contents of soils. The procedure, detailed in the appendix, involves calibration of a common kitchen type microwave and the use of the oven in the same manner as a conventional oven for drying aggregate and mix.

A comparison of test results from the microwave procedure, and the distillation procedure and a conventional oven is contained in the next chapter. Based on these comparative test results, the microwave procedure was deemed to be adequate for this study.

Wet-Dry Indirect Tensile Test. The conditioning and testing followed the procedures suggested by Tunnicliff and Root (22). Field mix specimens were prepared as previously described. Laboratory mix specimens were generally prepared according to ASTM D1559, but mixes with controlled moisture contents required special treatment. The procedure for preparing mix with controlled moisture content is described in the following section.

Bulk specific gravity and void content of compacted specimens were determined in accordance with ASTM D2726 and ASTM D3203, respectively. Specimens were compacted to 7 ± 1% air voids. Specimens were divided into two groups of three having approximately the same average air void content. One group was set aside as control, the specimens in other group are subjected to accelerated moisture conditioning.

Specimens in the moisture conditioned group were first partially saturated with distilled water by submersion and application of a vacuum. After specimens achieved 60-80% saturation, they were placed in a 140° F water bath for 24 hours.

At the end of the conditioning period, all specimens were placed in a 77° F water bath for one hour. Specimens were then measured for thickness and loaded diametrically until failure at a deformation rate of 2 inches per minute.

Tensile strength of each specimen was calculated from the maximum applied load using the formula:

$$S_t = \frac{2P}{\pi dt} \qquad \dots\dots\dots\dots\dots\dots\dots\dots (1)$$

where:

S_t = tensile strength, psi

P = maximum load, pounds

d = specimen diameter, inches

t = specimen thickness, inches

Tensile strength ratio was calculated by dividing the average tensile strength of conditioned specimens by the average tensile strength of control specimens.

$$TSR = \frac{\text{average conditioned strength}}{\text{average control strength}} \qquad \dots\dots\dots\dots\dots\dots (2)$$

After tensile testing, representative specimens for each group (conditioned and control) were split along the failure surface and the percent of asphalt coating visually retained. The VSI is a ratio of the percent coating retained of conditioned to control specimens, and provides an indication of the relative degree of stripping caused by the conditioning.

Mix Preparation with Controlled Moisture Content. Incomplete drying of aggregate during mix production can result in "wet" mix. It proved difficult to simulate, in a controlled manner, partial drying in the laboratory. A review of literature on the subject revealed a method developed by Western Laboratories in their efforts to study laydown problems of "wet" mixes (15). The concern of hat research was not stripping, but rather the effects of residual moisture on stability of the mix. Nonetheless, the procedure used to fabricate laboratory samples seemed applicable to this research. The procedure described below was used to prepare mix with residual moisture.

For each set of specimens, sampled stockpile aggregates were combined according to job mix proportions. Aggregates were graded by size over eight sieves to the specified percentages. The aggregates for the entire set was then split at the No. 4 sieve into a coarse portion and a fine portion. The coarse aggregate portion (+ #4 sieve) was placed in a can filled with tap water and set in a water bath at 140° F overnight. This soaking period allowed the coarse aggregate to achieve saturation and served as a warm up phase in the heating process. The fine aggregates were combined in another can and placed in a convection oven at 425° F overnight.

At the end of the soaking period, the saturated coarse aggregate and water were emptied into a household 6-quart pressure cooker. Hot water was added, as required, to cover all aggregates. The pressure cooker and contents were heated on a hot plate at 15 psi pressure until the rocker valve began to release pressure. Typically, this phase took 30 minutes. Meanwhile, asphalt cement, standard 4 inch compaction molds, and a large mixing bowl were heated to 300° F. When the coarse aggregate had reached pressure, the fine aggregate and asphalt cement were combined in the mixing bowl. Pressure on the cooker was released, and the coarse aggregate was drained over a colander. Once the water had drained, the aggregate dried quickly on the surface and was added to the mixing bowl. Mixing was accomplished by a large mixer until all particles were coated.

The mixture was then divided into four molds, a moisture content dish and a boil test specimen. The moisture content sample was immediately weighed and placed in the microwave oven. Two molds were covered while the other two specimens were compacted simultaneously with a twin hammer automatic Marshall compactor. The covered samples were compacted immediately after the first pair was completed. The boil test specimen was sealed to prevent moisture loss until tested with the procedure described in the following section.

The moisture content of the mix achieved by this procedure depended on the absorption of the coarse aggregate and the length of time the aggregate was allowed to drain. It was difficult to achieve a specific moisture content but variations were obtained by slightly adjusting the time between draining and mixing the coarse aggregate.

Boil Test. Boil tests were run on field samples, standard laboratory prepared samples and laboratory samples prepared with controlled moisture contents. The boil test procedure used in this study is an adaptation of several procedures including ASTM D3625, but most closely resembles the procedure by Kennedy, Roberts and Lee (25).

The sample is placed in boiling water for 10 minutes, and stirred with a glass rod at three minute intervals. Stripped asphalt is skimmed from the surface with tissue. After 10 minutes the sample is cooled to room temperature, the water decanted and the sample spread to dry on a paper towel.

A panel of judges subjectively rated the percent asphalt coating retained. A lighted magnifying glass was used to examine samples. The average of the ratings is rounded to the nearest 5%.

PRESENTATION AND ANALYSIS OF RESULTS

Results are presented in four sections. Moisture content measured with three methods (microwave, distillation and conventional oven) are presented and analyzed in the first section. In the second section, moisture contents measured during mix production and placement are analyzed. Results from indirect tension tests on moisture conditioned and control samples prepared with field mix, conventional laboratory mix and special "wet" laboratory mix are presented and analyzed in the third section. In the final section, boil test results are presented and analyzed.

Tests for Measuring Moisture Content

The only standardized method for measuring moisture content of asphalt-aggregate mixtures is the distillation procedure (ASTM D1461). This procedure is time consuming, requires toxic materials, and is generally not suited for field or routine production testing. However, the alternative, heating of the mixture either by conventional or microwave ovens to remove moisture, has not been generally accepted. This is primarily because of concern that heat will drive off light ends from the asphalt. In the course of this study, data on the various methods were accumulated and analyzed to select a method for moisture content determination.

Moisture contents determined with microwave, conventional oven and distillation procedures are listed in Table 2. The top portion of the table is for asphalt-aggregate mixtures and the bottom portion for aggregate only. The data from Table 2 were plotted and analyzed to establish trends for and relationships between the various methods of moisture content measurement.

Figure 1 shows a plot of microwave versus distillation moisture content with

Table 2. Moisture Contents with Various Methods

Microwave %	Distillation %	Oven %	Comments
0.14	0.15	–	Porous Gravel, Field Mix
0.13	0.04	–	Porous Gravel, Field Mix
0.25	0.09	–	Porous Gravel, Field Mix
0.15	0.07	–	Porous Gravel, Field Mix
0.06	0.05	–	Porous Gravel, Field Mix
0.06	0.04	–	Porous Gravel, Field Mix
0.07	0.20	–	Porous Gravel, Field Mix
4.06	3.70	–	RAP Stockpile
0.12	0.03	–	Marble, Field Mix
0.10	0.00	–	Marble, Field Mix
3.70	3.43	–	RAP Stockpile
0.74	0.15	–	Porous Gravel, Lab Mix
0.83	0.50	–	Porous Gravel, Lab Mix
1.10	0.69	–	Porous Gravel, Lab Mix
0.46	0.09	–	Limestone, Lab Mix
0.49	0.21	–	Limestone, Lab Mix
0.75	0.42	–	Limestone, Lab Mix
1.06	0.77	–	Limestone, Lab Mix
0.10	0.02	0.10	Marble, Lab Mix
0.15	0.01	0.08	Granite, Lab Mix
0.03	0.02	0.04	Porous Gravel, Lab Mix
0.66	0.39	0.68	Marble Aggregate
1.26	0.98	1.26	Granite Aggregate
2.17	1.90	2.35	Porous Gravel Aggregate
3.88	2.70	3.11	Porous Gravel Agg. Soaked 2 weeks, SSD
9.84	–	9.68	Porous Gravel Agg. Soaked 2 weeks, SSD
0.06	–	0.09	Fine Hot Bin Aggregate
0.22	–	0.36	M. Fine Hot Bin Aggregate
0.30	–	0.35	M. Coarse Hot Bin Aggregate
1.00	–	1.20	Coarse Hot Bin Aggregate

All values are average of a minimum of 2 tests.

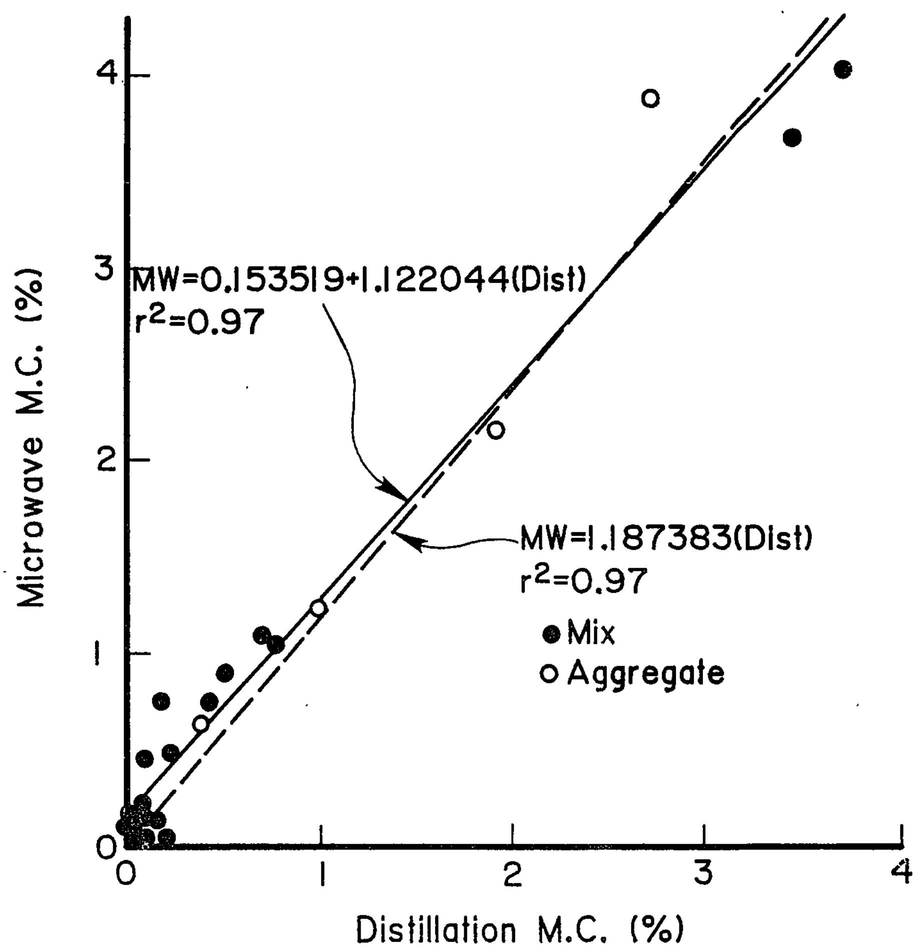

Figure 1. Microwave versus Distillation Moisture Content, Linear Fits, All Data.

unconstrained and constrained (through the orgin) linear regression equations fit to the data. The unconstrained fit has an intercept of about 0.15 on the microwave axis and both equations have slopes greater than one, indicating that microwave moisture contents are larger. Since moisture contents of asphalt-aggregate mixtures are normally less than about 1%, as demonstrated by the distribution of data points in Figure 1, the reduced data set shown in Figure 2 was analyzed. The unconstrained linear regression equation has an intercept of about 0.11 on the microwave axis and both equations have slopes greater than one; again indicating that microwave moisture contents are larger. The equations for the reduced data set also have lower coefficients of determination (r^2) than the equations for the total data set.

Examination of Figures 1 and 2 indicated that curves through the orgin might provide a better fit of the data than straight lines. Relationships of the form

$$y = a[\ln(x+1)] \qquad (3)$$

and

$$y = a[\ln(x+1)]+bx \qquad (4)$$

were tried. The latter provided the best fit. For small values of x, the $a[\ln(x+1)]$ term is dominate and provides the desired curved shape through the origin. As x increases, the bx term becomes more dominate and the relationship approaches a straight line.

The curves fit to all the data and to only the lower values, using equation 4, are shown in Figures 3 and 4, respectively. The goodness of fit, as measured by the coefficient of determination, is only slightly better for these equations than for the linear equations. However, visually the log relationships seem to fit the data better, particularly for the low values.

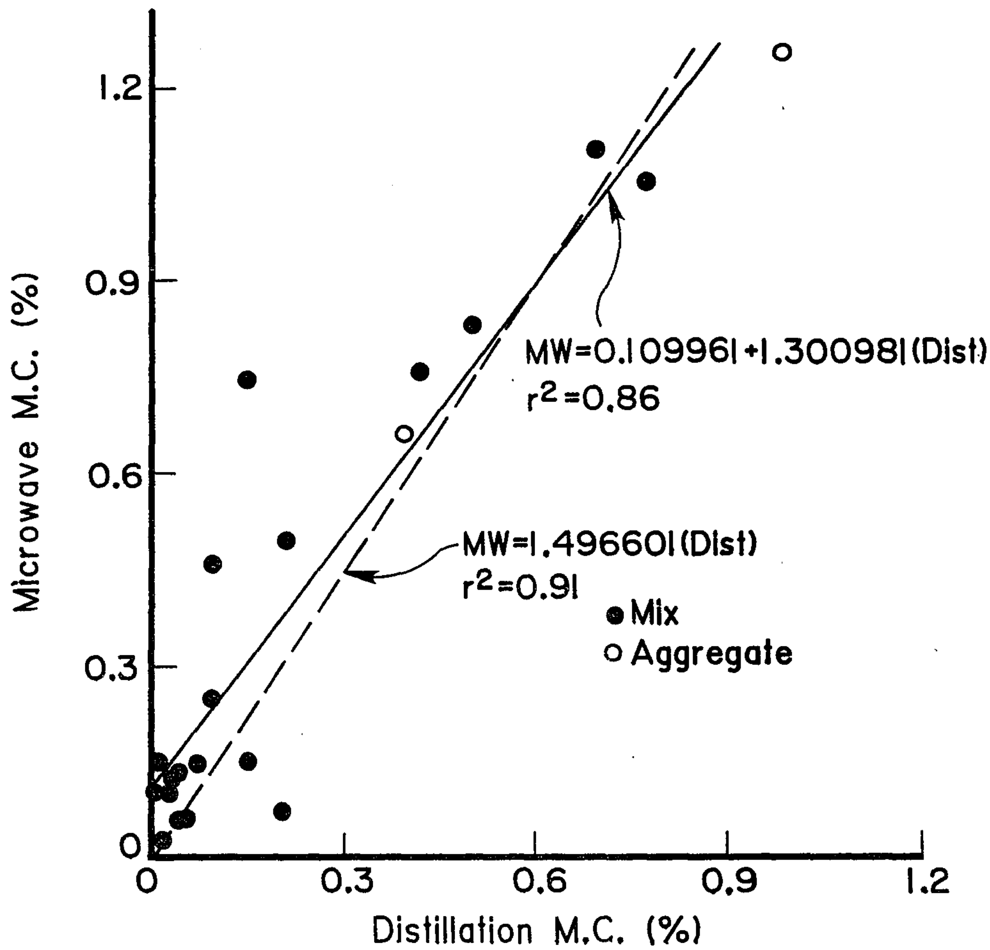

Figure 2. Microwave versus Distillation Moisture Content, Linear Fits, Low Values.

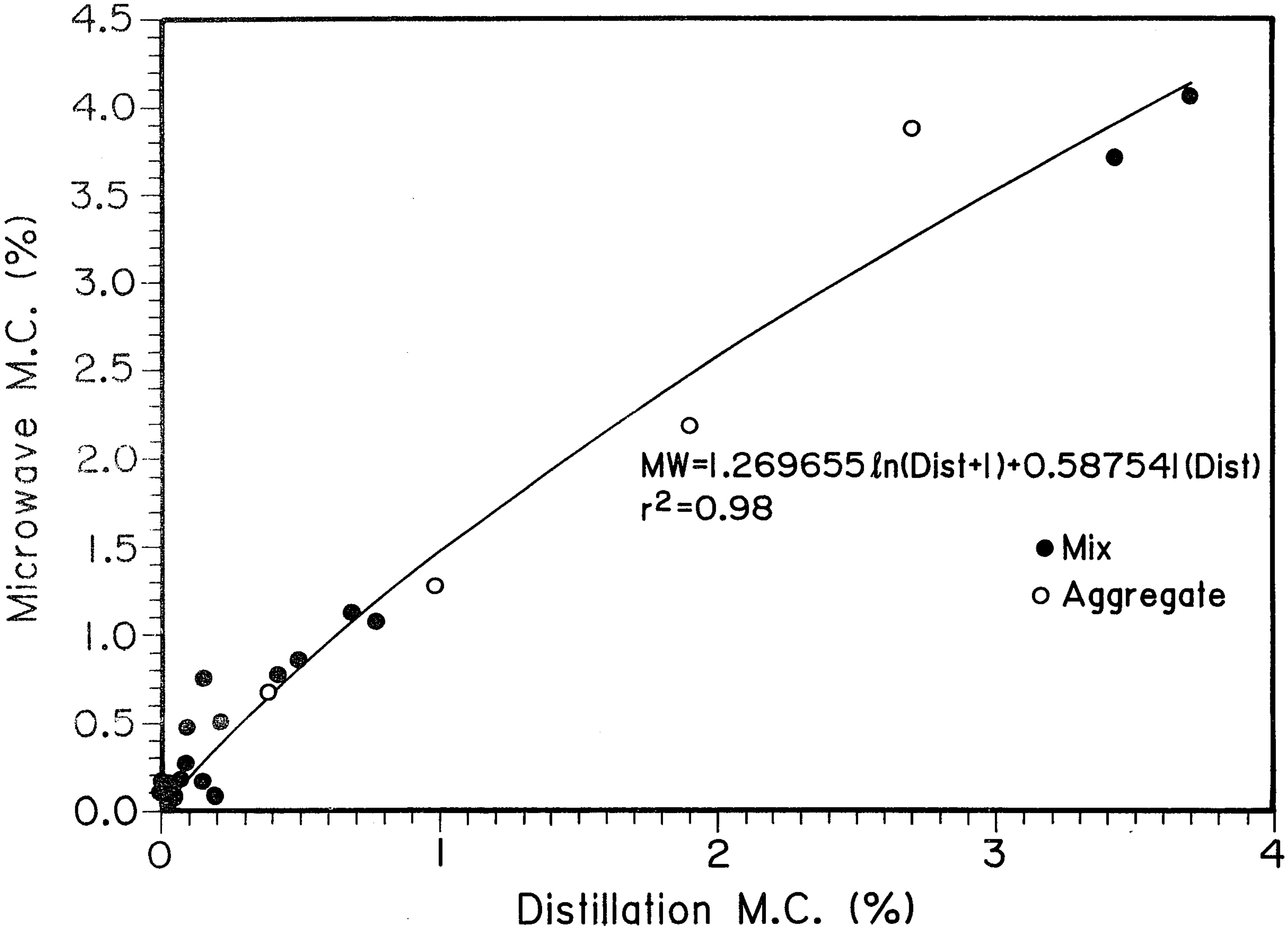

Figure 3. Microwave versus Distillation Moisture Content, Log Fits, All Data.

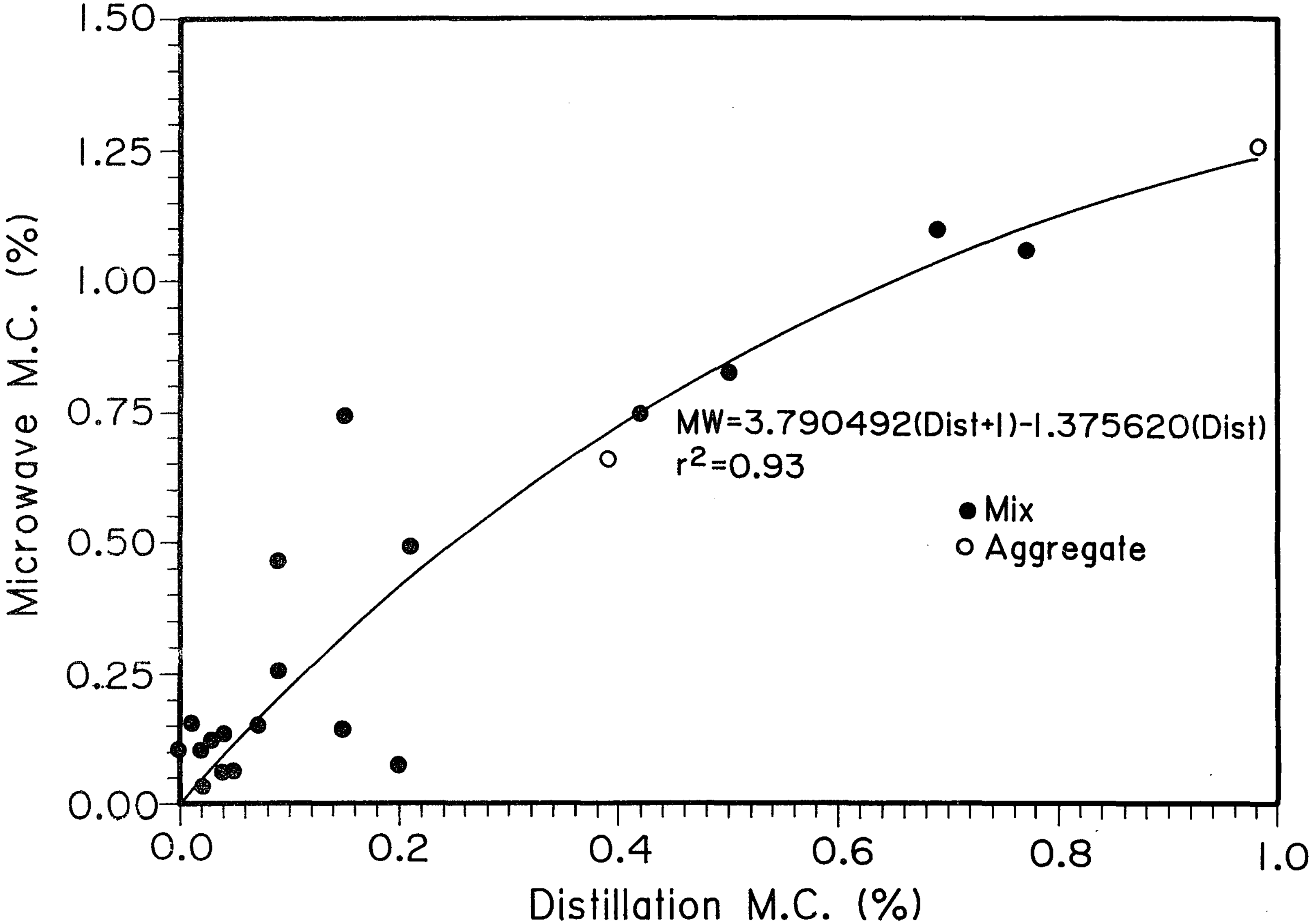

Figure 4. Microwave versus Distillation Moisture Content, Log Fits, Low Values.

The shape of the curves may provide an indication of the reason(s) for differences in measured values. If evaporation of light ends by the microwave was the primary reason for the differences, then the differences should be relatively constant, and there would not be a tendency for the relationship to go through the origin (0,0). However, the cluster of points about the origin strongly suggests the relationship should go through or close to the orgin. The tendency of the relationship to approach a straight line as moisture content increases, and the fact that microwave moisture contents tend to be larger for smaller moisture contents suggests the primary difference may be the efficiency of moisture removal. The microwave heats aggregate from within and appears to be more efficient in removing moisture. At small moisture contents, a small amount of moisture not removed during distillation or a small additional amount of moisture removed by the microwave would mean large percentage differences in moisture content, thus, the curved relationship near the origin. However, as the total amount of moisture in the sample increases, the difference in the moisture removed would have smaller relative influence; thus, a linear relationship develops.

Figures 5 and 6 show distillation versus moisture contents using a conventional oven. The figures indicate that the distillation process may not be as efficient as the oven in removing moisture from aggregate. The unconstrained linear regression equations have an intercept on the oven moisture content axis and the slopes are less than one indicating larger moisture contents measured with the oven.

Figures 7 and 8 compare moisture contents measured with conventional and microwave ovens. The constrained and unconstrained linear regressions are almost identical and both indicate close agreement between moisture contents. The efficiency

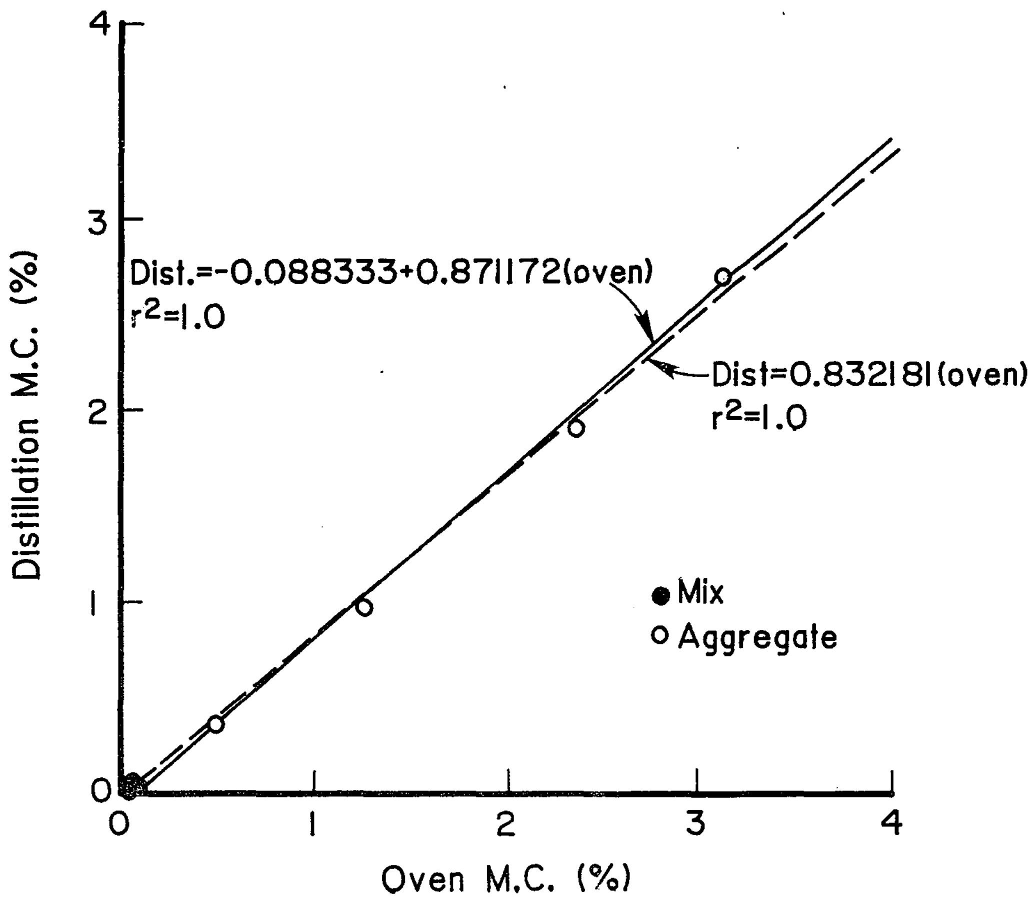

Figure 5. Distillation versus Oven Moisture Content, Linear Fits, All Data.

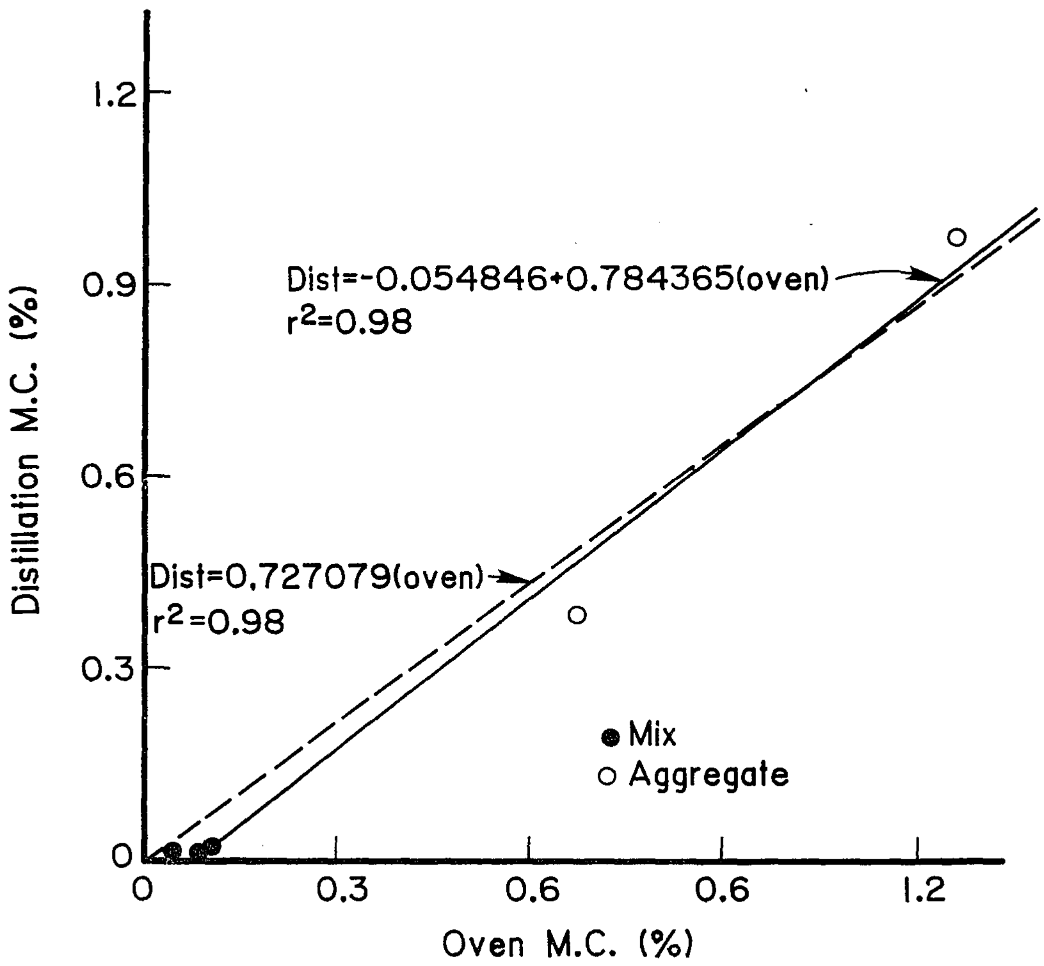

Figure 6. Distillation versus Oven Moisture Content, Linear Fits, Low Values.

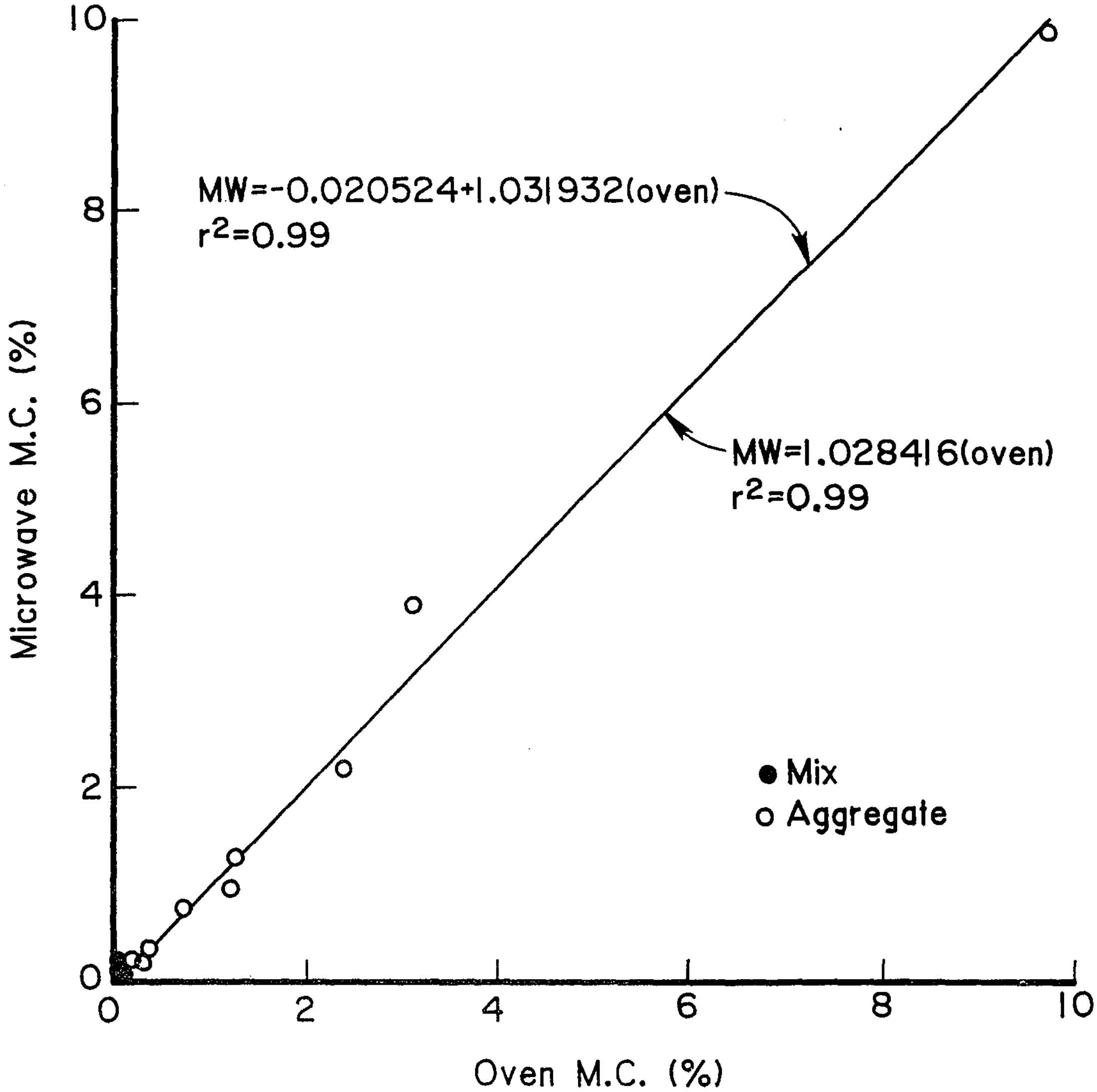

Figure 7. Microwave versus Oven Moisture Content, Linear Fits, All Data.

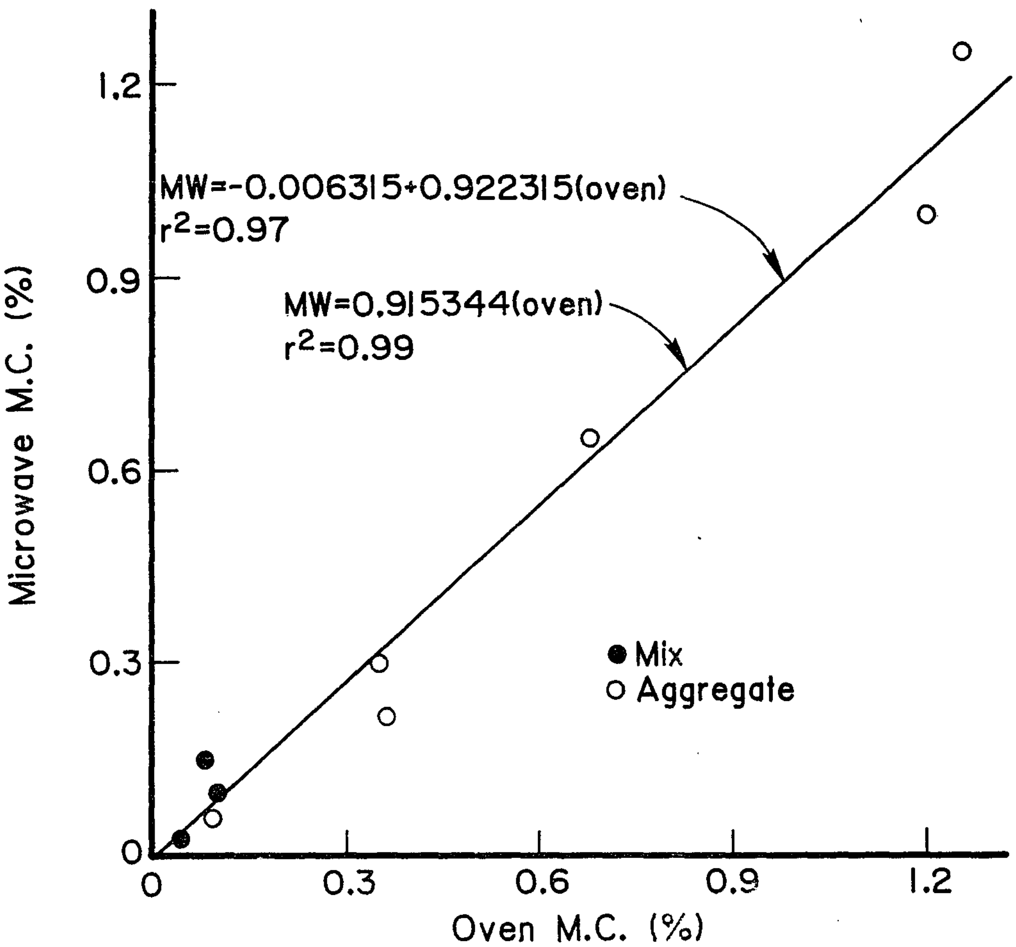

Figure 8. Microwave versus Oven Moisture Content, Linear Fits, Low Values.

of the two methods in removing moisture from aggregate is apparently similar. For all the data, including one sample at about 10% moisture content, the microwave moisture content is slightly higher (Figure 7). But, for only low values (Figure 8) the microwave moisture content is slightly smaller.

The comparisons with conventional oven moisture contents are primarily for aggregate only (Figures 5 - 8). The comparisons of microwave and distillation (Figures 1 - 4) show no apparent difference between asphalt-aggregate and aggregate only, although there are only four data points for aggregate.

In summary, Figures 1 - 8 show the following:

Microwave M.C. > Distillation M.C.,

Oven M.C. > Distillation M.C. and

Oven M.C. ≈ Microwave M.C.

Two proposed reasons for the differences between the distillation moisture content and microwave or oven moisture contents are as follows:

1. The distillation process is not as efficient in removing moisture and may leave some residual moisture in the aggregate.
2. The microwave and conventional oven may drive of volatiles from the asphalt cement.

The shape of the curves in Figures 3 and 4, and their apparent tendency toward the orgin suggests that incomplete drying in the distillation process may be the more important factor.

The magnitude of weight loss in asphalt cement during heating can be used to substantiate the above speculation. Table 3 was extracted from a paper by

Table 3. Average Percent Weight Loss in TFOT (Puzinauskas, AAPT 1979)

Viscosity Grade	Avg of Samples With Gain (%)	Avg of Samples With Loss (%)	Avg of all Samples (%)
2.5	+0.06 (4)	-0.21 (2)	-0.03 (6)
5	+0.04 (5)	-0.34 (11)	-0.22 (16)
10	+0.05 (4)	-0.37 (16)	-0.29 (20)
20	+0.05 (6)	-0.31 (9)	-0.17 (15)
40	+0.04 (3)	-0.27 (8)	-0.19 (11)

Number of samples in parentheses.
+ indicates weight gain.
- indicates weight loss.

Puzinauskas (26) and gives percent weight loss in the thin film oven test (TFOT). The average percent weight loss for all grades of asphalt cement is (0.03 - 0.29%) and the average for only those samples losing weight is (0.21 - 0.37%).

If the average for only those AC-20 samples losing weight is used, 0.31%, a typical example will illustrate the relative influence of weight loss in the asphalt cement. For example, assume the moisture content for a 500 gm sample of mix with 6% asphalt cement was measured in the microwave as 0.2%. The mass of asphalt in the sample would be 0.06 x 500 gm = 30 gms. The mass loss for the asphalt cement would then be 30 x 0.0031 = 0.093 gms. The total water and light end volatile loss in the moisture sample would be 500 x 0.002 = 1 gm. If the light end volatile loss is subtracted from the total loss, the true water loss would be 0.907 gms and the true water content would be (0.907 ÷ 500)100 = 0.18%. This constitutes a 10% difference.

The above calculation is intended only to illustrate the approximate difference that could be caused by a loss of light end volatiles. Conditions in a TFOT sample and a moisture content sample of asphalt-aggregate mix are quite different. The asphalt film thickness and, thus, the exposed asphalt surface is much greater in the sample of mix. However, the temperature and time in the moisture content test are less and should somewhat counteract the effect of the larger exposed surface. In the TFOT the sample is heated to 325°F for 5 hours while the moisture content tests were run at 235°F for about 2-1/2 hours. Two samples each of an AC-10, AC-20 and AC-30 from the same source were heated at 235°F for 2-1/2 hours to see if weight losses comparable to TFOT losses would be achieved. The average percent weight losses were 0.05%, 0.13% and 0.05% for the AC-10, AC-20 and AC-30, respectively.

After examining and analyzing the moisture content data, the microwave method was selected for use in the study. Moisture contents reported for the remainder of the report will be measured with the microwave.

Field Moisture Contents

Residual moisture in hot mix asphalt concrete is a reality. Figure 9 shows the not uncommon phenomenon of steam rising from a recently loaded truck of mix. Conditions for and the consequences of residual moisture were discussed earlier.

Hot bin and mix moisture contents were measured for the five mixes sampled in the field. Hot bin moisture contents are listed in Table 4 along with comments. It can be noted that there is a direct correlation between the amount of residual moisture in the aggregate and the weather conditions, hot and dry or cool and rainy.

The moisture contents are plotted in Figure 10 to illustrate the influence of particle size. The data confirms the strong influence of particle size and provides justification for the laboratory process used to prepare "wet" mixes.

Moisture contents for field mixes are listed in Table 5. Again there is a positive correlation between weather conditions and moisture content. For mix F there is also evidence that plant startup may lead to higher moisture content in the mix, but as plant conditions stabilize the moisture content decreases and stabilizes. For mixes D and F there are indications that moisture is lost during hauling and spreading.

To summarize, field moisture measurements confirm the presense of moisture, the concentration in coarse particles and the dependence on weather and plant operating conditions. Construction variability may provide an explanation for the observed inconsistencies in stripping occurance between and within projects which

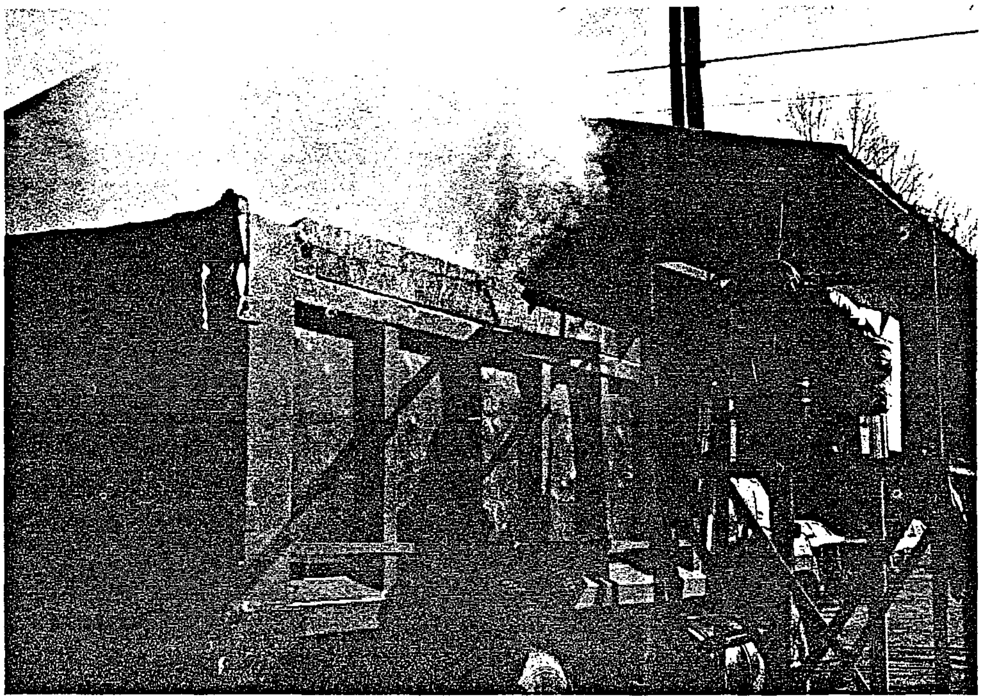

Figure 9. Steam Rising From Recently Loaded Truck of Hot Mix.

Table 4. Hot Bin Moisture Content

Mix	Bin				Comments
	Coarse	M. Coarse	M. Fine	Fine	
A	0.07%	0.10%	0.08%	0.06%	Sampled 6/16/88, Dry
F	1.10%	0.32%	0.29%	0.08%	Sampled 4/12/88, Rainy
G	0.07%	0.06%	0.05%	0.03%	Sampled 5/17/88, Dry
H	0.65%	0.36%	0.07%	0.03%	Sampled 10/26/88, Rainy
I	0.38%	0.13%	0.03%	0.01%	Sampled 11/3/88, Rainy

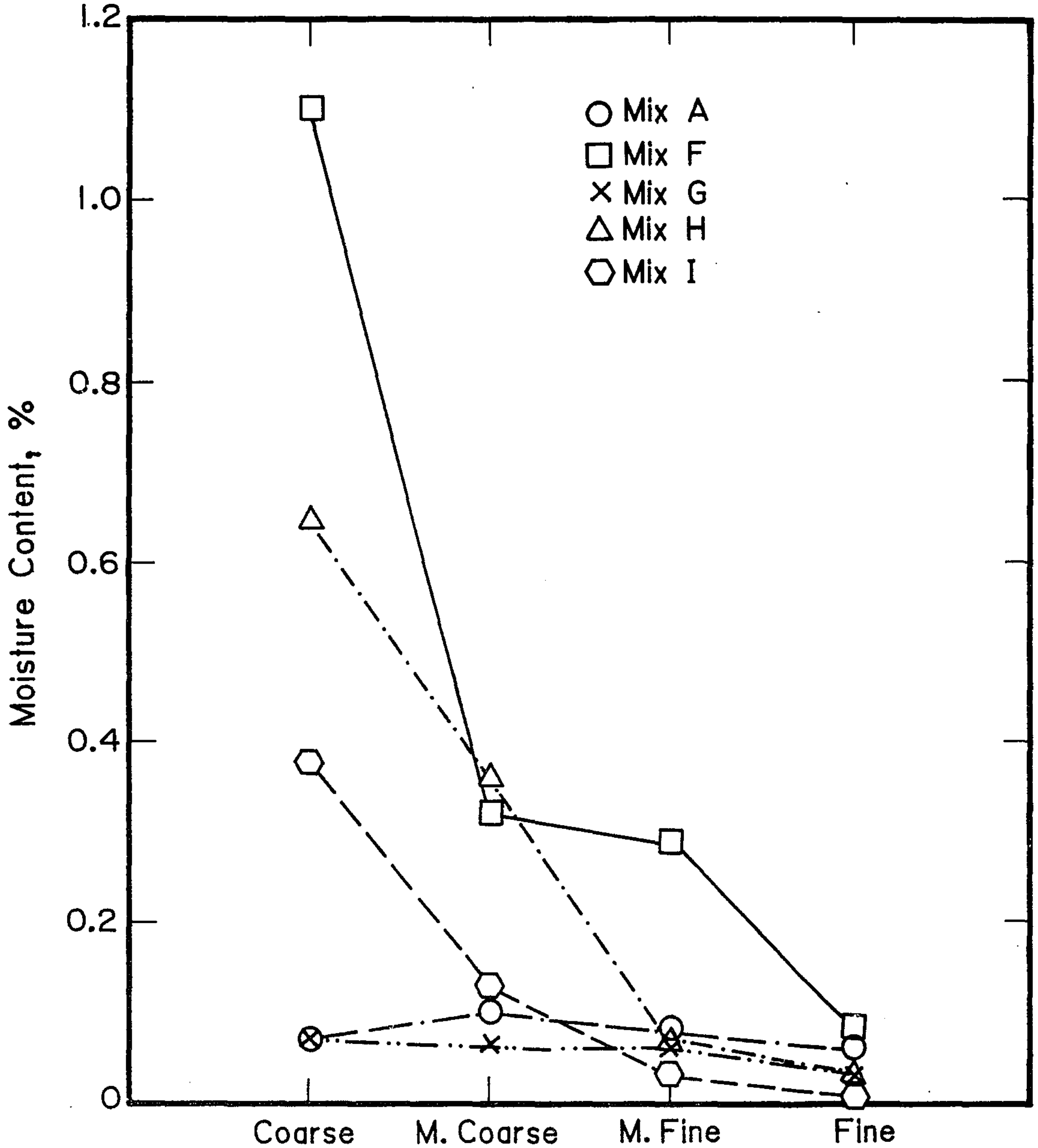

Figure 10. Hot Bin Moisture Content.

Table 5. Moisture Contents of Field Mixes

Mix	Pug Mill	Spreader	Comments
A	0.08%	–	Sampled 6/16/88, Dry
D*	0.20%	0.07%	Sampled, 11/10/87
F	0.57%	–	Sampled 4/12/88, 8:30 a.m.
	0.41%	–	Sampled 4/12/88, 2:00 p.m.
	0.39%	–	Sampled 4/12/88, 4:00 p.m.
F	0.58%	–	Sampled 4/13/88, 8:30 a.m.
	0.26%	–	Sampled 4/13/88, 11:20 a.m.
	0.30%	–	Sampled 4/13/88, 1:30 p.m.
F	0.35%	0.21%	Sampled 4/14/88, Rainy
	0.48%	0.23%	Sampled 4/14/88, Rainy
G	0.03%	0.03%	Sampled 5/17/88, Dry
	0.05%	–	Sampled 6/7/88, Dry
H	0.39%	–	Sampled 10/26/88, Rainy
I	0.25%	–	Sampled 11/3/88, Rainy
	0.30%	–	Sampled 11/3/88, Rainy

*Data for mix tested in earlier study, reference 1.

have basically the same mix.

Indirect Tensile Tests

Indirect tensile test results for all six mixes are tabulated in Table 6. Included are results from field mixes, laboratory mixes prepared with standard procedures, and "wet" laboratory mixes. Each row contains average moisture content, voids and percent saturation for sets of six samples. Unconditioned and conditioned strengths are averages for sets of three samples each, and the TSR and VSI are ratios of the tensile strengths and percent retained coatings for the sets.

Dolomitic Limestone Mixes. Mixes A and J have base/binder gradations and the mineral aggregate is comprised of 90% dolomitic limestone. Mix composition and properties are given in Table 1. The source for the dolomitic limestone for Mix A (S1) is the same as used in the earlier study (1). The source for Mix J (S11) is different, but from the same geographic area and geologic formation.

From Table 6 it can be noted that the low TSR's for the standard laboratory samples (A = 31.3 and 55.4%, J = 0 and 10.2%) are contrary to the generally good reported field performance. However, the values for Mix A are consistent with results from the previous study (1). As expected, the inclusion of RAP in Mix A increased unconditioned strength, conditioned strength and TSR. For Mix A, field samples had higher strengths and retained strength ratios than comparable laboratory prepared samples.

To study the effects of residual moisture, data from Table 6 were plotted in Figures 11-17. Least square straight lines were fit to the data. Plots were made with data from only laboratory samples with 6-8% voids, and with all available data points

Table 6. Summary of Indirect Tensile and Boil Test Data

	Indirect Tensile Test							Boil Test
Mix	M.C. (%)	Voids (%)	Sat. (%)	U.C. Str. (psi)	C. Str. (psi)	TSR (%)	VSI (%)	Coating Ret. (%)
A-Lab	0	7.3	75	109.4	34.2	31.3	65	95
	0.18	7.8	68	68.5	32.8	47.9	65	--
	0.44	7.4	78	83.5	42.5	50.9	65	--
	0.54	7.6	68	74.6	47.9	64.1	70	--
	0.46	8.3*	70	78.1	36.9	47.2	70	--
w/RAP	0	7.3	67	132.4	73.4	55.4	80	95
A-Field	0.08	7.4	78	134.5	84.1	62.5	60	95
w/RAP	0.28	9.4*	90**	164.3	93.5	56.9	65	100
F-Lab	0	7.6	68	125.7	88.4	70.3	85	95
	0.21	7.1	69	110.1	35.7	32.4	65	--
	0.66	7.1	70	101.6	43.0	42.3	60	--
	0.90	10.7*	79	78.8	25.6	32.8	65	--
	1.50	8.6*	79	86.6	34.3	39.6	55	--
w/AS	0	6.9	62	165.4	128.7	77.8	100	--
F-Field	0.58	7.8	69	117.6	74.5	63.4	55	95
	0.30	9.7*	79	120.1	68.5	57.1	--	--
	0.30	8.8*	73	134.0	79.1	59.0	60	--
w/AS	0.26	8.4*	77	114.8	76.4	66.6	95	--
Cores	--	10.5*	73	72.7	58.7	80.7	--	--
G-Lab	0	6.2	71	137.1	77.7	56.7	70	95
	0.20	8.1*	66	134.4	72.7	54.1	60	--
	0.40	8.4*	78	88.4	47.2	53.4	--	--
	0.45	7.2	76	124.7	49.6	40.0	60	--
	0.75	8.5*	67	110.3	46.7	42.3	55	--
G-Field	0.05	6.6	78	121.3	65.2	53.8	65	65
	0.03	5.9*	75	108.3	59.4	54.8	--	90
H-Lab	0	7.7	76	77.8	43.8	56.3	80	60
	0.42	7.7	70	91.6	37.2	40.6	60	30
	0.43	6.7	70	106.9	42.8	40.0	70	40
	0.48	7.5	80	88.4	27.6	31.3	60	30
H-Field	0.39	7.0	72	104.5	85.5	81.8	65	40
I-Lab	0	6.2	73	205.8	129.6	63.0	65	35
	0.27	7.9	77	137.4	77.2	56.2	65	50
	0.54	8.2*	67	120.2	78.5	65.3	65	30
	0.70	7.4	76	158.1	63.6	40.2	55	35
I-Field	0.25	5.3*	82**	268.2	169.2	63.1	65	35
w/AS	0.30	8.2*	72	161.6	109.9	68.0	70	--
J-Lab	0	7.2	79	--	0	0	50	50
(Set 1)•	0.19	7.1	74	80.9	14.9	18.4	70	50
	0.32	6.3	68	72.3	27.0	37.3	65	55
	0.40	6.6	76	72.1	23.5	32.7	70	50
J-Lab	0	6.3	75	127.9	13.0	10.2	55	--
(Set 2)•	0.17	6.9	76	115.9	16.3	14.3	55	--
	0.24	6.8	71	121.6	17.3	14.3	50	--
	0.38	6.8	70	112.0	33.1	29.5	50	--

*Voids ≠ 6-8%   **Saturation ≠ 60-80%   •Set 1 and Set 2 with different sources of AC20

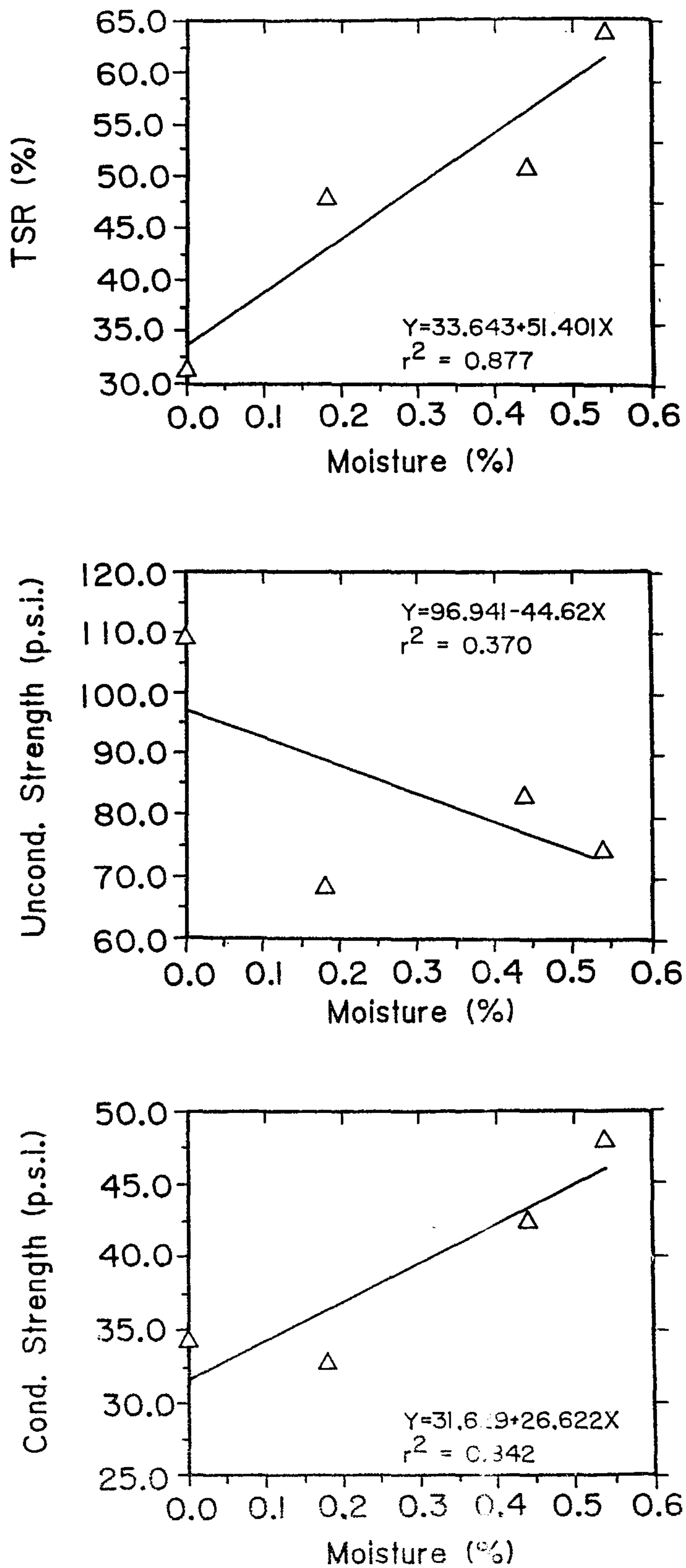

Figure 11. Mix A, Wet-Dry Tensile Test, Lab Data.

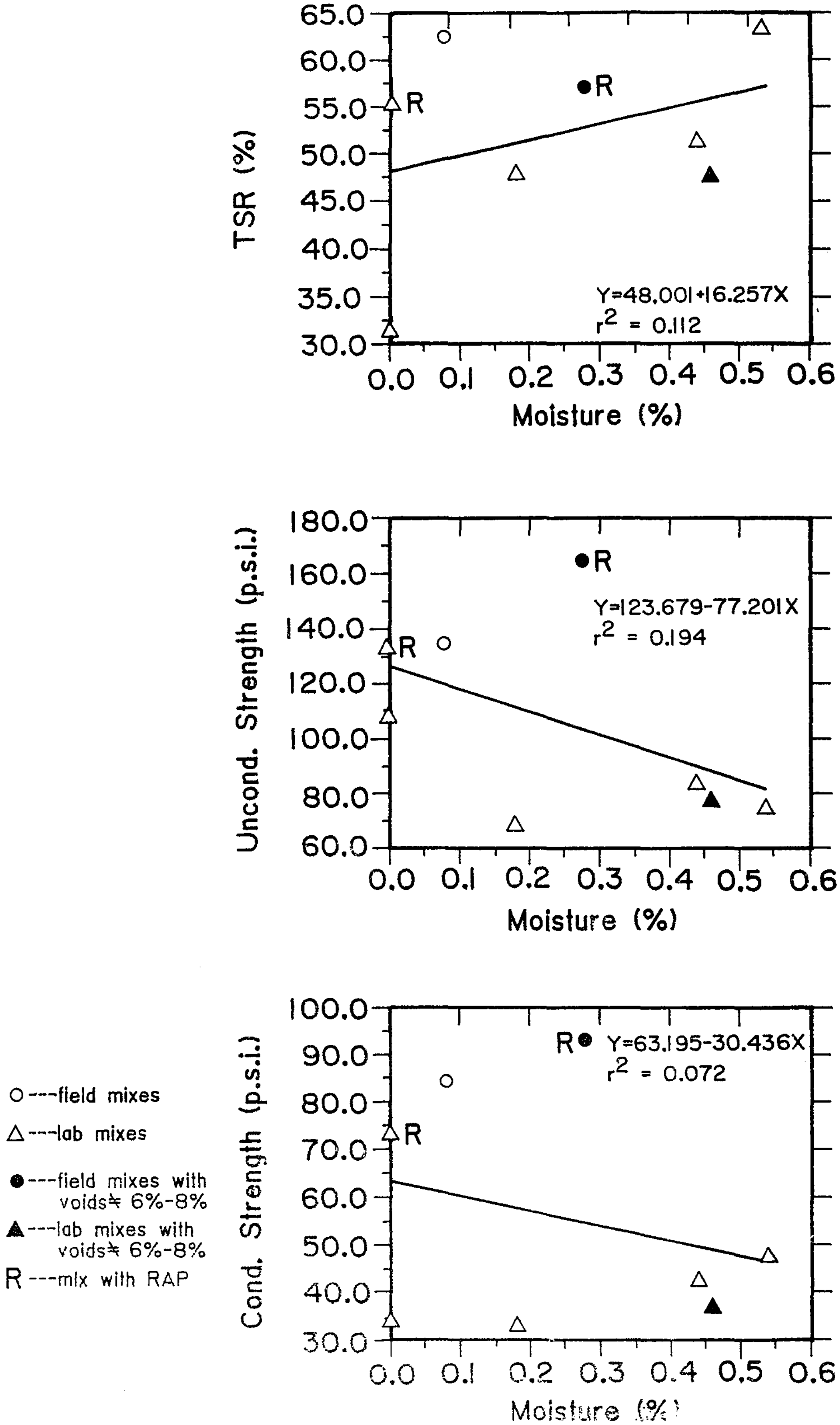

Figure 12. Mix A, Wet-Dry Tensile Test, All Data.

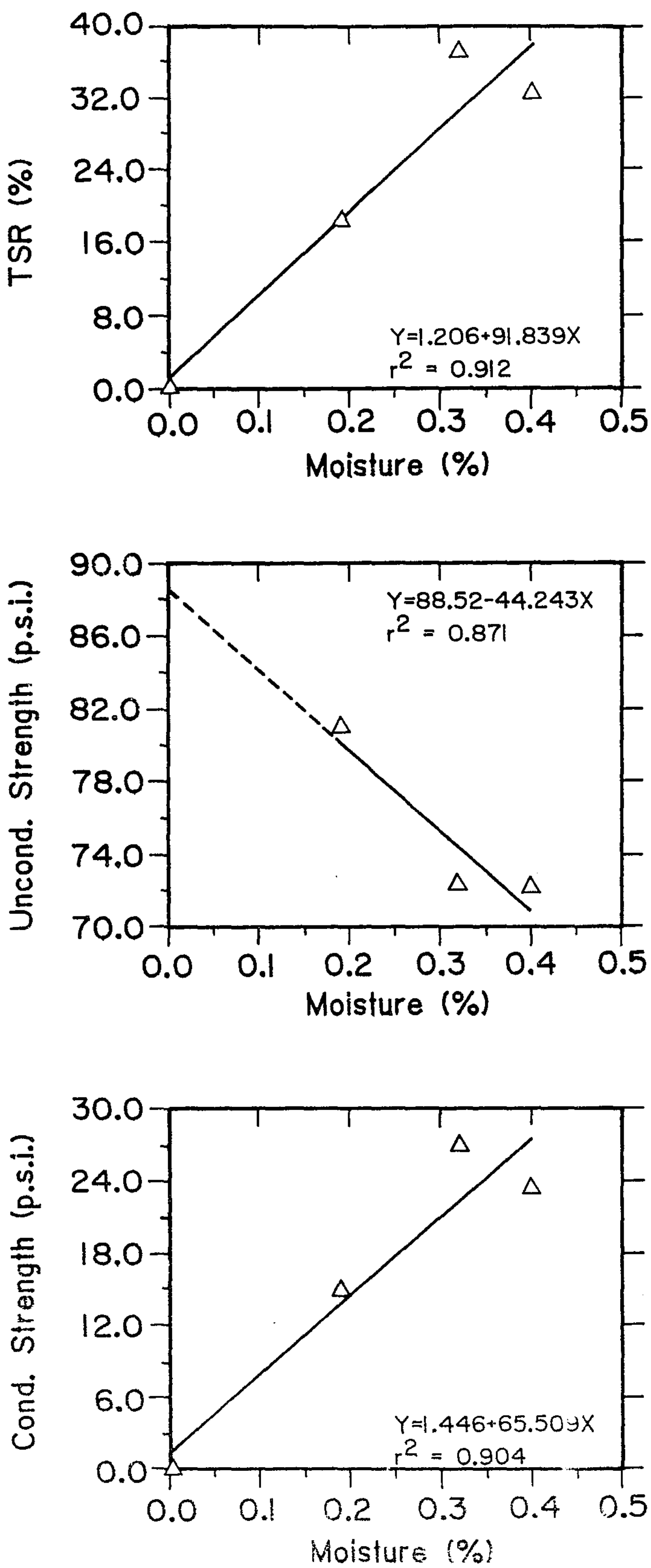

Figure 13. Mix J, Set 1, Wet-Dry Tensile Test, Lab Data.

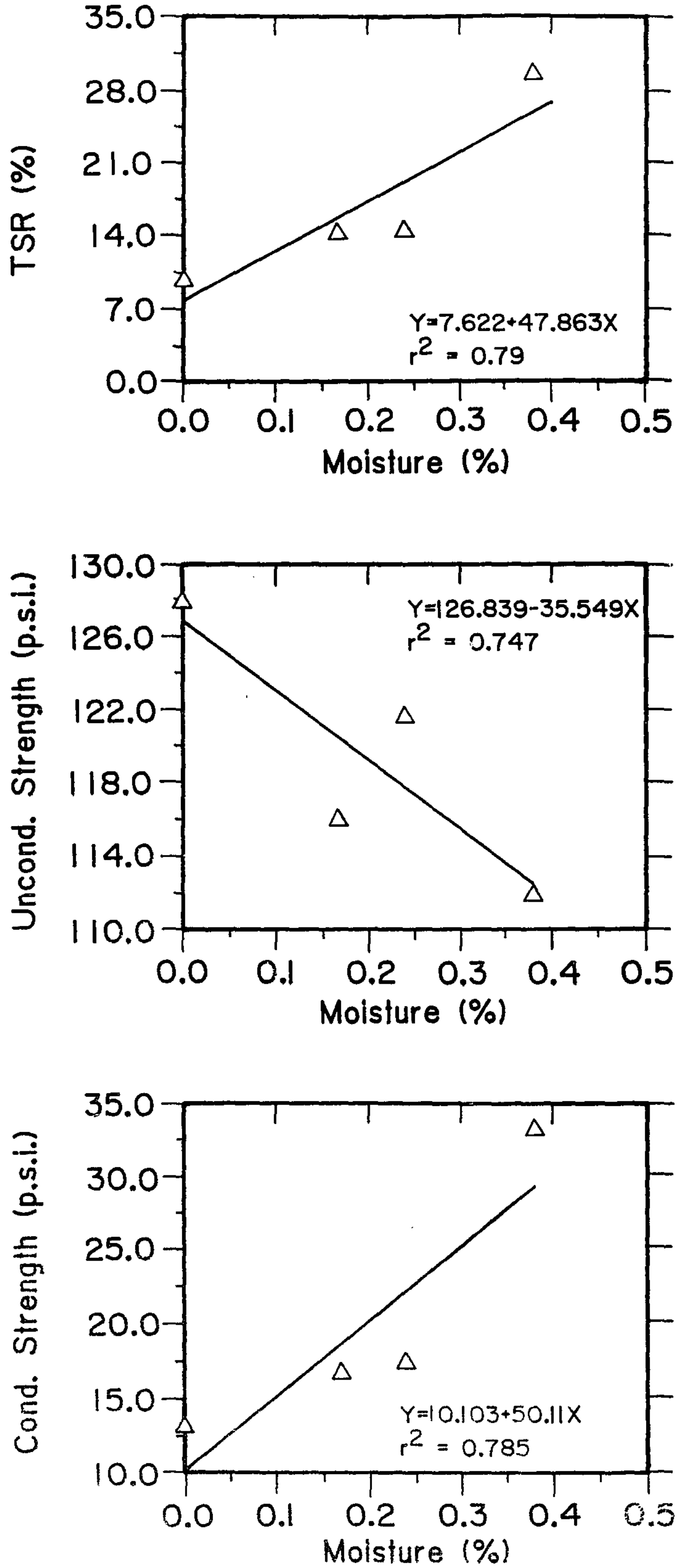

Figure 14. Mix J, Set 2, Wet-Dry Tensile Test, Lab Data.

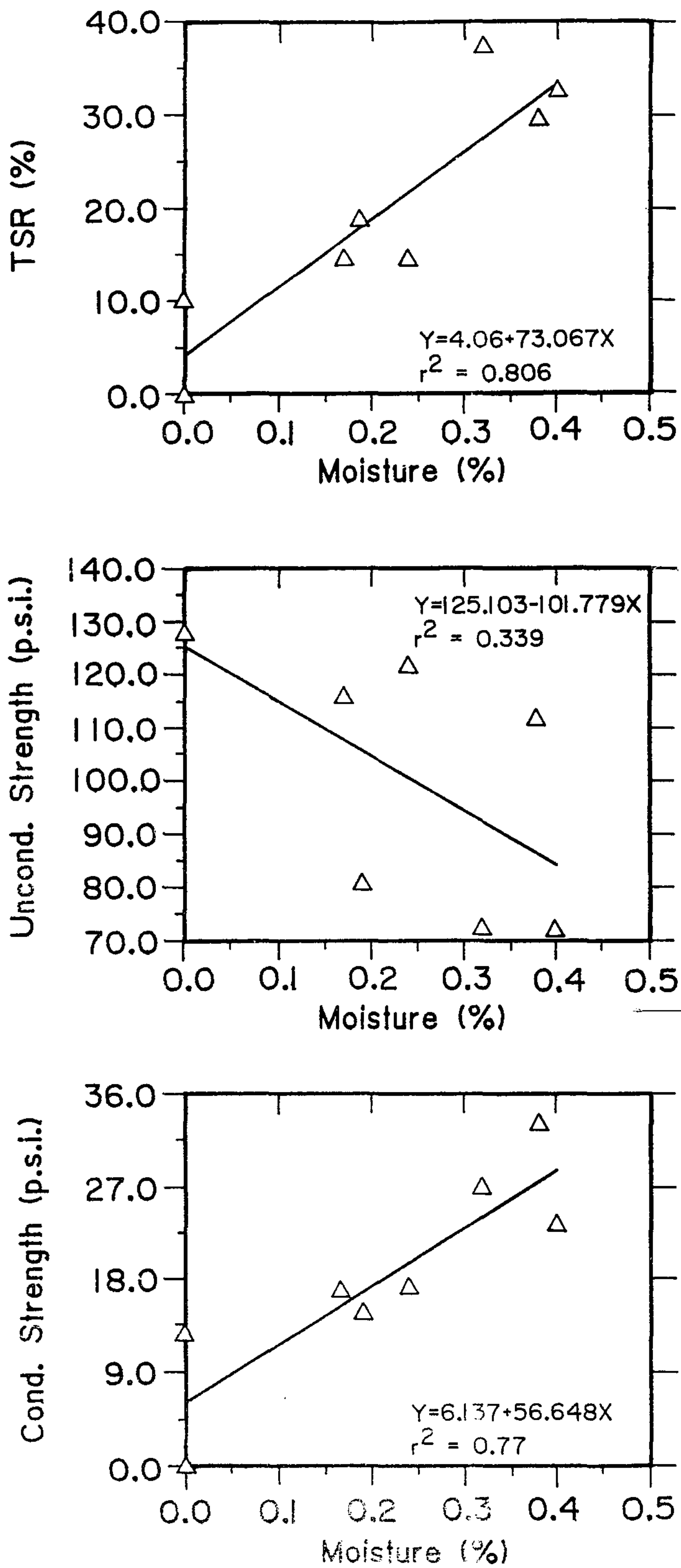

Figure 15. Mix J, Sets 1 & 2, Wet-Dry Tensile Test, Lab Data.

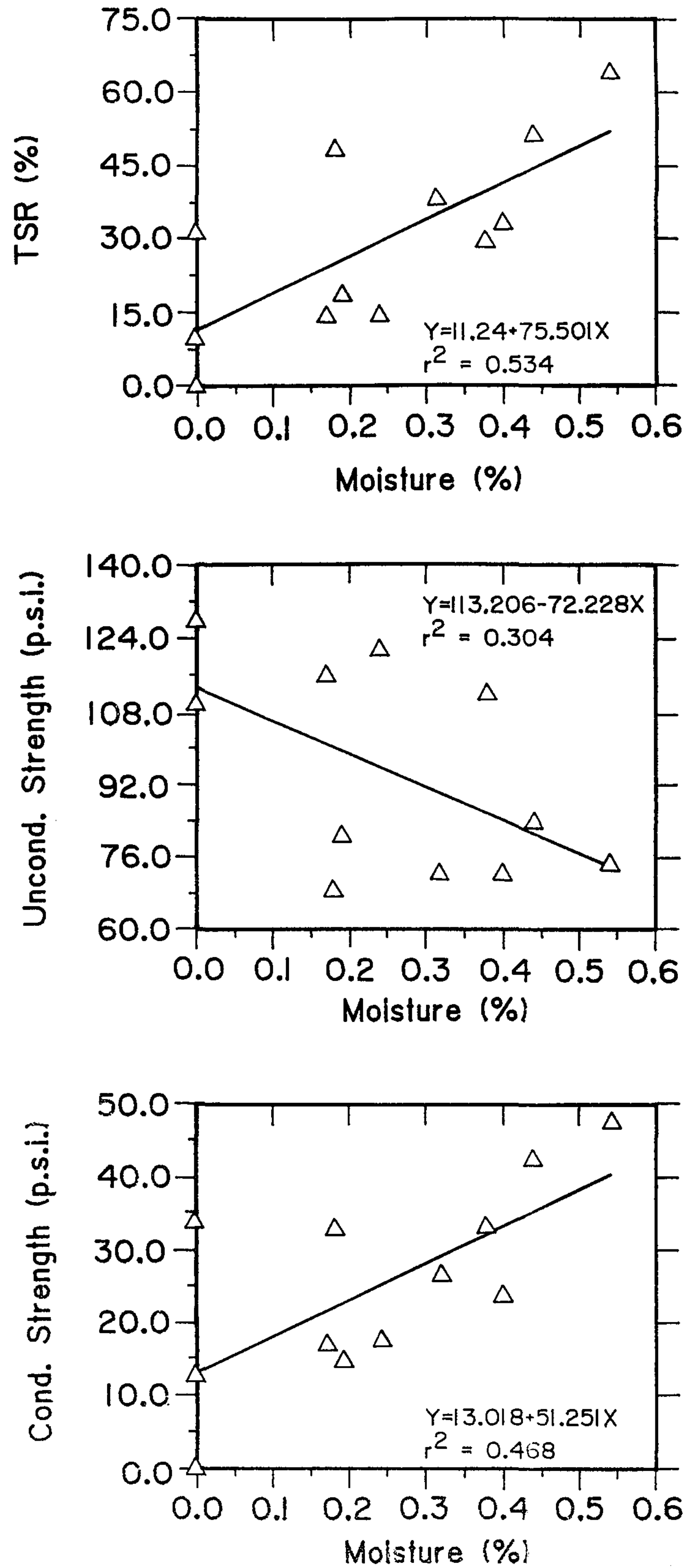

Figure 15. Mixes A & J, Wet-Dry Tensile Test, Lab Data.

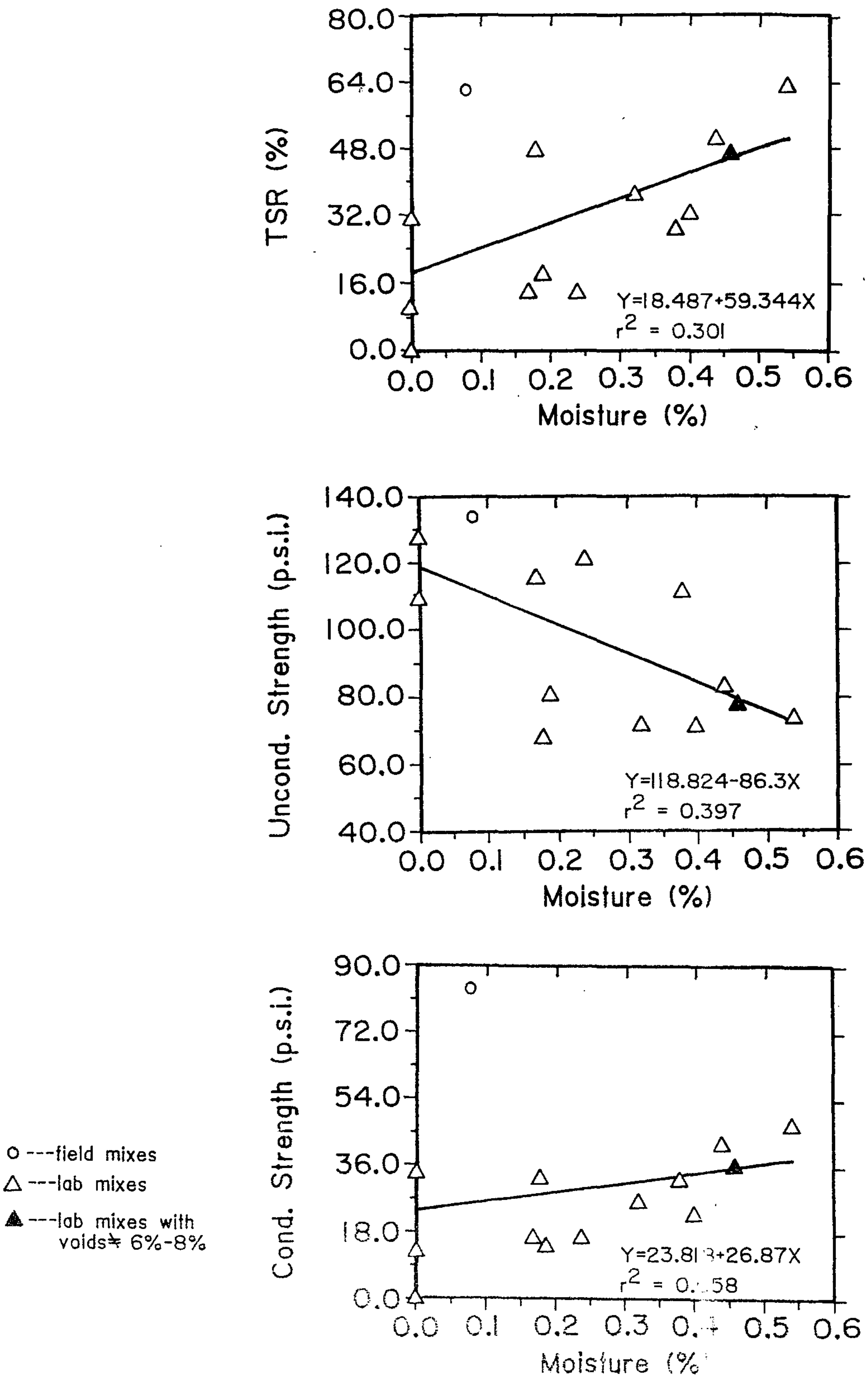

Figure 17. Mixes A & J, Wet-Dry Tensile Test, All Data.

which included field samples as well as samples that did not have the specified 6-8% voids.

Equations for both mixes and all data sets, unexpectedly, show that TSR increases as moisture content increases. For only laboratory data (Figures 11, 13, 14, 15 and 16), the coefficients of determination (r^2) indicate good correlations, with values ranging from 0.912 for Mix J, set 1 to 0.534 for Mixes A and J combined. When field samples and samples with voids $\neq$ 6-8% are included (Figures 12 and 17), r^2 values are lower but the trend remains the same. However, the poorer correlations are probably due, in part, to variability in mix type, sample preparation and test conditions.

In all cases, except for Mix A with all data included (Figure 12), the increase in TSR as moisture content increases is the result of decreasing unconditioned strength and increasing conditioned strength. The $r^2 = 0.072$ for the exception suggests that there is no relationship between conditioned strength and moisture content. However, examination of the data points in Figure 12 reveals that the field mixes and mixes with RAP are quite different from the laboratory mixes and are responsible for the poor correlations and the negative slope of the line for conditioned strength.

The causes or reasons why residual aggregate moisture in the dolomitic limestones produces asphalt-aggregate bonds that are more resistant to the detrimental effects of water is not known. However, the evidence, increasing TSR and conditioned strength for two aggregate and three asphalt cement sources, strongly suggests that the observed trends are real. The explanation is likely a surface chemistry phenomenon resulting from unusual chemical composition and/or crystal structure.

Both limestones are quite dense (apparent specific gravities greater than 2.8) and have relatively low absorptions. Complete drying, as in standard laboratory mix preparation, produces bonds that are somewhat stronger if kept dry, but which dramatically lose strength when exposed to water. Conversely, small amounts of residual aggregate moisture produces bonds that are not as strong if kept dry, but which are more effective in resisting the detrimental effects of moisture.

The observed influence of moisture may offer an explanation for the inconsistency in observed good field performance and poor performance predicted by low TSR. The small amounts of residual moisture in field mixes may produce moisture resistant bonds which are not properly modeled with standard laboratory mix preparation procedures.

However, residual moisture does not provide a complete explanation of differences between observed and predicted performance. Even with residual moisture, TSR values for Mixes A and J are well below widely used criteria of 70 to 80%. In addition, conditioned strengths for Mixes A and J are not dramatically different from conditioned strengths of the four siliceous gravel mixes that will be considered in the next section. Other factors, including field mixing and possibly storage, may also affect field performance. As illustrated in Figure 12, TSR's, unconditioned strengths and, most importantly, conditioned strengths of the field mixes are higher than comparable laboratory mixes.

Siliceous Gravel Mixes. Mixes F and G have base/binder gradations and mixes H and I have surface gradations. The mineral aggregate in all four mixes is comprised primarily of siliceous sands and gravels, but Mixes H and I have 8 and 10%, respectively, limestone filler. Mix composition and properties are given in Table 1. The materials for Mixes F, H and I are from the northwestern part of the state and have a history of stripping problems. The materials for Mix G are from the southwestern part of the state and has a history of only moderate stripping problems.

From Table 6 it can be noted that the TSR's for the standard laboratory samples are generally consistent with poor reported field performance for Mixes H and I, i.e., TSR < 70%. However, the TSR's of 56.3 and 63.0% were somewhat higher than expected. For Mix F with a history of poor performance, the TSR = 70.3% is right on the limiting criteria of 70% and also higher than expected. For Mix G, the TSR = 56.7% is generally consistent with a history of moderate stripping performance.

With the exception of Mix G; TSR, unconditioned strength and conditioned strength are higher for field samples than for comparable laboratory samples. This is consistent with observations for MIx A and may reflect the influence of better mixing and possibly storage in the field. However, for Mix G field values do not follow this trend and are somewhat smaller than comparable laboratory values.

To study the effects of residual moisture, data from Table 6 were plotted in Figures 18-27 and least square straight lines fit to the data. The same format was used for these plots and regression equations as was used for the dolomitic limestone mixes.

The plots and regression equations show that TSR, unconditioned strength, and conditioned strength decrease as moisture content increases except for unconditioned strength of Mix H. These are the expected trends and illustrate the detrimental effect of residual moisture. Examination of Figures 22 and 23 reveals poor distribution of the

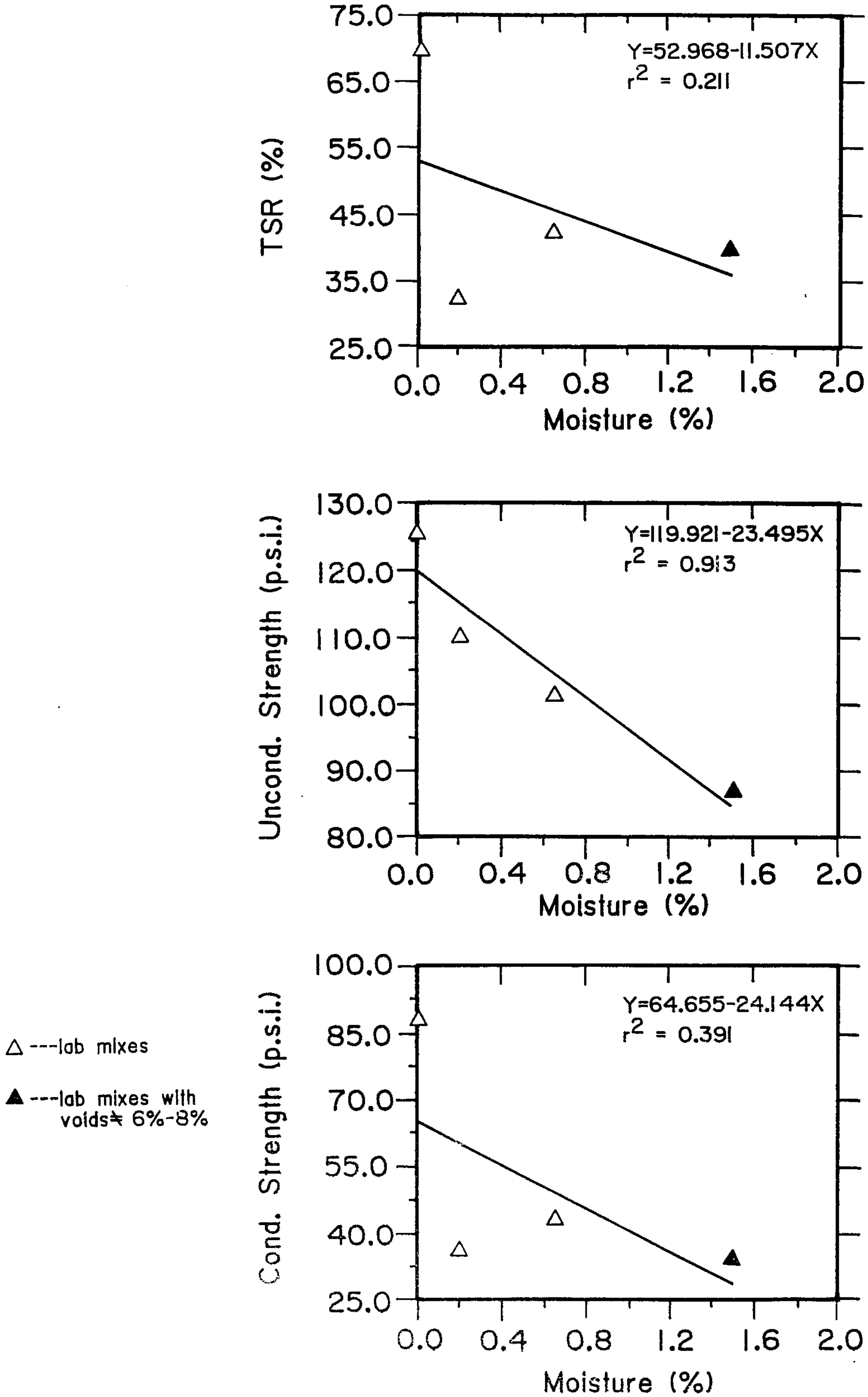

Figure 18. Mix F, Wet-Dry Tensile Test, Lab Data.

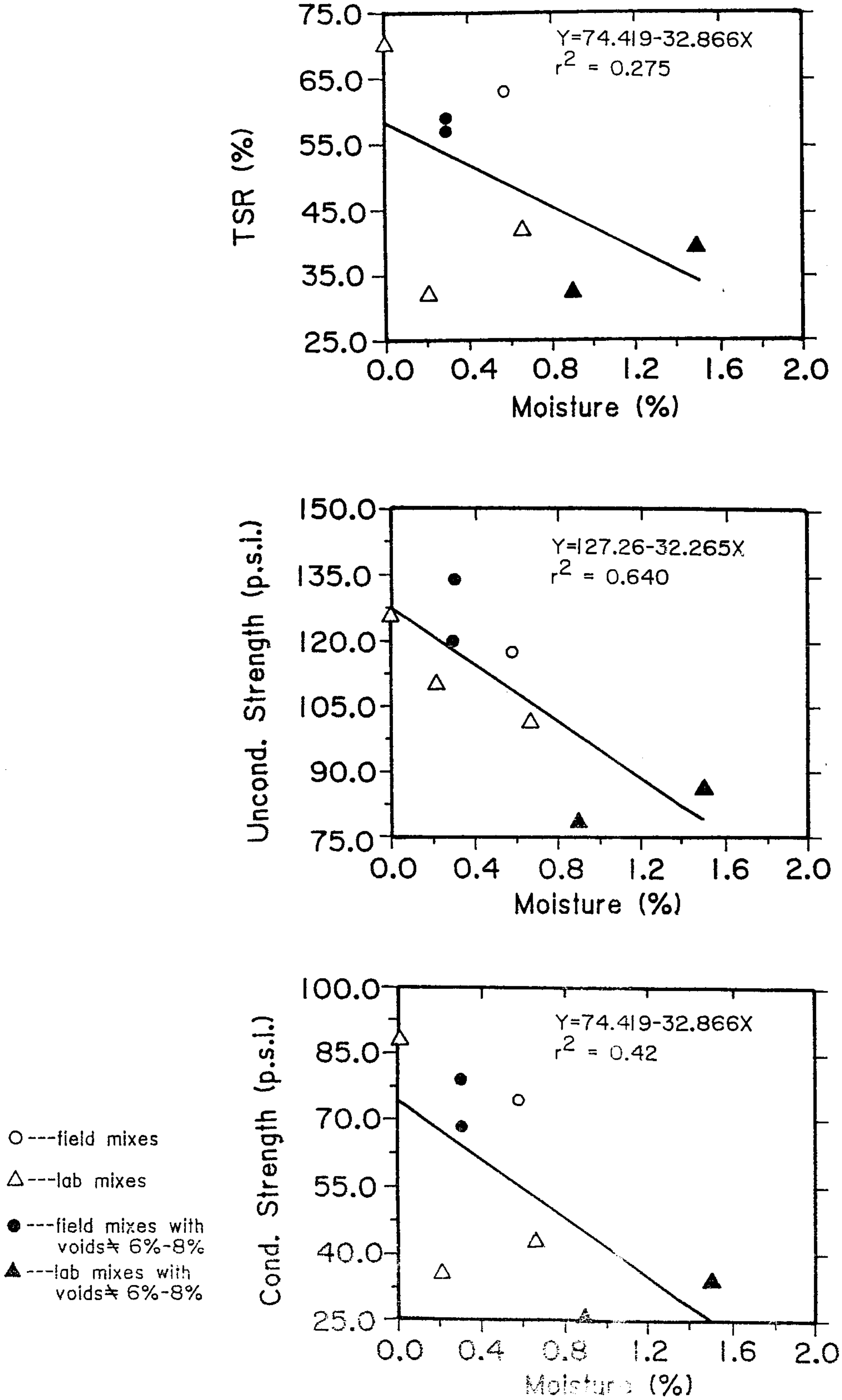

Figure 19. Mix F, Wet-Dry Tensile Test, All Data.

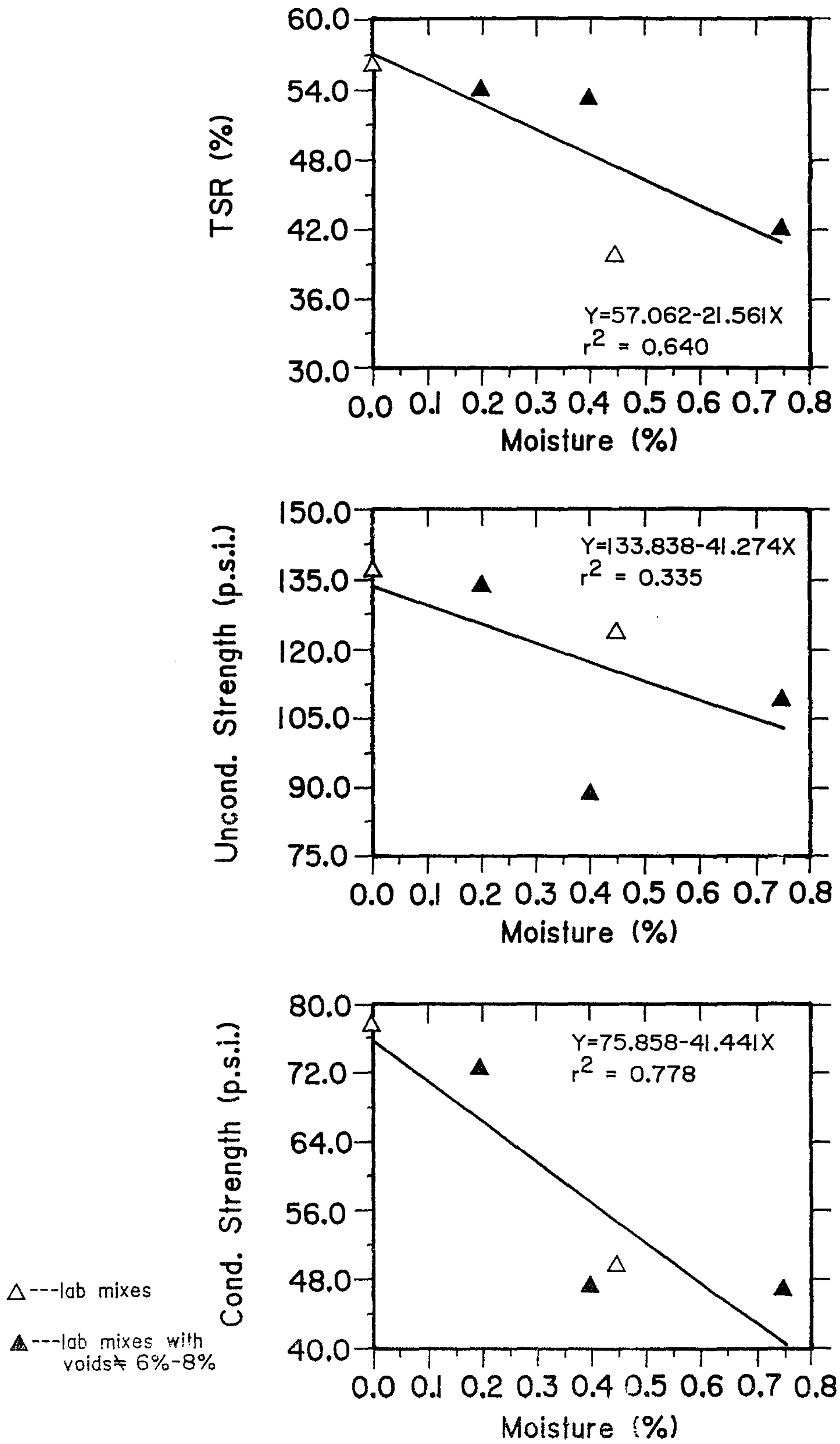

Figure 20. Mix G, Wet-Dry Tensile Test, Lab Data.

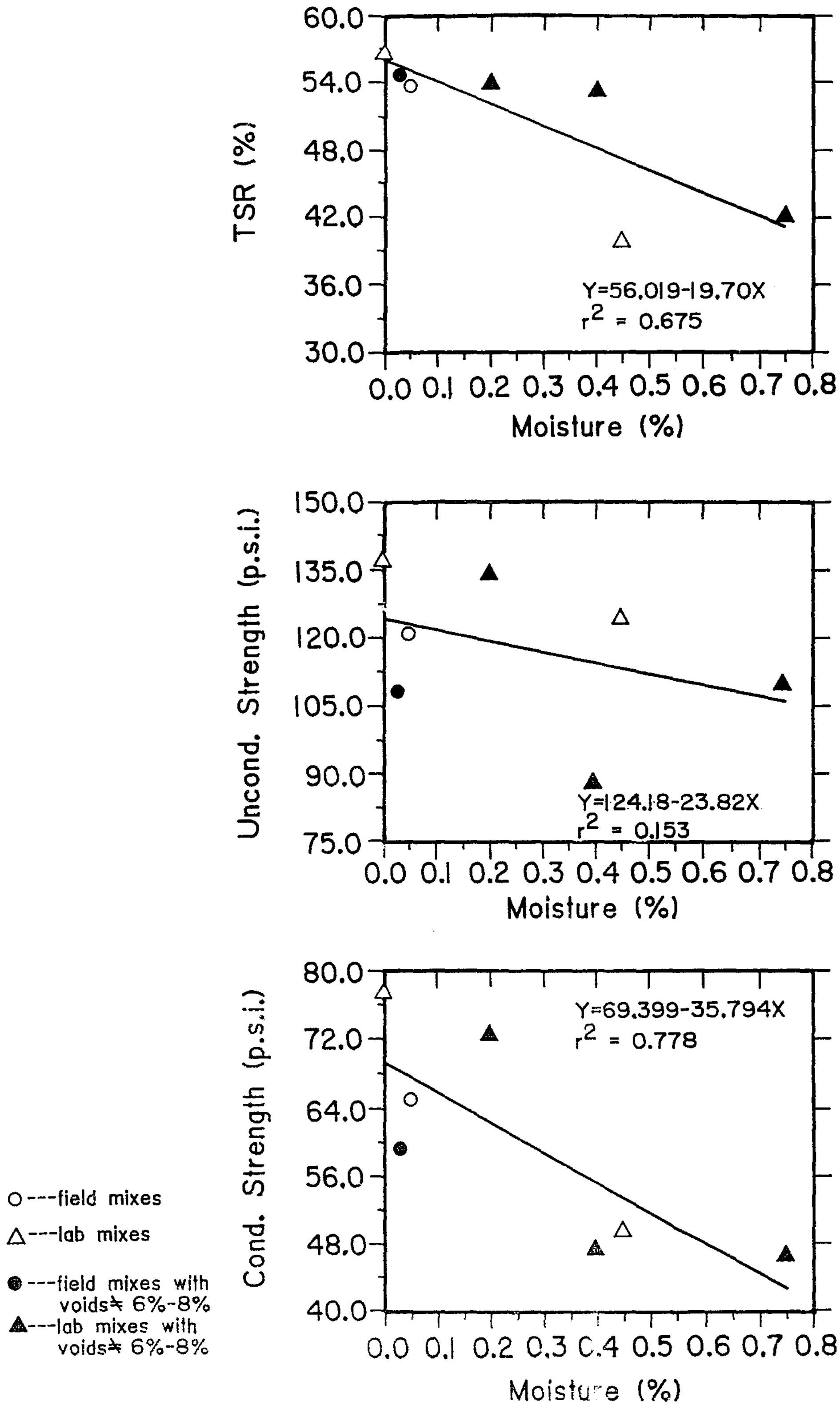

Figure 21. Mix G, Wet-Dry Tensile Test, All Data.

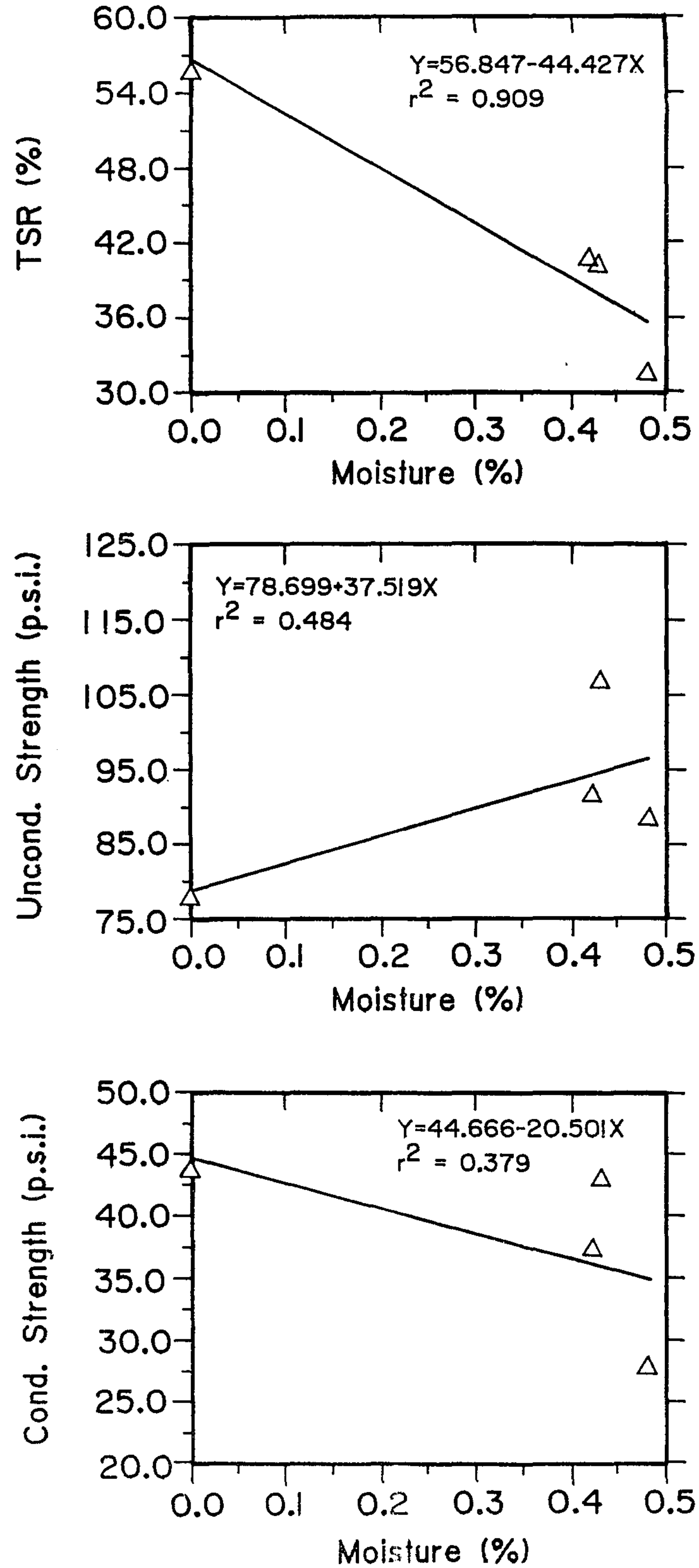

Figure 22. Mix H, Wet-Dry Tensile Test, Lab Data.

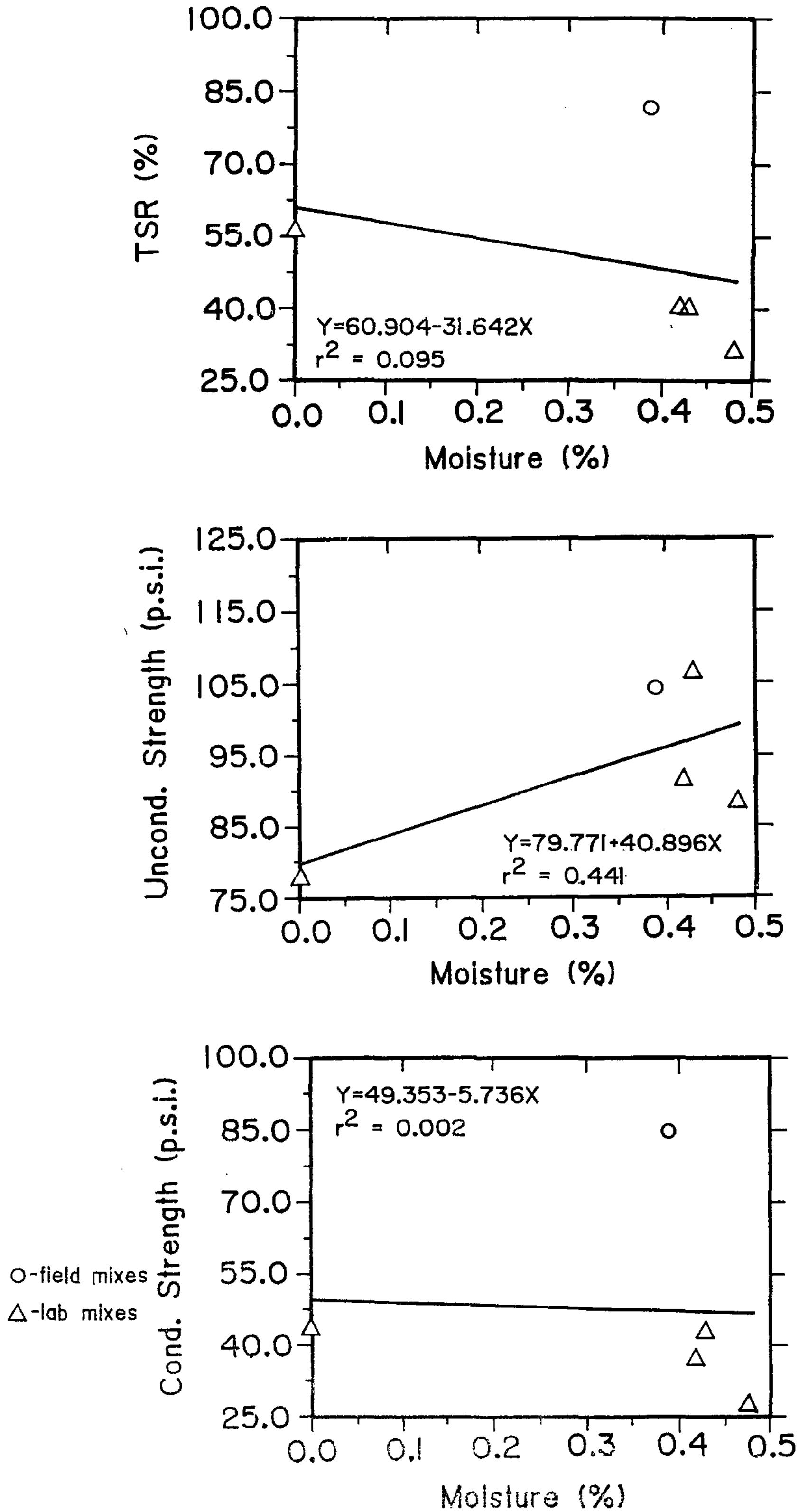

Figure 23. Mix H, Wet-Dry Tensile Test, All Data.

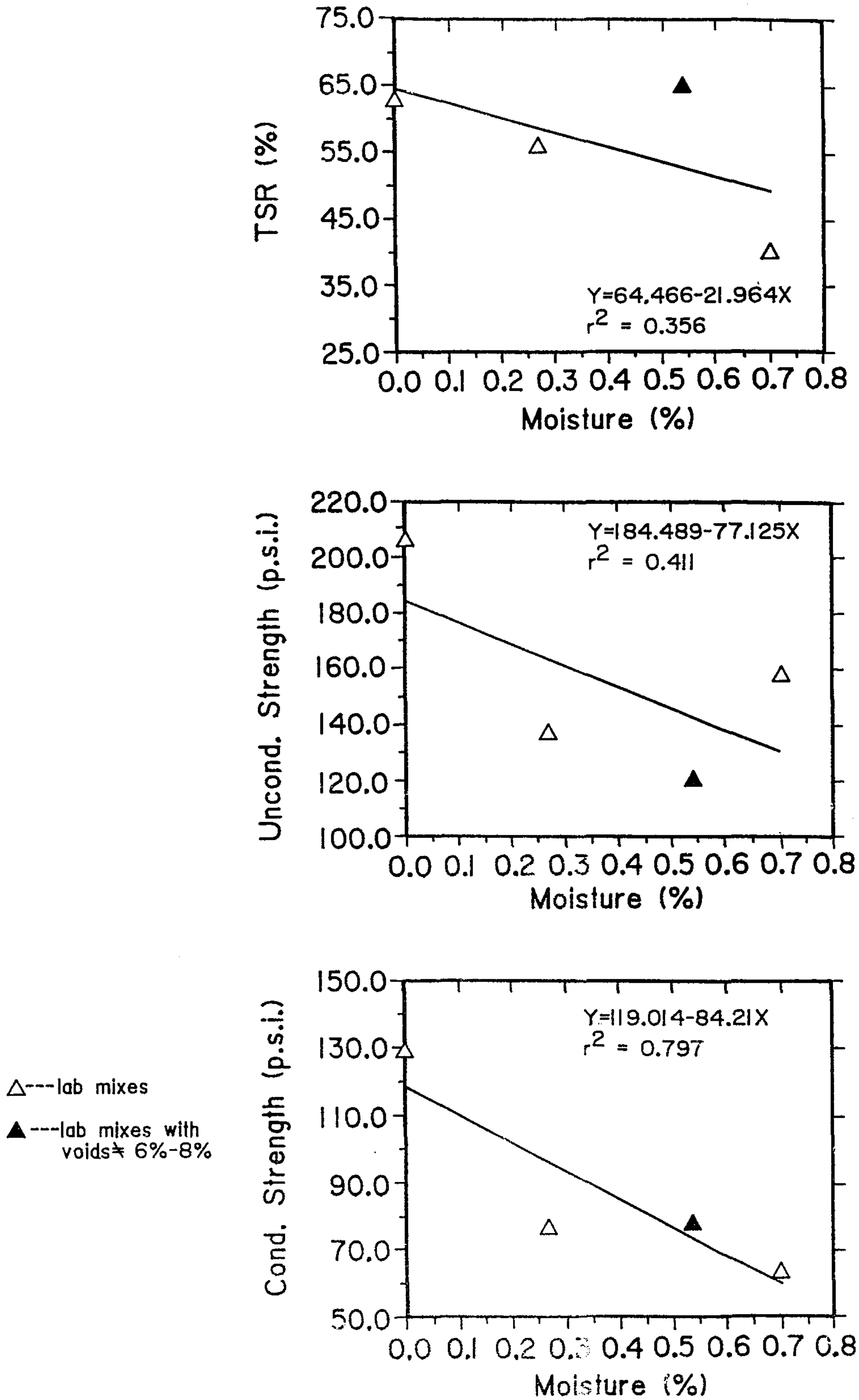

Figure 24. Mix I, Wet-Dry Tensile Test, Lab Data.

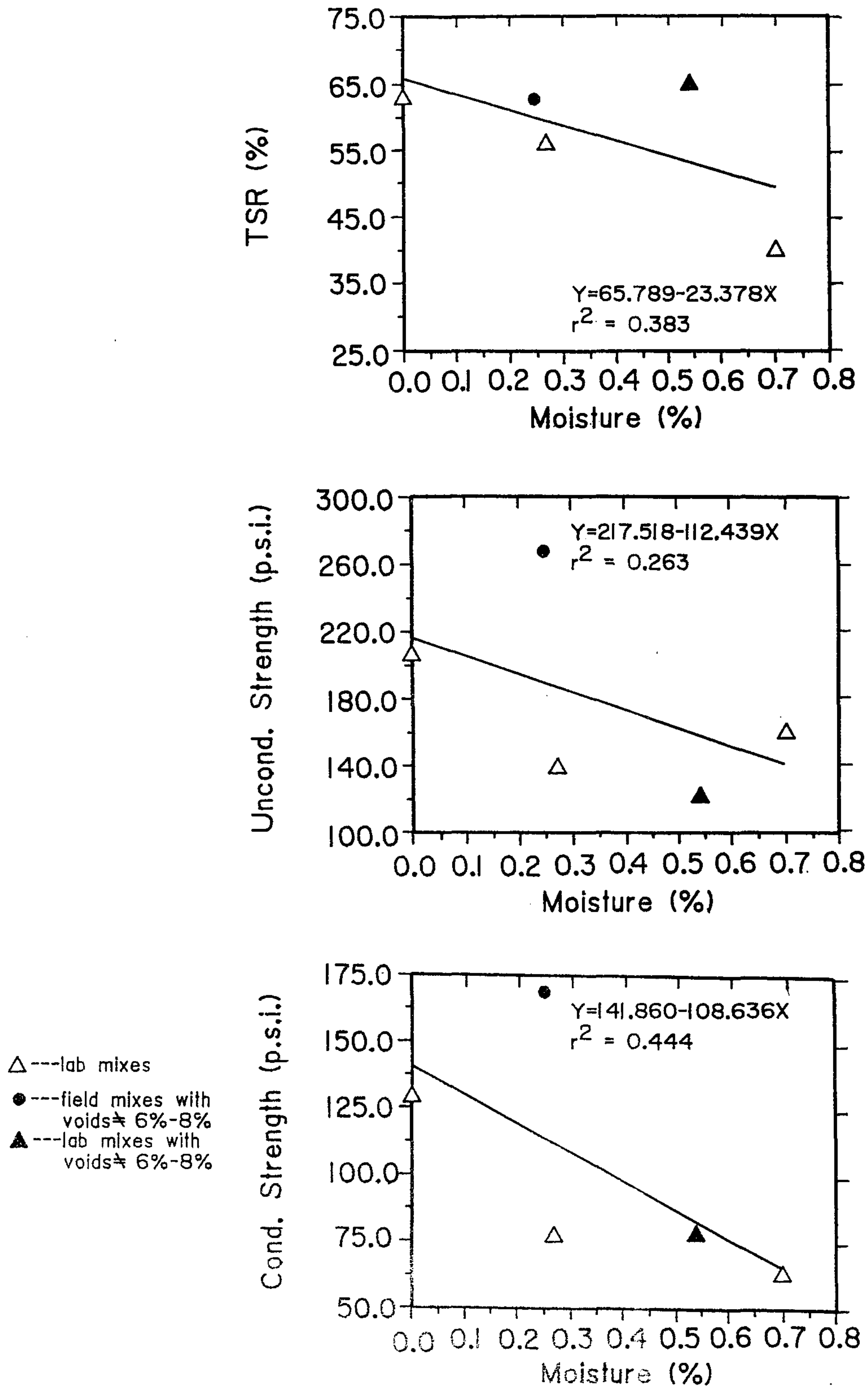

Figure 25. Mix I, Wet-Dry Tensile Test, All Data.

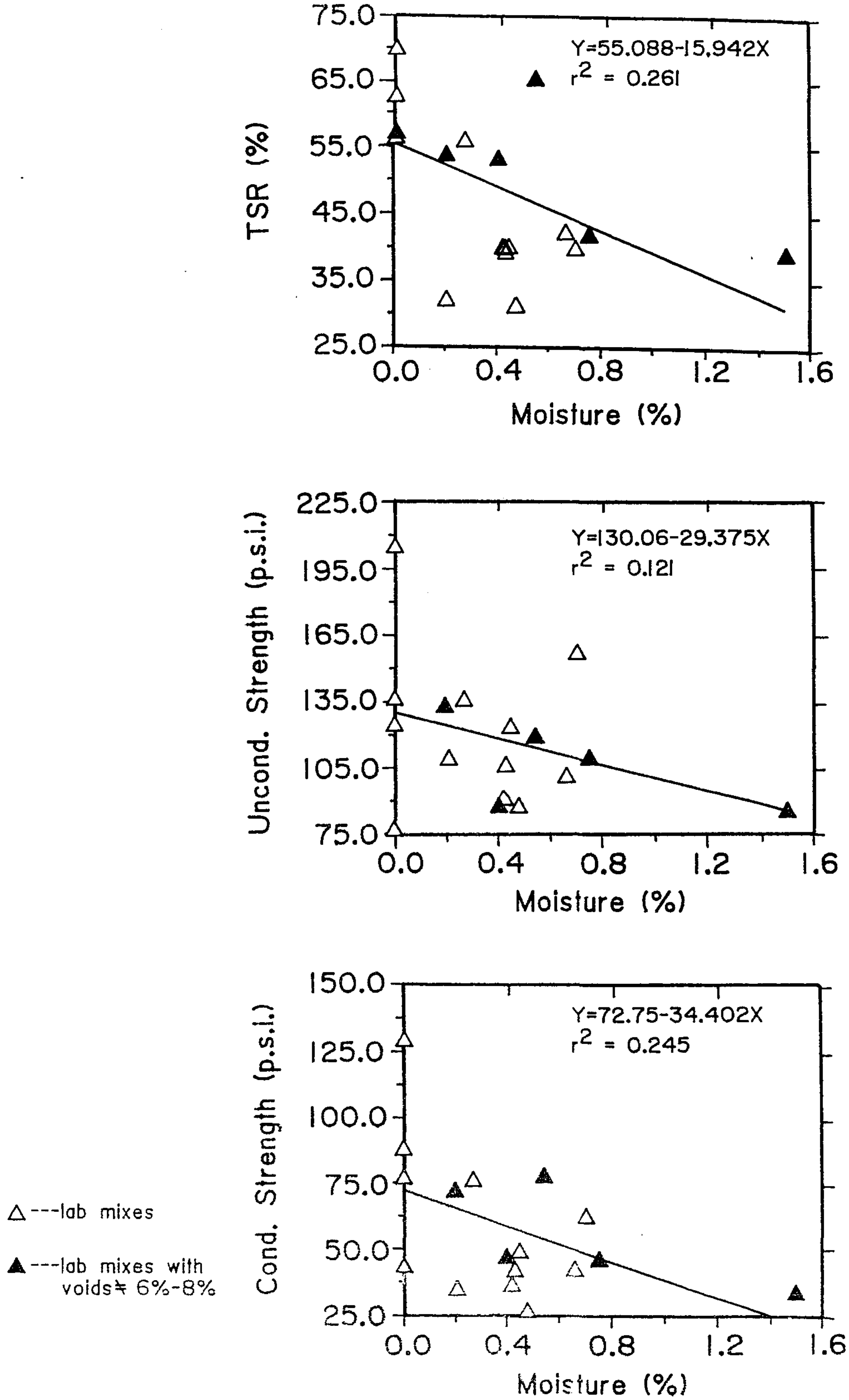

Figure 26. Mixes F, G, H & I, Wet-Dry Tensile Test, Lab Data.

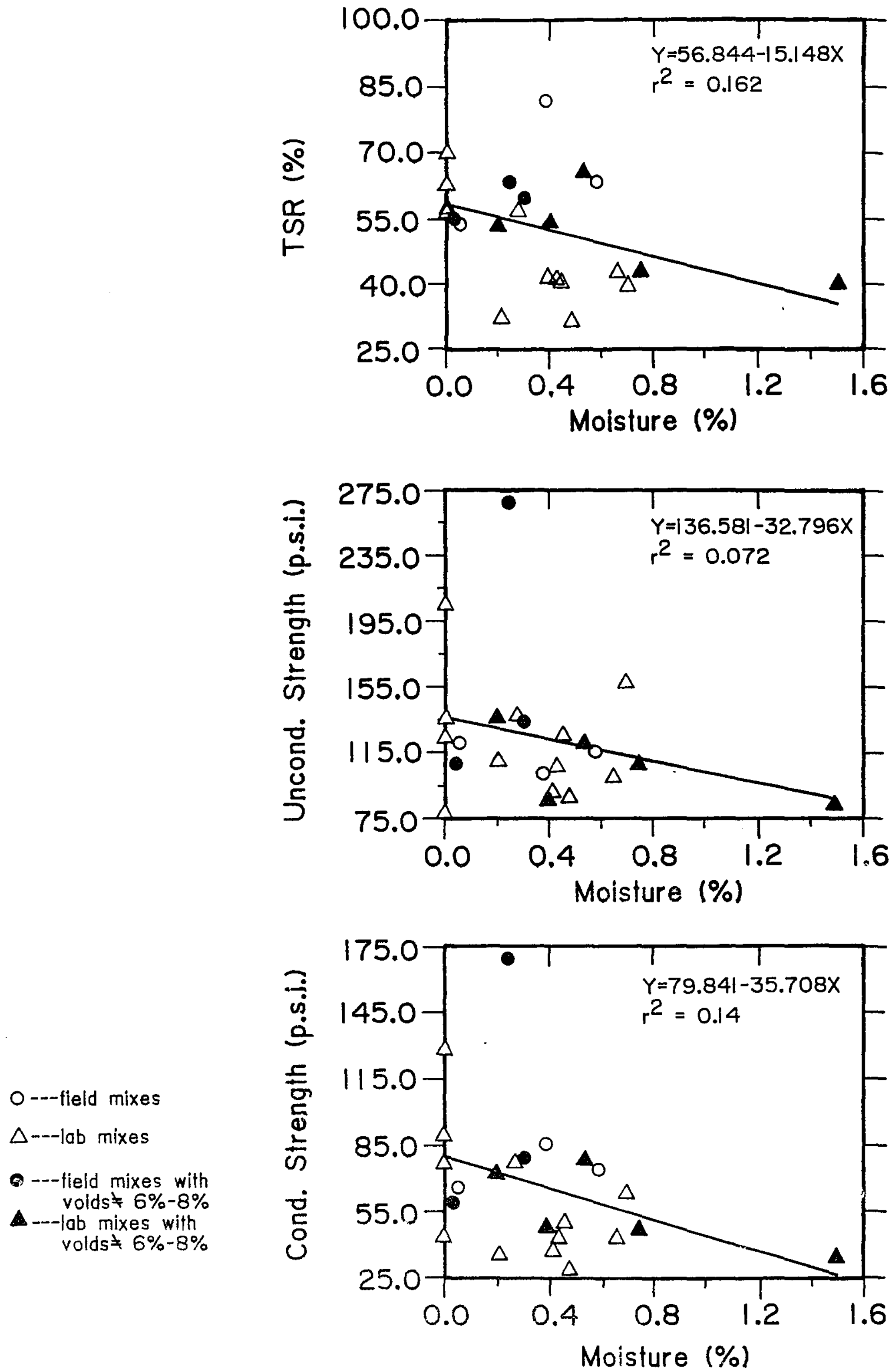

Figure 27. Mixes F, G, H & I, Wet-Dry Tensile Test, All Data.

limited data which may have contributed to the upward slope of the least square straight lines for the unconditioned strength of Mix H.

With the exception of Mix H, the r^2 values indicate reasonably good correlation of TSR, unconditioned strength and conditioned strength with moisture content. For individual mixes, excluding Mix H, r^2 ranges for TSR, unconditioned strength and conditioned strength are 0.211-0.675, 0.153-0.913, and 0.379-0.797, respectively. For the combined data for all mixes (Figures 26 and 27), the correlations are not as strong (TSR - 0.261 and 0.162), but this is likely due to the increased variability in mix type, sample preparation and test conditions. In Figures 26 and 27 it is apparent that one or two high strength values contributed significantly to the low r^2 values for unconditioned and conditioned strength. These unusually high strengths are for Mix I which, in general, had strengths higher than the other mixes.

The cause or reasons why residual aggregate moisture in siliceous gravel is detrimental to the development of strong moisture resistant asphalt-aggregate bonds are well established. It is generally accepted that the mineralogy produces acidic surfaces which are hydrophilic in nature and are, thus, susceptible to interference of bond development during mixing (decreasing unconditioned strength with increasing moisture content) and to loss of bond during subsequent exposure to moisture (decreasing conditioned strength with increasing moisture content). As discussed in the **Background** section, surface texture and absorption will also play a roll in asphalt-aggregate bond development and the resistance of bonds to the detrimental affects of water. When completely dry absorption of asphalt into pores in the aggregate will provide mechanical interlock and enhance bond. However, aggregate absorption will slow the drying process and residual moisture in aggregate pores can be detrimental to bond formation and stripping resistance.

The data (including the dolomitic limestone mixes A and J) were examined for trends or relationships between strengths or strength retention and absorption. None were obvious. The apparent reason is that interaction makes isolation of particular factor difficult. An example of this is illustrated in Figure 28 where average aggregate absorption and TSR are plotted. The TSR's plotted are values from the standard laboratory samples (0% moisture) and values computed from the linear regressions equations at 0.4% moisture. Mineralogy reverses the role of residual moisture, and there are no apparent relationships between TSR or change in TSR and absorption.

Comparison of TSR and VSI. As part of wet-dry tensile tests, examination of samples along fracture planes and estimation of coating retention is suggested. The VSI is computed to give an indication of the relative influence of moisture conditioning. This is done with the notion that retention of asphalt coatings on the aggregate is related to strength retention and that such examinations will provide insight into which aggregate materials and/or sizes are contributing to stripping.

Values of TSR and VSI for all test are plotted in Figure 29. A least square straight line was fit to the data, primarily, to estimate the intercept on the VSI axis. The data and consideration of the physical process suggests that a curve through the point (100, 100) might be more appropriate. Theoretically, there should be no loss of asphalt coatings if 100% tensile strength is retained.

The intercept at VSI ≈ 50% and the upward slope of the straight line provides insight into what happens as water interacts with the mix and as the sample fails in

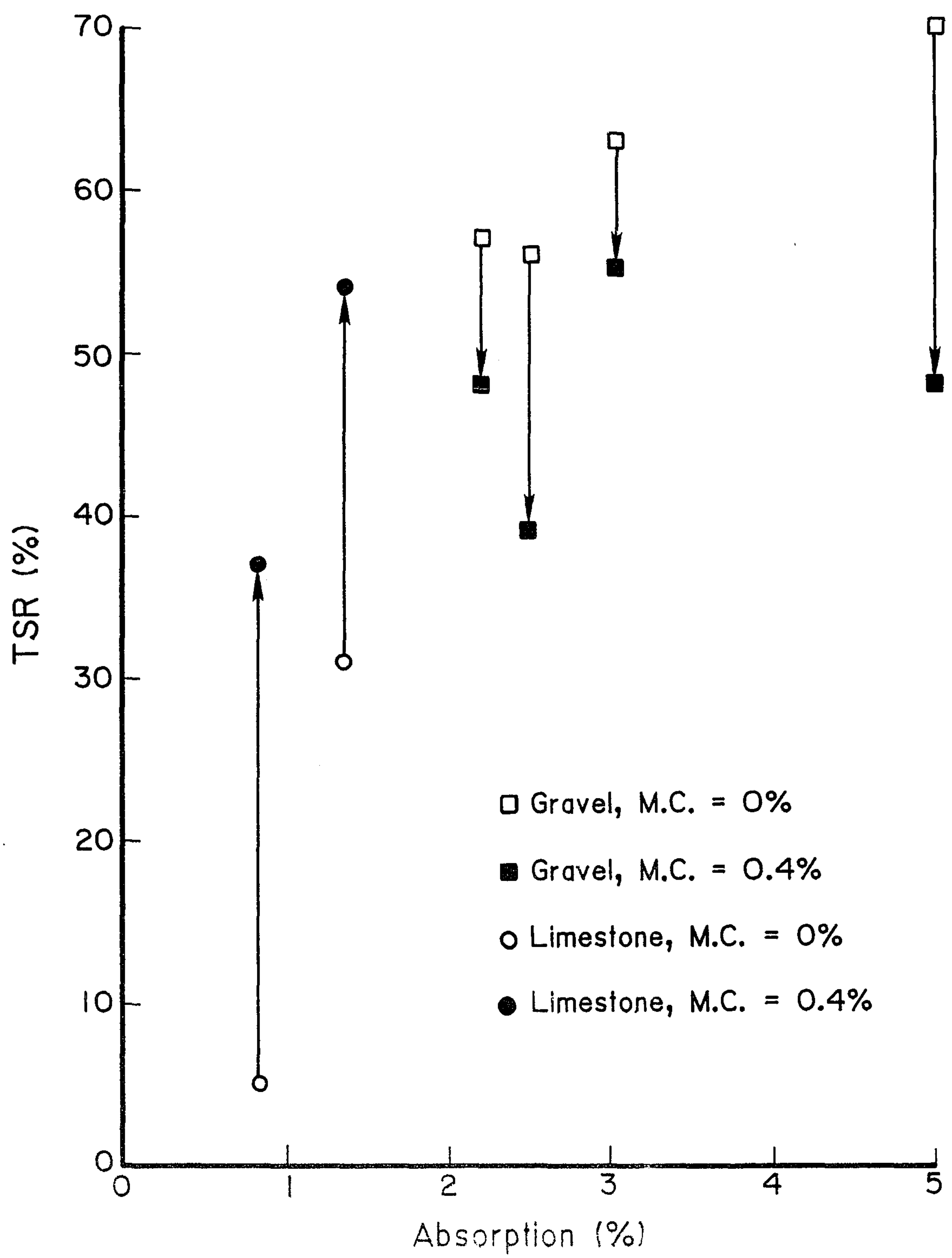

Figure 28. Effects of Moisture and Absorption on TSR.

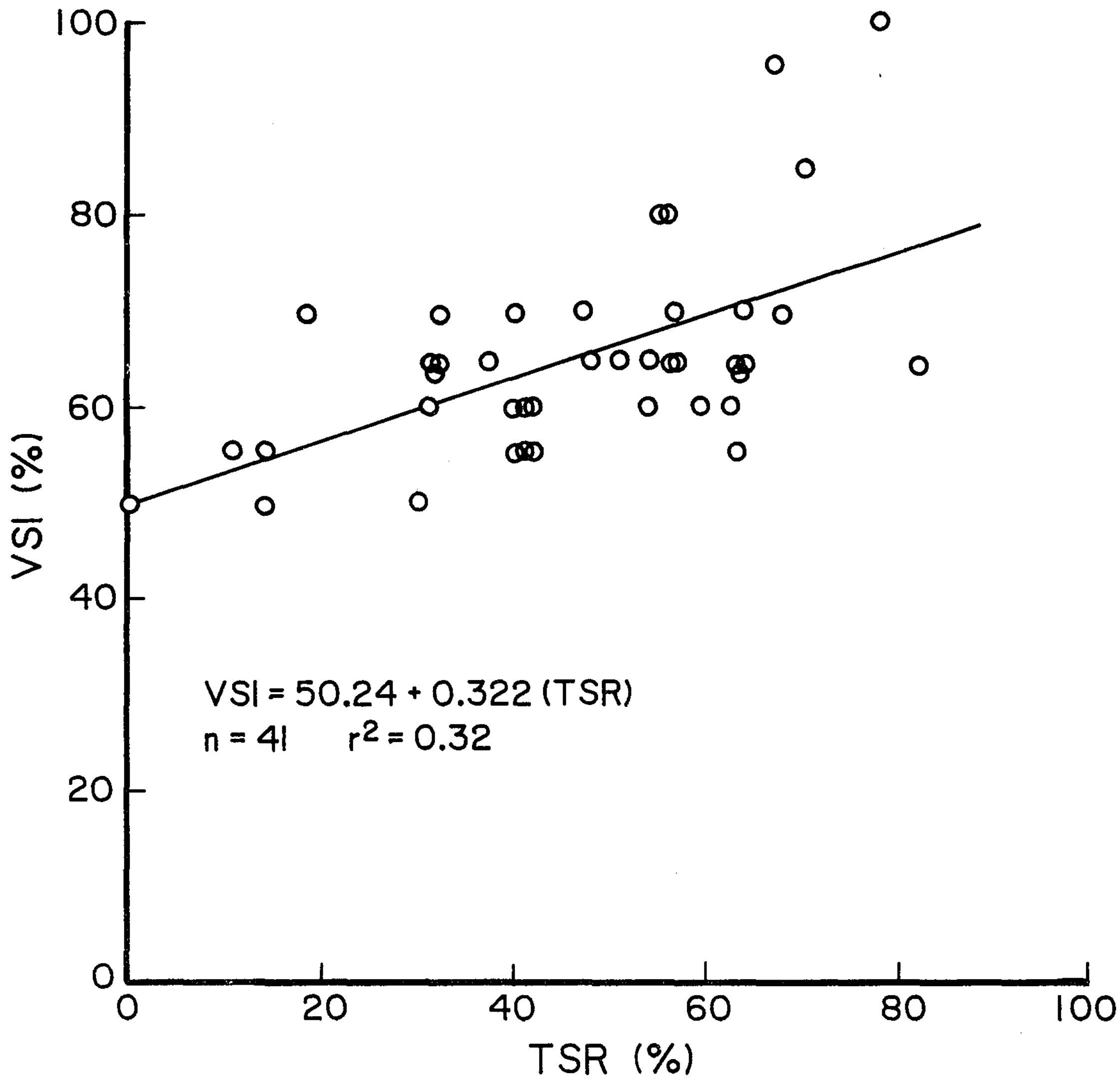

Figure 29. Relationship Between TSR and VSI.

tension. Unlike the boil test where asphalt films are physically stripped from aggregate surfaces and removed by skimming, the stripped asphalt films are not removed as they are debonded during moisture conditioning. When the sample fails in tension the films pull away from larger particles exposing their surface. However, there is no visible separation on fine particles and the fines-asphalt cement matrix appears to remain intact. The visual rating is, therefore, based mainly on the exposed coarse aggregate surfaces and the intercept at VSI ≈ 50% plausible. Even if coating retention could be accurately estimated, a one to one correlation of TSR and VSI is not likely.

Prediction of Stripping Propensity with TSR. Limiting TSR for separating stripping and nonstripping mixes is usually set in the 70-80% range. TSR values for the six mixes tested in this study and four mixes from the earlier study (1) are graphically illustrated in Figure 30, along with stripping characterizations based on field performance and a 70% limiting criteria. The open symbols are for standard laboratory tests and the solid symbols represent values estimated with linear regression equations at 0.4% moisture content.

For limestone mixes TSR correctly categorizes Mix E as a nonstripper, but incorrectly categories Mixes A and J. The aggregate in Mix E is a high calcium limestone with specific gravity of about 2.65, and the aggregates in Mixes A and J are dense dolomitic limestones with specific gravities about 2.85. Mix A was tested in this study and in the earlier study (1) with similar results. Mixes A and J were each tested using two asphalt cement sources with similar results. Residual moisture, unexpectedly, increases TSR moving them towards the nonstripping characterization zone. Field samples also gave higher retained strength than comparable laboratory

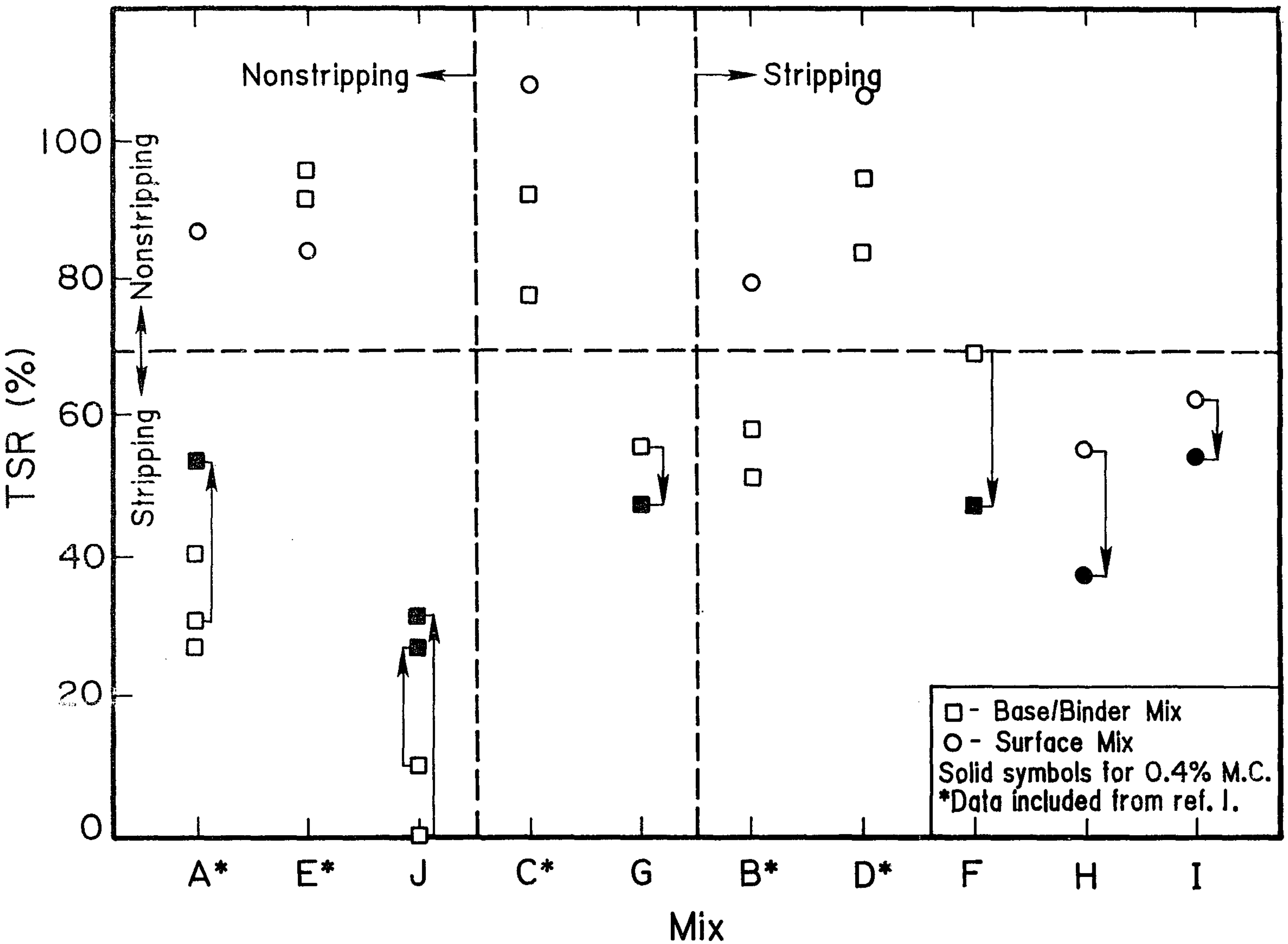

Figure 30. Prediction of Stripping Propensity with TSR.

samples.

This evidence indicates that the low retained strength measured for Mixes A and J is real. The evidence also suggests that the poor correlation with field performance may be due to inadequate simulation of field conditions. Residual moisture and field conditions (mixing and possibly storage) have a positive effect on strength retention. Based on this evidence the wet-dry tensile tests should not be used to determine the need for antistrip agents in mixes that are comprised of predominately dense dolomitic limestones. This recomendation assumes that such mixes are truely not prone to stripping, as is the prevailing consensus. Inclinations that such mixes might actually strip in the field should lead to a study that will verify their performance.

For siliceous gravel Mixes C and G, one is catagorized as a stripper and one a nonstripper. Residual moisture reduces TSR and field samples had a slightly smaller TSR than comparable laboratory samples for Mix G. The variable predictions are considered consistent with the characterization of Mixes C and G as moderately susceptible to stripping.

Mixes B, D, F, H and I are characterized as susceptible to stripping, and predictions for all but Mix D are consistent with this characterization. The behavior of Mixes F, H and I lead to the conclusion that the prediction rather than the characterization is incorrect for Mix D. A unique combination of aggregate mineralogy, surface texture and porosity apparently results in moisture resistant bonds with asphalt when the aggregate is completely dry. However, residual moisture would likely have the same detrimental effect for Mix D as it did for Mixes F, H and I.

As with the dolomitic limestones, field samples for the siliceous gravel mixes generally had higher TSR's than comparable laboratory samples. This would somewhat counteract the effects of residual moisture and move the points toward the nonstripping characterization zone. It is just such conflicting trends that may result in the erratic occurrence of stripping. A mix with a given aggregate combination certainly does not strip all the time. On a particular project stripping usually does not occur uniformly, but rather it usually occurs sporadically. This may be due, in part, to variable moisture conditions in the pavement, but variable stripping propensity of the mix may also be a factor. For a mix to be susceptible to moisture damage likely requires that several conditions, of which residual moisture is one of the more important, occur simultaneously. It is this variability in mix production conditions that leads to the need for antistripping additives.

The response of Mixes B, G, F, H and I indicate that the standard wet-dry tensile test (22) is adequate for evaluating the stripping propensity of siliceous gravel mixes. However, the effect of residual moisture and the response of Mixes C and D indicate otherwise. There are two approaches to the problem. Antistrip additives may be required in all predominatly siliceous gravel mixes or the test procedure may be modified to account for the effects of residual moisture. The former will provide a short term solution, but the latter is the preferred solution. Implementation of a modified test procedure will require 1) selection of a realistic moisture content range for testing, 2) refinement of laboratory mix preparation procedures for controlling residual aggregate moisture content, and 3) additional testing and field observations to verify the apparent influence of residual moisture.

Boil Tests

Boil test results, as percent asphalt coating retained, are included in Table 6. Unlike the earlier study (1), a poor correlation between TSR and percent coating retained is indicated. However, this may be due, in part to differences in technicians running the tests and/or differences in the behavior of dolomitic limestone and siliceous gravel.

Figure 31 shows a plot of TSR versus percent asphalt coating retained. Except for one point, the test run by technician 1 (Mixes A, F and G) group well above the line of equality. This is contrary to results from the earlier study and results obtained by technician 2 (Mixes H, I and J). Since there were raters of the percent coating common to tests run by both technicians, it was concluded the tests run by technician 1 were somehow flawed.

A second observation made on Figure 31 is that data for the dolomitic limestone mixes are grouped above the line of equality, and generally above data for the siliceous gravel mixes. This may be due to similar or contrasting colors that make consistant and accurate coating retention difficult or differences in the size of particles that strip. In either case, the differences in percentages will be due to the inability to accurately estimate coating retention rather than real differences in response. However, the materials may indeed respond differently to each test condition; in which case the observed differences in percentages will be real.

Because of the subjective nature of the boil test, the demonstrated operator sensitivity, and poor correlation with wet-dry tensile tests; the boil test is not recommended for determining the need for or dosage rate of antistrip additives.

However, because of its simplicity it has value as a field test for quality control and should be used primarily as an indicator of change during construction as outlined in reference 1.

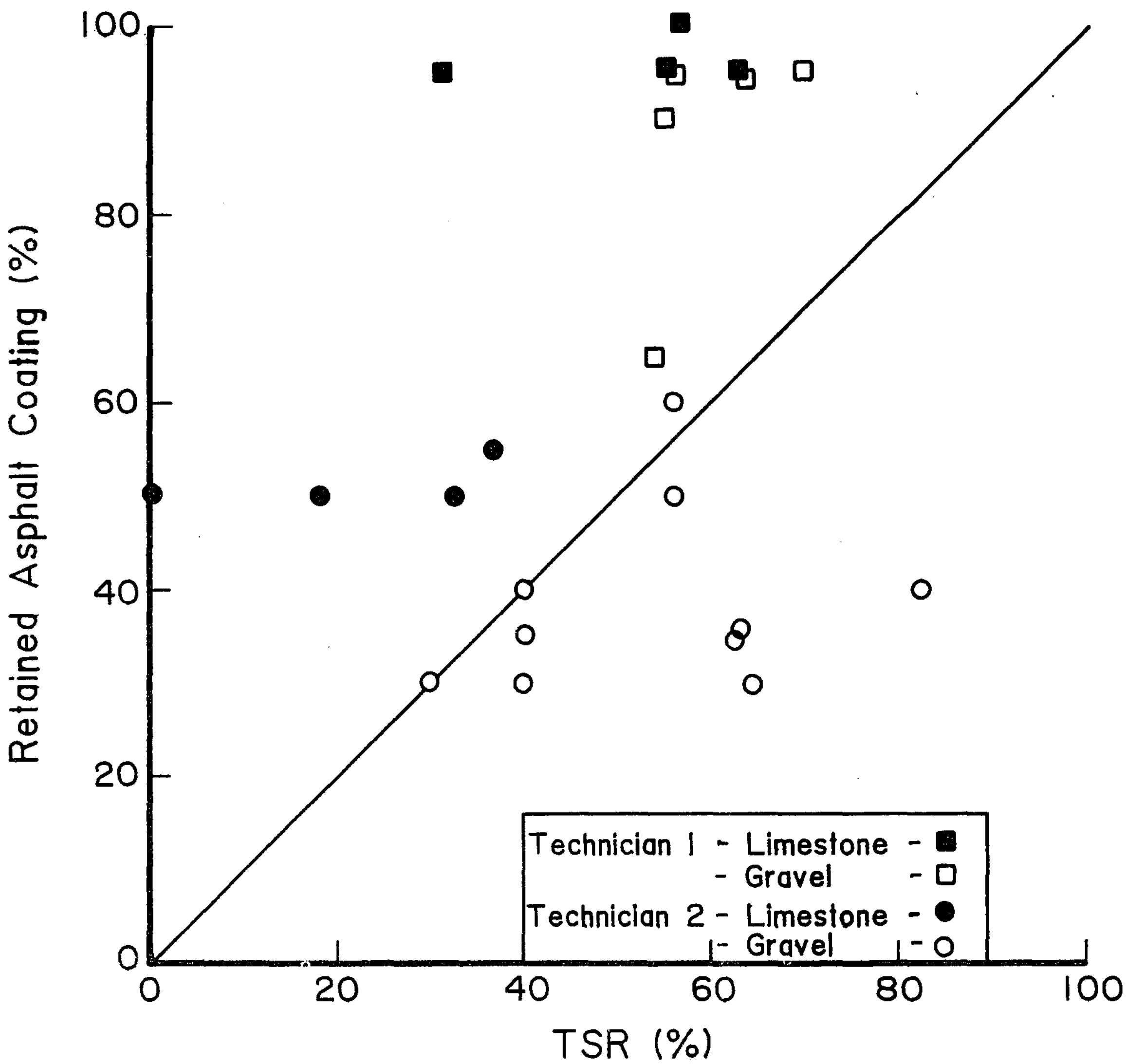

Figure 31. Relationship Between Asphalt Coating Retained and TSR.

CONCLUSIONS AND RECOMMENDATIONS

Mix production conditions can affect stripping propensity. Residual aggregate moisture is a major factor, but mixing and possibly storage may also contribute. Lack of simulation of field conditions in standard laboratory tests can lead to poor correlation between observed and predicted mix performance.

Aggregate and mixture moisture contents were measured during production. Comparison of several methods for measuring moisture content lead to the adoption of the microwave oven method. Moisture contents were dependent on environmental conditions (temperature and rainfall) with higher moisture contents during cool rainy conditions. Moisture contents also appeared to be higher during plant startup, and although not measured, rate of production will also influence aggregate drying. Residual moisture is higher in coarse particles than in fine particles.

A procedure was developed for preparing mix with controlled aggregate residual moisture. The moisture content that can be realistically maintained during mix preparation is dependent on aggregate absorption. Higher residual moisture can be obtained with higher absorptive aggregate.

Wet-dry tensile test results indicated that residual moisture affects dolomitic limestone mixes differently than siliceous gravel mixes. Residual aggregate moisture increases conditioned strength and TSR for dolomitic limestone mixes, but decreases these parameters for siliceous sand-gravel mixes. Values for field mixes were also generally higher than values for comparable laboratory mixes. This difference is one of the reasons for poor correlation between predicted and observed stripping propensity.

The wet-dry tensile test does a reasonably good job of evaluating mixes comprised primarily of siliceous sand-gravel with a history of moderate to severe stripping problems. High retained strength ratios obtained with standard test conditions for some mixes indicate a need for modifications to consider the influence of residual moisture during mix design. Implementation of a modified testing procedure during mix design will require 1) selection of a realistic moisture content range for testing, 2) refinement of the laboratory mix preparation procedure for controlling residual aggregate moisture content, and 3) additional testing and field observations to verify the apparent influence of residual moisture. Development of a procedure for including residual moisture would identify problems during mix design rather than after production begins.

The influence of residual moisture on retained tensile strength accentuates the need for routine testing during mix production. Residual moisture content will vary during production and routine testing will indicate when conditions are developing that could lead to unacceptable retained tensile strength levels. A set of retained tensile strength samples should be tested for each 5000 tons of mix produced. Should daily moisture content measurements indicate moisture content 0.1% larger than the previous days measurements, a set of retained tensile strength samples should be immediately prepared and tested.

The unusual and, at this state, unexplained response of mixes containing dense dolomitic limestone provides justification for caution and conservatism during mix design and construction. While there are no perceived performance problems, and while residual moisture has an apparently beneficial effect on retained tensile strength;

the continued use of current mix design and construction control procedures is recommended until a more refined procedure that includes the influence of residual moisture is developed and verified. During mix design this approach may occasionally lead to the overuse of antistripping additives, but lack of knowledge vindicates the conservative approach.

The boil test is simple and easy to perform, but consistent testing techniques and sample evaluation are difficult to maintain. The boil test should only be considered as a field control test to indicate changes during mix production.

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APPENDIX

MICROWAVE OVEN METHOD FOR DETERMINATION OF MOISTURE CONTENT OF BITUMINOUS MIXTURES

MICROWAVE OVEN METHOD FOR DETERMINATION OF MOISTURE CONTENT OF BITUMINOUS MIXTURES

1. SCOPE

This procedure is used to determine the moisture contained in asphalt concrete mixtures.

2. APPARATUS

1 - Standard kitchen type microwave oven with variable power setting and built in timer
2 - Microwave safe dish
3 - Balance with capacity of 6000 grams, sensitive to 0.1 gram
4 - Thermometer to measure temperature between 0-250° F
5 - Insulated gloves

3. TEST PROCEDURE

3-1 Calibration of Microwave Oven

Before moisture contents can be measured, the power setting on the microwave must be determined that will adequately dry a sample without overheating and burning the asphalt cement.

a. Pour 500 ml of tap water into a microwave-safe dish.
b. Measure and record temperature of water, T_1.
c. Set microwave power setting to 75%.
d. Place dish and water inside and heat for 5 minutes.
e. Determine temperature of water, T_2.
If $T_2 - T_1 = 75 \pm 10°$ F then power setting of 75% is adequate
If $T_2 - T_1 < 65°$ F, increase power setting, repeat step a through e.
If $T_2 - T_1 > 85°$ F, decrease power setting repeat step a through e.

3-2 Moisture Content Determination

a. Weigh microwave safe dish, record mass, M_A.
b. Place at least 500 grams of sample in dish, record mass, M_B.
c. Place dish and sample in microwave oven. Set oven to calibrated power setting. Heat for 30 minutes.
d. Record mass of dish and sample, M_C, return dish and sample to microwave and heat 5 more minutes.

e. Record mass of dish and sample, M_D.
If $M_C - M_D < 0.5$ grams go to step f.
If $M_C - M_D > 0.5$ grams repeat step d until the loss of moisture is less than 0.5 grams.

f. Calculate moisture content of sample:

$$M.C. = [(M_B - M_D)/(M_D - M_A)] * 100$$

g. Moisture content with total sample mass as the basis for computing the percentage (ASTM D 1461 and AASHTO T110) may be calculated with the following:

$$M.C. = [(M_B - M_D)/(M_B - M_A)] * 100$$