

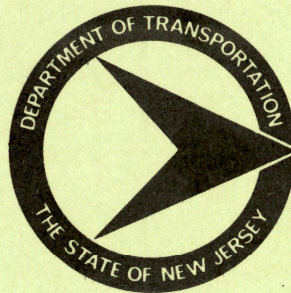
**EVALUATION OF BITUMINOUS MIXTURES
PRODUCED BY THE
DRYER-DRUM PROCESS**

FINAL REPORT

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ABSTRACT

A study to determine the advisability of adopting the dryer-drum process as an alternate to conventional batch plants is reported. The study involved an assessment of the as-produced quality of materials produced by a dryer-drum plant for parking lot construction at the New Jersey Sports Complex.

Findings from this evaluation of dense-graded surface and binder drum-mixes were generally favorable. The uniformity of the drum-mix asphalt content, mix gradation and Marshall stability was comparable to that of conventionally produced mixtures. In contrast, substantial discrepancies between the design and production means were generally observed for each of the parameters. Given the uniformity of the drum-mix product, achievement of desired target values on future projects should not prove difficult with appropriate process adjustments. To effect an improvement in process gradation control, additional weighing equipment and associated instrumentation is required.

The drum-mix displayed no detrimental strength loss when tested according to standard immersion compression conditions. However, lower-than-normal retained strengths were indicated when the material was subjected to the NJDOT's special extended soaking tests. Excessive adherent fines on the project coarse aggregate are believed to have played a role in reducing both the as-produced Marshall stability and retained strength levels.

Mechanical and chemical tests performed on the asphalt cement indicated that, for a given mix discharge temperature, the degree of hardening caused by dryer-drum and conventional processing are essentially the same.

The dryer-drum process was observed to increase production rates while reducing fuel requirements relative to conventional plants, thus yielding a general savings in production costs. A reduced fuel requirement for any construction operation also furthers the national policy of energy conservation.

It is recommended that the use of the dryer-drum process be permitted on NJDOT projects. Proposed specification requirements are presented.

TABLE OF CONTENTS

	<u>Page</u>
<u>SUMMARY</u>	1
<u>CONCLUSIONS</u>	13
<u>RECOMMENDATIONS</u>	20

PART ONE: INTRODUCTION

1.1 Research Objective	22
1.2 Background	
1.2.1 Study Overview and Nature of the Dryer-Drum Process	22
1.2.2 Description of First Dryer-Drum Project in New Jersey	26
1.3 Research Scope and Approach	
1.3.1 Limited Scope of the Work	29
1.3.2 Research Methodology	30

PART TWO: PLANT EQUIPMENT AND OPERATION

2.1 General	34
2.2 Production Equipment and Operation	
2.2.1 Plant Layout	35
2.2.2 Charging Aggregate Bins	36
2.2.3 Metering Aggregate Materials	36
2.2.4 Aggregate Weighing and Asphalt Supply System	39
2.2.5 Drum-Mixing	40
2.2.6 Mix Storage and Delivery	41
2.3 Plant Instrumentation	
2.3.1 Overview of Control Room Panel	41
2.3.2 Temperature Controls	43
2.3.3 Total and Proportional Controls	44
2.3.4 Plant Output Controls	47

TABLE OF CONTENTS (CON'T)

	<u>Page</u>
2.4 Plant Production and Mix Temperatures	
2.4.1 Plant Production	49
2.4.2 Mix Temperature	50
2.5 Fuel Consumption	51
2.6 Pollution Control	53
PART THREE: <u>SAMPLING AND TESTING PROCEDURES</u>	
3.1 General	54
3.2 Aggregate Sampling	54
3.3 Mixture Sampling	56
PART FOUR: <u>FINDINGS</u>	
4.1 General Approach to the Analysis of Data	60
4.2 Asphalt Content	
4.2.1 Nature of Sample	61
4.2.2 Variability of Asphalt Content	62
4.2.3 Expected Conformance with Department of Transportation Acceptance Criteria	64
4.2.4 Factors Affecting Observed Asphalt Content	66
4.3 Mixture Gradation	
4.3.1 Variability of Extraction Results	82
4.3.2 Expected Conformance with Department of Transportation Gradation Acceptance Criteria	89
4.3.3 Factors Affecting Gradation of the Product at Various Stages of Production	91
4.4 Stability and Immersion Compression Tests	
4.4.1 Stability Samples	113
4.4.2 Variation of Mix Stability	113
4.4.3 Expected Conformance with Department of Transportation Acceptance Criteria	116
4.4.4 Factors Affecting Mix Stability	119
4.4.5 Retained Strength	127

TABLE OF CONTENTS (CON'T)

	<u>Page</u>
4.5 Asphalt Hardening: Conventional Mechanical Tests	
4.5.1 General	135
4.5.2 Consistency of Asphalt Processed Thru Drum-Mixer	136
4.5.3 Consistency of Conventionally Processed Asphalt and a Note on Test Reliability	153
4.5.4 Thin-film Oven Tests	167
4.6 Asphalt Hardening: Special Chemical Tests	
4.6.1 Nature and General Significance of the Testing	174
4.6.2 Comparative Compositional Changes for New Jersey Conventional and Drum-Mix Plants	180
4.7 Pavement Construction	
4.7.1 General	191
4.7.2 Compaction	191
<u>REFERENCES</u>	197

APPENDICES

Appendix A: Mix Designs for Sportsplex Project	201
Appendix B: Comparison of Tonnage of Mix Constituents: Scale House versus Control Room	202
Appendix C: Relative Effects of Individual Proportioning System Errors on Drum-Mix Asphalt Content Acceptability	203
Appendix D: Proposed Dryer-Drum Specifications	204

LIST OF TABLES

	<u>Page</u>
Table 1 - Plant Production Data	49
Table 2 - Mix Temperature	50
Table 3 - Summary of Mixture Asphalt Content Sampling	61
Table 4 - Simulated Application of DOT Composition Acceptance Criteria to Dryer-Drum Mixtures	66
Table 5 - Gross Comparison of Indicated Input of Raw Materials and Output of Finished Drum-Mix	69
Table 6 - Summary Comparison of Tonnage of Mix Con- stituents -- Scale House Versus Control Room	71
Table 7 - Components of Asphalt Metering System Inaccuracy	75
Table 8 - Influence of Aggregate Moisture Content Correction Factor on the Quantity of Asphalt Supplied to Mix	78
Table 9 - Relative Effects of Individual Proportioning System Errors on Drum-Mix Asphalt Content Acceptability	80
Table 10 - Relative Variability of Drum-Mix Extracted Gradations	86
Table 11 - Simulated Application of DOT Gradation Acceptance Criteria to Dryer-Drum Mixtures	90
Table 12 - Variability of Stockpile Gradations	96
Table 13 - Comparison of Expected and Observed Drum-Mix Extracted Gradations	99
Table 14 - Comparative Aggregate Gradations of Extraction and Belt Samples	106
Table 15 - Adherent Fines on Project Coarse Aggregate	111

LIST OF TABLES (CON'T)

	<u>Page</u>
Table 16 - Simulated Application of Department of Transportation Stability Acceptance Criteria to Dryer-Drum Mixtures	118
Table 17 - Summary of Step-Wise Regression Parameters for Stability vs Other Mix Variables	122
Table 18 - Average Asphalt Consistency Before and After Drum-Mixing	139
Table 19 - Estimate of Hardening Associated with Low Mix Discharge Temperatures	148
Table 20 - Consistency of Asphalt Processed Through New Jersey Conventional Bituminous Plants	156
Table 21 - Summary of Compaction Study Results	195

LIST OF FIGURES

	<u>Page</u>
Figure 1 - View of Stadium Parking Lot Construction	28
Figure 2 - Overview of Sportsplex Drum-Mix Plant	35
Figure 3 - Charging Cold Bins	36
Figure 4 - Feeder and Collector Belts	37
Figure 5 - Discharge of Combined Aggregates from Collector Belt Onto Main Feed to Drum-Mixer	38
Figure 6 - Main Feed to Drum-Mixer	39
Figure 7 - Drum-Mixer	40
Figure 8 - Mix Being Discharged From Surge-Bin Into Delivery Trucks	42
Figure 9 - Overview of Plant Control Console at Sportsplex	42
Figure 10 - Temperature Control and Recordation	43
Figure 11 - Total and Proportional Controls	44
Figure 12 - Digital Totalizer	48
Figure 13 - Wet Scrubber System	53
Figure 14 - Automated Sampling Device	55
Figure 15 - Stop-Action Photo of Sampling Tray Beginning to Intercept Stream of Combined Aggregates	55
Figure 16 - Mixture Sampling and Shaping Equipment	57
Figure 17 - Sketch of Supporting Arrangement Used in Obtaining Mixture Samples at Discharge End of Drum	57

LIST OF FIGURES (CON'T)

	<u>Page</u>
Figure 18 - Shaping and Freezing of Asphalt Recovery Samples	59
Figure 19 - Asphalt Content of Finished Drum Mixtures	63
Figure 20 - Effect of a Unit Error (+1.0%) In Any Element of The Dryer-Drum Proportioning System on the Average Asphalt Content of the Finished Mix	74
Figure 21 - Gradation of Finished Drum-Mix Surface Course ..	83
Figure 22 - Gradation of Finished Drum-Mix Binder Course ...	84
Figure 23 - Sketch of Alternate Instrumentation for Cold-Feed Control	94
Figure 24 - Wet Fines Beginning to Accumulate Beneath Dryer Feed	108
Figure 25 - Stability of Binder Mix	114
Figure 26 - Stability of Surface Mix	115
Figure 27 - Immersion Compression Test Results	129
Figure 28 - Relationship Between Retained Strength and Retained Stability	134
Figure 29 - Asphalt Consistency Changes Displayed by Individual Mixture Recovery Samples	138
Figure 30 - Penetration - Viscosity Relationships for Original and Processed Drum-Mix Asphalt	144
Figure 31 - Influence of Mix Discharge Temperature on Consistency of Drum-Mix Asphalt	147

LIST OF FIGURES (CON'T)

	<u>Page</u>
Figure 32 - Relationship of Drum-Mix Penetration and Viscosity Changes	151
Figure 33 - Influence of Mix Discharge Temperature on Consistency of Conventionally Processed Asphalt	159
Figure 34 - Asphalt Consistency Changes for Low and High Mix Discharge Temperatures	166
Figure 35 - Penetration - Viscosity Relationships for Processed Drum-Mix Asphalt and Thin-Film Oven Residue	169
Figure 36 - Change in Chemical Composition Occurring on Processing: Literature Reports	177
Figure 37 - Comparison of Changes in Chemical Composition Occurring on Conventional Processing and Drum-Mixing	181
Figure 38 - Change in Chemical Composition Occurring on Thin-Film Oven Processing	182
Figure 39 - Relationship of Asphalt Consistency and Asphaltenes Content	188
Figure 40 - Relationship Between Pavement Core Density and Nuclear Gage Measurements	193

SUMMARY

Research Objective: Use of an innovative method of producing bituminous concrete -- the "dryer-drum" process -- has been reported by some agencies to afford a significant reduction in bid prices. The comparative economy for the dryer-drum process is basically attributed to a reduction in required plant operating equipment and in the amount of fuel consumed per unit of product. In the dryer-drum process, aggregate drying and mixing with asphalt are achieved in the same heated drum, with gradation control being limited to cold-feed proportioning only. The pugmill, intermediate screening operation and hot bins typical in a batch type plant are eliminated.

This report presents the results of a study undertaken to determine whether use of this alternate process on New Jersey Department of Transportation projects is advisable and, if so, to develop specification provision and control requirements to govern the equipment's operation.

Research Methodology: A decision to permit use of the dryer-drum process fundamentally entails a determination of whether any initial savings afforded by use of drum-mixing may be offset by subsequent increased maintenance costs associated

with decreased product quality. While the ultimate answer in this regard would require awaiting the outcome of long-term performance tests, a reasonable assessment of potential drum-mix performance is provided by an evaluation of the degree to which the as-constructed material complies with current quality acceptance standards. This approach was adopted for the present study.

The evaluation of the as-produced quality of dryer-drum mixtures undertaken in this research was based on samples of mix produced for parking lot and access road construction at the Giants Stadium sports facility. The paving mixtures studied included dense-graded surface and binder mixtures, the latter material being employed as a combined binder/stabilized base. The bituminous concrete items of the \$5.6 million paving contract totalled approximately a quarter of a million tons.

The studied project was not under the supervision or control of the New Jersey Department of Transportation. The important point in this connection is that the specifications governing this parking lot paving were significantly less restrictive than those conventionally applied to NJDOT projects. Since the NJDOT acceptance criteria did not in fact apply, the thrust of our analyses was directed at determining if the usual tolerances could be met.

Findings:

A. Asphalt Content: Evaluation of the composition of the finished drum-mix was based on extraction tests performed on a total of 41 samples of each mixture obtained on nine production days. The test days were randomly selected over a three-month period.

Analysis of these extraction results indicated that the percentage of asphalt in successive samples of finished drum-mix was of comparable uniformity to historical data for conventionally produced New Jersey mixtures. The standard deviation for the samples of binder mix was about equal to that historically observed for the "average" conventional plant product (0.23 versus 0.26 percent), while the variability of the surface mix was only slightly higher (0.33 versus 0.26 percent). However, the overall mean asphalt content of each type of drum-mix was significantly lower than the corresponding design target value. The observed differences between the production mean and design target values for the surface and binder mix (0.40 and 0.45 percent, respectively) were more than 2 and 3 times greater than the departure typically observed for similar mixes produced at New Jersey conventional plants.

The fact that the job-mix formula misses for the sampled drum-mixtures were greater than those normally observed is not considered to be of particularly great moment. That is, since the dryer-drum asphalt content results are uniform in terms of the process standard deviation, it would normally not be difficult to make adjustments to achieve the desired mean value (e.g., by changing the percent AC dial setting on the control console).

To gain information on the actual controllability of the finished asphalt level, an effort was made to identify the specific causes for the observed low asphalt content in the sampled project materials. These analyses indicated that inaccuracies in both of the key elements of the dryer-drum proportioning system -- the aggregate and asphalt delivery systems -- apparently contributed to the observed shortfall from the design AC content on the studied project. On an average basis, the control console readings for the asphalt input were calculated to be erroneously high by about 3 percent, while the aggregate weigh belt signal was apparently consistently low by about 5 percent. Further, apart from being inaccurate, the control instrumentation readings were not inherently in accord: The quantity of asphalt and aggregate indicated by the control instrumentation, even if correct, generally would not have yielded the AC percentage dialed in on the control console. The fundamental significance of the results of these proportioning checks is that they confirm that, absent the application of suitably frequent calibration verification procedures, electronic displays of materials input clearly should not be accepted as gospel.

B. Gradation: The New Jersey Department of Transportation uses three design sieves -- the numbers 8, 50 and 200 -- for gradation acceptance purposes. The larger design sieves are used merely for control purposes.

A comparison of the variability of the drum-mix gradations for the acceptance sieves to that historically observed reveals that, with one notable exception, the uniformity of the drum-mix product was comparable to that of conventional plants. Only the #8 sieve results for the surface mix exhibited excessive variability. However, apart from the number 200 sieve results -- which were uniformly close to the design target value -- the average misses from the job-mix target values for the dryer-drum materials were about 2 to 5 times larger than typically observed on NJDOT projects. If the Department's specifications had been in effect, these job-mix deviations would have resulted in a significant number of failing acceptance lots for the surface mix.

Various analyses were undertaken to discover the source(s) of the significant gradation job-mix formula misses observed in this research. These analyses indicated that the departures from the intended percent passing for the cited sieves were for the most part unrelated to variations in the stockpile materials (the average percent passing), but rather to a problem of metering the binned materials in the correct proportions. The important point here is that the straight volumetric cold-feed control procedure employed on this project yielded neither the type nor number of measurements needed for the timely discovery and remedy of a proportioning problem. In the researchers' opinion, this inability to discover which bin or bins contributed to the control problem mandates that additional commercially available gradation control equipment and associated

instrumentation be provided on any future NJDOT drum-mix project. Such would consist of furnishing belt scales (load cells) beneath certain of the aggregate bins. Installation of several such belt scales beneath the cold-feed bins would provide direct bin proportioning checks on both a continuous basis (from a rate meter display in tons per hour for each bin) and an overall basis (from bin totalizer displays).

While the inadequacy of the cold-feed control instrumentation used on this project is considered to be the basic source of the observed disparity between the target and extracted gradation, other factors played some role. These included loss of weighed fines from the main feed belt to the drum-mixer (remedy: appropriate belt scraper), apparent bulking and/or bridging in the fine aggregate bins (remedy: bin vibrators) and excessive dirtiness of the project coarse aggregates (remedy: washing or rejection).

C. Stability: To assess the strength of the drum-mix product, Marshall stability specimens were obtained along with each of the composition samples.

Comparison of the collected Marshall results to historical data for conventionally produced mixtures indicated no statistically significant difference in the variability of mixture stability.

For both drum-mixtures, however, there was a substantial overall disparity between the design stability and the production mean (600 and 900 pounds, respectively, for the surface and binder mix). In fact,

the overall as-produced stability level for the binder material was so low that about a 40 percent failure rate would have occurred had the Department's strength requirements been in effect.

It seems reasonable to assume that if the Department's more stringent acceptance criteria and associated payment reduction schedule were actually in effect, a producer employing normal process control procedures would have been aware of this low stability situation early-on and would have taken steps to avoid payment reductions.

The average mix discharge temperature at the Sportsplex project was 245⁰F. This temperature is significantly lower than that of the "typical" conventional product (300⁰F) and, more importantly, is lower than the specific value (280⁰F) used in the project mix design. Analysis reveals that use of discharge temperatures lower than those contemplated in the design and the previously described low overall finished asphalt content were the major causes for the shortfall between the design and as-produced stability. In particular, these two factors together account for about 75 and 90 percent of the total observed miss in strength for the binder and surface mix respectively.

The problem of low AC and the associated detrimental effect on stability is easily avoidable and is thus not considered an obstacle to the use of the dryer-drum process on a Department project. However, the finding regarding the effect of temperature on achievable mix stability strongly suggests that the Department move cautiously should the use of low temperature mixes be considered. In any event, if a

decision is made to permit lower-than-conventional mixing temperatures in future work, mix designs for those projects should of course be based on intended mix discharge temperatures. Proper consideration of discharge temperature is obviously a must if the design value is in fact to provide a realistic estimate of achievable mix strength.

The restricted range of moisture contents in the finished drum-mixes (0.5 to 1.6%) precluded any definitive findings regarding the effect of this factor on achievable mix strength. It is worth noting, however, that the general trend indicated by the study data -- that achievable stability increases with increasing mix moisture -- tends to support what others have suggested: Residual moisture in the mix aids compaction. Further work in this area may prove beneficial.

D. Retained Strength: One concern regarding the durability of drum-mixes is whether free moisture in the finished mix and/or residual moisture in the partially-dried aggregates has any implications for a detrimental in-service strength loss. Quite apart from the as-produced stability then, another key measure of the strength properties of any bituminous mixture is its ability to retain that stability in a highway environment. AASHTO T165, which involves comparing the compressive strength of freshly-molded and cured bituminous mixture specimens with that of companion samples which have been immersed in water under prescribed conditions, provides such a measure. A retained strength after soaking of 70 to 75% of the dry strength is generally considered adequate.

Immersion compression testing performed for this research indicated that the average retained strength for the studied drum-mixtures would satisfy conventional criteria. However, the results of a special series of extended soaking tests yielded lower retained strengths than required when this special soaking procedure is applied for approval of mineral fillers on Department projects. The specific cause(s) for the latter condition were not determined. One possibility is the excessive dirtiness of the Sportsplex coarse aggregates: About 2.5 percent of the total weight of coarse aggregate consisted of "adherent fines". Such adherent fines are potentially detrimental to retained strength if the adherent material is sensitive to water and/or prevents the large coarse aggregate particles from being properly coated with asphalt cement.

E. Asphalt Hardening: In the dryer-drum process, the asphalt cement is introduced in the presence of hot burner gases. An obvious concern then is whether such exposure may result in premature age-hardening of the asphalt cement. To determine whether drum-mixing inherently entails any such detrimental effect, samples of the as-supplied and as-processed asphalt cement were subjected to a program of conventional mechanical tests (penetration and viscosity), as well as a special series of chemical composition tests (Rostler-Sternberg procedure).

Comparison of the observed consistency changes occurring on drum-mixing to historical data from conventional plants indicates that no detrimental or beneficial effect inherently accrues from drum-mixing. That is, while the overall degree of hardening

observed for the studied drum-mix materials was less than that typically observed at conventional plants, various temperature-consistency relationships developed in this work indicated that such lesser hardening was substantially (if not completely) due to the significant difference in average discharge temperature as between the drum-mix and conventional plants (245⁰F versus a typical 300⁰F). Our analyses indicate that if the drum-mix had been produced to discharge at conventional temperatures, the observed asphalt consistency change could reasonably be expected to be of the same magnitude as that from a batch plant operated at the same temperature.

Unfortunately, some rather protracted analyses were required to establish the effect of drum-mixing on recovered penetration and viscosity. As a result of deficiencies in the consistency testing procedure employed by our central laboratory -- which deficiencies were not discovered until after the completion of the research -- a considerable effort was required to determine the general reliability of the data (i.e., whether any definitive analysis of the data was possible). As it turns out, the principal effect of these testing deficiencies was to create general underestimates of the true amount of hardening occurring on processing.

The results of the Rostler-Sternberg analyses indicate that the chemical composition of asphalt processed thru the dryer-drum remains relatively unchanged from its original values. Further, what little change does occur is generally less than that for either

simulated (thin-film oven conditioned) or actual pugmill mixing. Thus, the results of this chemical testing are viewed as confirming the findings based on consistency testing that drum-mixing does not inherently entail any detrimental effect on the asphalt cement.

While the various hardening tests performed in this work indicated that asphalt cement is not inherently harmed by drum-mixing, it is recognized that -- under other operating conditions -- such an effect might occur. For example, in some drum-mix units, the asphalt may be introduced as close as six feet from the burner flame as compared to the sixteen feet used in this study. It thus appears advisable that if use of a drum-mix unit is permitted on a NJDOT project, as a preliminary matter, tests on the original and processed asphalt should be made to determine whether any excessive hardening occurs for those particular project conditions.

F. Pavement Construction: Based on numerous observations of the Sportsplex paving operations, the constructability of bituminous mixtures produced by the dryer-drum process appears to be essentially the same as that for the conventional product.

Unfortunately, it was not possible to obtain definitive information relative to the compaction characteristics of drum-mix. The rollers used at the Sportsplex differed from the Department of Transportation's standard roller system (i.e., 3-wheel breakdown and tandem finish rollers). Also, the inherent compactability (achievable Marshall density) of the project surface mixture during the compaction

evaluation was appreciably less than that typically expected for Department projects. However, given the other findings of this study, it seems reasonable to expect that with appropriate process control for asphalt content, the mixture from a dryer-drum plant would be as compactable as mixtures of equivalent temperature from a conventional plant.

It was not possible to verify the claim that retained moisture in drum-mixes may offset the influence of low temperature to the extent that the field compactability of dryer-drum mixtures is comparable to conventionally produced high temperature mixtures. That is, although analysis of the factors influencing stability suggested the existence of an apparent "lubrication" effect for retained moisture, whether such effect would be a significant factor in achieving the desired field density in low temperature mixes remains to be confirmed.

CONCLUSIONS

1. The average daily production at the Sportsplex drum-mix plant was about double that of a typical batch-type facility in New Jersey.

2. Use of the dryer-drum process and a relatively low mix discharge temperature resulted in a reduction in the quantity of fuel required per ton of product compared to batch type operations. A general savings in terms of both energy consumed and production costs is thus indicated.

3. The dryer-drum plant used at the Sportsplex, equipped with a wet scrubber system, satisfied both state and federal environmental regulations.

4. The average asphalt content of the drum-mix binder and surface course evaluated in this study was significantly lower than the percentage called for in the respective mix designs. However, for both mixtures, the variation of asphalt content about the mean level was not excessive and quite comparable to that of conventionally produced New Jersey mixtures. Based on this finding of product uniformity, it is concluded that the drum-mix asphalt proportioning system is indeed inherently controllable. Accordingly, on any future NJDOT dryer-drum project, a producer can reasonably be expected to successfully make appropriate process adjustments to avoid any payment reductions due to non-compliant asphalt content levels.

5. Various analyses indicate that the shortfall between the production means and the design target asphalt contents were due to inaccuracies in both the asphalt and aggregate proportioning system.

While it is the responsibility of the producer to maintain his plant in calibration, a plant inspector may make various simple comparisons among data displays on the plant control console to detect gross discrepancies in plant operation. Generally, these internal checks relate to verification of the indicated total production rate and design asphalt content. Comparison of the indicated input of raw materials (control room data) to the proven output of finished mix (scalehouse weights) also provides a useful check on the control operation.

6. The cold-feed aggregate proportioning procedure employed on this project generally yielded gradations for the acceptance sieves which were at least as uniform as those from conventional plants. The one exception in this regard (abnormally high standard deviation) was apparently due in large part to the variability of the stockpiled material, rather than to control of the aggregate metering process per se.

While the production process was thus indicated to be in control in one sense, there was a general lack of compliance with target gradation values. An effort to account for the substantial differences between the gradation expected for the given raw materials and control equipment settings and that actually observed in the

finished product proved unsuccessful. This result was to some extent pre-ordained: absent suitably frequent calibration checks, proportioning controls such as those employed at the studied plant (i.e., belt speed indicators) simply do not provide the requisite reliable, direct indication of the quantity of material being metered from each bin. While it is possible that a producer for a future drum-mix project might be able to remedy a problem by performing such timely calibration checks, it appears equally likely that -- absent a continuous positive indication of the tonnage of material from each bin -- adequate gradation control would be difficult at best.

Thus, it is here concluded that if the NJDOT is to permit generalized use of the dryer-drum process, the cold-feed control set-up must be supplemented by additional weighing equipment (load cells under each bin) to provide the producer with a reasonable opportunity to discover and remedy any possible gradation control problem. The equipment required is within the state-of-the-art and available at reasonable cost.

7. An automated belt sampling device is a highly desirable item of equipment at a drum-mix plant since it provides a safe means of obtaining aggregate for both moisture and gradation control purposes. The sampling equipment used in this research did not yield the requisite representative samples. It is clear then that approval of any type of automated gradation sampling device will be required, based on a program of reliability testing prior to production.

8. Comparison of the Marshall stability results from this study to historical data revealed no statistically significant difference in the variability of mixtures produced by the dryer-drum process and conventional batch-type plants in New Jersey.

9. The average Marshall stability of the sampled surface and binder mixes were lower than the design values by 600 and 900 pounds respectively. This shortfall in mix strength is largely attributable to the fact that average asphalt content and mix discharge temperature were both significantly lower than the values prescribed in the mixture designs.

It is estimated that had the Department's stability acceptance criteria been in effect, about 40% of the binder lots produced during this evaluation would have been judged non-compliant. However, by developing mix designs at intended mix discharge temperatures and with improved process control procedures for asphalt content, it is believed that adequate mixture strength levels are achievable.

10. Marshall stability/temperature relationships developed during this study confirm that stability decreases in direct proportion to discharge/molding temperature. Our best estimates of the specific stability decrease accompanying each unit (1°F) decrease in molding temperature during this study are 12 pounds per degree for binder and 11 pounds per degree for surface mix. In view of this finding, it is concluded that dryer-drum mixtures for any future Department project should not be permitted to be produced at

temperatures lower than those currently required for conventional batch-processing. The reduction in stability associated with the low temperature experienced at the Sportsplex was too large for accommodation on NJDOT projects.

While general use of low temperature drum-mixing is considered inadvisable, some limited experimentation in this regard would be useful in view of the energy savings and associated potential initial economy offered by use of such mixes.

11. The binder and surface drum-mix each yielded adequate retained strengths when tested in accordance with AASHTO T165. However, the average retained strength of drum-mix specimens subjected to a NJDOT modification of the standard test method (a 14 day immersion period) were lower than the minimum 70% required by the Department.

12. One factor believed to have exerted some effect on the stability values in this study (both as-produced and retained) was the excessive dirtiness of the project coarse aggregate.

The precise impact that such adherent fines had on the stability and retained strength results was not determined. Nonetheless, the presence of excessive aggregate dirtiness is at least potentially detrimental to these parameters. This would appear to be particularly true if the adherent material is sensitive to water and/or prevents the large coarse aggregate particles from being properly coated with asphalt cement. The solution to this problem on any future drum-mix project -- indeed, on a conventional project -- would be to require washing or to reject.

13. In producing mix at a given discharge temperature, the dryer-drum process can generally be expected to cause changes in the chemical composition and associated physical properties of the asphalt cement which are similar to those which would occur on conventional processing.

In a specific case, however, introduction of the asphalt cement close to the flame end of the drum-mixer conceivably might result in excessive oxidation-volatilization of the asphalt cement. Before permitting full-scale drum-mix production on any Department of Transportation project, an initial program of consistency testing should be undertaken at the particular plant involved to determine whether any such detrimental effect in fact occurs.

14. Subsequent to the completion of the testing for this study, the Department was apprised of some general deficiencies in the consistency test procedures employed by our central laboratory. In response, the Department converted from the AASHTO to the more detailed ASTM Abson recovery procedure.

Various analyses presented in this report suggest that these deficiencies apparently affected only the penetration test results. There was a consistent bias in favor of underestimates of the true amount of hardening occurring on processing. Importantly, other analyses suggest that the new testing procedures may have eliminated such characteristic bias.

Given the fact that consistency test results form the basis for many important decisions by this Department, further study in this regard is warranted.

15. Various relationships between mix discharge temperature and asphalt hardening developed in this study indicate that, for any type of asphalt plant, substantial differences in asphalt hardening can be expected when production is at the ends of the usual temperature spectrum (270 to 320°F).

One implication of this finding is that in evaluating whether the equipment set-up at any future drum-mix plant results in "atypical" hardening, mix temperature clearly will have to be taken into account. Additionally, since this Department's current procedure for evaluating surge-silo systems is predicated on the assumption that no significant hardening occurs during mixing, our silo evaluation methodology may require modification.

16. Based on numerous observations of paving operations during the course of this study, it is concluded that the drum-mix laydown operation presents no unique problems.

17. The compaction characteristics of drum-mix were not definitively established in this study. Basically, this is attributed to both the compaction equipment used (not the Department's standard roller system) and a lower-than-normal achievable density for the surface mix evaluated. The latter factor was indicated by a Marshall air voids level of 5.5% which is higher than that normally encountered on a DOT project.

18. Due to the restricted range of moisture contents in the finished drum-mixtures studied (0.5 to 1.6 percent), it was not possible to specifically determine the extent to which such moisture acts as a lubricant and thus aids in attaining density in relatively low temperature mix.

RECOMMENDATIONS

A. Specifications: It is recommended that the Standard Specifications be modified to permit the optional use of the dryer-drum mixing process on NJDOT projects. A description of the proposed drum-mixing provision in a suggested specification format is presented in Appendix D of this report.

The recommended specification modifications apply exclusively to the production process: If a contractor elects to use the drum-mix process, none of the current quality requirements applied to the finished product should be waived or relaxed. This is particularly important in regard to the temperature requirements. Our analysis suggests that producing dryer-drum mix at temperatures less than that normally required for batch-type plants could result in significant losses in mixture stability.

B. Future Research:

1. If and when a contractor elects to use drum-mixing on a Department project, pavement performance test sections should be established and monitored so as to provide more definitive answers as to drum-mix durability.

As a part of this future work, some limited experimentation with low temperature mixes would be useful in view of the energy savings and associated potential initial economy offered by use of such mixes. The effects on mixture quality, especially stability, will have to be monitored closely during such experimentation.

2. Various analyses performed in this research suggest that measures undertaken to remedy the general deficiencies in the Department's consistency testing procedures may have been successful. It is recommended that the Department's central laboratory undertake an appropriate program of testing to confirm whether this is in fact the case. Certain of the data formats/analyses presented in the report may provide a guideline as to the form which such reliability testing might take.

Depending on the results of the recommended program of consistency testing, it may be necessary to modify the Department's current surge-storage silo evaluation criteria.

3. Certain mix stability investigations undertaken in this work indicated that conventional Marshall specimens can be used interchangeably with standard immersion compression cylinders to determine an index of retained strength for bituminous mixtures. Because of the greater ease of fabrication (without additional specialized equipment) and a more direct relationship to design criteria, it is recommended that the central laboratory consider using Marshall specimens rather than standard size cylinders in their ongoing immersion compression testing program. A decision in this regard would entail performing tests (on companion compression cylinders and Marshall specimens) sufficient to determine the extent to which the specific Marshall stability/compressive strength relationship derived in this work is of general applicability.

PART ONE: INTRODUCTION

1.1 RESEARCH OBJECTIVE

An innovative process for producing bituminous concrete -- variously referred to as the "turbulent mass" or "dryer-drum" process -- is reportedly more cost effective than conventional methods. The comparative production economy for the dryer-drum process is basically attributed to a reduction in required plant operating equipment and in the amount of fuel consumed per unit of product.

This report presents the results of a study undertaken to determine the advisability of permitting this alternate, "dryer-drum", process to be used for producing paving mixtures on New Jersey Department of Transportation projects. If such use is found warranted, a further objective is to develop specification provisions and control requirements to govern the equipment's operation.

1.2 BACKGROUND

1.2.1 Study Overview and Nature of the Dryer-Drum Process: The conventional process for producing bituminous concrete mixtures comprises several steps, culminating in the mixing of batches of dried, heated and screened aggregates with hot asphalt in a pugmill. In the dryer-drum process -- with proprietary variations, actually

basis, it has recently been noted^(6,7) that some highway agencies are realizing as much as one to two dollars per ton savings by using the dryer-drum process.

Given that the dryer-drum process has a real potential for savings in the initial cost of bituminous paving mixtures, a decision to permit the general use of the process basically entails a determination of whether such initial savings might be offset by any subsequent increased costs resulting from decreased product quality. In particular, such a determination requires resolution of the following questions, which are the subject of this research:

- . At the plant: Is the dryer-drum product consistently of comparable quality and uniformity as conventionally produced mixtures?

- . On the construction site: Do the lower temperatures and/or higher moisture contents characteristic of dryer-drum mixtures pose any construction problems (e.g., compaction, smoothness)?

- . In service: Are dryer-drum mixtures as durable as conventionally produced mixtures?

Based on a literature search and responses to a survey questionnaire, most agencies feel that the answer to the first question posed above -- "Is the as-produced dryer-drum product of comparable quality and uniformity as conventionally produced mixtures" -- is "Yes". Not unexpectedly, such affirmative responses are often accompanied by the qualifying provision that the dryer-drum

plant must be well-controlled and well-calibrated. Of particular interest with regard to the as-produced quality is the report that the asphalt is not harmed by exposure to direct heat in the drum-dryer and the finding that with proper "cold-feed"* control, the process is indeed capable of producing satisfactory gradations.

The questions relating to the constructability and durability of dryer-drum mixtures are not as well resolved. For example, a number of agencies have pointed out the need for particularly timely and adequate compactive effort on dryer-drum mixes, and one state⁽¹⁶⁾ has reported at least isolated instances of substandard density.

The relatively recent advent of the dryer-drum process has precluded definitive answers to the all-important question of long-term performance of drum-mixes. Further, apart from time considerations, the in-service performance observed in at least some states would be less than completely applicable to New Jersey's high traffic conditions since their first trial usage of the process has understandably been on less important (secondary) roadways.

1.2.2 Description of First Dryer-Drum Project in New Jersey: While mix produced by the dryer-drum process constitutes an increasing

*Proportioning the graded wet aggregates by means of adjustable storage bin gate openings and variable speed conveyor belts, without the conventional intermediate screening operations.

share* of the total yearly production in some states, particularly those in the western part of the country, only one New Jersey contractor is known to have acquired one of the units. Obviously, contractors are reluctant to make such an investment without an advance commitment that use of the process will be permitted on Department of Transportation work.

An opportunity to conduct the present evaluation of the capabilities and product quality of the dryer-drum process was presented in connection with a contract let by another state agency, the New Jersey Sports and Exposition Authority.

In the fall of 1976, the Sports Authority opened to service a \$300 million sports complex on a 588 acre site in the Hackensack Meadowlands, located just across the Hudson River from New York City.

*From the first installations in 1969, the number of dryer-drum plants in the United States increased to 34 in 1973 and to about 150 at present. By way of comparison, there are on the order of 4,500 conventional plants in this country. (Source: Reference 8 and informal estimates by National Asphalt Pavement Association.)

The principal facilities of the Meadowlands complex are a 77,000 seat football stadium (Figure 1) and 35,000 seat race track. Parking for some 20,000 cars is provided.

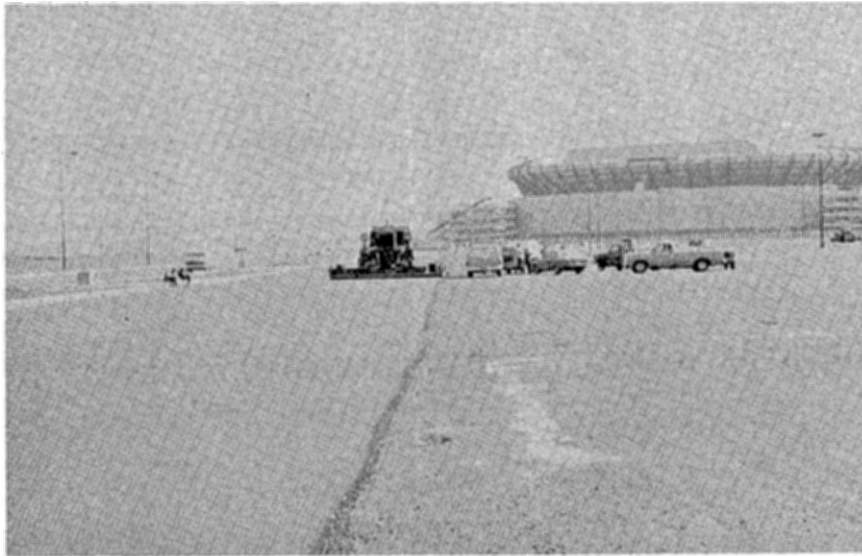


Figure 1: View of Stadium Parking Lot Construction

The successful bidder for the parking lots and access roads for this facility -- a New York-based contractor -- employed a Boeing Model 600 dryer-drum asphalt plant. This same plant was used in the first successful trials of the dryer-drum process in New York⁽⁹⁾.

The paving mixtures produced included dense-graded, stone-mix surface and binder courses, the latter material being employed as a combined binder/stabilized base. The bituminous concrete items of the \$5.6 million* paving contract totaled approximately 250,000 tons.

*Since this contract was bid on a lump sum basis and contained items other than blacktop, it obviously is not possible to directly determine the magnitude of any savings in the cost of the bituminous mixtures accruing from the use of the dryer-drum process. However, it seems reasonable to assume that use of the alternate process did, in fact, effect some significant savings: The second low bid, by a contractor who did not have an existing dryer-drum capability, was about \$600,000 higher than the successful offer.

While the New Jersey Department of Transportation was not contractually involved in the supervision or materials testing for this paving, the contracting authority kindly permitted monitoring of the Sportsplex dryer-drum plant for purposes of this study.

1.3 RESEARCH SCOPE AND APPROACH

1.3.1 Limited Scope of the Work: At the outset of this research, it was realized that the Sports Complex work alone would not provide a sufficient basis to fulfill the needs of the study. That is, while tests and observations of plant production and parking lot construction would permit assessment of the as-produced quality and relative constructability of the dryer-drum product, it was apparent that a realistic evaluation of the durability and performance of drum-mixtures would require monitoring pavement behavior under some type of representative (highway) traffic conditions. To this end, it was planned that drum-mix from the Meadowlands plant would be incorporated into test sections on a nearby heavily-traveled highway which was then being widened and resurfaced to accommodate traffic generated by the sports facilities.

However, due to a condition not directly related to the dryer-drum process per se -- the occasional presence of excessive fines adhering to the project coarse aggregate -- the researchers concluded that installation of the planned performance test sections was inadvisable. Our concern was that this fines condition might

result in premature distress if the drum-mix was subjected as planned to high volumes of mixed traffic. This possibility was suggested by some early marginal or unsatisfactory immersion-compression test results. As a consequence, the scope of this study is generally limited to an evaluation of the as-produced quality of the dryer-drum product.

1.3.2 Research Methodology:

A. Evaluation of As-Produced Quality

Concurrent with informal observations designed to familiarize Department of Transportation personnel with the dryer-drum process, the as-produced quality of the drum mixtures was gauged by samples obtained on eight* production days in accordance with the following program of testing:

Gradation and moisture tests: To determine the adequacy of the critical cold-feed proportioning system and the associated process control requirements at various stages of production, the mineral aggregates were tested for gradation and moisture content in the form of stockpiled raw materials, as a blend on the main belt feeding the dryer and as a finished product exiting from the drum and/or storage bin.

Asphalt tests: The AC-20 asphalt cement used at the Sportsplex plant was tested in original form from plant tank samples and in processed form from mixture recovery samples.

*On one additional day, a more limited program of testing was undertaken.

The samples of original asphalt were subjected to routine specification tests and special thin-film oven and chemical composition tests. The special thin-film oven tests were conducted at an oven temperature lower than that used in the standard procedure (250°F versus 325°F).

The purpose of the temperature modification was to provide an estimate of the amount of hardening which the studied asphalt might undergo if processed thru a conventional plant operated to discharge mix at the relatively low temperatures employed at the Sportsplex (average: 245°F). The chemical analyses (Rostler-Sternberg procedure) were undertaken in an effort to more fully characterize the nature of the asphalt, and in particular, to provide a basis for ascertaining the nature of any compositional changes occurring on processing thru the drum-mixer.

The samples of processed asphalt (Abson residue) were analyzed to determine the extent of any premature age-hardening caused by exposure to the direct heat in the dryer-drum. These determinations of relative hardening were based on before/after comparisons of conventional mechanical tests (viscosity and penetration) and the Rostler-Sternberg results.

Determination of the chemical composition of asphalt is a new procedure in this state. Consequently, to provide the necessary basis of comparison for the dryer-drum analyses, tank and recovery samples from four randomly selected conventional plants were subjected to an identical program of chemical and mechanical

testing. (An opportunity to obtain ideal control data -- use of the Sportsplex vendor's asphalt by the operator of a conventional plant -- did not develop.)

Tests of Relative Strength and Density: Samples of the finished dryer-drum mixtures were subjected to the usual schedule of tests to determine conformity with the New Jersey Department of Transportation's specified Marshall criteria. In addition to these tests of relative strength and density, samples of each day's production were tested for retained strength in accordance with the standard immersion-compression procedure and variations thereof.

The retained strength of a bituminous mixture is an expression of the relative decrease of strength on soaking and provides an indication of any tendency for loss of adhesion between the asphalt and aggregate in that particular mix. Here the purpose of the retained strength test was to determine whether the free moisture in the drum mix itself or residual moisture in the partially-dried aggregates created any such stripping tendencies.

The retained strength testing performed in this work occasionally departed from the standard procedures in two respects. First, certain of the samples were fabricated and tested as Marshall specimens rather than as the conventional compression cylinders, thus yielding a "retained stability" value. Second, certain of the Marshall and compression samples were soaked for two weeks, this non-standard soaking period being conventional in New Jersey.

B. Evaluation of Constructability

An evaluation of the constructability of the dryer-drum product was based on observations of the laydown operation together with a program of tests designed to determine the relative density and voids level achieved. Evaluation of the degree of in-place compaction was based on nuclear gauge relative density measurements and the analysis of drilled cores, the core locations being keyed to specific deliveries of materials having known Marshall properties.

PART TWO: PLANT EQUIPMENT AND OPERATION

2.1 GENERAL

As previously noted, the paving contractor at the Sportsplex project used a Boeing drum-mix plant, Model Series 600, to produce the more than 250,000 tons of bituminous mixtures required for access road and parking lot construction.

The Sportsplex drum-mix unit was evaluated by the State of New York on a 1974 Interstate Highway project⁽⁹⁾. Subsequent to the New York evaluation, the contractor opted to modify the plant's asphalt delivery system. Specifically, the location at which asphalt cement is introduced into the drum-mixer was changed from 6 to some 16 feet from the burner end of the drum. This was apparently done as a precautionary measure to alleviate the potential for oxidizing the asphalt.

The contractor elected to stockpile about half the total quantity of aggregate required for this work at the plant site prior to the start of production. This early stockpiling was apparently undertaken in consideration of the size of the project and the high production rates anticipated for the drum-mix plant.

Although various thicknesses of plant mix were specified for the Sportsplex work, a total thickness of 6 inches of bituminous concrete was typically required. This total was comprised of

4 inches of base course (NJDOT binder, Mix I-3) and 2 inches of surface course (Mix I-5) with nominal aggregate top sizes of 3/4 and 3/8 inches, respectively. The mix designs for the bituminous mixtures used at the Sportsplex are presented in Appendix A.

2.2 PRODUCTION EQUIPMENT AND OPERATIONS

2.2.1 Plant Layout: An overview of the Sportsplex plant layout is shown in Figure 2.

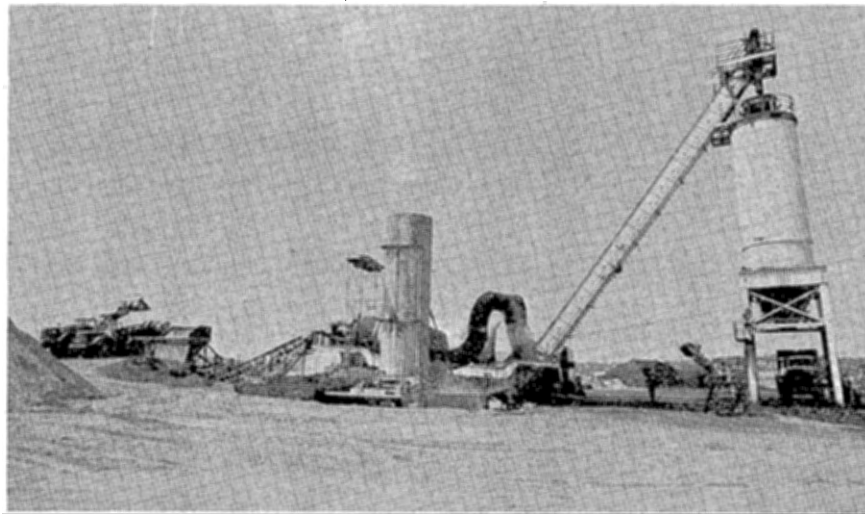


Figure 2: Overview of Sportsplex Drum-Mix Plant ("leaning tower" effect results from use of wide-angle lens).

The major elements of the drum-mix plant shown in this photo are the cold bin system, aggregate feed belt, drum-mixer, hot elevator leading to a 150 ton capacity surge-bin, and hanging-type scales (located just under the storage silo).

The operations involved in producing drum-mixtures are illustrated by a series of photographs presented in the following subsections.

2.2.2 Charging Aggregate Bins: The production process starts when the cold bins are charged with material from the appropriate aggregate stockpiles. As shown in Figure 3, the contractor used a 5 cu. yd. capacity front-end loader to accomplish this transfer of aggregates from the stockpiles to the cold bins. On this particular project there were four bins. The first of these



Figure 3: Charging Cold Bins

contained sand, the second screenings, while the third and fourth each contained the particular coarse aggregate ($3/4$ or $3/8$ inch stone) being used that day. On some days, two front-end loaders were needed to charge the bins in order to maintain pace with plant production (reported daily high: 4,500 tons).

2.2.3 Metering Aggregate Materials: The importance of this step in the dryer-drum process cannot be overemphasized since this is the point where final mix gradation is accomplished. That is, the mixture exiting the drum-mixer can be expected to have

essentially the same gradation as achieved at the bins.

The metering of graded wet aggregates from the individual bins into the desired mix proportions is achieved by the combination of variable speed belts and bin gate openings. More specifically, the bottom of each bin has a mechanically adjustable gate, and directly under each gate opening there is a short "Feeder" conveyor belt as shown in Figure 4. Thus, the volume

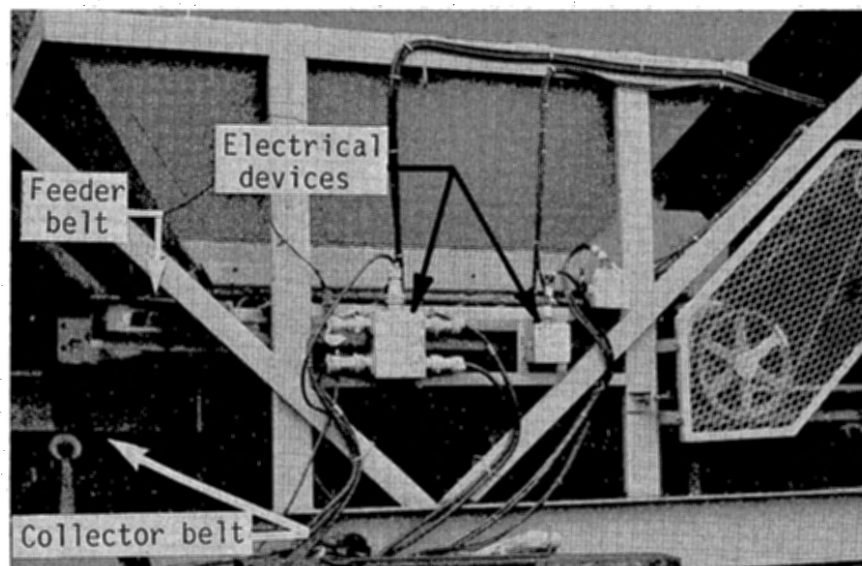


Figure 4: Feeder and Collector Belts

of material flowing from a bin is dependent on both the speed of the feeder belt and the gate opening. The specific bin gate openings and feeder belt speeds necessary to deliver a total volume of flow corresponding to the design proportions by weight for a given mix are initially established when the plant is calibrated (i.e., prior to the start of production).

From the four feeder belts, the materials fall onto a "collector" belt which travels under the full length of the four bins. The electrical fixtures shown in Figure 4 house various input and output devices which relay belt speed signals to and from the control room.

Figure 5 is an end view of the bin system showing the combined aggregates being deposited from the collector belt onto the main feed to the drum-mixer. The automatic sampling device shown in this Figure will be described in detail in subsection 3.2.

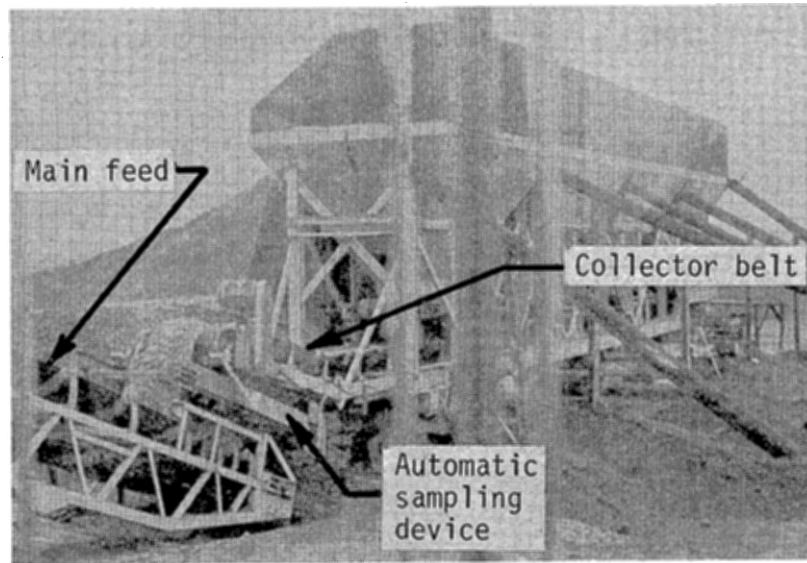


Figure 5: Discharge of Combined Aggregates from Collector Belt Onto Main Feed to Drum-Mixer

2.2.4 Aggregate Weighing and Asphalt Supply System: Figure 6 shows the composite wet aggregates on the main conveyor belt to the drum-mixer. As noted earlier, the aggregate metering and blending process is complete, thus, final mix gradation is essentially established at this point. Here, the finished wet aggregate blend is weighed for the first and only time by a continuous reading device (load-cell) positioned about mid-way up the main conveyor.

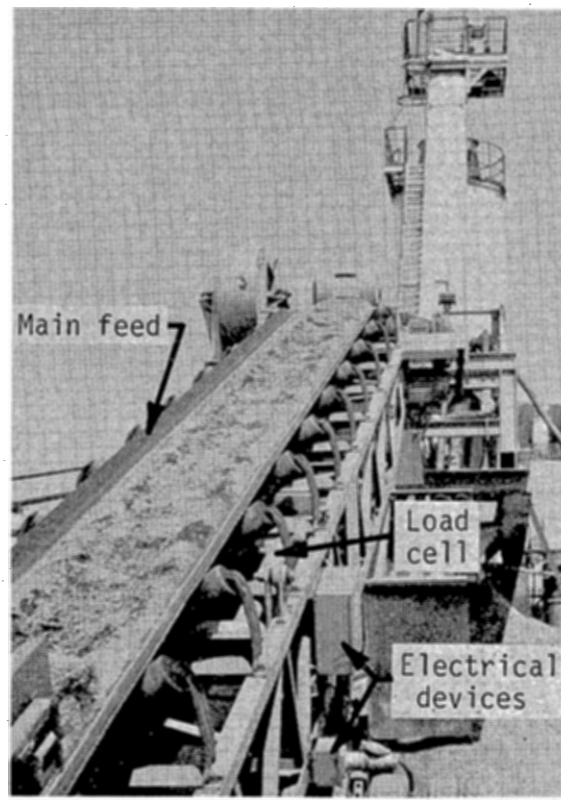


Figure 6: Main Feed to Drum-Mixer

The electrical devices shown on the side of the main conveyor belt transmit signals to the plant control room as to the quantity of wet aggregate passing over the belt in tons per hour.

Since final proportioning is on a dry weight basis, an adjustment for moisture is made by means of a dial setting in the control room to obtain a dry aggregate weight. An electronic signal representing the dry aggregate weight is interlocked with a positive displacement asphalt pump to maintain the desired asphalt content during mixing.

2.2.5 Drum-Mixing: The heart of the process -- the drum-mixer -- is shown in Figure 7. The equipment shown at the left of the drum-mixer is a Genco burner unit with a rated capacity of some 200 million BTU/hour. The burner flame is shielded or redirected so as to prevent direct contact with the material.

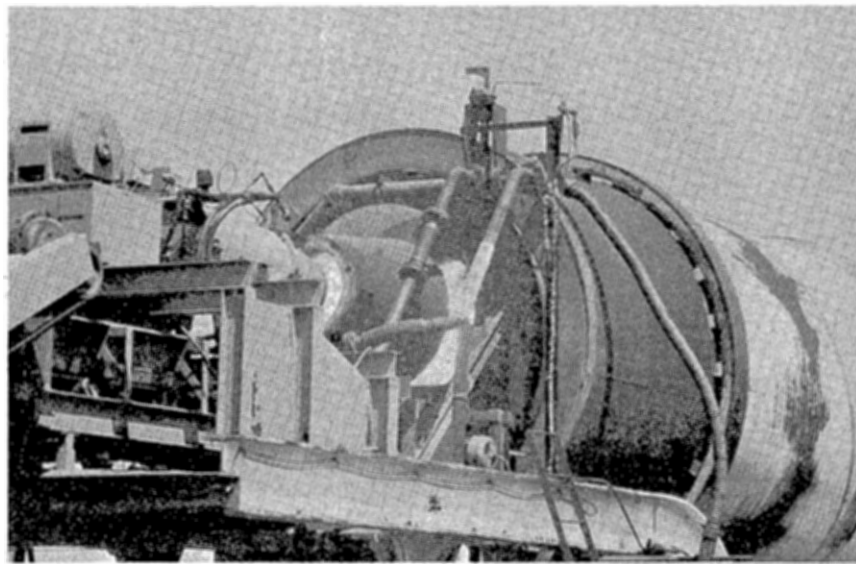


Figure 7: Drum-Mixer

The drum-mixer is similar in configuration to the dryer units used at conventional batch type plants. The major difference between the two is that a drum-mixer entails "parallel flow" operation (i.e., the aggregates flow in the same direction as the burner flame), while in a typical dryer, the flame and aggregate flow are in opposite directions ("counter flow").

As the blended aggregates enter the (10' x 40') drum, a series of mixing flights, similar to large pieces of angle iron, catch and continuously agitate the material as the drum rotates. At this point the aggregates are partially dried by the shielded flame. When the aggregates are about 16 to 18 feet into the drum -- and in the presence of hot burner gases -- an appropriate quantity of asphalt for the given mix and production rate is introduced by means of a spray bar.

2.2.6 Mix Storage and Delivery: The hot-mix exiting the drum discharge is transported by means of a slat conveyor (hot elevator) to a surge-bin where it is subsequently weighed and discharged into trucks for delivery to the paving site (Figure 8).

2.3 PLANT INSTRUMENTATION

2.3.1 Overview of Control Room Panel: The various control instrumentation for the dryer-drum process was displayed on a console housed in a trailer located near the burner end of the drum-mixer. As shown in Figure 9, there are basically three

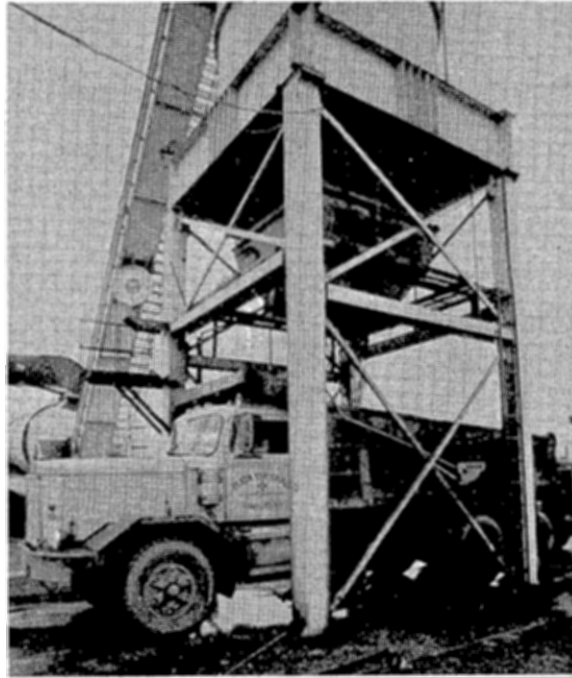


Figure 8: Mix being Discharged from Surge-Bin into Delivery Trucks.

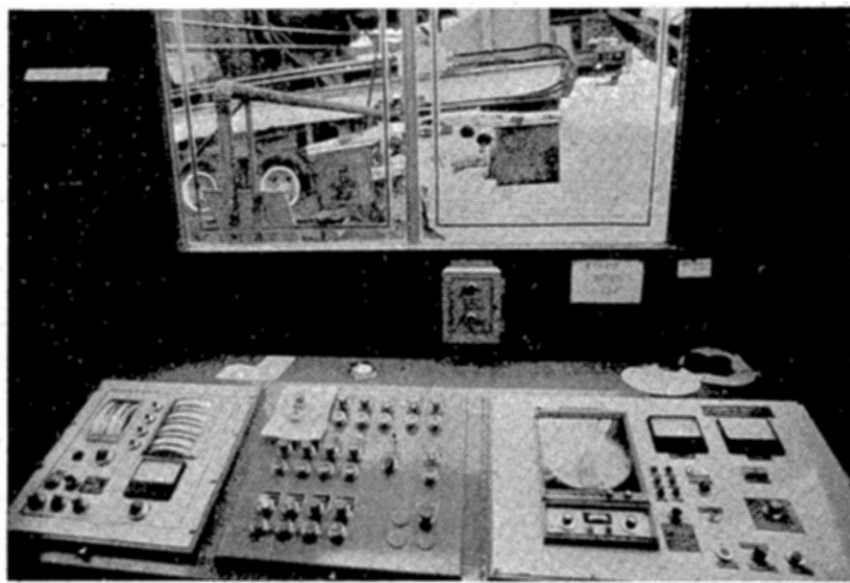


Figure 9: Overview of Plant Control Console at Sportsplex

segments to the operator's control console. The center portion contained various indicator lights (e.g., burner, conveyor belts, etc.), and are thus primarily the concern of the producer. The two outer sections of the console display information that would be of considerable interest to a state plant inspector, and consequently are described separately in the two subsections to follow.

2.3.2 Temperature Controls: The right-hand section of the control panel, shown separately in Figure 10, contains various types of temperature control and recordation equipment. For example, the circular plot shown in this segment of the panel continuously records the discharge temperature of the mix.

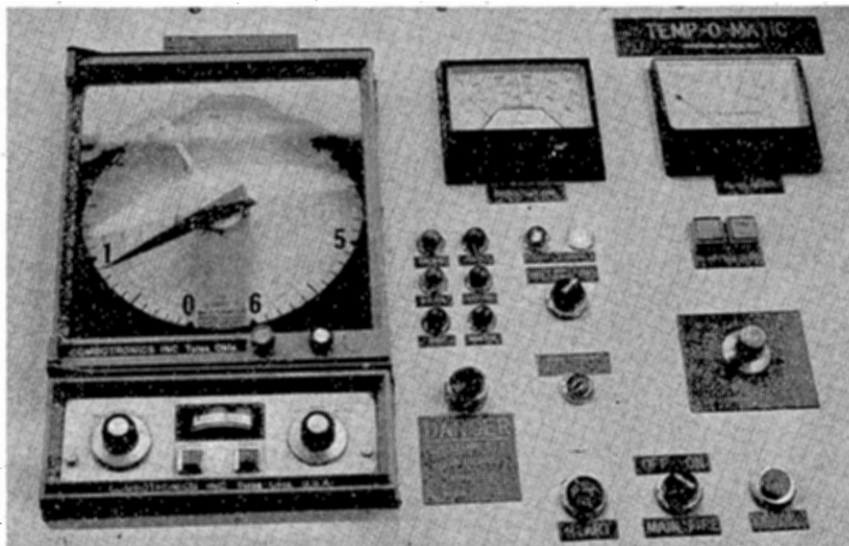


Figure 10: Temperature Control and Recordation

2.3.3 Total and Proportional Controls: The left-hand section of the operator's console contained the plant's total and proportional controls. This instrumentation is shown in closer detail in Figure 11.

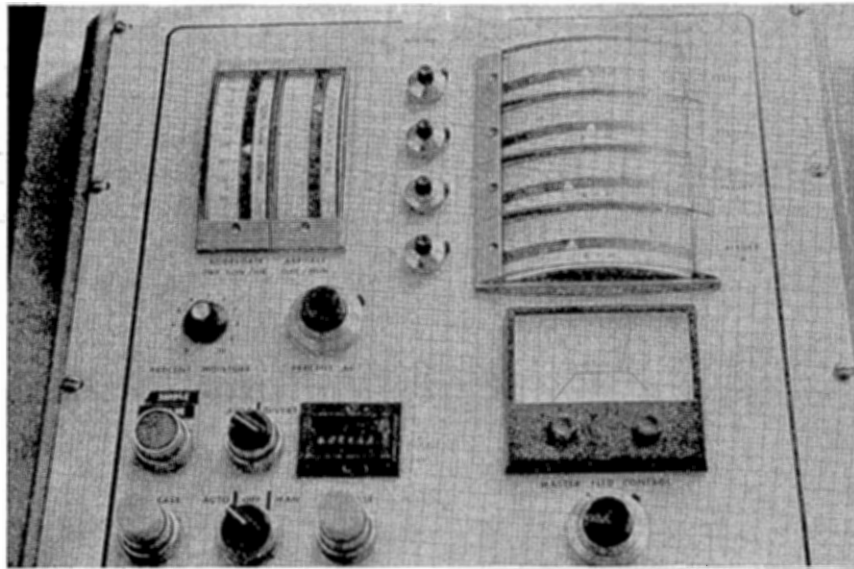


Figure 11: Total and Proportional Controls

Total control refers to the plant's overall production rate in tons per hour, while proportional control pertains to the relative quantity of aggregate fed from each bin and the percentage of asphalt cement added. In order to maintain positive proportional control when the production rate is changed, the feed rate from each bin (as indicated by the respective feeder belt speeds) and the rate of asphalt delivery must automatically adjust to that required for the given total output. The total output of the plant is varied by the master

feed control shown at the lower right in Figure 11. The studied plant had a rated capacity of 300 to 600 tons per hour.

At this plant, verification of the production rate (controlled by the master feed dial) required a calculation based on the two rate meter displays shown in the upper-left portion of Figure 11. That is, the delivery rate of dry aggregate in tons per hour must be added to the asphalt cement delivery rate (converted from gal/min to tons/hr). The output of the above two rate meters can also be used to determine whether the instrumentation is inherently in accord (i.e., in resolving whether the percentage of asphalt being introduced into the mix based on dial readings is in fact the desired percentage). As will be described later, such obvious (albeit, rough) checks can indeed be useful since certain of the control instrumentation used at the Sportsplex was not internally consistent.

The four dials and indicators in the upper-right portion of Figure 11 are the aggregate proportioning controls for the individual bins. The main difference between the total aggregate output display and these proportional indicators is that the total aggregate feed rate is expressed directly in tons per hour while the bin feed rates are displayed as belt speeds in revolutions per minute. A direct determination of the quantity of material, in tons per hour, being fed from any bin thus cannot be obtained from these proportioning indicators. In practical effect, if achieving the mix design required "X" tons per hour

from a particular bin, neither the plant inspector nor a casual observer would know if the bin in question was in fact delivering the required "X" tons per hour from the control instrumentation. In order to obtain the desired information -- that is, whether the plant is in gradation control -- would require knowledge of the current plant calibration data.*

The researchers were not present when the Sportsplex plant was calibrated. In general, the calibration procedure for dryer-drum plants involves running the project materials from each of the bins (individually) thru the plant or diverting them into a truck for a fixed period of time with a given gate opening and belt speed and then weighing to determine the tonnage delivered. This procedure is repeated for various belt speeds so as to establish sufficient points to plot a calibration chart for each bin depicting the tons per hour delivered for particular RPM settings. These charts are then used in conjunction with design proportions to determine the individual bin RPM settings necessary to produce the given mix gradation for various production rates.

The desired asphalt percentage is set manually using the knob shown directly underneath the asphalt rate meter display in Figure 11. The small box in the center portion of this figure totalizes the number of gallons (in terms of pump revolutions)

*It should be noted that the installation of additional weighing equipment (load-cells) under the collector belt would provide a direct readout in tons per hour for each bin. This alternate arrangement will be detailed in subsection 4.3.3.

of asphalt cement used each day. This information provides a means for detecting gross differences between the indicated and required quantities of asphalt cement. Such a check is accomplished by comparing the quantity displayed on this device (converted to tons) at the end of a given day to the theoretical tonnage of asphalt cement required based on the quantity of mix produced that day and the mixture's design asphalt content.

The small knob shown just to the left of the percent AC dial is set manually for the amount of moisture in the combined aggregates as determined from the results of conventional lab tests. As noted earlier, the setting on this device adjusts the total wet weight of aggregate flow to a dry weight which is then relayed by electronic signal to the asphalt pump.

The needle display shown in the lower-right portion of Figure 11 provides a continuous moisture measurement from a probe in the sand bin. This display was used as a secondary or back-up system to laboratory determinations of the moisture contained in the combined aggregates. This needle display was provided so that if a sudden surge of wet or dry sand differing from rather extreme pre-set low and high moisture values was encountered, a signal would be activated to warn the operator.

2.3.4 Plant Output Controls: The instrumentation previously described dealt predominantly with rates of production. The unit shown in Figure 12 is a totalizer which accumulated the tonnage of wet aggregate that had passed over the belt scale since the start of production.

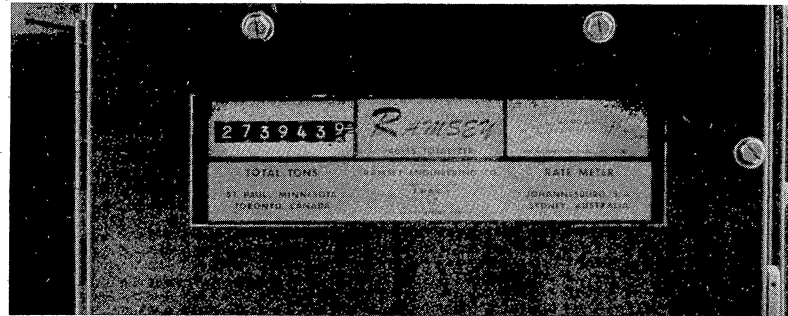


Figure 12: Digital Totalizer

Use of this aggregate totalizer reading (converted to a dry weight basis) together with that of the asphalt totalizer (converted from pump revolutions to tons) provides a basis for calculating both the total daily tonnage of mix produced and its asphalt content. Comparisons of the tonnage of mix based on these control console readings to the proven weight of material produced as measured at the scalehouse provides a plant inspector with a rough check on the adequacy of the control instrumentation on a daily basis. For the eight test days at this particular plant, such gross comparisons revealed differences between the control room and scale-house daily tonnage which ranged from about 1/2 to 8 percent (i.e., up to 266 tons). The apparent causes for this disparity and the effect on the finished product are detailed in subsection 4.2.4.

2.4 PLANT PRODUCTION AND MIX TEMPERATURES

2.4.1 Plant Production: One of the major advantages of the dryer-drum process is its high production capability relative to conventional plants. The total tonnage and the average production rate for each day the full research testing program was applied at the Sportsplex project are presented in Table 1.

Table 1: Plant Production Data

Test Day	Mixture	Total Hours Worked ^a	Total Output (tons)	Average Production Rate (tons/hr)
1	Binder	7.33	1,553	212
2	Surface	8.50	2,380	280
3	Surface	8.67	2,955	341
4	Binder	8.25	3,388	411
5	Surface	7.47	2,637	353
6	Surface	----	584	---
7	Surface	----	973	---
8	Binder	9.50	3,680	387
Totals		49.72	16,593 ^b	
Averages		8.29	2,766 ^b	334

^aBased on total elapsed time, including moderate down-times (typically 1/2 hour per day). If down-time is excluded, an overall average production rate of 355 tons/hr is indicated.

^bDays 6 and 7 excluded.

As shown in Table 1, daily production for the drum-mix plant ranged from 1,553 to 3,680 tons and averaged about 2,800 tons. The data for days 6 and 7 was excluded since they involved low production, stop-and-go work (e.g., mix for sidewalk areas) and/or inclement weather. The average tonnage rate for these six days was about 330 tons/hr. As mentioned earlier, a daily high of some 4,500 tons was reportedly achieved during the Sportsplex work. In comparison to the average daily production for a "typical" conventional batch type plant in New Jersey, the average output of the drum-mix plant for the six study days represents about a two-fold increase.

2.4.2 Mix Temperature: Mix temperature data obtained during each day of this evaluation is presented in Table 2.

Table 2: Mix Temperature

Binder Course ^a				Surface Course ^a			
Mix Temperature (°F)				Mix Temperature (°F)			
Day	Range	$\bar{X}$	N	Day	Range	$\bar{X}$	N
1	230 - 270	252	7	2	250 - 275	257	6
4	230 - 260	244	16	3	215 - 305	251	8
8	205 - 250	224	18	5	220 - 255	242	12
				6	225 - 255	240	4
				7	225 - 250	239	6
				9	227 - 242	235	5
Wtd. Averages		237				244	

^aDrum and truck temperatures have been combined since no significant difference was observed.

Temperatures were taken at two locations: at the discharge end of the drum-mixer and from trucks. As shown, the temperatures of the binder mix ranged from 205°F to 270°F while those for the surface course ranged from 215°F to 305°F. For the nine test days, the average temperature (drum and truck) of the binder and surface course was 237°F and 244°F, respectively. The average mix temperature measured at the drum discharge was about 245°F.

While mix moisture is, of course, not solely a function of discharge temperature, considering that the average temperature of the Sportsplex mixes were about 50°F below that of conventional mix, a surprisingly low quantity of moisture was retained in the finished mix. Specifically, the moisture content of mixture samples obtained for this study averaged only about 1 percent.

2.5 FUEL CONSUMPTION

The energy crisis of 1973 brought to light the necessity for conserving all existing forms of energy. In line with this, the federal government has encouraged states to adopt appropriate energy conservation measures in the production of bituminous mixtures. As previously indicated in this report, one of the economic benefits attributed to the dryer-drum process is reduced fuel costs. That is, since drum-mixes are normally produced at relative low temperatures compared to conventional plant mixtures, a general fuel savings is realized.

A contractor's representative provided the necessary information to permit a rough comparison of the fuel requirements for the studied dryer-drum process to those of conventional plants. Based on the data provided -- which represented over 20 percent (or about 56,000 tons of mix) of the total quantity of bituminous concrete required for this project -- an average of 1.375 gallons of fuel was consumed for each ton of mix produced.

Information obtained from two conventional plants indicated a rather large range in fuel requirements (i.e., from 1.6 to 2.38 gal/ton). However, a reduced fuel demand is indicated for the drum-mix process even when compared to the lowest value reported for the conventional plants (1.375 vs 1.6 gal/ton). Based on the latter comparison then, a conservative estimate of the fuel reduction would be 0.225 gal/ton. For a moderate day's production, say 2,000 tons, this would result in a savings of some 450 gallons of fuel. Obviously, the indicated fuel reduction for the drum-mix process reflects particular conditions (e.g., efficiency of burner equipment, amount of aggregate moisture, mix temperatures) encountered at the Sportsplex and must be viewed accordingly. The actual rate of fuel consumption by the dryer-drum process on another project can be expected to vary with the previously indicated factors.

2.6 POLLUTION CONTROL

The studied dryer-drum plant complied with both state and federal government environmental protection criteria. In New Jersey, the specified maximum limit for particulate emissions from an asphalt plant is 15 pounds per hour. At the Sportsplex, this requirement was satisfied by equipping the drum-mix plant with the wet scrubber system shown in Figure 13.

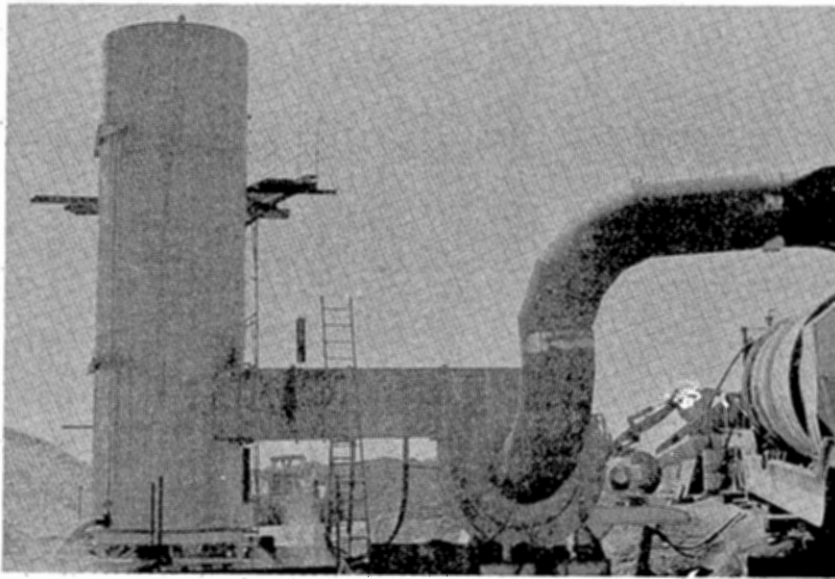


Figure 13: Wet Scrubber System

PART THREE: SAMPLING AND TESTING PROCEDURES

3.1 GENERAL

The sampling and testing procedures employed in this research were generally the same as standard inspection practices used at conventional asphalt plants. However, due to the nature of the dryer-drum operation and the particular needs of this study, some non-routine methods of obtaining, storing and testing samples were required. The principal purpose of this report section is to outline those non-routine procedures.

3.2 AGGREGATE SAMPLING

The raw mineral aggregates were sampled and tested for gradation and moisture content as individual stockpiled materials and as a composite blend.

The various stockpiles of sand, screenings, and coarse aggregate were sampled twice per day (morning and afternoon).

In order to provide a direct basis of comparison between the aggregate gradation entering and exiting from the drum-dryer, the sampling of the aggregate blend entering the dryer was timed to coincide with the taking of mixture samples at the discharge end of the drum. Generally, these two types of samples were taken within several minutes of each other.

The composite aggregate samples were obtained using the automatic sampling device shown in Figures 14 and 15. This device consists of a chain-driven sampling tray which intercepts the stream of composite aggregate as it drops from the bin collector belt onto the main feed to the dryer-drum and deposits the sampled material into a receiving hopper.

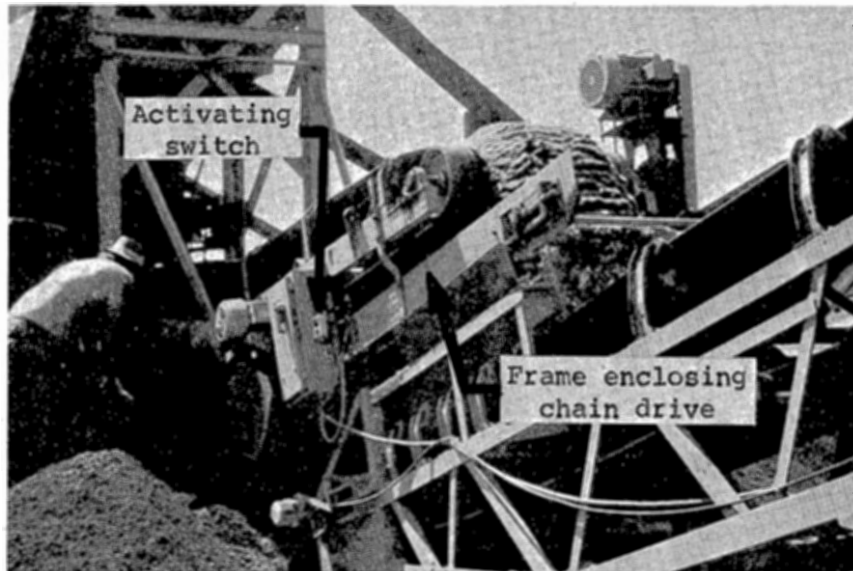


Figure 14: Automated Sampling Device

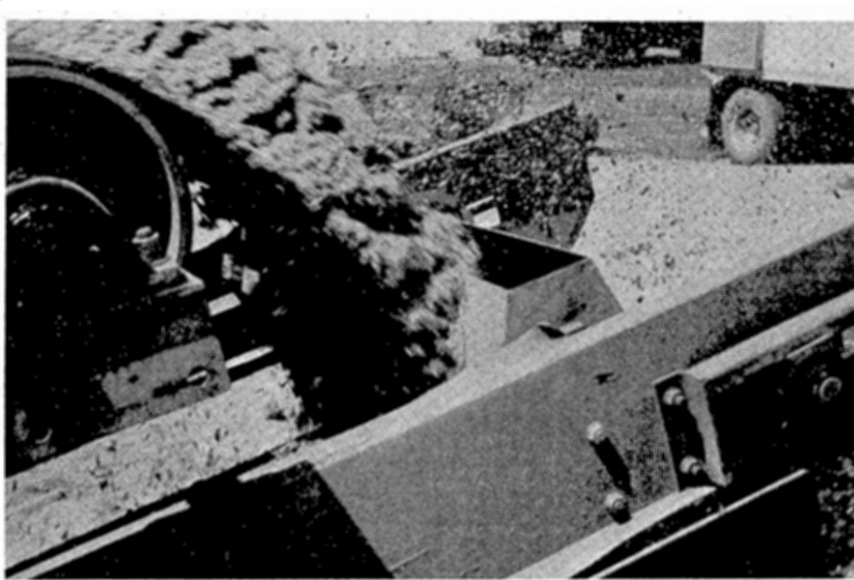


Figure 15: Stop-Action Photo of Sampling Tray beginning to Intercept Stream of Combined Aggregates. Note spray of fines.

3.3 MIXTURE SAMPLING

The characteristics of the finished bituminous mixtures produced at the Sportsplex plant were determined from tests performed on two general types of samples: "Drum" samples obtained at the discharge end of the mixer and "Truck" samples from project delivery vehicles.

Truck samples, obtained at the rate of one sample per 3 to 4 hundred tons of production, are the conventional basis for determining conformance with New Jersey's specified bituminous concrete gradation, asphalt content, and stability requirements. While such samples would thus be used to gauge the quality of the product on any future Department of Transportation drum-mix project, it was felt that exclusive reliance on truck samples might confound the results of this study. That is, since the characteristics of truck samples obviously reflect the influence of variable holding times in the storage silo -- more particularly, possible segregation and penetration loss -- such samples could obscure the true "as-produced" quality of the drum-mix. The purpose of the drum samples was to provide the most direct indication of the characteristics and quality of the drum-mix product, eliminating the storage silo as a possible variable.

Sampling at the discharge end of the dryer-drum is not a standard procedure; consequently, there were no ready-made provisions for such work. To ensure the safe taking of a truly representative sample, the equipment and set-up shown in Figures 16 and 17 was employed. Figure 16 shows the special (wide) sampling

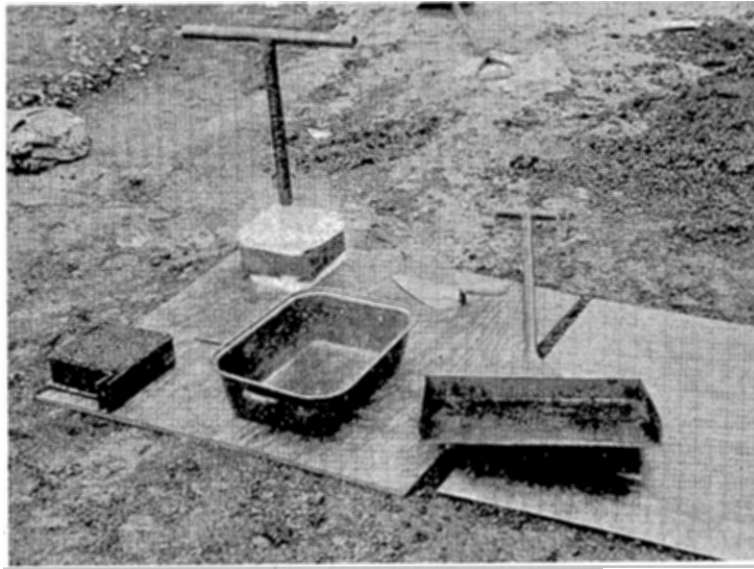


Figure 16: Mixture Sampling and Shaping Equipment

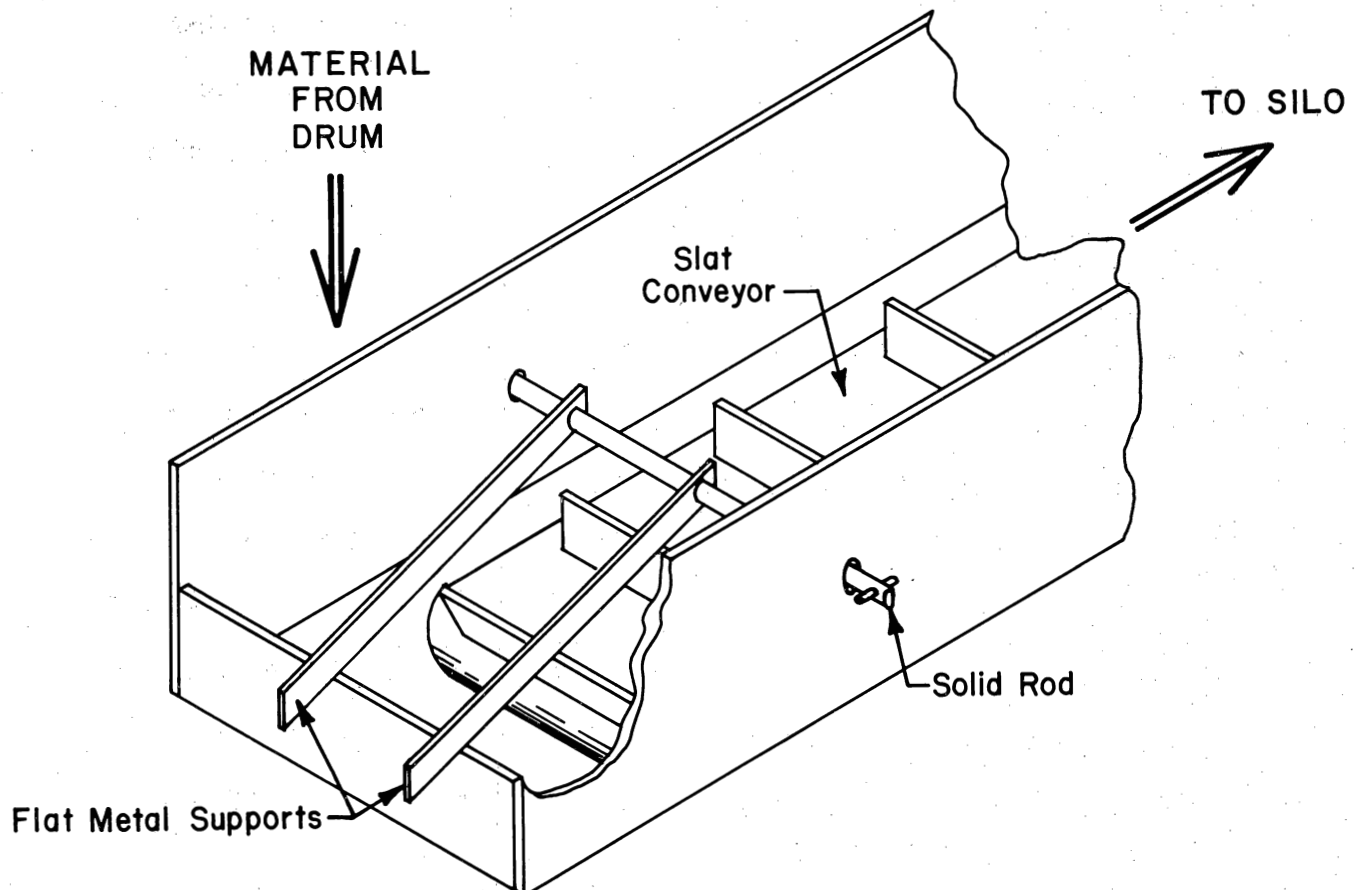


Figure 17: Sketch of Supporting Arrangement Used In Obtaining Mixture Samples at Discharge End of Drum

shovel used. This equipment was wide enough to intercept the full stream of finished mix discharged from the drum onto the lower end of the storage silo elevator. Figure 17 shows the simple set-up used to support the shovel (and thus prevent personnel injury) during sampling. The supporting arrangement consists of two strips of flat metal stock hinged on a solid rod attached to the slat conveyor enclosure. During sampling, the shovel was slid up the flat metal supports while they were in the position shown. After sampling, the supporting strips were moved aside by sliding them along the solid rod to the sides of the enclosure.

Drum samples obtained by the above-described procedure were placed on a steel platform, tested for temperature and then quartered. Two of these quarters were immediately molded into conventional extraction and Marshall specimens. The third sample fraction -- used to determine the properties of the recovered asphalt -- was shaped, frozen using dry ice and stored in a styrofoam chest (Figure 18). (On delivery to the laboratory, and after every intermediate stage of testing, these recovery samples were stored in a freezer so as to preserve their "as-produced" character.) A one-quart sample of the remaining material was sealed in a tared can, weighed and subsequently tested for moisture content. These (non-standard) moisture content determinations were based on the weight loss on heating for 3 hours at 325°F. The latter temperature was selected since it is the same as that used

in the thin-film oven test and thus provides some assurance that the extent to which volatilized asphalt is erroneously reported as moisture will be minimal.*



Figure 18: Shaping and Freezing of Asphalt Recovery Samples.

*The maximum allowable loss of asphalt volatiles under the TFO conditions of 325°F for five hours is 0.5%. For a mixture containing 5% asphalt, this would correspond to a maximum loss of on the order of $0.05 \times 0.005 = 0.0025\%$ by weight of mixture.

PART FOUR: FINDINGS

4.1 GENERAL APPROACH TO THE ANALYSIS OF DATA

Given that the principal purpose of this study is to evaluate the capabilities of the dryer-drum process, the parameter of major interest in certain of the subsequent analyses is the uniformity of the finished product (i.e., the process standard deviation), rather than the particular mean test values. Implicit in this approach is that if the variability of mixtures produced by the drum-mix process and conventional plant systems are comparable, compliance with current New Jersey Department of Transportation acceptance limits based on the conventional process might reasonably be expected with normal process control (e.g., calibration). This is not to say, however, that a comparison of the project mean test results to job mix values is unimportant: Determination of the factors causing any observed job mix formula "miss" provides a specific indication of required process adjustments.

To some extent, this emphasis on process variability in the analysis of data was dictated by the fact that the specifications for the Sportsplex paving differed from those conventionally applied to New Jersey Department of Transportation projects. For example, in this work, the composition of the finished product (gradation and asphalt content) merely had to comply with the

Department of Transportation's master design limits rather than with the usual, more restrictive, job-mix formula tolerances. Additionally, the project specifications contained none of the usual Department of Transportation provisions for reduced payment in the event of non-conformance with the various acceptance parameters. Since the New Jersey Department of Transportation acceptance criteria did not in fact apply, some of the following analyses are of necessity directed at determining if the usual tolerances could be met.

4.2 ASPHALT CONTENT

4.2.1 Nature of Sample: As indicated in Table 3, the asphalt content determinations made in this work comprised tests on a total of 82 mixture samples obtained on nine production days.

Table 3: Summary of Mixture Asphalt Content Sampling

Mixture	Days Tested	Tonnage		Number of Samples		
		Daily Range	Total	Drum	Truck	Total
Binder	3	1,600 - 3,700	8,600	24	17	41
Surface	6	600 - 3,000	11,500*	25	16	41
TOTALS			20,100*	49	33	82

*On test day 9, only a portion of the day's production was sampled.
Estimated fractional sample: 2,000 tons

The test days were randomly selected over a three month period. Individual truck and drum samples were obtained at an average rate of one sample per 365 tons from a total of some 20,000 tons of mix.

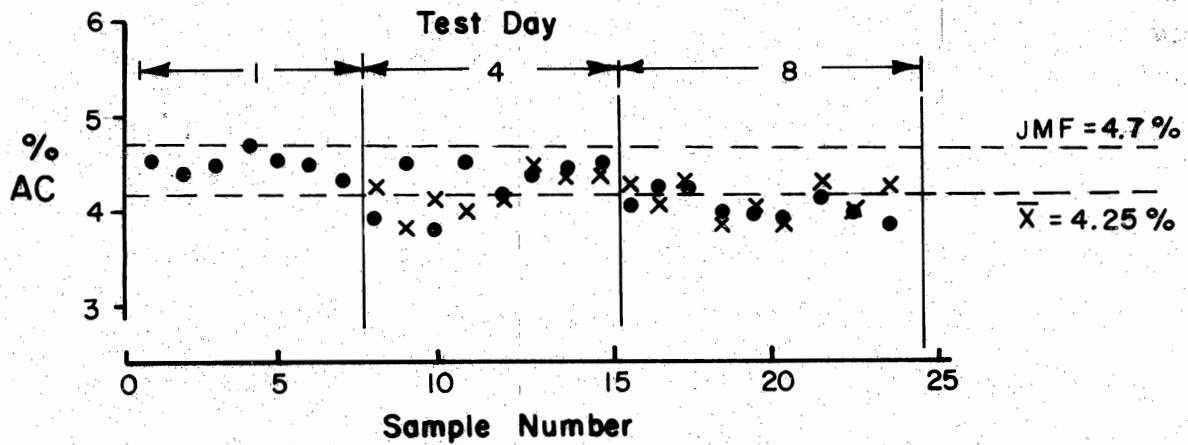
4.2.2 Variability of Asphalt Content: The most recent comprehensive analysis⁽¹⁰⁾ of the compositional variability of New Jersey bituminous concrete was performed in 1972. At that time, analysis of more than a thousand asphalt content determinations yielded average standard deviations for our binder and surface mixtures which were nearly identical at about 0.26 percent. The average observed difference between the design asphalt content and production mean was 0.12 percent for binder and 0.17 percent for surface mix.

Analysis of the extraction test results obtained in this study (plotted in Figure 19) indicates that the percentage of asphalt in successive samples of finished drum-mix is of very comparable uniformity to the described historical data for conventionally produced similar mixtures. Specifically, the standard deviation of the combined* (truck and drum) samples of binder course is about equal to that historically observed for the "average" conventional plant (0.23 versus 0.26%), while the

*Pooling the asphalt content test results for the truck and drum samples appears to be a valid procedure. Conventional statistical tests indicate no real difference between the test statistics for the two types of samples at the 95% confidence level.

Figure 19: Asphalt Content of Finished Drum Mixtures

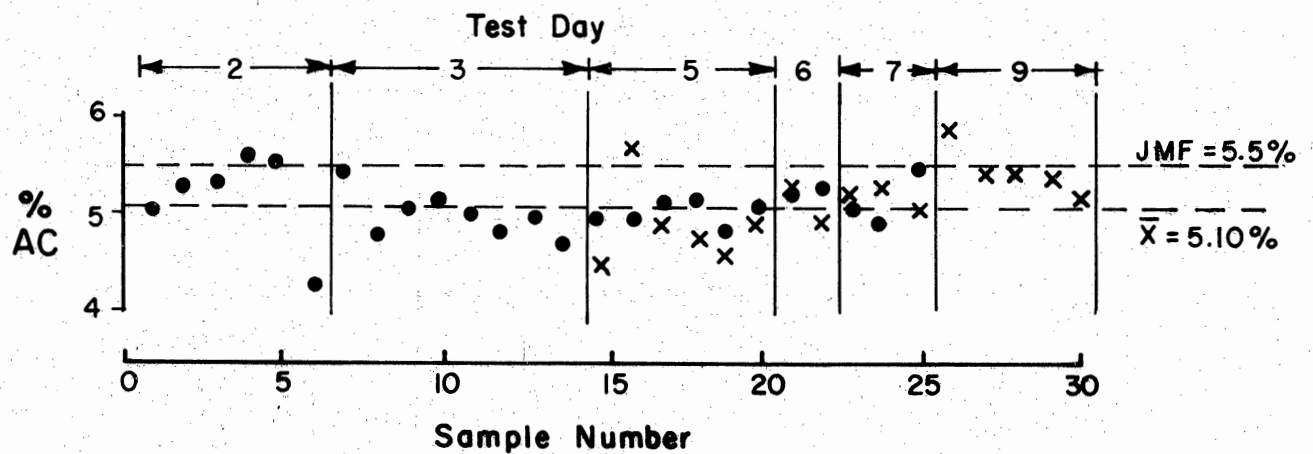
A. BINDER COURSE



SAMPLE	N	$\bar{X}$	σ
DRUM	24	4.29	0.25
TRUCK	17	4.18	0.19
COMBINED	41	4.25	0.23

Key:
 ● = Drum Sample
 X = Truck Sample

B. SURFACE COURSE



SAMPLE	N	$\bar{X}$	σ
DRUM	25	5.08	0.30
TRUCK	16	5.14	0.39
COMBINED	41	5.10	0.33

variability of the surface mix is only slightly higher (0.33 versus 0.26%).

It is apparent from Figure 19, however, that the mean asphalt content of each of the Sportsplex drum-mixtures is significantly lower than the corresponding job-mix formula. In particular, the observed differences between the production means and design target values for surface and binder course (0.40 and 0.45%, respectively) are more than two and three times greater than the departure typically observed for similar mixtures produced by conventional plants.

4.2.3 Expected Conformance with Department of Transportation

Acceptance Criteria: On New Jersey Department of Transportation projects, the mean asphalt content of a mixture lot is acceptable if the five-sample average is within 0.45% of the design asphalt content. For the Sportsplex job-mix formula, this would mean that the five-sample average for a given lot would have to be at least 4.25% for the binder and 5.05% for the surface course to be considered acceptable according to the usual (versus the actual) specification criteria. Considering that the observed overall average for each of the sampled drum-mixtures either exactly or approximately coincided with the respective lower acceptance limit, it is obvious that many (roughly, half) of the sampled lots of each mixture would have been considered deficient in asphalt had the Department of Transportation tolerances in fact been in effect.

Since the samples obtained in this work represent only a fraction of the total production at the Sportsplex, it is not possible to directly apportion the samples into actual (1500 $\pm$ ton) acceptance lots and determine the specific extent of non-conformity. Simply, given the nature of the research sample, it is not possible to determine with which additional four samples a particular sample should be grouped for acceptance purposes.

Notwithstanding the above, it is possible and useful to provide at least some particularized indication of the extent to which the sampled material departed from the conventional acceptance criteria. That is, given the uniformity of the asphalt content data, it seems reasonable to assume that for purposes of simulation, successive samples of each mix might be considered to be from consecutive production days (i.e., assuming no time gap existed between test days). Once this assumption is made, it is possible to apportion the extraction results into simulated acceptance lots by calculating running averages of five, representing all possible consecutive five-sample averages. Using this procedure, N samples yield N-4 lots to which the acceptance criteria may be applied.

As shown in Table 4, applying this simulation procedure to the Sportsplex asphalt content data indicates that nearly half of all the lots for each mixture would be unacceptably low in average asphalt content. As suggested earlier, this result was generally quite foreseeable since the average asphalt content levels were so close to the Department's lower specification limit. If the

studied mixtures had in fact been presented for acceptance on a New Jersey Department of Transportation project, the low asphalt content lots would have been expected to result in payment reductions of two percent of the bid price. (New Jersey Department of Transportation specifications provide for three penalty levels: 2, 5 and 10%.)

Table 4: Simulated Application of DOT Composition
Acceptance Criteria to Dryer-Drum Mixtures

Mixture	Number of Simulated Acceptance Lots			Number of Simulated Lots Deficient in Asphalt Content			Deficient Lots, Percent
	Truck	Drum	Total	Truck	Drum	Total	
Binder	13	20	33	8	7	15	45
Surface	12	21	33	5	11	16	48

4.2.4 Factors Affecting Observed Asphalt Content: Frequent checks performed throughout the course of the research indicated that the asphalt metering control (console dial) was set to achieve the design asphalt content. Notwithstanding any differences between the actual/usual acceptance criteria applied to the mix then, there was clearly a shortfall with respect to the indicated and actual asphalt contents. As will subsequently be shown, this general deficiency in asphalt content was due to apparent inaccuracies in

both of the key elements of the dryer-drum proportioning system (i.e., the asphalt and aggregate delivery systems). As it turns out, the other factor affecting the composition of the mix -- the moisture correction factor applied to the wet aggregate -- played a relatively insignificant role.

One overall indication that something was awry with the proportioning controls at the studied plant was an occasional, significant discrepancy between the production tonnage calculated from control room equipment readings and the proven weight of material measured at the scale house.

If a dryer-drum plant is performing exactly as intended, the moisture content of the blended aggregate is known and corrected for, the weight belt is completely accurate, there are no losses of the weighed materials during processing*, and the asphalt pump delivers constant temperature asphalt at the calibrated rate. Under these conditions, the tonnage of finished mixture measured at the plant scales and the plant output based on the recorded data at the operator's station will differ only with

*As will be discussed in Section 4.3.3 of this report, this plant did not operate as a closed system: Fines were observed to be lost from the main feed belt. However, while such losses in fines are thought to have contributed to departures from the intended gradation, they are not believed to have been of such magnitude to have affected the AC content of the mix. In any event, such loss of weighed materials would have reflected as a higher than intended AC content in the finished mix; the reverse of the observed situation. Other more normal losses of weighed material (dust collector fines) would have a similar, ostensibly negligible, effect.

regard to the weight of residual moisture in the finished mix. The extent to which these two measures of daily production tonnage differ thus provides an indication of the extent to which the process control equipment and procedures depart from the above-described ideal conditions.

Table 5 presents such a comparison between the input of raw materials to the dryer-drum (based on control console totalizer readings) and the output of finished mix (based on the accumulated deliveries at the scale house). The particular comparison shown is obviously the grossest type of check on proportioning which can be made: Input tonnage is expressed as the simple total of asphalt and wet aggregate, with no correction for aggregate moisture. When, as in Table 5, such a gross check indicates that the output generally exceeds the input (i.e., on 6 of 8 days), a producer might normally be expected to be more than a bit concerned. When output exceeds apparent input by more than 250 tons (test day 4), the time to reflect on the equipment calibration and/or operation has clearly arrived.

In an attempt to determine the source(s) of the apparent discrepancy in total mix weights, an analysis of the comparative tonnage of the constituents of the finished mix (scale house data) and the raw materials (control console data) was made for the eight test days on which the complete research testing program was applied. The detailed calculations involved in this input-output analysis are presented as Appendix B. Briefly, determination

Table 5: Gross Comparison of Indicated Input of Raw Materials and Output of Finished Drum-Mix

	OUTPUT	INPUT	DIFFERENCE
Test Day	Tonnage of Mix Measured At Scale House	Tonnage of Wet Aggregate And AC Measured In Control Room	Output Less Input (tons)
1	1553	1526	27
2	2380	2436	-56
3	2955	2909	46
4	3388	3122	266
5	2637	2574	63
6	584	582	2
7	973	985	-12
8	3680	3549	131

of the output quantity of the various constituents of the finished mix for a given day entailed converting the delivered weights of (wet) mix to a dry weight basis using representative moisture contents, and apportioning this quantity between asphalt and aggregate using the day's extraction test results. Tonnage of asphalt input is calculated by applying the producer's calibration factor to the asphalt totalizer reading. The dry weight of aggregate input is determined by applying the results of moisture tests

performed on the blended aggregates to the (wet) aggregate totalizer readings. This research test data (rather than the producer's console moisture setting) is used to make the conversion since such data (up to 9 tests per day) are believed to be the best estimate of the "true" moisture in the blended aggregate.

A summary of the appended analysis of the output and input tonnages is presented in Table 6. As indicated in the tabulation, inaccuracies in both of the proportioning controls -- the asphalt metering system and the aggregate weigh belt system -- apparently contributed to the observed general deficiency in asphalt content. That is, on 6 of the 8 test days, the absolute (as well as relative) quantity of asphalt actually incorporated in the finished mix is calculated to be less than the amount shown on the control console totalizer. On an average basis, the control console readings for the asphalt input are indicated to be erroneously high by about 3 percent. Compounding the problem, the weigh belt totalizer is indicated to have consistently yielded erroneously low readings. Since the delivery of asphalt to the dryer-drum is keyed to the aggregate delivery, these erroneously low readings ("missed" aggregate tonnage) reflected as a concomitant departure from the intended quantity of asphalt in the finished mix. On an average basis, the apparent inaccuracy of the signal from the aggregate weigh belt amounted to about 5.6 percent.

Table 6: Summary Comparison of Tonnage of Mix Constituents -- Scale House Versus Control Room

Test Day	Mix	Scale House				Control Room		Differences (output-input)			
		Tonnage of (Wet) Mix Delivered	Calculated Constituents of Mix, Tons			Tons AC Supplied	Tons Dry Aggregate Supplied	Asphalt		Aggregate	
			Water	Asphalt	Aggregate			Tons	Percent	Tons	Percent
1	Binder	1,553.0	16.9	69.3	1,466.8	68.7	1409.7	0.6	0.9	57.1	3.9
2	Top	2,380.0	18.9	122.3	2,238.8	127.7	2201.0	-5.4	-4.4	37.8	1.7
3	Top	2,954.9	26.4	146.1	2,782.4	152.6	2618.1	-6.5	-4.4	164.3	5.9
4	Binder	3,388.0	20.2	143.8	3,224.0	140.1	2909.4	3.7	2.6	314.6	9.8
5	Top	2,637.0	26.1	129.0	2,481.9	133.9	2344.4	-4.9	-3.8	137.5	5.5
6	Top	584.4	5.2	29.9	549.3	31.8	532.5	-1.9	-6.4	16.8	3.1
7	Top	973.1	8.7	50.0	914.4	52.9	891.8	-2.9	-5.8	22.6	2.5
8	Binder	3,680.1	25.6	150.9	3,503.6	160.7	3299.4	-9.8	-6.5	204.2	5.8
Totals		18,150.5	148.0	841.3	17,161.2	868.4	16,206.3	-27.1		954.9	
Overall Weighted* Averages								-4	-3.2	158.9	5.6
								Binder	-1.5	Binder	7.0
								Top	-4.5	Top	4.2

*Bases of weighting are the scale house quantities.

An interesting general basis for assessing the above-described relative errors in the Sportsplex plant proportioning controls is provided by a recently promulgated AASHTO draft specification for the dryer-drum process.⁽¹³⁾ In the cited document, AASHTO proposes that the materials delivery systems of dryer-drum plants should calibrate to within 1.0 and 0.5 percent, respectively, of the true quantity of asphalt and aggregate delivery. The relative errors observed here exceed these suggested limitations (and at least by implication, good practice) by factors of about 3:1 (asphalt) and 10:1 (aggregate). On a more fundamental basis, it is interesting to note that if a dryer-drum plant were to be operated within these AASHTO guidelines, the suggested maximum allowable proportioning system errors would be expected to affect the average extracted asphalt content of a 5.5% design mix such as that studied here by at most 0.08%.

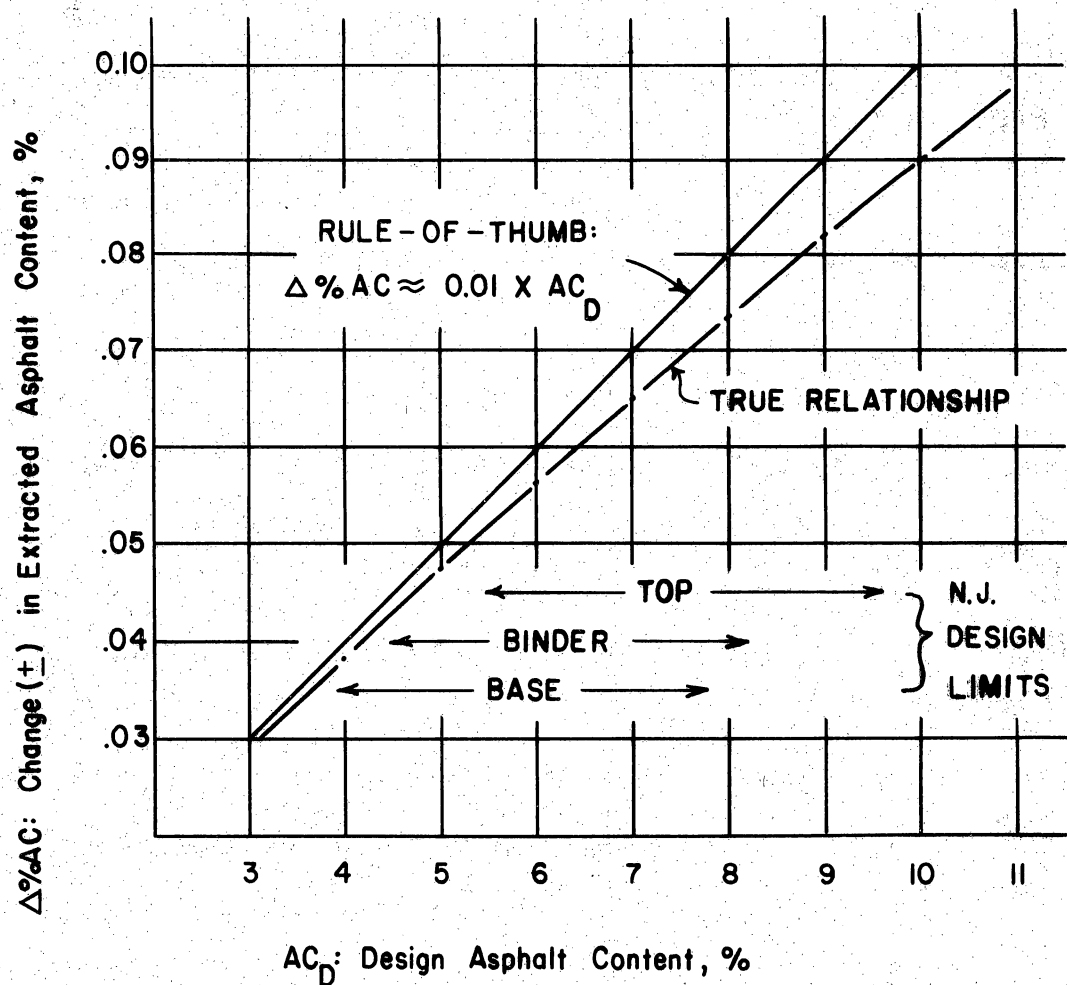
The specific role that the observed inaccuracies in the Sportsplex proportioning system played in the acceptability of the finished drum-mixtures will be addressed later. However, it is considered appropriate at this point to note that the reader (or in future, a plant inspector) may quickly estimate the influence of a given percentage proportioning error on the final asphalt percentage of the mix by an easily remembered rule-of-thumb. Namely, each ± 1% error in any of the elements of the drum-mix proportioning system -- asphalt or aggregate delivery or moisture content -- will affect the final extracted asphalt content

percentage by slightly less than 0.01 times the design asphalt content. Applying this rule -- illustrated in Figure 20 -- to the respective errors of Table 6 indicates that the inaccuracy of the aggregate delivery system decreased the asphalt percentages in the finished mixtures by about 0.33% in the case of binder and 0.23% in the case of the surface course. (Example calculation (binder): $\Delta \% AC = .01 \times 4.7\% AC \times 7\% \text{ error} = 0.33\%$) In the case of the asphalt delivery system, the inaccuracy indicated in Table 6 reduced the average AC content of the finished surface and binder mixtures by about 0.25% and 0.07%, respectively.

Returning to the analysis, it is to be noted that the inaccuracy in the asphalt metering system indicated in Table 6 is only one component of the overall asphalt delivery system error. That is, those calculations reflect only the difference between the indicated (totalizer) tonnage and the actual tonnage of asphalt based on extraction results; they do not address the question of whether the indicated quantity is in fact the required quantity. In other words, not only must we determine "did the asphalt pump deliver the quantity indicated on the totalizer?" but also "what should the totalizer have read (and delivered) for the measured quantity of aggregate?" The latter question is resolved in Table 7.

In Table 7, the column headed "required" asphalt tonnage represents the quantity which should have been registered on the asphalt totalizer to yield the design asphalt content for the given

**Figure 20: Effect of a Unit Error ($\pm 1.0\%$) In
Any Element of The Dryer-Drum
Proportioning System on The Average
Asphalt Content of The Finished Mix**



In General,

$\Delta \% AC \approx 0.01 \times AC_D \times [\text{Moisture} + \text{Pump} + \text{Belt \% Errors}]$ Where :

$\Delta \% AC$ = Estimated Overall Departure from Desired Asphalt Content

Moisture Error (%) = True Aggregate Moisture Content (%) - Console Setting (%)

Pump Error (%) = $\frac{\text{True AC Tonnage} - \text{Totalized AC Tonnage} \times 100\%}{\text{True AC Tonnage}}$

Belt Error (%) = $\frac{\text{Totalizer Tonnage} - \text{True Wet Tonnage} \times 100\%}{\text{True Wet Tonnage}}$

Table 7: Components of Asphalt Metering System Inaccuracy

Test Day	Tons Dry Aggregate Supplied, W_T Calculated From Totalizer Using Console Moisture Setting	Asphalt Tonnage			Asphalt Metering Errors				
		Required	Indicated	Actual	ΔAC_1 : Indicated - Required		ΔAC_2 : Actual - Indicated	Δ Total: Actual - Required	
		$\frac{AC_D \times W_T}{100 - AC_D}$	Calculated From AC Totalizer	Calculated From Scale House Tonnage	Tons	Percent*	Tons	Tons	Percent*
1	1401.5	69.1	68.7	69.3	-0.4	-0.6	0.6	0.2	0.3
2	2220.0	129.2	127.7	122.3	-1.5	-1.2	-5.4	-6.9	-5.3
3	2625.6	152.8	152.6	146.1	-0.2	-0.1	-6.5	-6.7	-4.4
4	2895.2	142.8	140.1	143.8	-2.7	-1.9	3.7	1.0	0.7
5	2369.4	137.9	133.9	129.0	-4.0	-2.9	-4.9	-8.9	-6.5
6	539.3	31.4	31.8	29.9	0.4	1.3	-1.9	-1.5	-4.8
7	913.6	53.2	52.9	50.0	-0.3	-0.6	-2.9	-3.2	-6.0
8	3289.8	162.2	160.7	150.9	-1.5	-0.9	-9.8	-11.3	-7.0
Totals	16,254.4	878.6	868.4	841.3	-10.2	-1.2**	-27.1	37.3	-4.3**
								Binder	-2.7
								Top	-5.4

*based on AC required

**weighted average

(albeit erroneously low) aggregate totalizer readings and console moisture settings. Comparison of these required amounts to the totalizer quantity reveals that the totalizer quantity on 7 of 8 test days was from about one-half to three percent less than the quantity actually required to achieve the design AC content.

This instrumentation error -- amounting to an average of slightly more than one percent -- when combined with the delivery error discussed in Table 6, results in an indicated overall inaccuracy in the asphalt metering system of slightly more than 4 percent.

While the described discrepancy between the required and observed asphalt totalizer readings alone might be expected to have a relatively minor overall effect on resultant asphalt contents (rule-of-thumb approximation: about 0.05%), it did have a relatively significant effect on the acceptability of mix produced on particular days (e.g., test day 5). In any event, such a discrepancy is clearly undesirable inasmuch as it is symptomatic of an inherent internal inconsistency in the proportioning controls.

Another factor generally affecting the quantity of asphalt incorporated into the finished drum-mix is the moisture correction applied to the blended raw aggregates. On this project, reasonably close control of the moisture correction problem -- minimizing undesirable differences between the console moisture setting and the "true" aggregate moisture content -- resulted in this factor playing a relatively insignificant overall role in the observed

overall deficiency in asphalt. In fact, in the case of one mix (surface course), the moisture contents selected for proportioning generally mitigated somewhat the effects of other proportioning system inaccuracies.

The preceding point is illustrated by the data of Table 8. This tabulation shows the difference between the console moisture settings for each production day and the observed average moisture in test samples, together with the resultant effect of such differences on the tonnage of asphalt added to the mix. As indicated in Table 8, on the five test days on which top course was being produced, the moisture settings used in proportioning were on the conservative side (i.e., an average of about 1% lower than the "true" aggregate moisture content). In effect then, on those days the proportioning system was "told" that a fraction of what was in fact water was instead aggregate, resulting in the addition of more than the theoretically required quantity of asphalt being added to the mix. On the other hand, for the three test days on which binder course was being produced, the console moisture settings were slightly (0.5%) higher than the test sample averages. On those three days then, a quantity of dry aggregate was "missed" by the proportioning system (assumed to be water), resulting in the addition of less asphalt than the quantity theoretically required for the measured tonnage of blended aggregate.

On an overall basis, use of the indicated console moisture settings rather than the "true" moisture contents resulted in the addition of a total of nearly 5 tons more asphalt than theoretically

Table 8: Influence of Aggregate Moisture Content Correction Factor on the Quantity of Asphalt Supplied to Mix

Test Day	Measured Tonnage of Wet Aggregate	Aggregate Moisture Content, %			Tonnage of Dry Aggregate "Missed" due to Moisture Δ	Tonnage of Asphalt Which Would Have Been Added If $M_c = M_o$
		Console Setting, M_c	Observed Sample Average, M_o	$\Delta = M_o \text{ less } M_c$		
1*	1457.6	4	3.4	-0.6	8.2	0.4
2	2308.8	4	4.9	0.9	-19.0	-1.1
3	2756.9	5	5.3	0.3	-7.5	-0.4
4*	2982.1	3	2.5	-0.5	14.2	0.7
5	2440.5	3	4.1	1.1	-25	-1.5
6	550.1	2	3.3	1.3	-6.8	-0.4
7	931.9	3	4.5	2.5	-21.8	-1.3
8*	3388.5	3	2.7	-0.3	9.6	0.5
*denotes binder course production Averages				binder top -0.5 1.2	Totals	binder top 1.6 -4.7

required in the case of the top course drum-mix and about 1 1/2 tons less than theoretically required in the case of binder. In terms of the percent asphalt in the finished mix, the net effect of the average console/true moisture differences was to cause a relative increase of about 0.06% in extracted asphalt for the top course and a decrease of about 0.02% for the binder materials.

In the preceeding discussions of the percentage inaccuracies of the studied dryer-drum proportioning system, some general estimates of the role which such errors played in the observed extracted asphalt content were made using a rule-of-thumb approximation. Table 9 summarizes the results of a more precise analysis in this regard and expresses the influence of the metering system inaccuracies in a more fundamental and useful format: Namely, the expected effect of eliminating particular metering errors on the percentage of compliant composition acceptance lots. (Here again, "acceptability" is based on the conventional New Jersey Department of Transportation criteria.)

The calculation details involved in deriving Table 9 are presented as Appendix C. In essence, these calculations are merely a recapitulation of the information previously presented in Tables 6 thru 8. For example, the average increase in asphalt content expected to accompany elimination of the asphalt metering error is based on the AC totalizer registering and delivering the required quantity of asphalt for the given (erroneous) weight belt readings and moisture correction for each day. These

Table 9: Relative Effects of Individual Proportioning System
Errors on Drum-Mix Asphalt Content Acceptability

A. ACTUAL MIX COMPOSITION

Course	Design AC%	Average Extracted AC%	JMF Miss	Estimated % Acceptable Lots
Binder	4.7	4.25	0.45	50
Top	5.5	5.06	0.44	52.8

B. EFFECT OF PROPORTIONING SYSTEM IMPROVEMENTS

NATURE OF IMPROVEMENT	Course	Expected Average AC%	Δ AC: Expected - Actual	% of Observed JMF Miss	Estimated % Acceptable Lots
Eliminate Asphalt Delivery System Inaccuracy	Binder	4.36	0.11	24.4	86
	Top	5.34	0.28	63.6	98.5
Eliminate Aggregate Delivery System Inaccuracy	Binder	4.57	0.32	71.1	99.9
	Top	5.28	0.22	50.0	95.6
Use "True" Aggregate Moisture Content In Proportioning	Binder	4.27	0.02	4.4	57.5
	Top	5.00	-0.06	-13.6	35.6

quantities are shown in Table 7. The tabulation of the expected percentage of acceptable lots associated with a particular processing improvement is derived from properties of the standard normal distribution.*

As indicated in Table 9, while an improvement in either the aggregate or asphalt delivery system would have improved the relative acceptability of the composition lots, the aggregate delivery system generally played somewhat the greater role. Specifically, the aggregate metering error amounted to about $3/4$ and $1/2$ of the total JMF miss in the case of binder and top, respectively. The asphalt delivery error would have been expected to have eliminated about $1/4$ and $2/3^{**}$ of the observed JMF misses for binder and top. As a consequence, had the weigh belt error alone been eliminated, the Sportsplex binder course would have been expected to have been completely acceptable according to the conventional criteria, while the producer's risk of unacceptable

*These calculations involve a determination of the area of the normal curve to the right of a Z-score equal to the Department of Transportation specification lower acceptance limit for a distribution having the particular mean asphalt content. In making such estimates, it was (conservatively) assumed that the standard deviation of the product would not change if a particular proportioning improvement was made.

**The reason that the sum of the percentages of the surface course JMF miss accounted for by the asphalt and aggregate delivery system errors total greater than 100% is that, for the conservative moisture correction used, elimination of these proportioning system errors would have resulted in an AC percentage greater than the design.

top course lots would have been less than two percent greater than normal. (New Jersey Department of Transportation acceptance criteria are constructed with balanced producer's and consumer's risks of 2.5 percent.)

Given the previous discussion of the moisture correction factor, the indicated effect of this factor on overall lot acceptability is not surprising. That is, the data of Table 9 confirms that for the conditions encountered in this study, use of the true aggregate moisture content in proportioning the binder would have been slightly beneficial to lot acceptability, whereas use of the true moisture in proportioning the top course would have had a detrimental effect.

4.3 MIXTURE GRADATION

4.3.1 Variability of Extraction Results: The extracted gradations from 41 samples of each of the finished drum-mixtures are shown in Figures 21 and 22.

The most obvious overall characteristic of the finished drum-mixtures revealed in these gradation plots is their relative coarseness with respect to the intermediate sieve sizes -- particularly in the case of the surface mix -- as contrasted to their near-perfect conformity with the target values for the top and, more importantly, the #200 size materials.

Only three of the design sieves presented in the gradation plots -- the numbers 8, 50, and 200 -- are formally used for acceptance purposes by the New Jersey Department of Transportation.

Figure 21: Gradation of Finished Drum-Mix Surface Course

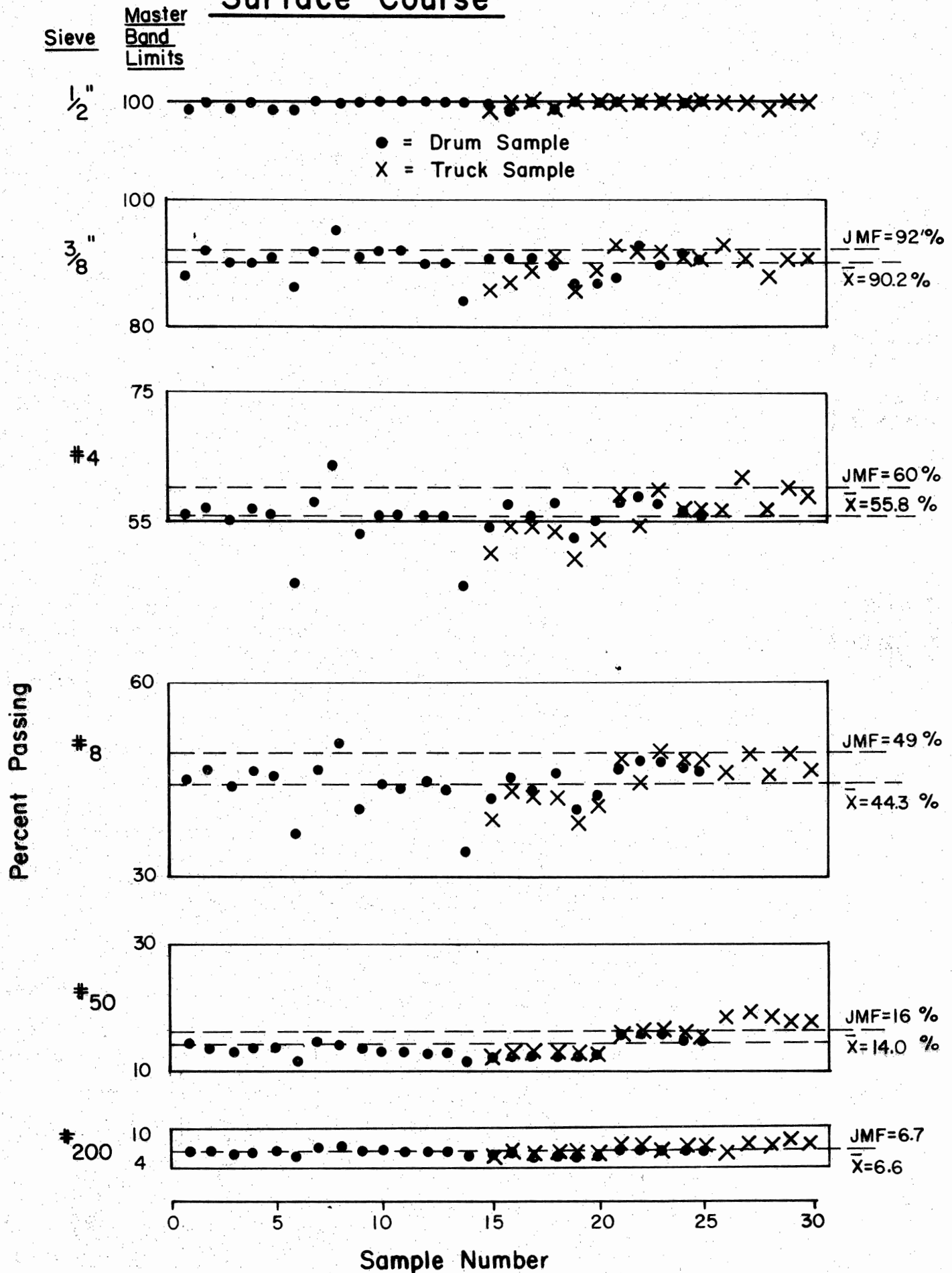
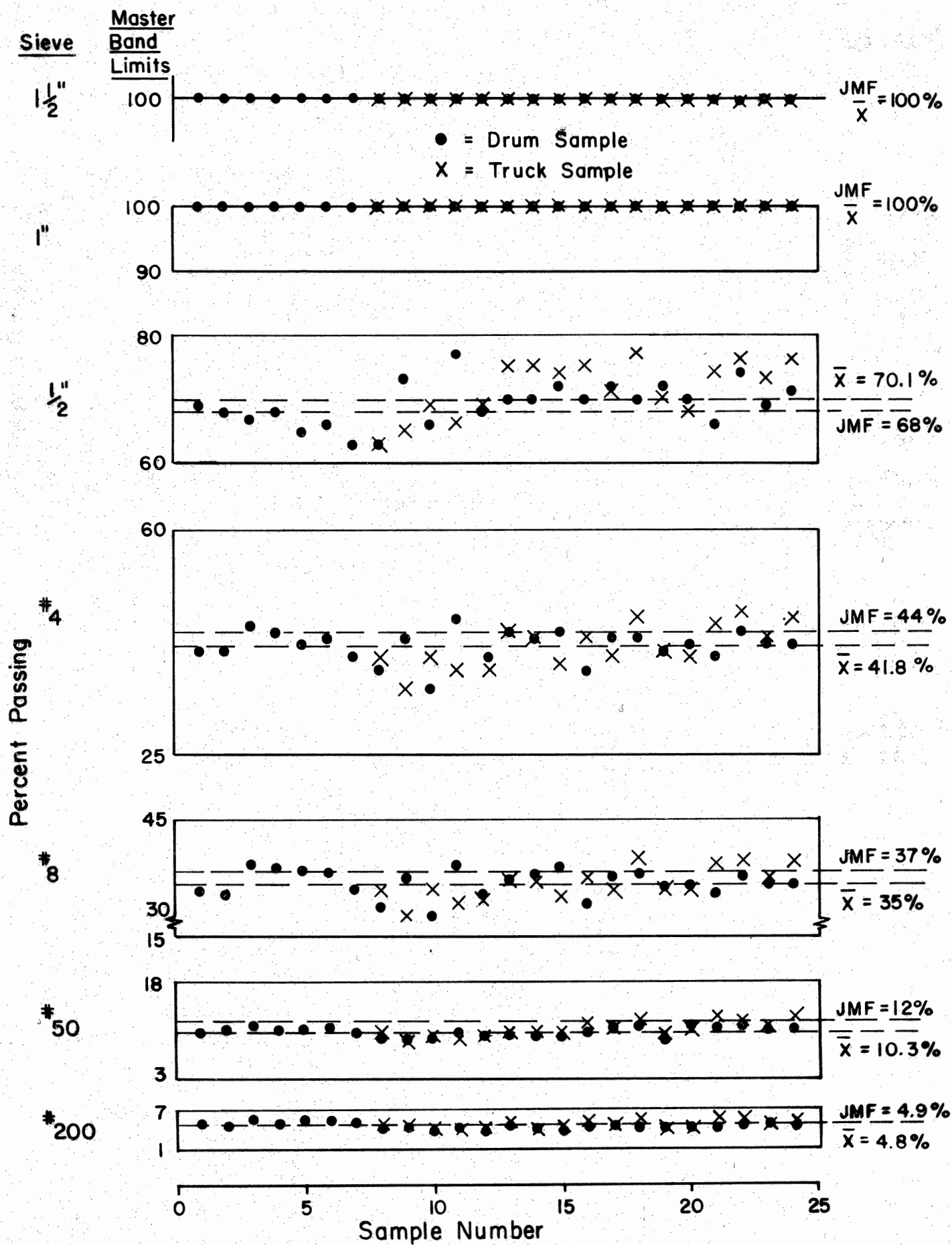


Figure 22: Gradation of Finished Drum-Mix Binder Course



Associated with those sieves is a tighter (JMF) tolerance than the master design limits shown and a schedule of payment reductions for non-conforming results. The latter are based on the average and range of five samples from a 1500⁺ ton lot. The #4 and larger sieves are used strictly for control purposes. Whenever the mixture proportions for these control sieves depart significantly from the job mix target values, a process change is recommended; if the departure causes the results to fall outside the master design limits, a processing improvement is required.

As indicated in Figure 21, a substantial number of test results for the drum-mix surface course fall outside the master design limits for the #4 sieve. Ordinarily then, this non-conformity would have necessitated a processing improvement on a Department of Transportation project.

A comparison of the uniformity of the drum-mix gradations for the acceptance sieves to that historically observed ⁽¹⁰⁾ for mixtures produced in conventional plants is presented in Table 10.

Note that in the tabulation, the overall "variability" of the product is again expressed in terms of two statistics: the average standard deviation of the individual test results and the average miss from the job mix target value. As alluded to earlier, the reason for separately analyzing these components of variability is that while both in fact represent the inherent "capability" of the process, the standard deviation statistic, generally speaking, is more indicative of the "controllability" of the process. That is, if the process results are uniform

Table 10: Relative Variability of Drum-Mix Extracted Gradations

Mixture	Acceptance Sieve	Standard Deviation (σ)		JMF Miss (Δ) = Job Mix-Production Mean		Standard Deviation plus JMF Miss ($\sigma + \Delta$)**		NJ DOT Acceptance Tolerance (+)
		Conventional Plant Average	Dryer- Drum Project	Conventional Plant Average	Dryer- Drum Project	Conventional Plant Average	Dryer- Drum Project	Applied to $\bar{X}_5$
Binder	#8	2.77	2.23	0.92	2.00*	3.5	4.0	4.0
	#50	1.58	0.94*	1.10	1.70*	2.5	2.5	3.0
	#200	0.89	0.49*	0.37	0.10*	1.3	0.6	1.4
Top	#8	2.70	3.59*	0.87	4.70*	3.5	8.5	4.0
	#50	1.92	2.00	0.90	2.00*	3.0	4.0	3.0
	#200	1.10	0.65*	0.18	0.10	1.3	0.8	1.4

* Indicates significant difference between test statistics at 95% confidence level.

** All values rounded to account for test precision.

(in terms of standard deviation), it is normally not difficult to make adjustments to achieve the desired mean value (e.g., by varying bin pulls in the case of gradation or changing a dial setting in the case of asphalt content). On the other hand, achieving the converse type of control (reducing the process standard deviation) generally requires a considerable effort by the producer.

The New Jersey Department of Transportation gradation acceptance tolerances (shown in the last column of Table 10) are in fact constructed so as to reflect both of the above measures of process variability. That is, the tolerance for a particular sieve is about equal to the sum of the historical average job-mix miss and standard deviation for that sieve. In practical effect, use of these tolerances means that if a producer exercises "average" gradation control -- that is, if the overall variability of his product equals the historical norm -- his risk of lot rejection will be only slightly more than one percent.

Examination of the gradation statistics presented in Table 10 reveals that, with one notable exception, the uniformity of the drum-mix product is comparable to that of conventional plants. That is, except for the #8 sieve results for the surface mix, the average standard deviations for the acceptance sieves are about the same or less than those observed for conventionally produced surface or binder course. Regarding the latter, Table 10

shows that the standard deviations for the combined* (truck and drum) samples of drum-mix binder are less than the historical average. Except for the #200 sieve results, however, the average miss from the job-mix target values for the Sportsplex material is about twice that normally encountered for binder mix produced at conventional plants. The net effect of this relatively lower standard deviation and higher job-mix miss is to cause the overall variability of the drum-mix binder to be similar to that of the "average" conventional plant product and generally within the indicated Department of Transportation tolerances.

The most significant point in connection with the surface course data of Table 10 is the relatively high variability of the drum-mix results for the #8 sieve, both in terms of standard deviation and departure from the intended design average. This observed high overall variability for the #8 sieve, together with a greater than average departure from the intended mean for the #50 sieve, obviously suggests that much of the sampled surface mix would be considered non-conforming according to the Department's usual acceptance provisions.

*As in the case of asphalt content, there is no statistically significant difference in the mean or standard deviation of the truck and drum extracted gradations. Thus, pooling of the two types of sample results is valid.

4.3.2 Expected Conformance with Department of Transportation

Gradation Acceptance Criteria: To provide a more specific indication of the extent to which the sampled drum mixes would comply with conventional gradation acceptance criteria, the simulated acceptance procedure (running average technique) described earlier in this report was applied to the extraction results.

In view of the general discussion in the preceding subsection, the results of this simulation (Table 11) were quite predictable. That is, the drum-mix binder is indicated to be in general conformity with the current Department of Transportation acceptance criteria. On the other hand, if judged by the Department's relatively stringent criteria, the sampled drum-mix surface course would be considered to possess multiple deficiencies: Nearly 2/3 of all possible running averages of five for the top course (simulated acceptance lots) fail to comply with the usual tolerance for the #8 sieve and half of these are also non-conforming with respect to the #50 sieve.

As further indicated in Table 11, had the sampled surface mix been presented for acceptance on a Department project, the extent of non-conformity with the #8 sieve criteria would not only be expected to be cause for frequent rejection, but also the imposition of moderate (5%) rather than slight (2%) reductions in pay.

Table 11: Simulated Application of DOT Gradation Acceptance Criteria to Dryer-Drum Mixtures

A: Expected Frequency of Non-complaint Lots

Mixture	Total Number of Simulated Acceptance Lots (Truck + Drum)	Number of Simulated Lots Having Non-Compliant 5-Sample Averages* for the Indicated Sieve			
		#8	#50	#200	Percent Rejectable
Binder	33	1	0	0	3
Top	33	20	10**	0	60

*3 top course lots would also fail DOT range requirements for the #8 sieve ($R_5 > 13\%$).

** Indicated lots also failed #8 sieve requirements

B: Expected Severity of Payment Reductions

Mixture	Number of Simulated Lots Receiving Indicated Payment Reduction*		
	2%	5%	10%
	$ JMF - \bar{X}_5 = 1.01 \text{ to } 1.5$ times tolerance	$ JMF - \bar{X}_5 = 1.51 \text{ to } 2.0$ times tolerance	$ JMF - \bar{X}_5 >$ twice tolerance
Binder	1	0	0
Top	11	9 **	0

* In accordance with DOT criteria, when more than one reduction due to nonconformance to the JMF gradation is indicated for a lot, only the greater single adjustment is applied.

** All incurred for #8 sieve results.

4.3.3 Factors Affecting Gradation of the Product at Various

Stages of Production:

A. General Limitations of Cold-Feed Gradation Control

Subsequent discussions in this report subsection are directed at assessing the effect of various production operations on the gradation of the finished drum-mixtures and, in particular, determining possible sources of the observed relatively high variability of the surface mix. While most readers are familiar with the cold-feed method of control in general and its potential drawbacks in particular, it is useful to state at the outset that -- due to inherent limitations of this type of control procedure -- the subsequent discussion of factors affecting gradation must of necessity be of a relatively qualitative rather than quantitative nature. That is, as a general proposition, proportioning controls such as those employed at the studied plant (i.e., belt speed indicators) may not yield either the type or number of measurements required to discover or remedy a proportioning problem. In this specific instance, it is concluded that they did not.

In the first place, while the gradation of a bituminous mixture is designed and accepted on a weight basis, achieving the correct aggregate proportions by the cold-feed method of control obviously depends on (and thus yields instrumentation readings based on) maintaining correct volumetric proportions. The point here is axiomatic: When a proportioning problem occurs, it can be expected to be more quickly discovered and corrected if the data

for production control and product acceptance are directly on the same (weight) basis.

Secondly, it is evident that when multiple stockpiles contribute to the percent passing a given sieve and there is only one direct measure for determining if the intended multiple combination is in fact achieved (i.e., the extraction result), one can expect more than occasional difficulties in isolating the specific cause of any subtle discrepancy between the desired and observed proportions. Simply, in the case of three stockpiles with overlapping gradations, there are three unknowns (stockpile contributions) and only one equation (extraction result). While various algebraic and graphical methods are available for examining more than one or all of the sieve results so as to assess the source of a proportioning problem, such methods are known to be laborious and often only approximations. Consequently, they may yield only one of several possible aggregate combinations resulting in the problem extracted gradation. Further, while after-the-fact calibration checks would be appropriate, such might not detect certain problems such as aggregate bulking or other temporary interference with bin flow.

If a dryer-drum plant is fitted with a belt sampling device which yields representative gradation samples, such samples would provide an additional (or at least, more rapid and direct) indication of the accuracy of the aggregate delivery system.

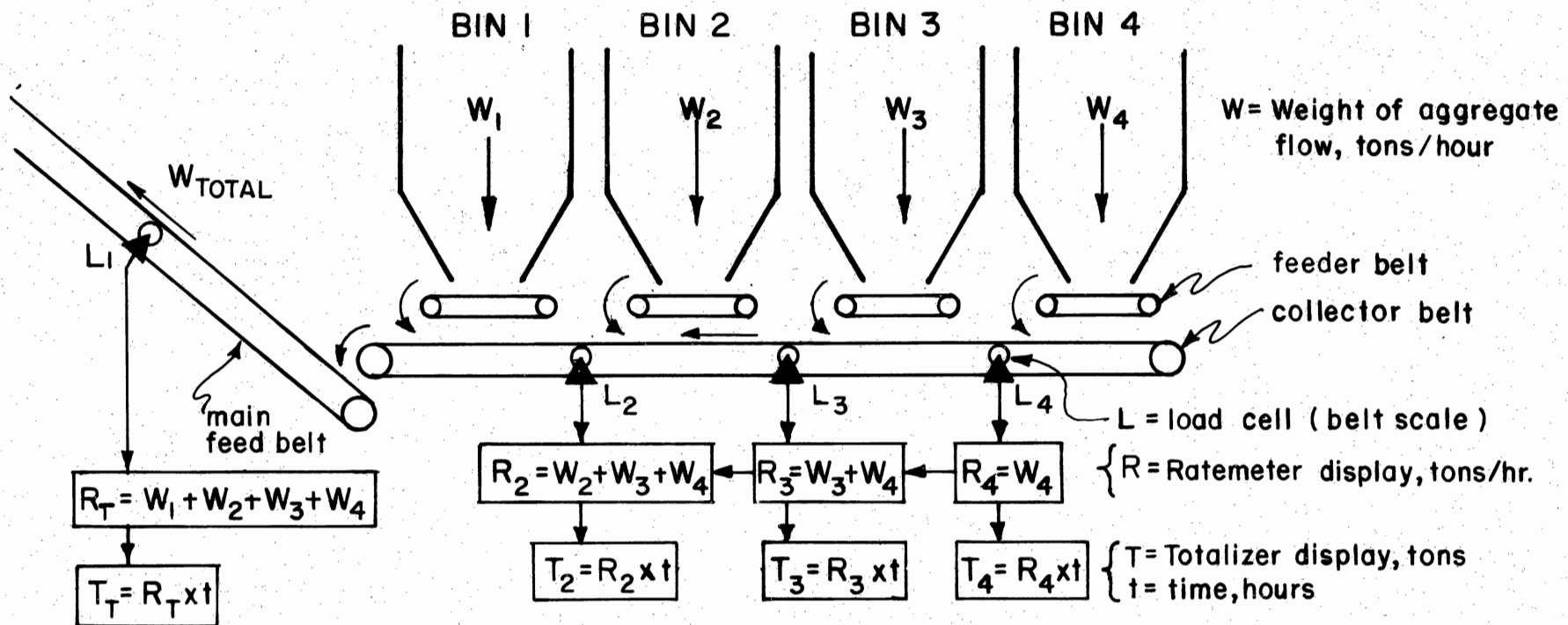
However, as will be described later, the particular belt sampling device used on this project apparently did not yield representative samples.

In the context of any future dryer-drum installation, it is important to note that the shortcomings of a straight volumetric cold-feed control method can potentially be overcome by equipping the dryer-drum plant with additional, commercially available weighing equipment (load cells) and associated control console readouts. One possible layout for such an installation is shown in the sketch of Figure 23. As indicated in the sketch, installation of several* such belt scales beneath the cold feed bins would provide direct checks on the bin proportioning on both a continuous basis (from a rate meter display in tons/hour for each bin) and an overall basis (from bin totalizer displays).

While such direct measures of the relative weight of aggregate from each bin, of course, will not in themselves ensure achievement of a consistently acceptable product, the number and type of measurements yielded by the additional load cells clearly would give the producer a better opportunity for maintaining proper gradation control. Interestingly, several states presently

*While the particular instrumentation set-up shown in Figure 23 is considered most desirable, there are obviously alternative arrangements. For example, if (as on this project) bins 3 and 4 contain the same coarse aggregate, a lower-cost option would be to eliminate load cell 4. In that case, the relative proportion of total coarse aggregate would be indicated by load cell 3. This change might reduce the producer's additional plant investment by about \$10,000.

Figure 23: Sketch of Alternate Instrumentation for Cold-feed Control



Calculation of Bin Pulls Using Displayed Data			
BIN 1	BIN 2	BIN 3	BIN 4
$P_1 = \frac{R_T - R_2}{R_T} \times 100\%$ or $= \frac{T_T - T_2}{T_T} \times 100\%$	$P_2 = \frac{R_2 - R_3}{R_T} \times 100\%$ or $= \frac{T_2 - T_3}{T_T} \times 100\%$	$P_3 = \frac{R_3 - R_4}{R_T} \times 100\%$ or $= \frac{T_3 - T_4}{T_T} \times 100\%$	$P_4 = \frac{R_4}{R_T} \times 100\%$ or $= \frac{T_4}{T_T} \times 100\%$

require at least certain of the described additional weighing equipment and readouts (bin rate meters expressed in tons/hour). Further, in their responses to a survey questionnaire, several states which do not currently require belt scales beneath the bins suggest that such would be highly desirable. Perhaps most persuasively, NAPA ⁽¹⁴⁾ reports that at least as early as 1974, a number of contractors -- apparently at their own option -- equipped their plants with multiple weigh belt systems.

B. Stockpile Gradations

As indicated in the preceeding subsections, the problems with the as-produced drum-mix proportions primarily involved only the surface mixture and three sieves: the #4 control sieve and, more importantly, the #8 and #50 acceptance sieves. While there were differences in the proportions of sand and screenings used for the two mixtures, the basic difference in the constituents of the binder and surface course was the coarse aggregate size. This fact obviously suggests that the high variability and miss from the target gradation value for the surface course may at least in part be a reflection of relatively high variability and/or a departure from the design gradations of the 3/8" stone stockpile.

Table 12 presents a comparison of the stockpile gradations used for mixture design and those observed in eight days of plant testing. The test results shown represent washed analyses (ASTM C-117) performed on two samples per day from each of the three stockpiles being used on that production day.

TABLE 12: Variability of Stockpile Gradations

Sieve	PERCENT PASSING INDICATED SIEVE											
	SAND			SCREENINGS			3/8" STONE			3/4" STONE		
	Design Mean	Actual Mean	σ	Design Mean	Actual Mean	σ	Design Mean	Actual Mean	σ	Design Mean	Actual Mean	σ
1"	100	100	0	100	100	0	--	--	--	100	100	0
1/2"	100	99.9	0.3	100	99.2	0.7	100	99	0	43	52.3	4.8
3/8"	100	99.8	0.5	100	98.7	0.9	84	83.8	4.0	--	--	--
#4	98.7	98.4	0.5	100	97.7	1.0	16.5	18.9	5.9	2.8	6.8	2.5
#8	92.3	91.7	1.7	80.5	80.7	2.1	7.3	9.6	3.7	0	4.4	2.1
#50	21	15.9	3.1	33.1	38.9	3.1	2.9	5.3	1.8	0	3.7	1.2
#200	2.3	2.9	1.0	19.0	23.8	2.1	1.8	4.2	1.5	0	2.9	1.2
Number of Tests		16		16		10		6				

As indicated in Table 12, the standard deviations of the #4 and #8 sieve results for the 3/8" stone stockpile are generally greater than those for the corresponding results from the other stockpiles. Indeed, the standard deviation of the #4 sieve is greater than that for any of the other stockpile sieve results. While it obviously would be of considerable interest at this point to know whether the indicated variability of the studied stockpile gradations is "typical", similar data for conventional plants, unfortunately, is not tabulated by the New Jersey Department of Transportation. However, from the data we do have, it does appear that the 3/8" aggregate stockpile was in fact a major source of the high variability observed for the #4 and #8 sizes in the finished mix.

While the variability of the raw materials apparently contributed significantly to one component of mix acceptability (the standard deviation of the finished surface mix), stockpile gradation apparently did not play the major role as regards the other component (the significant JMF miss). That is, while Figure 21 indicated that the finished surface mix was consistently deficient in the percent passing the #4 and #8 sieves, Table 12 shows that each of the stockpiles contained sufficient of these sizes (the actual average stockpile gradations closely conform to the design gradations). This is also the case for the binder course raw materials. In fact, while the finished binder was somewhat low in the average percent passing the #8 sieve, the

stockpiles actually contained more of this size fraction than was contemplated in the stockpile design gradation. In other words then, it generally appears that the shortfalls in average percent passing the #4 and #8 sieves in the finished mix were not due to a problem of knowing what was delivered to the bins (the average percent passing), but rather to a problem in metering the binned materials in the correct proportions.

The effect of the stockpile gradations on the acceptability of the surface mix with respect to the #50 sieve are not so readily apparent from Table 12. While the stone stockpiles contained somewhat more minus #50 material than the design stockpile gradation, the sand contained an average of 5 percent less than the design mean for the minus #50 fraction and the screenings, 6 percent more than the design value. The extent to which these essentially equal high and low values compensated for each other -- and thus, did or did not contribute to the unacceptably low percent passing the #50 in the finished surface course -- obviously would require consideration of the relative proportions of each material used.

An attempt to provide a more specific indication of the part the stockpile gradations played in the gradation of the final product is presented in Table 13. The columns headed "Theoretical Combination" in Table 13 respectively show the gradation mean and standard deviation which would have been expected for eight days of plant testing had the project materials in fact been combined in the proportions originally contemplated (design bin pulls)

Table 13: Comparison of Expected and Observed Drum-Mix Extracted Gradations

	Sieve	Design Target	MEAN GRADATION (% PASSING)				STANDARD DEVIATION	
			Extracted	Theoretical Combination ^A		Δ : Extracted less Theoretical*	Extracted	Theoretical* Combination
				Design Pulls	Actual Pulls			
Binder	1"	100	100	100	100	0	0	0
	1/2"	68	70.1	72.1	70.4	-0.3	3.9	2.9
	#4	44	41.8	45.9	42.8	-1.0	2.8	1.5
	#8	37	35.0	39.2	37.2	-2.2	2.2	1.4
	#50	12	10.3	13.9	11.4	-1.1	0.9	1.0
	#200	4.9	4.8	7.5	5.6	-0.8	0.5	0.8
Surface Course	1/2"	100	99.8	99.2	99.1	0.7	0.4	0.2
	3/8"	92	90.1	92.4	92.6	-2.5	2.4	1.9
	#4	60	55.4	61.5	62.8	-7.4	4.0	2.7
	#8	49	43.9	50.4	52.0	-8.1	3.8	1.8
	#50	16	13.4	17.3	16.8	-3.4	2.	1.5
	#200	6.7	6.4	9.6	9.0	-2.6	0.7	0.9

-66-

A

Bin Pulls(%)

Mix	Pull	Sand	Screenings	Stone
Binder	Design	20	23	57
	Actual	25.3	14.2	60.5
Top	Design	25	28	47
	Actual	29.5	25.2	45.2

* Based on actual (weighted average) pulls

or according to the modified proportions used in practice (actual bin pulls). These calculations indicate whether successful combination of the given raw materials according to either the original or modified proportioning formula would have been expected to result in an acceptable mix gradation or at least a more acceptable gradation than that actually produced. The extent to which the theoretical mean gradation calculated using the actual bin pulls (console dial settings) differs from the actual extracted gradation provides a general measure of the overall inaccuracy in the cold-feed metering system.

The calculation details involved in developing Table 13 are not presented. As is generally well-known, for a particular sieve, the expected mean and standard deviation of an aggregate combination is derived by weighting the statistics for the individual stockpiles, the respective bases of weighting being the bin pulls (for $\bar{X}$) and the square of the bin pulls (for σ). In this work, the daily stockpile gradation results and the actual bin pulls were additionally weighted on the basis of daily production tonnage. The "actual bin pull" data were obtained by converting recorded control console dial settings (potentiometer readings) to an equivalent proportioning percentage using a formula furnished by the producer.

As indicated in Table 13, while the average extracted gradations for both mixtures were coarser than the design target, combination of the stockpiled aggregates using the design bin pulls

would have resulted in both mixtures being finer than the design for all but the respective top size sieves. In the case of the binder course, such a gradation would have been expected to be unacceptably fine. That is, as a consequence of an excess of minus #200 in certain of the stockpiles (notably, the screenings), use of the design bin pulls would have resulted in a finished mix having a minus #200 fraction outside the master design band. The gradation of the theoretical combination for the actual binder course bin pulls reflects a successful effort by the producer to avoid this excessive fines situation.

A somewhat similar situation is indicated for the surface course. That is, except for the #200 sieve, achievement of the theoretical combination corresponding to the design bin pulls would have been expected to result in gradation means which were considerably closer to the design target than the extracted means. In the case of the #8 and #50 acceptance sieves, such a reduction in the JMF miss would have substantially mitigated (but not eliminated) the observed non-conformance with the Department of Transportation acceptance criteria. On the other hand, as in the case of the binder course, use of the design pulls would have created a problem of unacceptable #200 sieve results; the expected (9.6) percent passing for this sieve would again border on the upper design limit. Such an inordinately large JMF miss (i.e., $\Delta = 2.9\%$) would in itself result in essentially a 100% rejection rate if the Department of Transportation acceptance

criteria for the #200 sieve applied (tolerance: $\pm 1.4\%$). Further, had the producer in fact achieved the gradation corresponding to the actual bin pulls set on the control console, the material would still have been excessively fine with respect to the #200 and a new problem of excessive fineness would have been created for the #8.

The reason that this situation did not in fact materialize is evident from the tabulation: For both mixes and for all sieves below the 1/2", there was a consistent shortfall (deficiency in percent passing) between the extracted gradation and that expected from the actual bin pull settings. In the case of the binder, this greater relative coarseness of the extracted gradations was relatively uniform at about one percent passing, whereas in the case of the surface mix, the apparent metering error range from about 2.5 to 8 percent passing.

Now, while it would be possible to make some further analyses of the tabulated gradation results (e.g., a determination of the bin pulls which might have yielded the design values or the bin pulls which could have resulted in the problem gradations), such would clearly be mere speculation. Simply, as suggested at the outset of this report subsection, the cold-feed control instrumentation used on this project did not yield the data needed to determine which specific bin(s) contributed to the disparity between the expected and observed aggregate proportions.

Admittedly, it is possible that if a producer were required to conform to more stringent gradation acceptance criteria than imposed on this project, he might be able to remedy a gradation control problem such as observed here by performing appropriate process calibration checks. However, in the writer's view, it appears equally likely that absent a continuous, positive indication of the tonnage of material from each bin (such as would be provided by the additional load cells described earlier), this would be a very difficult task. In such case, the producer would have merely the same level of information as the authors here: after-the-fact knowledge of a metering error in an unknown bin or bins.

Apart from the information regarding gradation means, a further point of interest in connection with Table 13 is the tabulated standard deviations. It is to be noted that the indicated standard deviations for the theoretical combinations are based on a relatively small number of samples and thus are very much only estimates of the true standard deviation. Nonetheless, these statistics do provide some particularized information regarding the relative contribution made by the raw aggregates to overall mixture variability. Specifically, notice that the standard deviations which would be expected for the #4, #8 and #50 sieves in the surface mix due solely to the variability of the raw materials are about the same as the standard deviations observed for these same sieves in the completely processed binder mix.

As suggested at the outset then, it appears that the relatively greater variability of the surface mix raw materials was indeed a reason why the finished surface mix would fail to comply with current Department of Transportation gradation acceptance criteria.

C. Belt Gradations

A total of 48 samples of the blended aggregates feeding the dryer-drum were obtained in this study. The principal objectives in sampling at this point in the production stream were to determine the accuracy of the aggregate metering system per se (i.e., the as-blended aggregate proportions) and to provide a basis for determining the nature of any gradation changes which might occur in the drum-mixer. That gradation changes may indeed occur on processing was recently confirmed in a research study conducted by the State of Maine⁽¹²⁾. In the cited study, the gradation of mixture samples obtained at the drum discharge were observed to be "several percent finer" than the material tested from the main feed belt. The increase in fines was attributed to the effect of "wear, abrasion and heat spalling" during the heating and mixing cycle. Unfortunately, it appears that the particular automated belt sampling device used in our research yielded non-representative samples, and thus little useful information regarding the as-blended aggregate proportions.

The results of washed gradation analyses performed on the binder and surface mix belt samples (23 and 25 samples, respectively) are presented in Table 14. As indicated in this tabulation, the average percentage passing the #4 and #8 sieves in the belt samples is about 3 to 6 percent lower than the corresponding extraction results for each of the finished mixtures. On the other hand, in comparison to the extraction results, the belt samples display about the same or more material passing the #50 and #200 sieves.

While the reason for the indicated greater coarseness of the belt samples relative to the extracted gradations for the plus #50 material is not known, such difference is consistent with a loss of larger sand sizes during sampling. As previously shown in Figure 15, fines were observed to spray off the sampling tray during the belt sampling operation. For the particular sample size used in this work, a relatively small loss of such "sprayed" fines (a total of about a half pound for the two sampling passes) would account for the observed disparity between the belt and extracted gradations. This circumstance, together with the fact that the belt samples generally display a somewhat higher percentage of the very smallest sizes as compared to the extraction samples, suggests that the belt samples are indeed non-representative. If the alternate hypothesis were correct -- that is, if the belt samples were in fact representative and the belt/extraction gradation differences were merely due to

Table 14: Comparative Aggregate Gradations of Extraction and Belt Samples

		MEAN GRADATION (% PASSING)		
	Sieve	Extracted	Belt	Δ : Extracted less Belt
Binder	1"	100	100	0
	1/2"	70.1	66.0	4.1*
	#4	41.8	36.1	5.7*
	#8	35.0	30.6	4.4*
	#50	10.3	10.1	0.2
	#200	4.8	5.4	-0.6*
Surface Course	1/2"	99.8	99.7	0.1
	3/8"	90.1	89.0	1.1
	#4	55.4	51.7	3.7*
	#8	43.9	41.1	2.8*
	#50	13.4	14.8	-1.4*
	#200	6.4	8.6	-2.2*

* Indicates statistically significant difference at 95% confidence level.

aggregate breakdown -- the extraction samples would be expected to reflect any such degradation by displaying at least the same degree of fineness as the belt samples for the smallest size sieves and certainly not less as is indicated for the actual situation.

An automated belt sampling device is a highly desirable item of equipment at a drum-mix plant, since it provides a safe means of obtaining aggregate for both moisture and gradation control purposes. It appears from this work, however, that if belt samples were to be depended on for control purposes on any future drum-mix project, some modifications to the sampling apparatus (or an alternate model) would be required to yield belt samples which provide a reliable estimate of the finished mixture gradation. In any event, it is clear that prior to the use of any type of automated sampling device, a program of reliability testing will be required. Such would involve analysis of the comparative gradations of mechanically and manually obtained aggregate belt samples.

D. Loss of Fines From Dryer Feed Belt

As noted earlier, the gradation of the binder and surface course drum-mixes were generally coarser than that contemplated in the design and expected from theoretical considerations (i.e., the given bin pulls and stockpile gradations). One factor affecting this result to some, albeit undetermined, extent was the loss of weighed fines from the main feed to the drum-mixer. This loss

resulted when wet fines in the blended aggregate would adhere to the feed belt, carry over the discharge end and be deposited on the ground rather than enter the drum-mixer.

Figure 24 is a photograph showing such fines beginning to accumulate beneath the feed belt early in a day's production. Notice that these wet fines* appear darker than their surroundings.

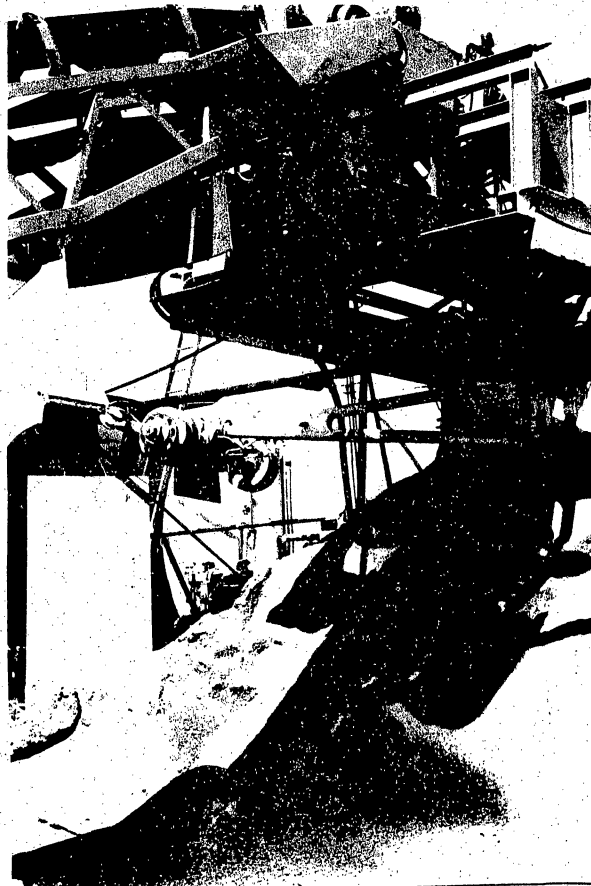


Figure 24: Wet fines beginning to accumulate beneath dryer feed.

*A gradation sample was taken to determine the specific size distribution of these "fines". Unfortunately, the sample was misplaced.

While the quantity of fines depicted in Figure 24 would only have a minor effect on the gradation of the finished product, the point is that the loss increased to the extent that the producer periodically had to bring in a front-end loader to remove the accumulation.

Again, while it is not known to what extent the fines lost from the belt contributed to a departure from the intended gradation, such a loss is clearly undesirable. It is believed that on any future drum-mix job, this undesirable situation might be minimized by the simple expedient of equipping the belt with an appropriate scraping device.

E. Volume of Flow from Cold Feed Bins

Since achieving the correct aggregate proportions by the cold-feed method of control depends on maintaining correct volumetric proportions, any condition which interferes with the intended volume of flow from the aggregate bins clearly will have some detrimental effect on final mix proportions.

Two such possible effects are "bulking" (changes in the volume of aggregates -- particularly sands -- caused by variations in moisture content) and "bridging" across a bin gate opening. Importantly, if bulking or partial bridging* occurs, it would not be detected by proportioning control equipment such as that furnished at the Sportsplex plant since belt speed indicators obviously measure only one variable affecting volume of flow.

*Cold-feed bins are commonly equipped with warning devices which indicate if complete interference with flow occurs.

On this project there was some evidence that at least occasional "bridging" and associated interruptions of the flow of cold aggregate feed occurred. That is, a plant laborer was periodically observed to hammer on the sides of the sand and screenings bins with a sledge to release bridged material.

While the effect of this apparent bridging phenomena on the Sportsplex final mix proportions is unknown, it is known that reliance on hand labor to remedy or prevent a significant bridging problem is not the best approach. A better practice would be to equip the cold-feed bins on any future dryer-drum installation with vibrators. Additionally, the fact that the effect of aggregate bridging or bulking is difficult to account for in a straight volumetric type of cold-feed control further suggests the advisability of requiring any future New Jersey drum-mix plant to be fitted with the weighing equipment previously shown in Figure 23. The control console readouts associated with the latter equipment would show any undesirable flow changes directly in terms of decreased bin delivery weights.

F. Adherent Fines on Coarse Aggregate

A factor which played a relatively minor role in the observed coarseness of the drum-mixtures (and the disparity between the theoretical and actual extracted gradations in particular) was the relative dirtiness of the project coarse aggregates. In brief, it appears that the solvent used in extraction testing yielded slightly different gradation results

for one sieve (#8) than those indicated by (water) washed analyses of the same samples.

By way of background, out of concern for potential durability problems (e.g., incomplete coating), the New Jersey Department of Transportation places an upper limit on the quantity of adherent fines on coarse aggregates, where "adherent" fines are those removed by washing over a #200 sieve after an initial dry sieving over the #16. As shown in Table 15, adherent fines testing performed on the Sportsplex coarse aggregates indicated respective averages of 2.3 and 2.6 percent for the binder and top course stone stockpiles.

Table 15: Adherent Fines on Project Coarse Aggregate

Stockpile	Number of Tests	Percent Adherent Fines		Tentative* Specification Maximum
		Range	Average	
3/4" (Binder)	2	2.3 - 2.4	2.3	1.5
3/8" (Top)	7	1.6 - 3.6	2.6	

*The Department is currently performing laboratory durability testing to determine if our present limitation of 0.5% can be safely increased, possibly to as much as 1.5%.

While the precise percentage of adherent fines which will be permitted on future Department of Transportation work is currently unsettled, the indicated percentage for the Sportsplex aggregates would doubtless be cause for their rejection under any acceptance plan ultimately adopted.

It is widely known⁽¹¹⁾ that the hydrocarbon solvents used in extraction generally recover a lower fraction of minus #200 material than that removed by the washed analyses typically employed to develop theoretical aggregate combinations for mix design and control. Since the Department does not routinely wash the plus #8 fraction of an extracted gradation, it was theorized that a part of the observed difference between the expected and actual mix gradations might simply be that our ordinary extraction procedure was removing only a fraction of the fines in these excessively dirty aggregates. To determine if this was the case, for each of the drum-mixtures, two samples of the combined aggregates from the feeder belt were subjected to the usual extraction procedure and then were washed and re-graded. (At the time of the testing, no samples of finished mix were available for test.) This testing indicated that the additional washing affected only the #8 sieve results, the binder and surface mix displaying increased fineness for this sieve of one-half and one percent passing, respectively. These results are considered relatively insignificant in view of the overall shortfalls on the #8 sieve for the binder and surface mixes (JMFΔ: 2.0 and 4.7%, respectively.)

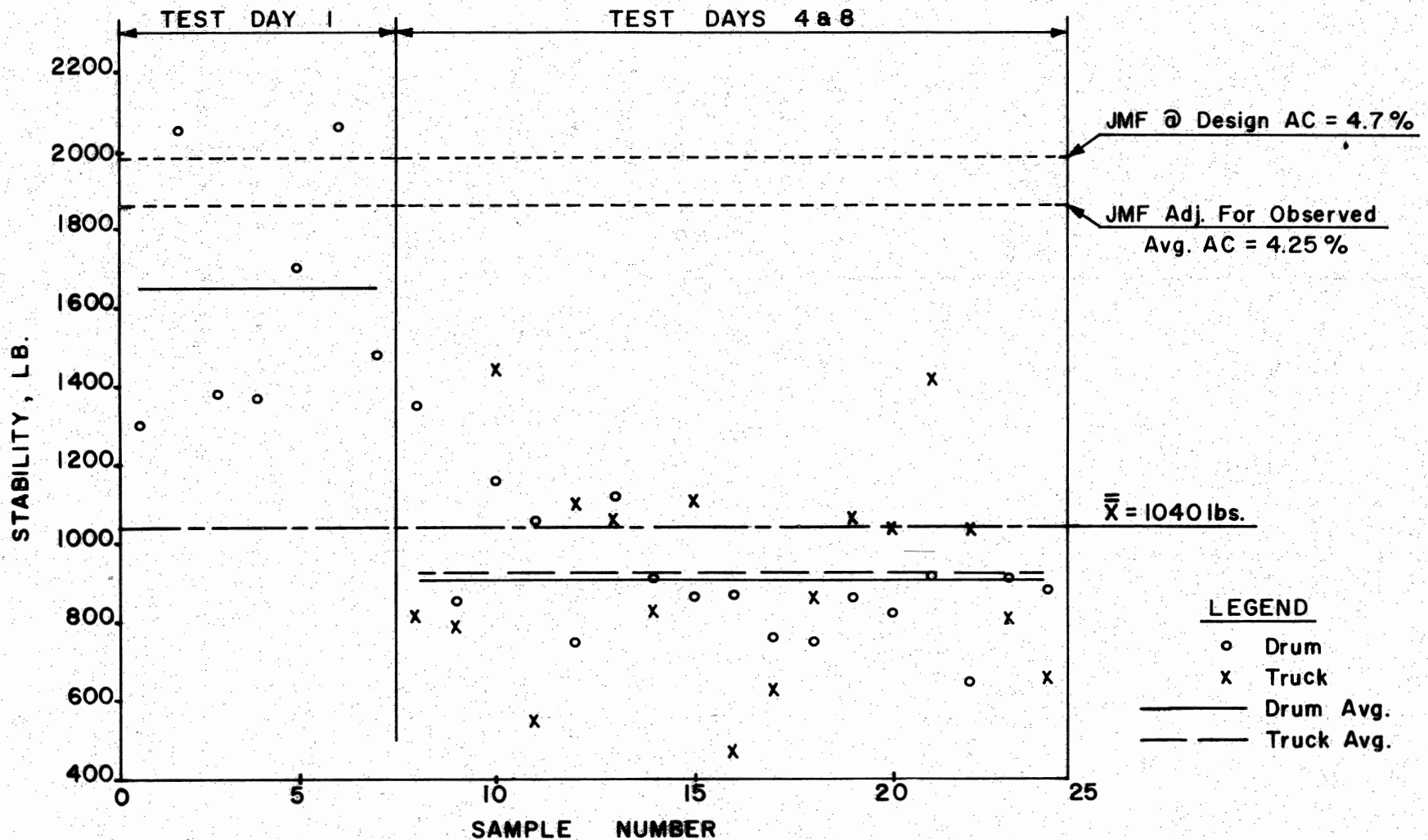
4.4 STABILITY AND IMMERSION COMPRESSION TESTS

4.4.1 Stability Samples: To assess the strength of the drum-mixes produced at the Sportsplex plant, a total of 82 Marshall stability specimens (41 of each mix) were obtained at the same rate and locations (truck and drum) as the composition samples described earlier in Subsection 4.2.1. The results of Marshall stability tests for the nine production days studied are presented in Figures 25 and 26.

4.4.2 Variation of Mix Stability: A 1970 study⁽²⁹⁾ indicated that the standard deviations of Marshall stability results for conventionally produced New Jersey binder and surface mix were approximately the same and equal to 300 pounds. At face, the computed standard deviations of stability test results for the Sportsplex binder and surface drum-mixtures shown in Figures 25 and 26 appear to compare favorably with this historical average. This observation can, of course, be confirmed utilizing various statistical techniques.

Applying a two-tailed F-test at the 95% confidence level indicates that for each Sportsplex mixture, there is no significant difference between the variability associated with the drum and truck samples. It follows that the standard deviations of each day's truck and drum samples for the respective mixtures can be combined for purposes of statistical comparison to the historical average.

FIGURE 25: STABILITY OF BINDER MIX (I-3)



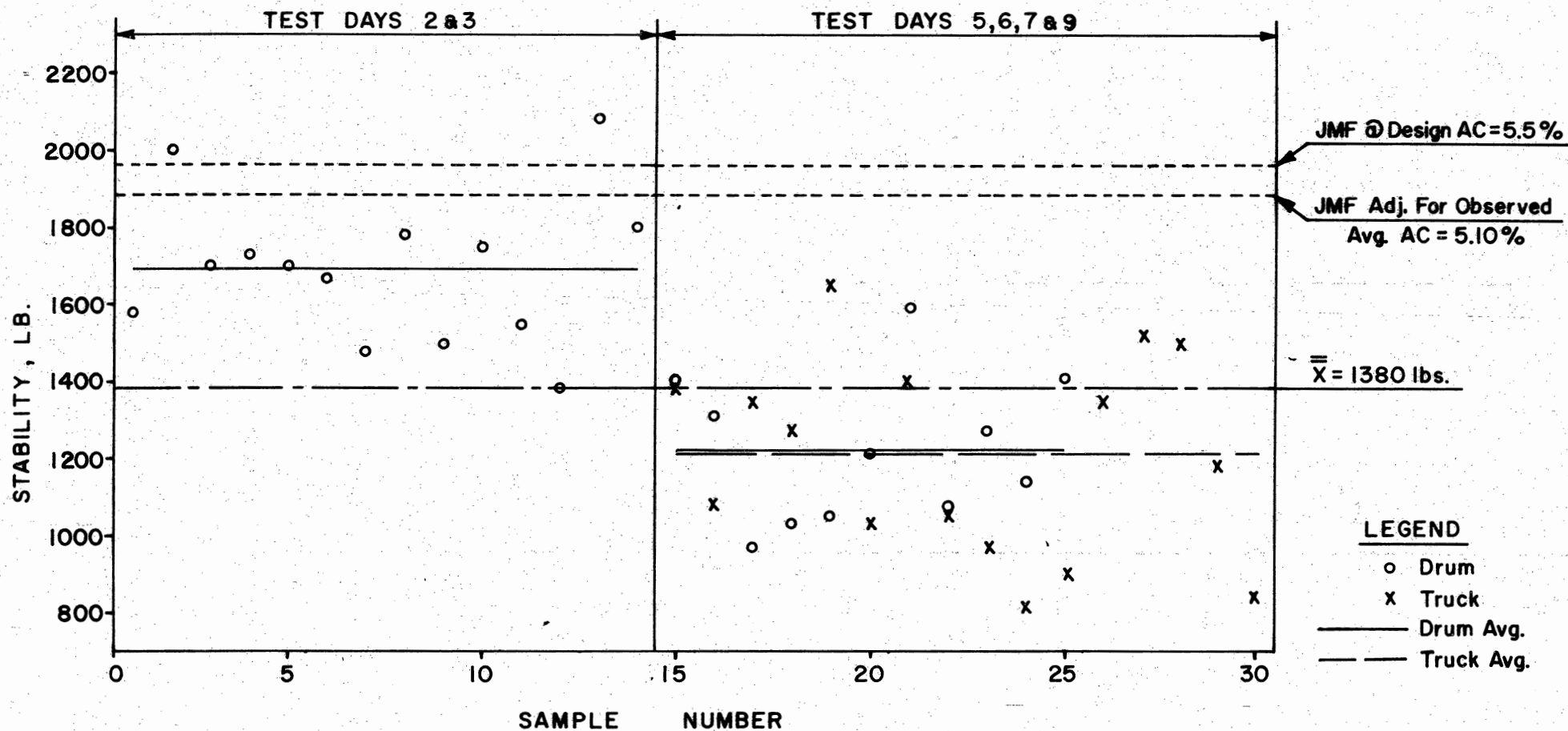
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TEST DAY 1			
SAMPLE	$\bar{X}$	σ	N
DRUM	1650	300	7

TEST DAYS 4 & 8			
SAMPLE	$\bar{X}$	σ	N
DRUM	910	170	17
TRUCK	920	270	17
COMBINED	920	230	34

ALL TEST DAYS			
SAMPLE	$\bar{X}$	σ	N
DRUM	1130	400	24
TRUCK	920	270	17
COMBINED	1040	360	41

FIGURE 26: STABILITY OF SURFACE MIX (I-5)



TEST DAYS 2&3			
SAMPLE	$\bar{X}$	σ	N
DRUM	1690	190	14

TEST DAYS 5,6,7&9			
SAMPLE	$\bar{X}$	σ	N
DRUM	1220	190	11
TRUCK	1210	260	16
COMBINED	1210	230	27

ALL TEST DAYS			
SAMPLE	$\bar{X}$	σ	N
DRUM	1490	310	25
TRUCK	1210	260	16
COMBINED	1380	320	41

Use of the F-test for this comparison reveals no real difference between the uniformity of the studied drum-mixes and the historical average. In essence, the results obtained in this study indicate that the variation in stability for mixtures produced by the dryer-drum process and conventional batch type plants in New Jersey can be considered equal.

For both mixtures, however, there is an obvious disparity between the design stability and that actually achieved during the production days sampled in this study. The overall average stability for the binder and surface mix are 1040 and 1380 pounds, respectively. In comparison to the essentially common mix design value of 2,000 pounds, these indicated averages represent reductions from the JMF on the order of 50 percent for the binder and 30 percent for the surface mixture.

4.4.3 Expected Conformance with Department of Transportation

Acceptance Criteria: The New Jersey Department of Transportation's acceptance plan for stability involves lot-by-lot acceptance with a five-sample average from a binder or surface mix lot being required to equal or exceed 900 pounds. The lot acceptance approach is predicated on uniformity of materials and conditions within any given lot. Inspection of the stability results shown in Figures 25 and 26 indicates that the present data sets do not satisfy this underlying premise. For each mixture, there are obviously instances of distinctly different day-to-day* mean

*Recall that since consecutive test days do not in all cases represent successive production days, the indicated variability is not in fact "day-to-day".

stability values. For example, in the case of the binder, the mean stability for test day 1 is over 700 pounds higher than that shown for days 4 and 8. A similar situation exists for the surface course, where the average stability for test days 2 and 3 exceeds that for days 5, 6, 7 and 9 by some 480 pounds. A conventional (t-score) statistical test indicates that these apparent differences in the mean stability levels for the data groups are indeed real (significant at the 95% confidence level).

Based on the preceeding then, it appears that for purposes of analysis, the data for particular mixes should logically be divided into groups. That is, it would not be valid to proceed with a simulated application of the New Jersey Department of Transportation stability acceptance criteria using all possible consecutive five-sample averages as was done in the case of asphalt content and mix gradation. However, it does seem reasonable to apply the procedure to each data group individually so as to provide an estimate of the sampled materials expected compliance with the Department's specification requirements. The results of such a simulation are shown in Table 16.

As indicated in Table 16, if the Sportsplex materials had been presented for acceptance on a New Jersey Department of Transportation project, about 40 percent of the binder mix stability lots would have been expected to incur a 2 percent payment reduction, while no reductions would be applied to the surface mix lots.

Table 16: Simulated Application of Department of Transportation Stability Acceptance Criteria to Dryer-Drum Mixtures

Mixture	Test Day (s)	Number of Simulated Acceptance Lots			Number of Simulated Lots Deficient In Stability			Deficient Lots, Percent
		Truck	Drum	Total	Truck	Drum	Total	
Binder	1	3	0	3	0	0	0	0
	4 & 8	13	13	26	7	4	11*	42
Surface	2 & 3	10	0	10	0	0	0	0
	5, 6, 7 & 9	7	12	19	0	0	0	0

*Three reduction levels are specified: 2, 5, and 10%. Only the 2% level applies here.

The general results of this simulated application of the Department's stability acceptance criteria (i.e., substantial non-conformity for the binder course) clearly could have been anticipated from a mere inspection of the data. That is, since the average stability of the binder mix produced on test days 4 and 8 was only 10 to 20 pounds higher than the 900 pound minimum acceptable value, fundamental notions of statistics immediately suggest a failure rate approaching 50 percent. The point here is that it seems reasonable to assume that if our more stringent

acceptance criteria and associated payment reduction schedule were actually in effect on the Sportsplex project, a producer employing normal process control procedures would have been aware of this situation early on and would have taken steps to avoid payment reductions. This could have been accomplished by modifying the binder mix design and/or production process to achieve an acceptable stability level prior to production on test day 8. A discussion of certain of the factors that might have effected a general increase in mix stability is presented in the next Subsection.

4.4.4 Factors Affecting Mix Stability: Given the substantial difference between the design stability and observed production mean for both of the studied drum-mixtures (JMF Δ : 960 and 620 pounds, respectively, for binder and surface course), the obvious questions at this point are whether the differences observed during this study can be explained in terms of some assignable cause(s) and if so, would such cause(s) be controllable on any future Department projects where use of the dryer-drum process was permitted. In an effort to provide some insight in this regard, the collected stability test results were analyzed in conjunction with test data for several other mix characteristics having the potential for influencing stability.

Before proceeding to the results of these analyses, it should be noted that the researchers did not expect to fully account for the disparities between the target and production

means but rather to identify the major factors which contributed to the shortfall in mix stability and which, by implication, might require the major control effort on any future drum-mix project.

A. Effect of Low Finished Asphalt Content: As previously described in subsection 4.2.2, the asphalt content production means determined from extraction tests performed on the studied drum-mixes were significantly lower than the JMF target values. These JMF misses amounted to 0.45% and 0.40%, respectively, for the binder and surface mix.

As is well-known, achievement of less than the intended quantity of asphalt in a mix will result in a shortfall from the design Marshall stability. Examination of the design curves for the studied drum-mixtures indicates that downward shifts in AC of the magnitude described above would decrease the design stability for both mixes by about 120 pounds (from some 2,000 to 1,880 lbs). Thus, for the binder mix the difference in the target and production mean asphalt content accounts for over 10 percent of the observed average miss in stability. In the case of the surface course, the relatively low asphalt content level accounts for some 20 percent of the average miss in mixture strength.

B. Effect of Temperature and Other Mix Parameters: In an effort to account for the remaining differences between design stability and the observed production mean (some 840 lbs for binder and 500 lbs for surface), a number of regression analyses

were performed on the stability results and test data for other mix variables such as temperature, mix moisture, and gradation (percent passing the number 4, 8, 50, and 200 sieves). These analyses entailed application of various regression techniques (e.g., linear with two variables, multiple linear, polynomial and step-wise multiple linear regression). Unfortunately, most of these attempts proved unsuccessful in determining meaningful relationships. As a general proposition, such a result may be attributed to either a lack of sufficient data points or a restricted range in the values for certain of the selected variables. In this particular case, the latter factor (restricted range) undoubtedly played a role in these correlation difficulties. For example, the total range of mix moisture contents observed in this study was only about one percent (0.5 to 1.6%).

As it turns out, the most useful tool in identifying the factors having the greatest influence on mixture strength was a computer analysis program for step-wise multiple linear regression. The main advantage of this step-wise regression program is that it selects the input variables having an effect on the prime variable (stability) and lists them in order of importance. As shown in Table 17, of the numerous variables evaluated, the most reliable relationships, in order of importance, were sample molding temperature, percent mix moisture, and the percent passing the number 200 sieve.

Table 17: Summary of Step-Wise Regression Parameters for Stability vs Other Mix Variables

A. Binder Mix

Step	Mix Variables*	Equation	N	r**	Syx
1	T	$S = 12T - 1672$	41	0.52	315
2	T + M	$S = 9.5T + 606M - 1673$	41	0.64	287
3	T + M + G	$S = 9.5T + 541M + 147G - 2313$	41	0.66	286

B. Surface Mix

Step	Mix Variables*	Equation	N	r**	Syx
1	T	$S = 11T - 1186$	41	0.56	266
2	T + M	$S = 12T + 453M - 1973$	41	0.62	254
3	T + M + G	$S = 13T + 489M + 76G - 2753$	41	0.63	256

*Key T = Temperature, °F
M = Mix moisture, %
G = Percent passing #200 sieve

**All correlation coefficients significant at 99% confidence level

Although the correlation coefficients shown in Table 17 are not large, they are nonetheless highly significant in each case. Consequently, while the observed correlations are probably not due to chance, certain of the indicated relationships are of limited value in predicting individual stability values. For example, while the two variable (temperature/mix-moisture) equations are indicative of a significant trend, it is believed that the coefficients for mix moisture were insufficiently defined from the study data. That is, confidence limits (95% significance level) computed for the mix moisture coefficients reveal that the true coefficients might be as much as plus or minus 85% from that indicated. As suggested earlier, this result may be due to the restricted range of moisture values observed during the nine production days studied.

A review of the statistical parameters shown in Table 17 further indicates that for either mix, no real improvement in correlation or predicting capability results from introduction of the third variable (percent passing the number 200 sieve). Thus, use of the three variable equation for either mix is not warranted and only the stability/temperature relationships shown in Table 17 will be used in the remainder of this analysis. For either mix, use of the latter equations in lieu of the combined expressions results in relatively small losses in correlation or predicting capability.

As expected, the stability/temperature relationship for each mix shows that stability increases in direct proportion to discharge/molding temperature. The best estimate of the specific magnitude of the stability increase accompanying each unit (1°F) increase in molding temperature is provided by the respective regression coefficients for the temperature variable: 12 pounds per degree for binder and 11 pounds per degree for surface mix.

In view of this significant general temperature/stability relationship, it is important to note that the molding temperature used in mix design and those used in compacting the field Marshall specimens differed considerably. That is, the design specimens were molded at $280^{\circ}\text{F} \pm 2^{\circ}\text{F}$, while the average plant molding temperatures for binder and surface mix specimens made during this evaluation were only 230°F and 240°F , respectively. It is generally evident then that as a result of the relatively low mix discharge temperatures used at the Sportsplex project, the achievable field stability was substantially lower than the design value. In particular, application of the derived stability/temperature relationships of Table 17 to the differential between the design and average field molding temperatures reveals that temperature accounts for some 600 pounds ($12 \text{ lbs}/^{\circ}\text{F} \times 50^{\circ}\text{F}$) of the observed shortfall in binder stability and about 440 pounds ($11 \text{ lbs}/^{\circ}\text{F} \times 40^{\circ}\text{F}$) in the case of the surface mix.

Thus, the difference between the design and average molding temperature at the plant during this evaluation accounts for over 60 percent of the observed miss in stability for the binder and for over 70 percent of the miss for the surface course.

On an overall basis, the combined effect of average asphalt content and temperature levels lower than that of the design accounts for about 75 and 90 percent of the total observed difference between the design stability and the production mean for the binder and surface mixes, respectively. Table 17 suggests that the remaining differences can be attributed at least in part to factors such as mix moisture and percent passing the number 200 sieve. An additional factor in this regard might be the substantial quantity of adherent fines on the project coarse aggregates (see Subsection 4.3.3). The precise role, if any, which aggregate dirtiness played on the stability results obtained in this study is not known. However, it is certainly conceivable that the surface friction between coarse aggregate particles may be reduced by adherent fines which, in turn, would cause some reduction in mix stability.

At this point, it is re-emphasized that the preceeding analysis was based on average stability and temperature data for each mix. Clearly, the difference between design and production stability for individual samples or even averages within a given mix may not be fully explained by simply adjusting

for asphalt content and temperature. For example, only about 40 percent of the difference in mean stability levels between the grouped test days shown in Figures 25 and 26 is explained by low asphalt content and temperature. This again indicates that other factors influenced the stability results for this study. Nonetheless, it is evident that stability was indeed significantly effected by discharge temperature. The latter suggests the New Jersey Department of Transportation move cautiously should the use of low temperature mixes be considered for future projects. In any event, if a decision is made to permit lower-than-conventional mixing temperatures in future work, mix designs for those projects should, of course, be developed based on intended mix discharge temperatures. Such a design procedure would obviously provide more realistic estimates of a mixtures as-produced strength.

A final brief comment on mix moisture seems appropriate here. The general trend indicated by the test data in Table 17 -- that stability increases with increasing mix moisture -- tends to support what others^(2, 5) have suggested: Residual moisture in the mix aids compaction. Further work in this area may prove beneficial. That is, laboratory and/or field experimentation with various known levels of mix moisture throughout the range of interest should provide realistic information regarding the true effect of moisture on stability. Any such future work would, of course, also require determining the influence of increased moisture levels on other essential mix properties (e.g., possible stripping).

4.4.5 Retained Strength: As noted earlier, the purpose of performing retained strength tests on the Sportsplex mixtures was to determine if drum-mixes are adversely affected by free mix moisture and/or residual moisture in the partially-dried aggregates. Generally, retained strength is a measure of a bituminous mixtures resistance tendency to stripping (loss of adhesion between the asphalt and aggregate particles).

Several states use the immersion compression test to assess the action of water on bituminous mixes when formulating mix designs. Basically, the immersion compression test (AASHTO T 165) involves comparing the wet and dry strength of a given mixture. In practice, the compressive strength of cylindrical specimens which have been immersed in water maintained at 120°F for a specified time period (either one or four days) is compared to that of companion, air-dried specimens. The ratio of wet to dry strength, expressed as a percentage, is reported as the "Index of Retained Strength" for the given bituminous mix. A minimum retained strength index on the order of 70 to 75 percent is reported to indicate a mix reasonably resistant to the detrimental effects of water⁽³⁰⁾.

Current New Jersey Department of Transportation design criteria do not require immersion compression testing. However, a modification of the procedure -- involving evaluation of specimens soaked for 14 days at 120°F -- is used informally to assess the effect of proposed mineral fillers on bituminous

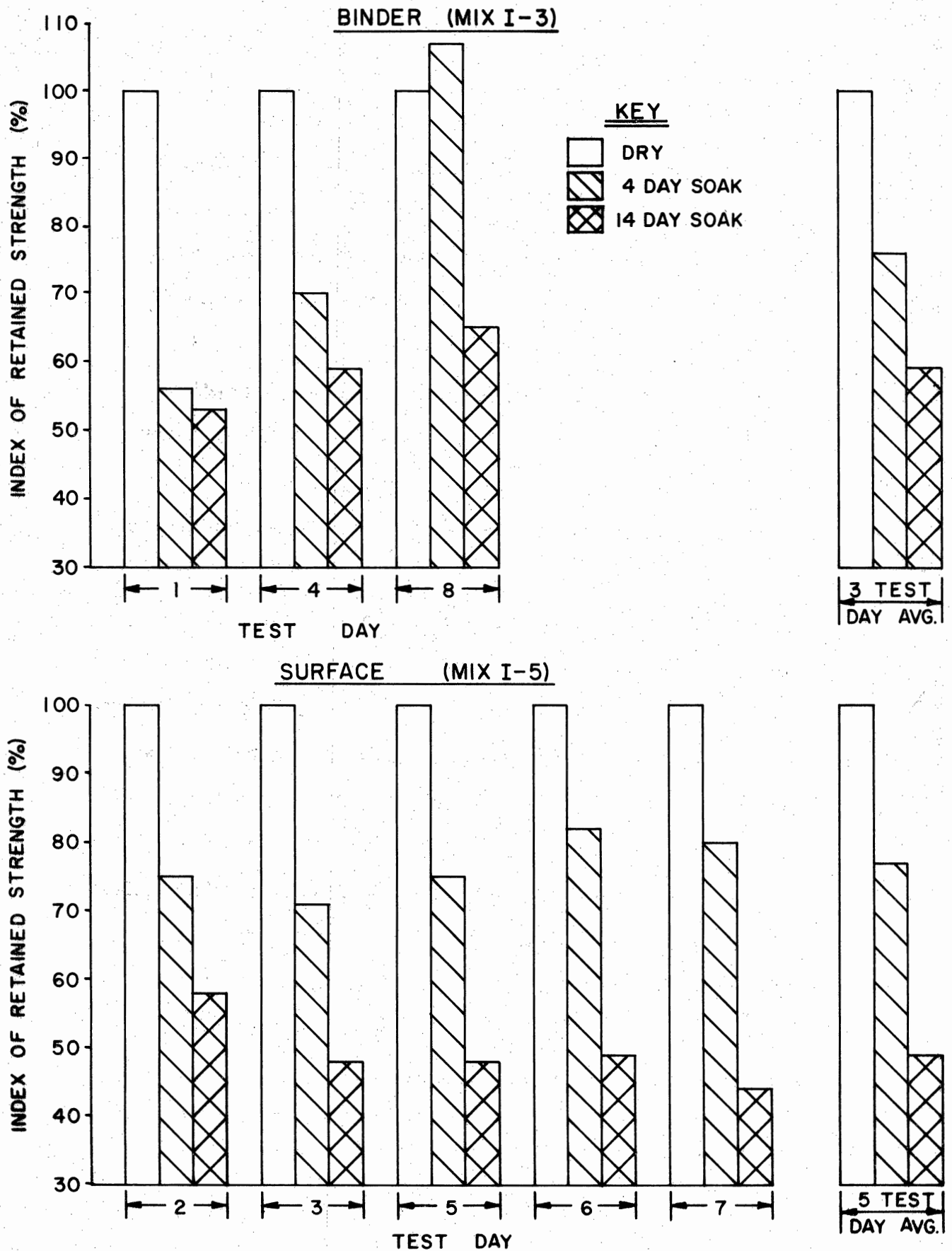
mixtures prepared in the laboratory using reference aggregates. A minimum retained strength of 70 percent is required in order for the tested mineral filler to be approved for use on Department projects. Although the Department's requirement is more severe than the standard test as regards the immersion period, few failures are encountered and a retained strength index of 80 percent or more is not uncommon.

To evaluate the effect of water on the drum-mix produced during this study, a mixture sample was obtained each test day and forwarded to the central laboratory for immersion compression testing. Sufficient material was obtained to mold nine, 4 x 4 inch cylindrical specimens which were then separated into three groups for testing. The first group of three specimens were tested dry, while the second and third groups were immersed in water maintained at 120°F for 4 and 14 days, respectively, prior to testing.

The immersion compression test results obtained in this study are presented in Figure 27.

4 Day Immersion Tests: Except for the binder mix produced on test day 1, the index of retained strength for both drum-mixes equals or exceeds the minimum of 70 percent considered adequate by others. As shown in Figure 27, the average retained strength for the binder (3 test days) and surface mixes (5 test days) were 76 and 77 percent, respectively. At least one other state (Oregon) has evaluated drum-mix on the basis of the standard immersion compression test and reported an average retained

FIGURE 27: IMMERSION COMPRESSION TEST RESULTS



strength of 84 percent, considerably above their specified minimum of 70 percent⁽³¹⁾.

14 Day Immersion Tests: As shown in Figure 27, strength tests performed on the samples conditioned for 14 days indicate that neither mix would have satisfied the Department's minimum value of 70 percent retained strength. The retained strength for the binder ranged from 53 to 65 percent and averaged 59 percent. Values for the surface mix ranged from 44 to 58 percent and averaged 49 percent. The retained strength values that would have been obtained had these mixtures been tested at the time they were designed is, of course, unknown.

In summary then, the average retained strength for the Sportsplex drum-mixtures would have satisfied the criteria applied to the short-term soaking test conditions employed by others, but would not have complied with the Department's long-term soaking requirements used to evaluate mineral fillers. The specific cause(s) for the relatively low 14 day retained strengths exhibited by the studied drum-mixes is not known. One possibility here is the excessive amount of adherent fines on the project coarse aggregates. As alluded to earlier, adherent fines are at least potentially detrimental to retained strength, particularly if the adherent material is sensitive to water and/or prevents the large coarse aggregate particles from being properly coated with asphalt cement.

As noted in subsection 4.3.3E, while the amount of adherent fines which will be permitted on future Department of Transportation work is currently unsettled, the excessive dirtiness of the Sportsplex aggregates would undoubtedly be cause for their rejection under any acceptance plan ultimately adopted. Thus, the cause(s) of the low (14 day) retained strength may be associated with a materials problem rather than the mixing process. In view of this, the true capability of the dryer-drum process to produce bituminous mixtures that would satisfy current New Jersey Department of Transportation retained strength criteria will not be determinable until some future project is studied where a rejectable level of adherent fines is not involved.

In this connection, it is worth noting that it is the researcher's opinion that if a given level of adherent fines is present on a coarse aggregate, such may pose a more critical problem on drum-mixing projects than at a conventional plant. That is, at a conventional plant, the less tenaciously held adherent fines will be given some opportunity to be dislodged in passing thru the dryer and hot screening deck. In fact, an attempt is made to reflect this condition in our adherent fines test procedure: Prior to washing, the aggregates are subjected to a preliminary dry screening over the #16 sieve. Since separate drying and screening operations are not employed in the drum-mix process, it seems reasonable to assume that a

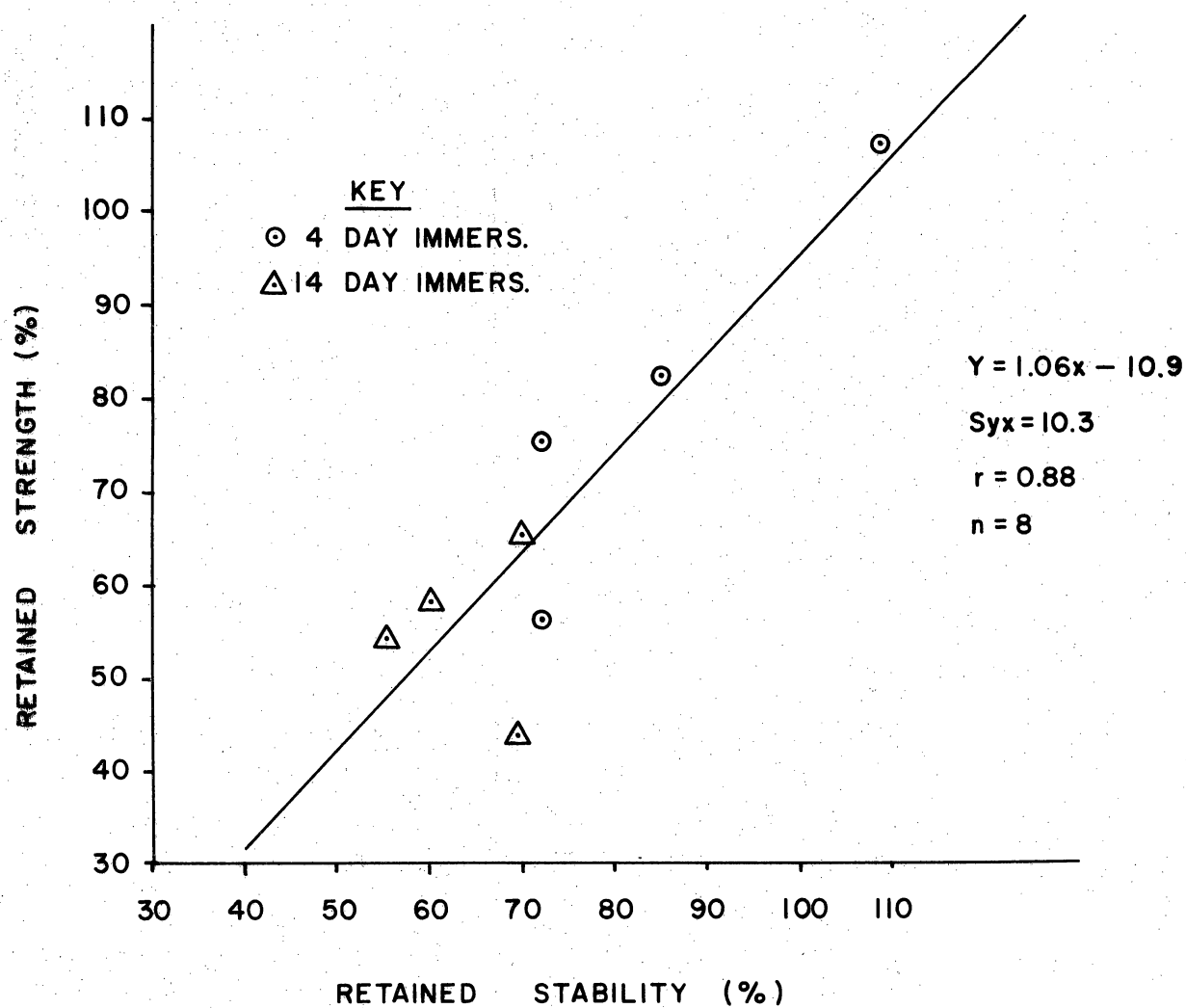
relatively greater percentage of the fines initially present may remain bound to the aggregate in the final product. Whether this speculation is correct or not would obviously require appropriate testing on a future project.

Marshall Specimens: Unlike standard immersion compression specimens, Marshall specimens are routinely molded at asphalt plants by Department of Transportation personnel. Molding of 4 x 4 inch cylindrical specimens, standard in the immersion compression procedure of AASHTO T165, would require the addition of specialized equipment. Consequently, it would be beneficial if Marshall's rather than standard test specimens could be used to determine the resistance of a given mixture to the action of water.

In an effort to determine if a correlation existed between the results for the two different types of test specimens -- and thus, whether they might generally be used interchangeably -- additional Marshall's were obtained on five test days and subjected to the same treatment (immersion in water for 4 and 14 days) as the standard size immersion compression specimens. Since the molding temperatures of these Marshall specimens differed from that required in the AASHTO procedure ($255 \pm 2^{\circ}\text{F}$), the Marshall results were adjusted to the standard temperature base using the stability/temperature relationship presented in report Subsection 4.4.4.

The results of a linear regression analysis retained strength and retained stability are presented in Figure 28. As shown, the two variables exhibit essentially a one-to-one relationship with "good" correlation being indicated ($r = 0.88$). The specific relationship shown may be applicable only to the particular project materials and mixtures used at the Sportsplex. However, the finding is sufficiently encouraging to warrant future research to determine if the relationship is valid for general application. Generally, any such future work should entail obtaining companion compression cylinders and Marshall specimens, molded at the same temperature, from several plants using various aggregate types in each class of bituminous mix used by the Department. The resultant data should permit development of a graph (for a given sample size) that describes a relationship between retained strength and retained stability of more general applicability. In fact, it may be necessary to establish several graphs, reflecting the various mixture and aggregate types used in New Jersey.

**FIGURE 28: RELATIONSHIP BETWEEN RETAINED STRENGTH
AND RETAINED STABILITY**



4.5 ASPHALT HARDENING: CONVENTIONAL MECHANICAL TESTS

4.5.1 General: To provide the reader with some sense of direction regarding the analyses in this subsection, it is important to note at the outset that the significance of the collected asphalt consistency data as a whole is colored by one fundamental issue: testing reliability. That is, subsequent to the completion of the Sportsplex work, the Department was apprised of some general deficiencies in the asphalt consistency testing procedures employed by our central laboratory. As a result of the "looseness" of these testing procedures during the period when the work of this project was ongoing, occasional unreliable penetration and viscosity data was obtained for both this and other projects.

This framework of at least occasional suspect consistency data for the historical sample from New Jersey's conventional plants (i.e., the base values on which the relative effect of drum-mixing is gauged), coupled with some apparent anomalies in the present data set, certainly suggests the possibility that the data may defy any definitive analysis.

However, it is here concluded that the reliability of the data is, in fact, sufficient to permit resolution of the central question of this subsection: Namely, is the asphalt harmed by exposure to the heat on processing through the drum-mixer? The author's conclusion: No. As it turns out, the principal effect of the deficiencies in our laboratory procedures was to cause a consistent bias towards erroneously high penetration values for

conventional and drum-mix recovery samples and thus, a general tendency for underestimates of the true amount of hardening occurring on processing.

The point of this introductory section is to note to the reader that, unfortunately, some rather protracted analyses are required to reach the above conclusions. Further, while some tentative inferences regarding the reliability of the data can be drawn based on consideration of the Sportsplex results alone, the report subsections on conventional and drum-mix processing must be viewed together to reach definitive conclusions. Simply, a determination that the error in our penetration values is indeed "characteristic" clearly requires consideration of results from more than one project.

4.5.2 Consistency of Asphalt Processed Thru Drum-Mixer: To determine the changes in asphalt consistency occurring on processing thru the studied drum-mix unit, penetration and viscosity tests were performed on a total of 14 samples of the AC-20 supplied to the plant storage tank and on 49 samples of the Abson recovery residue from the finished drum-mix. As noted earlier in subsection 3.3, the mixture recovery samples were obtained exclusively from the drum discharge and were specially cooled and stored so as to preserve their as-produced characteristics.

The results of this asphalt consistency testing are presented in Figure 29 and Table 18. Figure 29 shows the respective gain or

loss in penetration and viscosity observed for individual mixture recovery samples, while Table 18 shows the daily average changes in consistency. In these and subsequent data presentations, changes in asphalt consistency are calculated as the recovered value less the original (tank sample) value. As defined here then, asphalt hardening is indicated by a gain in viscosity or a loss in penetration.

Examination of these individual and overall test results reveals some surprising and apparently anomalous trends. For example, in the case of the penetration test results, the data obviously suggest that our initial concern with respect to the consistency of the processed drum-mix -- excessive hardening -- was misplaced. Rather, a reverse effect is indicated: As shown in Figure 29, individual instances of apparent softening of the asphalt are considerably more frequent than test results indicating hardening (ratio 2.5:1). This greater frequency of penetration gains to losses reflects as an average increase from the original penetration value for seven of the eight test days (Table 18). On an overall basis, the mixture recovery samples display an average of four units greater penetration than the original asphalt, a relative increase in softness of about 4.5 percent. The one day's test results which markedly depart from this overall average -- the limited sampling made on day 6 -- are believed to represent an outlier, since the indicated penetration results are inordinately high not only with

FIGURE 29: ASPHALT CONSISTENCY CHANGES DISPLAYED BY INDIVIDUAL MIXTURE RECOVERY SAMPLES

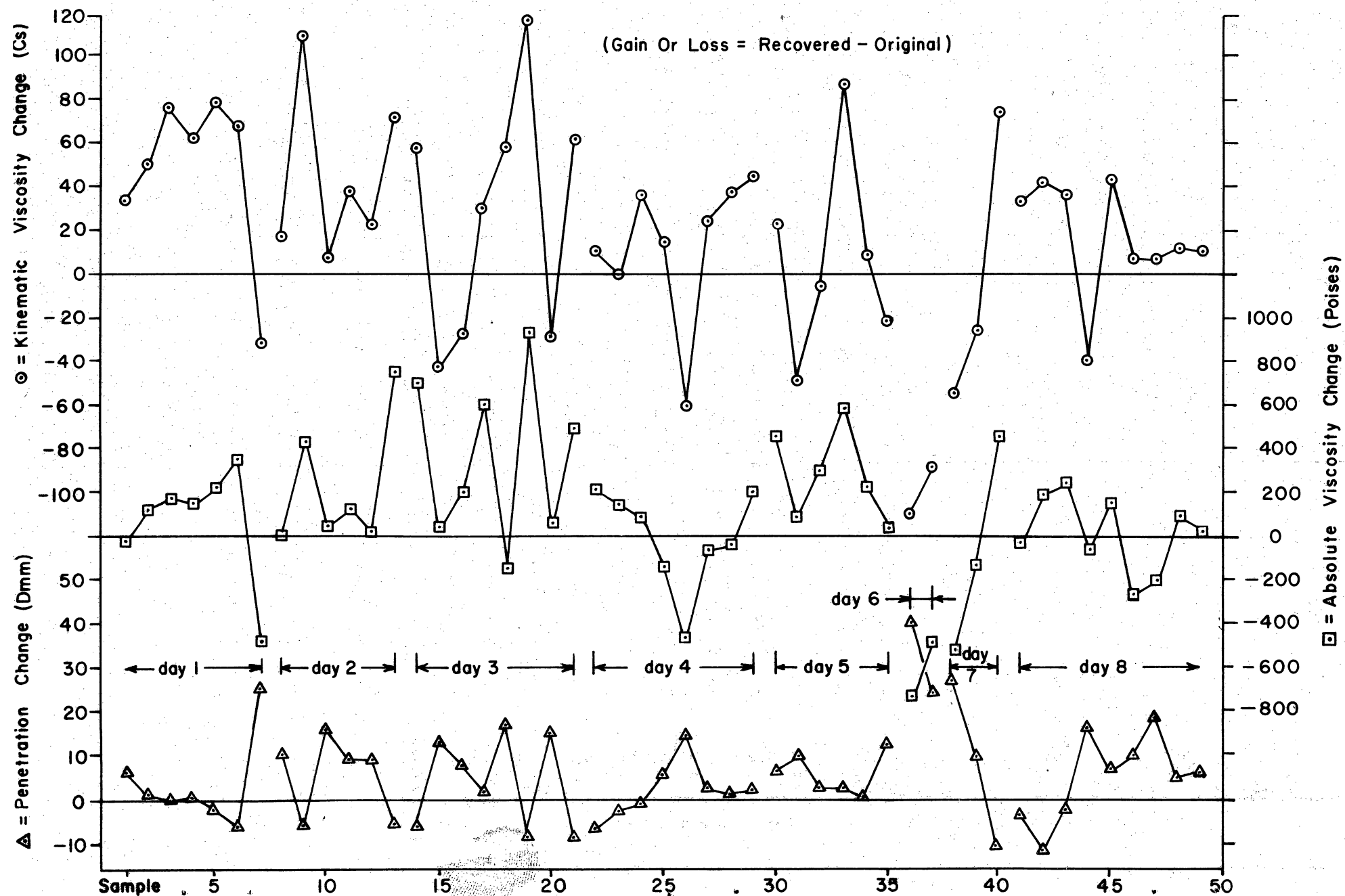


Table 18: Average Asphalt Consistency Before and After Drum-Mixing

ORIGINAL (AS-SUPPLIED) ASPHALT					RECOVERED ASPHALT				Δ = RECOVERED LESS ORIGINAL		
Test Day	N = Number of Samples	P = Penetration (Note 1)	V_A = Absolute Viscosity	V_K = Kinematic Viscosity	N	P	V_A	V_K	ΔP	ΔV_A	ΔV_K
1	2	81	2005	404	7	84	2081	452	3	76	48*
2	2	81	1906	412	6	86	2126	456	5	220*	44*
3	2	86	1822	402	8	90	2184	429	4	362*	27*
4	2	88	1894	404	8	88	1883	417	0	-11	13
5	2	83	1776	422	6	88	2056	429	5	280*	7
6	1	106	1734	390	2	139	1114	290	33*	-620*	-100*
7	1	98	1691	390	3	106	1612	388	8	-79	-2
8	2	92	1712	388	9	96	1723	405	4	11	17
Weighted Averages	$N_T = 14$	88	1832	403	$N_T = 49$	92	1934	421	4*	102*	18*
3 apparent outliers eliminated									4*	146*	25*

Note 1: All penetrations in this and subsequent data presentations are in decimillimeters (dmm) at 100 gm, 5 sec, and 77°F (AASHTO T-49 procedure). All absolute viscosities are in poises at 140°F (AASHTO T-202). Kinematic viscosities are in centistokes at 275°F (AASHTO T-201).

* Denotes statistically significant difference at at least 90% confidence level.

respect to the change from the original, but also as regards the original value itself. Further, as will be described later, the subject day's penetration and viscosity data depart significantly from an observed relationship between mix discharge temperature and processed asphalt consistency. As noted in Table 18, elimination of these two data points for day 6 (and one test result from day 7, suspect on similar grounds), does not effect a change in the indicated overall penetration gain.

Given the described overall trend for the asphalt to display relative increases in penetration after processing thru the drum-mixer, for the two measures of consistency to be in harmony, a corresponding general pattern of viscosity decreases (softening) would be expected. At face, the viscosity data does not appear to fit any such pattern. That is, while the viscosity results plotted in Figure 29 display a mix of viscosity losses and gains, viscosity gains (indicative of hardening) are more numerous than losses. Specifically, as in the case of the penetration data, the gain to loss ratio is about 2.5:1. Accordingly, the majority of the daily averages (Table 18) represent viscosity gains, with the overall sample displaying viscosity increases amounting to 146 and 25 units, respectively, for the absolute and kinematic tests. On an overall basis then, one measure of consistency (penetration) indicates that the net effect of processing thru the drum-mixer was to soften the asphalt by about 4.5 percent, while the other measure (viscosity) suggests that the effect was to harden the asphalt by a slightly greater percentage (6 and 8%, respectively, for the kinematic and absolute tests).

Faced with this apparent incongruity between the collected penetration and viscosity data, the obvious question which must be resolved is which (if any) of the indicated asphalt consistency changes are real and which are merely apparent (i.e., a function of testing variability alone). That at least certain of the indicated changes may indeed be insignificant is clearly suggested by their relatively small magnitude.

Various statistical analyses addressing this question will subsequently be undertaken herein. However, before proceeding to the application of such mathematical methods, it is useful to note at the outset that if one accepts for the moment that the collected data is not wholly unreliable -- that is, if the choice is between relying on penetration or viscosity -- several factors suggest that such choice be resolved in favor of the viscosity results. In the first place, common sense (if not statistics) suggests that a hypothesis which merely requires one assumption to be true is generally more likely to be correct than an alternate explanation in which multiple assumptions must be satisfied. In the present case then, it certainly appears more likely that the penetration rather than the viscosity results are in error, since for the latter to be correct, we must believe that there has in fact been a fundamental and unexpected change (softening) in the asphalt on exposure to heat and both the kinematic and absolute viscosity tests erroneously mask this true state of affairs. Secondly, while it is conceivable that the asphalt actually might somehow be softened during drum-mixing --

possibly, thru the mechanism of emulsification in the presence of the wet aggregates or by contamination with unconsumed burner fuel -- a review of the literature indicates that if such phenomena had occurred at the Sportsplex, it would apparently represent a unique result in the one case (emulsification) and an uncommon* one in the other (contamination).

A statistical test of the significance of means (Z-test, variability assumed known), while not definitive in resolving the asphalt softening/hardening anomaly, provides some first, instructive insight. As shown in Table 18, application of such a statistical procedure to the Sportsplex data reveals that while the indicated penetration and viscosity changes are statistically significant on an overall (total sample) basis, only the viscosity data displays significant individual (daily) results. In the case of the viscosity data, all but three days results display discernible (real) differences in consistency for the processed asphalt. In contrast, except for the apparently erroneous data of test day 6, all of the daily average changes in penetration are within the range of error of the test. While there certainly are cases where individually meaningless data may collectively become significant as the penetration results ostensibly do in the present case, the results of this first analysis suggest that a decision as to the true effect of drum-mixing on the consistency of the processed asphalt should at least

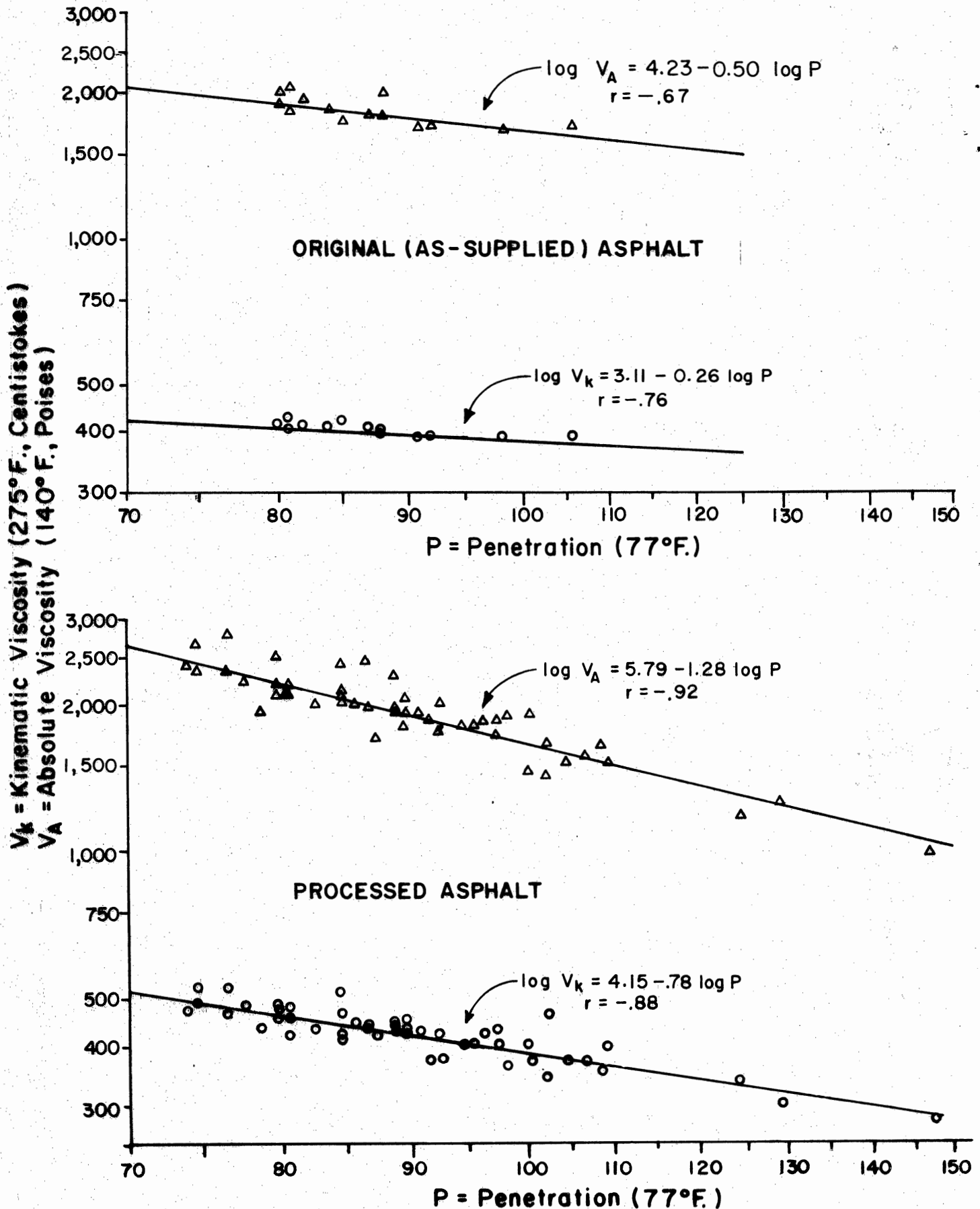
*In a 1974 California Study (16), a 40 percent average gain in penetration observed for finished drum-mix was attributed to such a fuel contamination problem.

be narrowed from a choice between hardening and softening to one between hardening and no change.

To determine if the present data set possesses the type of overall internal agreement expected of consistency results in general, a correlation analysis was performed on the individual penetration and viscosity results for the Sportsplex tank and recovery samples. The results of this analysis are plotted as a conventional logarithmic viscosity/penetration plot in Figure 30. Application of usual statistical standards to the best-fit lines shown relating the individual penetration and viscosity results indicates that a significant (inverse) relationship does in fact exist between these two measures of asphalt consistency. Contrary to the first impression conveyed by Figure 29 and Table 18 then, there is indeed a basic harmony among the Sportsplex consistency results.

It is important to note, however, that while there is a good penetration/viscosity fit for both the original and processed asphalt, the specific relationships (e.g., slope of the regression lines for particular types of consistency tests) differ significantly as between the before and after data. The significance of this point is that since the analysis of the effect of drum-mix processing is fundamentally based on before-after differences, if the relationships for the original and recovered asphalt generally differ (i.e., different viscosity values correspond to a given penetration), it clearly follows that some disparity in the respective estimates of asphalt hardening/softening are to be expected from the two classes

FIGURE 30 : PENETRATION - VISCOSITY RELATIONSHIPS FOR ORIGINAL AND PROCESSED DRUM-MIX ASPHALT



of tests. For example, examination of the kinematic viscosity-penetration best-fit relationship for the as-supplied asphalt indicates that the entire, relatively wide spectrum of penetration results (81 to 106 units, representing nearly a 30% "spread" about the mean) corresponds to an extremely narrow range of viscosities (383 to 411 units; 7% variation about mean). In contrast, for this same range of penetration in the processed asphalt, a three times larger range of kinematic viscosities would be expected (372 to 459 units). Consequently, assessing changes in asphalt consistency based on kinematic viscosity involves subtracting a nearly constant (original) value from varying (recovered) values, while an alternate assessment based on penetration data basically entails subtraction among widely varying values. Again, while this difference in the best-fit relationships does not suggest which of the two measures of consistency provides the more reliable estimate, it certainly suggests the possibility of generally different assessments.

While it is generally well-known, it is worth noting that the observed characteristics of the present penetration/viscosity data (an essentially constant original viscosity associated with widely varying original penetrations) is not some unique feature, representing cause for its rejection. Rather, numerous investigators have observed this same general characteristic (see, e.g., reference 17).

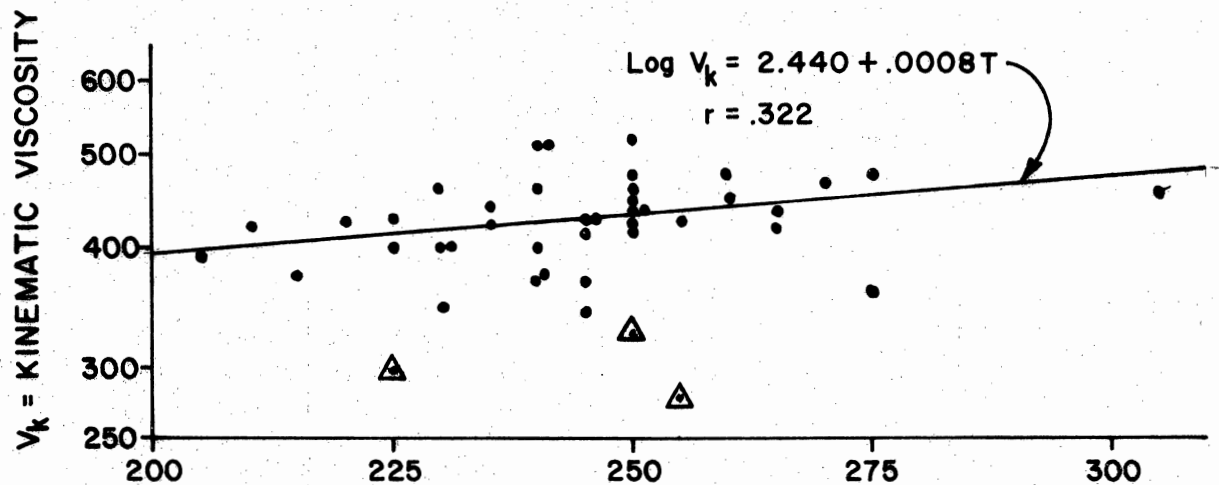
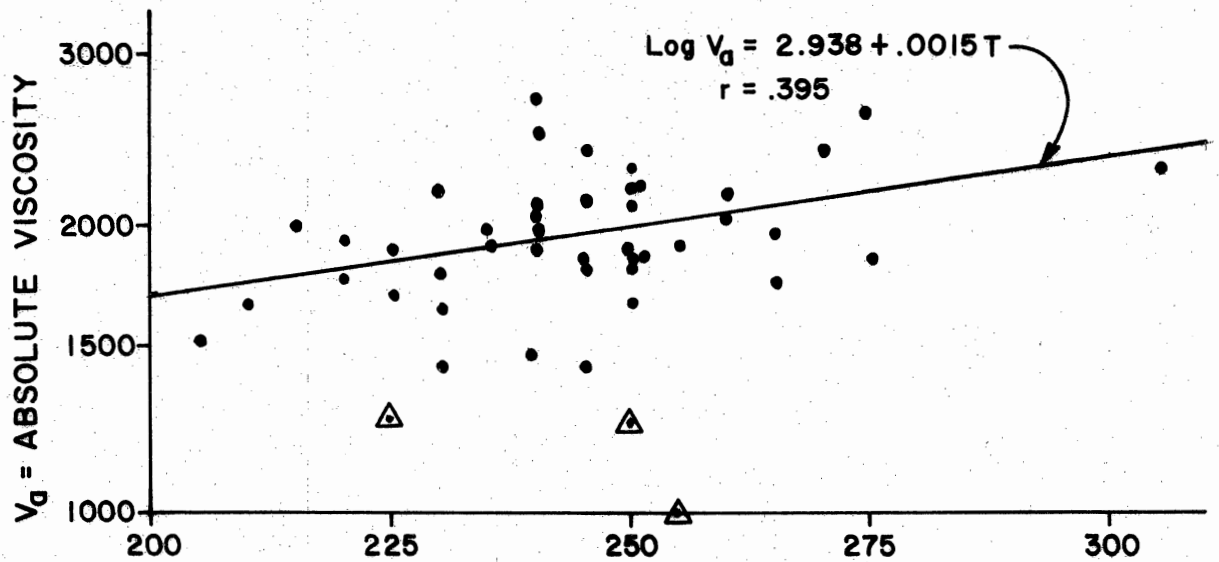
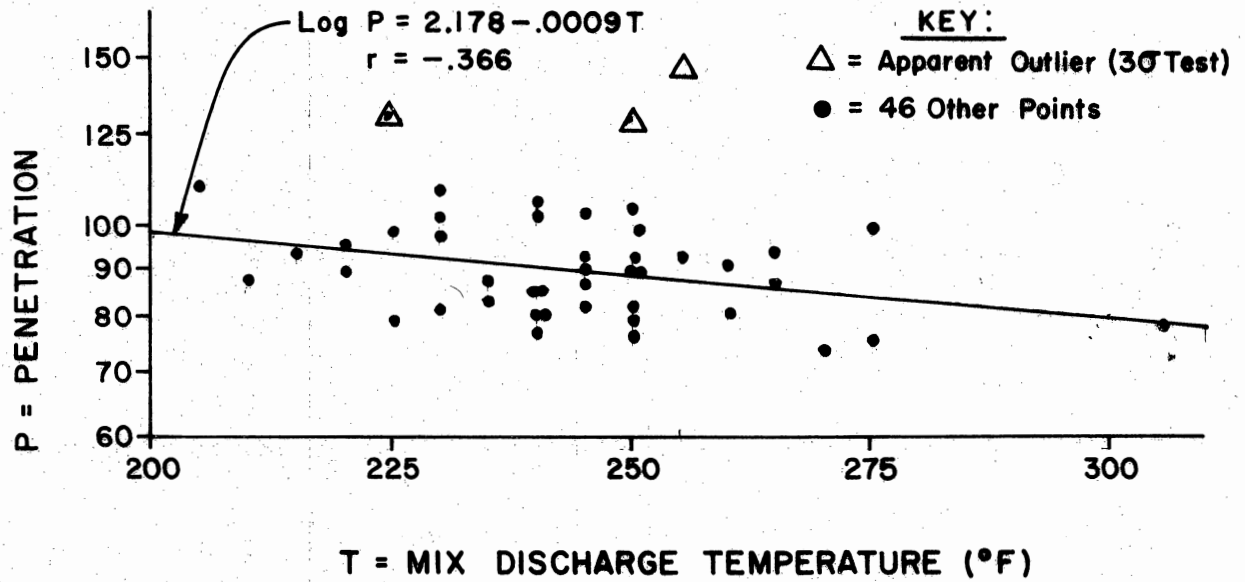
Given that the relationship between the viscosity and penetration results for the Sportsplex may be described by a best-fit line, a further analysis was undertaken to determine whether the

variations along that regression line -- that is, the within-day and day-to-day variations in processed asphalt consistency -- might at least in part be a reflection of an assignable cause; specifically, mix discharge temperature. The results of this temperature-consistency analysis are presented in Figure 31.

An evaluation of the statistical parameters for the regression lines of Figure 31 indicates that there is a highly significant but "poor" fit between the observed discharge temperature of the drum-mix and its consistency. In other words, while there is a clear trend for recovered viscosities to increase and recovered penetrations to decrease (i.e., indicate increased hardening) with increases in observed discharge temperature, the scatter of the data is such that estimates of the expected consistency level corresponding to a particular discharge temperature are very imprecise. For example, the penetration-temperature regression in Figure 31 indicates that if many samples of Sportsplex mix discharged at the overall sample average temperature of 245⁰F were to have been tested, penetration values would average 91 units, but individual results would be expected to range from as low as 73 to as high as 109 units (i.e., within ± 2 Syx).

The general relationships shown in Figure 31 are useful in at least two respects. In the first place, notwithstanding their relatively poor ability to predict consistency values for individual samples, the developed regression equations are useful to make some very interesting (albeit rough) estimates of the overall extent to

**FIGURE 31: INFLUENCE OF MIX DISCHARGE TEMPERATURE
ON CONSISTENCY OF DRUM-MIX ASPHALT**



which the consistency changes observed for drum-mixing are a function of the lower-than-conventional mixing temperatures employed at the Sportsplex. By isolating the approximate effect of temperature then, the effect of the dryer-drum process can be more directly assessed in subsequent comparisons to the results of conventional (high temperature) processing. For example, the penetration-temperature regression indicates that had the Sportsplex asphalt mixtures been produced to discharge at the 275 to 300°F levels common at conventional plants, average penetrations on the order of 85 and 81 units would have been expected. Compared to the 91 unit penetration for the 245°F average discharge temperature, this would translate as about a 7-11% expected increase in relative hardening. As shown in Table 19, use of high temperature mixing would exert a similar relative effect on viscosity data.

Table 19: Estimate of Hardening Associated with Low Mix Discharge Temperatures

Consistency Test	Average for 245°F Mix	Predicted Average for Conventional Temperatures		Relative Increase in Hardening			
				Units		Percent	
		275°	300°	275°	300°	275°	300°
Penetration	91	85	81	6	10	6.6	11.0
Absolute Viscosity	2021	2241	2443	220	422	10.9	20.9
Kinematic Viscosity	433	457	479	24	46	5.5	10.6

The relationships of Figure 31 are also useful in that they further suggest that the observed penetration/viscosity anomaly generally be resolved in favor of the viscosity results (hardening). That is, while alternate inferences are of course possible, one implication of the fact that the recovered penetration results expectedly decrease with increased discharge temperature, but unexpectedly do not display an overall decrease, is that the latter result may simply be due to the magnitude of the penetration testing error. This is, of course, the gist of what was suggested by the previously discussed significance tests.

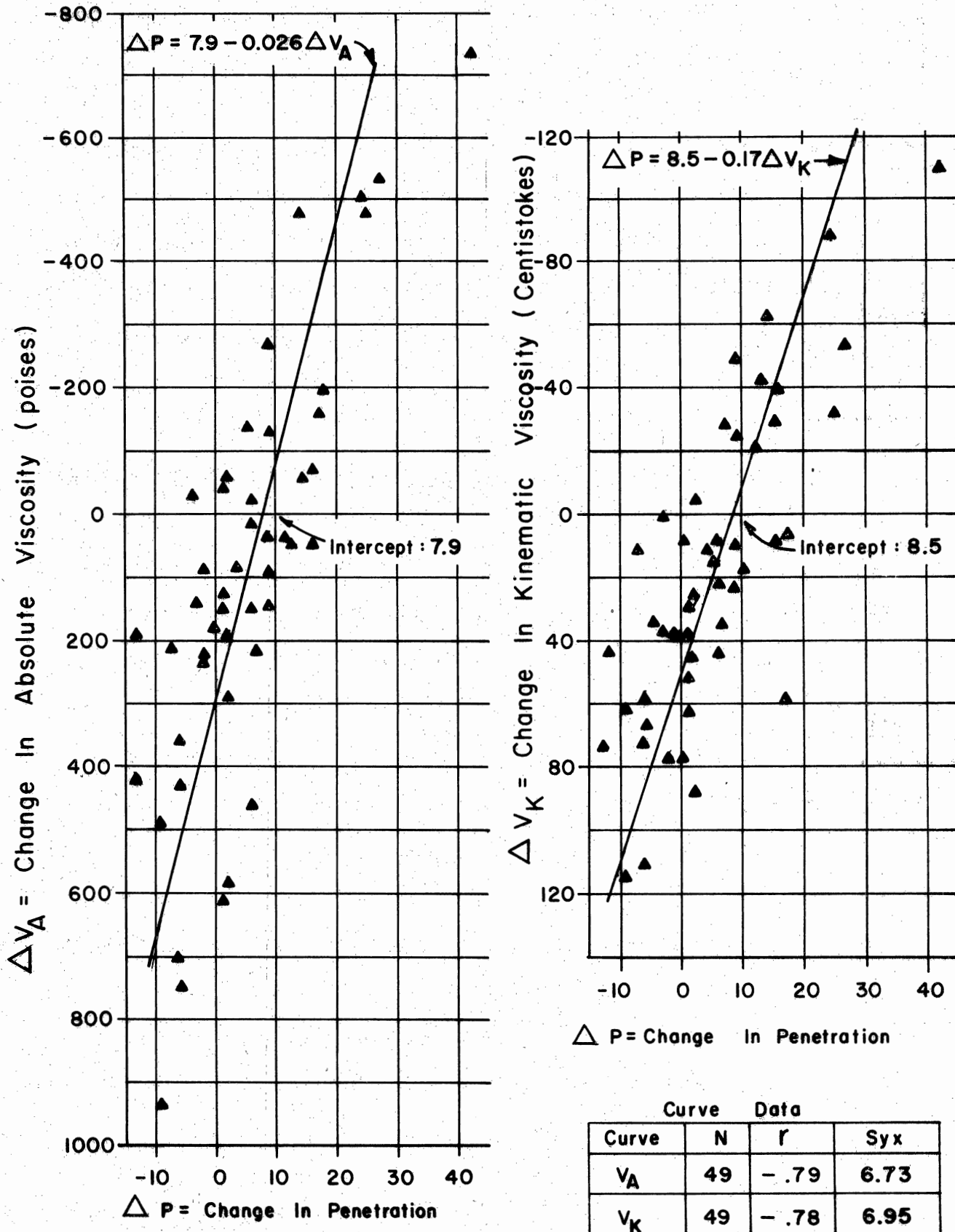
As briefly noted earlier in this report subsection, three apparent outlying consistency test results were eliminated from the analysis, due in part to their failure to fit the discharge temperature - consistency relationship followed by the remaining data. To be more specific, the penetration values for each of these outlying samples (plotted as triangles in Figure 31) lie beyond three standard errors of the estimate (S_{yx}) from the best-fit value corresponding to its respective temperature, and in two of three cases, this same situation prevails with respect to both of the viscosity regressions. Since virtually all of the data normally falls within plus or minus three standard errors from a regression line, the subject three samples definitely do not appear to be a part of the same population as the rest of the data.

Given the fact the collected consistency data provide different assessments of the true effect of drum-mix processing, a

further analysis was undertaken to determine the general magnitude of this disparity between the indicated changes in penetration and viscosity. The results of this analysis are presented as regression plots in Figure 32. These particular plots describe the relationship between the gains and losses in penetration and viscosity observed for the 49 individual mixture recovery samples.

Application of conventional statistical yardsticks to the best-fit lines of Figure 32 confirms that a significant relationship does in fact exist between the two measures of asphalt consistency change. It is important to note, however, that the regression lines shown depart from the ideal case in one significant respect: They do not pass thru the origin, but instead display intercepts. In the case of the penetration intercept, for example, the indicated offset from the origin amounts to about 8 penetration units for both the kinematic and absolute viscosity data plots. The obvious import of such offsets is that when, as here, it is known that a curve expressing the relationship between two variables should theoretically pass thru the origin, the extent to which a regression plot displays statistically significant intercepts provides a measure of some bias in the sampling and testing process employed to determine the values of the variables. Accordingly, to determine if the offsets from the origin shown in Figure 32 represent a real effect and, if so, their possible maximum and minimum values, a statistical determination of the confidence limits for the intercepts⁽¹⁵⁾ was made. This analysis indicated that the intercepts are real and that the

FIGURE 32: RELATIONSHIP OF DRUM MIX PENETRATION. AND VISCOSITY CHANGES



penetration intercepts for both regression lines lie between 6 and 10 units at the 95% confidence level. This suggests that even if no real change in consistency occurs during processing, 95% of our penetration results would erroneously indicate a gain (softening) of 6-10 units. In other words, it appears that our assessments of the amount of hardening occurring on processing using penetration data generally represent consistent underestimates. Alternatively, of course, since the regression plots of Figure 32 also intercept the viscosity axis, it could be that the apparent sampling/testing error is associated with the viscosity rather than the penetration results.

Which -- if indeed either -- of the above hypotheses are correct? That is, is the significant departure from the expected (theoretical) configuration for the regression line of Figure 32 indicative of a consistent bias or rather, are such departures indicative of an overall pattern of testing variability and thus, generally unreliable data? If there is indeed a consistent bias, the data would merely require an appropriate adjustment to be brought into accord and analyzed. For example, if one accepts that the penetration results are truly in error, a reasonable general estimate of the true average change in penetration of the asphalt can be made merely by subtracting the penetration axis intercept from the observed penetration change. If this is done, our estimate of the true effect of processing on the recovered penetration is changed from an average gain of 4 units to a loss of 4 units.

While the question of the reliability of the New Jersey Department of Transportation's consistency testing will be addressed specifically in the following subsection, to this point, it does not appear that the second hypothesis posed earlier (i.e., the apparent anomaly between the viscosity and penetration results generally reflects unreliable data) is true. In the writer's view, the fact that the present data set possesses the type of overall internal agreement expected of consistency results in general and displays expected types of trends (i.e., increased hardening with increased discharge temperature) suggests that while our assessment of the true consistency change may be imprecise, it is not unreliable.

4.5.3 Consistency of Conventionally Processed Asphalt and a Note on Test Reliability: While the New Jersey Department of Transportation has available a considerable body of penetration and viscosity results made in connection with routine control testing, such historical data are generally not useful in the context of this report. That is, such results predominantly represent tests exclusively on original asphalt, obviously precluding assessment of changes occurring on processing. Further, they are typically characterized by a limited number of replicates, thus generally negating the possibility for determining the repeatability aspect of test reliability. Fortunately, for purposes of determining the relative effect of dryer-drum processing on asphalt consistency,

a reasonably large sample of comparative consistency results from conventional plants has been obtained in connection with the Department's ongoing efforts in the area of surge-storage silo evaluations. In such silo evaluations, differences in temperature and consistency between the as-produced and as-stored material provide one basis for judging the adequacy of particular storage units. Here, the as-produced (pugmill) mixture samples -- which are specially cooled and stored in the same manner as the research samples -- provide a basis of comparison to the drum discharge consistency results.

By combining surge silo consistency data from a previous research study with results furnished by operations personnel, it was possible to initially compile a sample of the desired type of results (mix discharge temperature and before-after asphalt consistency) amounting to tests on 55 recovery samples obtained during 11 days of plant production. However, based on a statistical test similar to that applied to certain of the Sportsplex data (i.e., a 3 σ outlier test for results not conforming to a general temperature - consistency relationship), one entire days testing (7 samples) and two individual samples from other days work were omitted from consideration as being non-representative of the historical sample as a whole. Consequently, the net sample of representative results analysed here amounts to tests on 45 samples obtained for 10 days production at 8 conventional plants. This historical sample -- obtained during the period 1973 thru 1977 -- is thus of nearly

identical size to that from the research project (45 versus 46 samples).

Before proceeding to a specific discussion of the historical data from conventional plants (Table 20), it is worth noting that while it is not possible after-the-fact to determine the true reason for the above-noted non-representative nature of one day's tests, a likely reason can be stated. Specifically, it is believed that the subject anomalous recovery data -- which indicated apparent softening amounting to an average of 10 and 20 percent in the case of the penetration and viscosity results, respectively -- was due to incomplete removal of the Abson recovery solvent. In one other New Jersey Department of Transportation surge silo evaluation, a similar indication of an apparent inordinant softening of the asphalt for several individual samples was attributed to this same cause.

Returning to the analysis, there are three major points of interest in connection with the conventional plant data summarized in Table 20. First, it is evident that the conventional plant results in several instances display the same type of anomaly observed in the dryer-drum results: Apparent softening of the processed asphalt based on the indicated penetration change, as contrasted to indicated hardening based on viscosity changes for the same materials. Specifically, while each of the ten days viscosity results indicate some degree of overall hardening (average viscosity gain), three days penetrations results indicated either no change

TABLE 20: CONSISTENCY OF ASPHALT PROCESSED THROUGH
NEW JERSEY CONVENTIONAL BITUMINOUS PLANTS

[Sample: 45 Recovery Samples Tested During 10 Days at 8 Plants]

TEST	AS-SUPPLIED CONSISTENCY		AS-PROCESSED CONSISTENCY		Δ : CHANGE IN CONSISTENCY (Recovered less original)				
	Range of Daily Values*	Average	Weighted Average	Within- Day σ	Number of Days Results Indicating Hardening	Range of Daily Averages	Weighted Average		Day-to- Day σ
							Units	Percent	
Penetration	64 - 96	77	72	7.0	7 of 10	-15 to +10	-5	6.5%	8.0
Absolute Viscosity	1198 - 2017	1977	2296	416	All	80 to 1466	319	16.1%	410
Kinematic Viscosity	358 - 499	416	474	26	All	10 to 145	58	13.9%	37

* All represent single test result.

or an average gain in penetration (softening). As will subsequently be shown, the reason for this disparity definitely appears to be that suggested earlier in the analysis of the Sportsplex data set: A consistent bias in the New Jersey Department of Transportation penetration data in favor of underestimates of the apparent true amount of hardening. Importantly, while less definitively established, such subsequent analyses suggest that assessments of consistency change made using our viscosity data are generally reasonable (if not "correct").

The second major point of interest in connection with Table 20 is the relative magnitude of the indicated consistency change. On an overall basis, the average consistency changes observed for the present sample of New Jersey's conventional plants (i.e., 5% penetration loss; about 15% viscosity gain), are less than that reported as being "typical" in other states. For example, California ⁽¹⁶⁾ notes that the loss of volatiles and/or oxidation of the asphalt in a conventional plant can be expected to result in Abson recovery residues approximately 30 to 40 percent harder than the original*. However, it is apparent from the range column of Table 20 that certain of the daily average changes observed at particular New Jersey plants exceed this value. By implication then, at least some of the consistency

*In the cited report, the comparison was made in the context of a discussion of results for drum-mix samples which had been preserved with dry ice. It thus would appear that the author was referring to similarly cooled and stored samples from a conventional plant. Since some of the "typical" consistency changes for conventional plants reported in the literature are from samples not so treated, they are not particularly meaningful as regards the effect of processing per se.

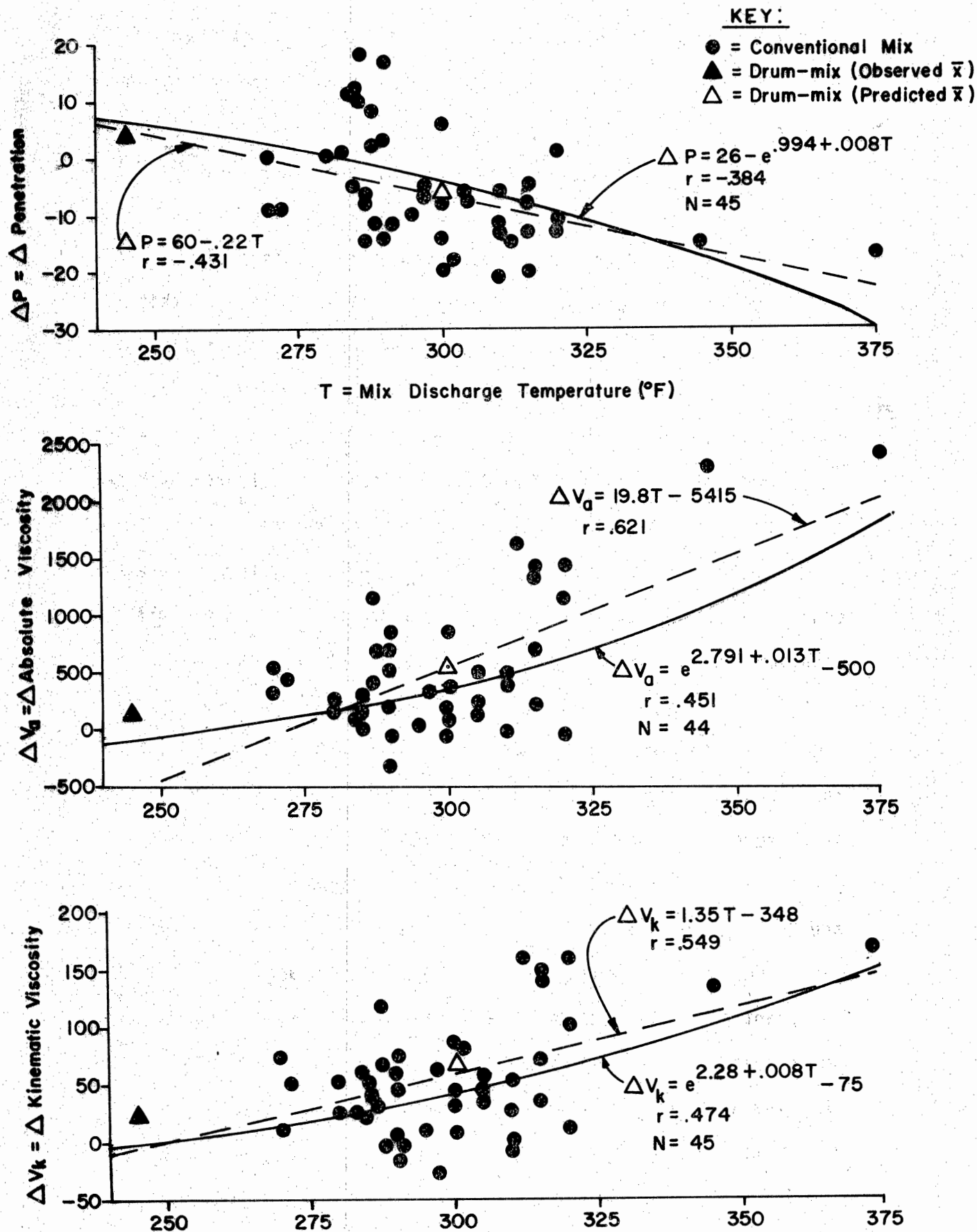
changes observed at New Jersey plants are in the typical range observed by others.

The third point of significance regarding to the conventional plant historical data is the considerable variability of the daily mean changes in consistency. That is, the range and standard deviation statistics for each of the various measures of consistency change indicate that the observed average values are very much "general" values, about which individual values are widely scattered. For example, in the case of absolute viscosity, the standard deviation statistic suggests that if many days of conventional plant testing were undertaken by the New Jersey Department of Transportation, the average daily viscosity gain observed at some plants might be as much as four times greater than the average shown in Table 20 (indicating up to 60% hardening), whereas the results at other plants might occasionally be indicative of an overall decrease in viscosity.

To determine whether the described substantial variability in the historical plant sample is indicative of generally erratic (unreliable) data or whether -- as in the case of the research sample -- these fluctuations might at least in part be a reflection of an assignable cause such as mix discharge temperature, a correlation analysis was performed. The results of a temperature - consistency analysis for the conventionally processed asphalt are presented in Figure 33.

Before proceeding to a specific discussion of the meaning of the regression plots of Figure 33, it might be well to characterize

FIGURE 33: INFLUENCE OF MIX DISCHARGE TEMPERATURE ON CONSISTENCY OF CONVENTIONALLY PROCESSED ASPHALT



their significance in general terms. Basically, each of the regression lines shown relating the various measures of consistency change and mix discharge temperature are indicative of a highly significant relationship (99% or higher confidence level) between these two variables. However, as is the case of the derived Sportsplex relationships, each line is characterized more by its ability to depict trends than to predict individual future values. In this connection, it is important to note that the scatter about the best-fit lines for the conventional plant data are to some extent due to material differences among the asphalt samples, which differences are unfortunately not quantifiable. That is, since the conventional plant data presents asphalts from a variety of sources, some of which certainly might be expected to have individual temperature - consistency relations which are truly different from the overall relationships shown, one could reasonably expect a reduction in scatter (increased predicting ability) were it possible to account for such differences. At bottom then, what Figure 33 shows is that mix discharge temperature is in fact an assignable cause for at least some of the previously discussed within-day and day-to-day variability in the conventional plant consistency results. Further, and more importantly as regards a key question of this research, since the consistency results for conventional plants and the drum-mix plant are a function of the same assignable cause (temperature), it is possible to put the results on the same temperature-equalized basis so as to permit direct comparisons of the relative effect of the two processes.

As shown in Figure 33, for each of the various tests of asphalt consistency, two different regressions were performed: one, a conventional straight-line best-fit; the second, a logarithmic curve fit. While the statistical parameters for each of these curves is indicative of a highly significant relationship, the correlation coefficient for each of the straight-line fits are higher than those for their companion logarithmic curves. Under most circumstances, given this choice between alternate curve fits, the one with the higher correlation coefficient would normally be selected as most representative of the "true" relation. Here, however, there are two common-sense reasons for choosing the lower correlation coefficient (logarithmic) curves as being most representative. First, since consistency is known to generally be a logarithmic function of temperature, it seems reasonable to assume that differences in consistency should be similarly related. Secondly, it is generally apparent that certain of the information conveyed by the straight-line fits cannot be indicative of a real situation. Specifically, a reduction in mix discharge temperature, per se, clearly will not cause softening of the asphalt (i.e., cause a negative viscosity intercept). Rather, certainly in the ideal case, consistency change should be asymptotic to zero in the zone of low mix discharge temperatures as indicated by log curves.

Having stated some generalities regarding the regression lines of Figure 33, the question now is what specific information do these plots convey? First, and most basically, within-plant and plant-to-

plant differences in mix discharge temperature account in part for the variations in the associated consistency changes occurring on processing. For example, the regression line for absolute viscosity change suggests that while many New Jersey Department of Transportation tests at a conventional plant operating at the low end of the usual temperature spectrum (270°F) would indicate essentially no average hardening, this same plant operating at the usual upper end of the temperature range (320°F) would be expected to harden the asphalt by nearly 30% (about 545 poises, $1\frac{3}{4}$ times overall sample mean). The penetration and kinematic viscosity regressions indicate a similar result for this same range of temperatures. Specifically, these measures would change from a very modest value to a value indicating about $4\frac{1}{2}$ times more hardening.

The second point of interest in connection with Figure 33, briefly noted earlier, is that the same apparent bias towards erroneously high penetration gains in the Sportsplex sample is also generally evident in the conventional plant sample. It thus appears that this bias is a characteristic deficiency of New Jersey Department of Transportation penetration data in general.

The feature of the regression curves which suggests the presence of a consistent error in the penetration assessments is the generally different characteristics of the viscosity and penetration curves in the range of lower mix discharge temperatures. That is, while the best-fit for each of the viscosity plots is nearly asymptotic to zero (indicating little or no average hardening for

lower temperature mixes), the penetration regression appears asymptotic to some positive offset from zero, indicating a general bias toward apparent penetration gains (softening) for low temperature mix. Significantly, the approximate magnitude of this bias as indicated by the penetration regression of Figure 33 is quite similar to that indicated by earlier analyses of the Sportsplex data set. In particular, the derived relationships of Figure 33 indicate that when there has been no change in the absolute or kinematic viscosity of the conventionally processed asphalt, the penetration data would indicate an average net gain (softening) of 5 and 8 units, respectively, or very nearly the same as the 8 ± 2 units previously shown for the drum-mix data in Figure 32.

The third, and perhaps most important point in connection with Figure 33 is that it indicates that the influence of mix discharge temperature on the consistency of the processed asphalt is very similar in the case of both the studied (low temperature) drum-mix and conventionally produced (high temperature) mixtures. In particular, using the best-fit relationships of Figure 33 to predict the average consistency changes expected for the 245°F average discharge temperature at the Sportsplex yields values quite close to the averages actually observed, the observed values being indicative of only about 3 to 5 percent more hardening than predicted. Similarly, use of the temperature-consistency regressions developed for the Sportsplex data (Figure 31 and Table 19, shown previously) to predict the average consistency change expected for the 300°F

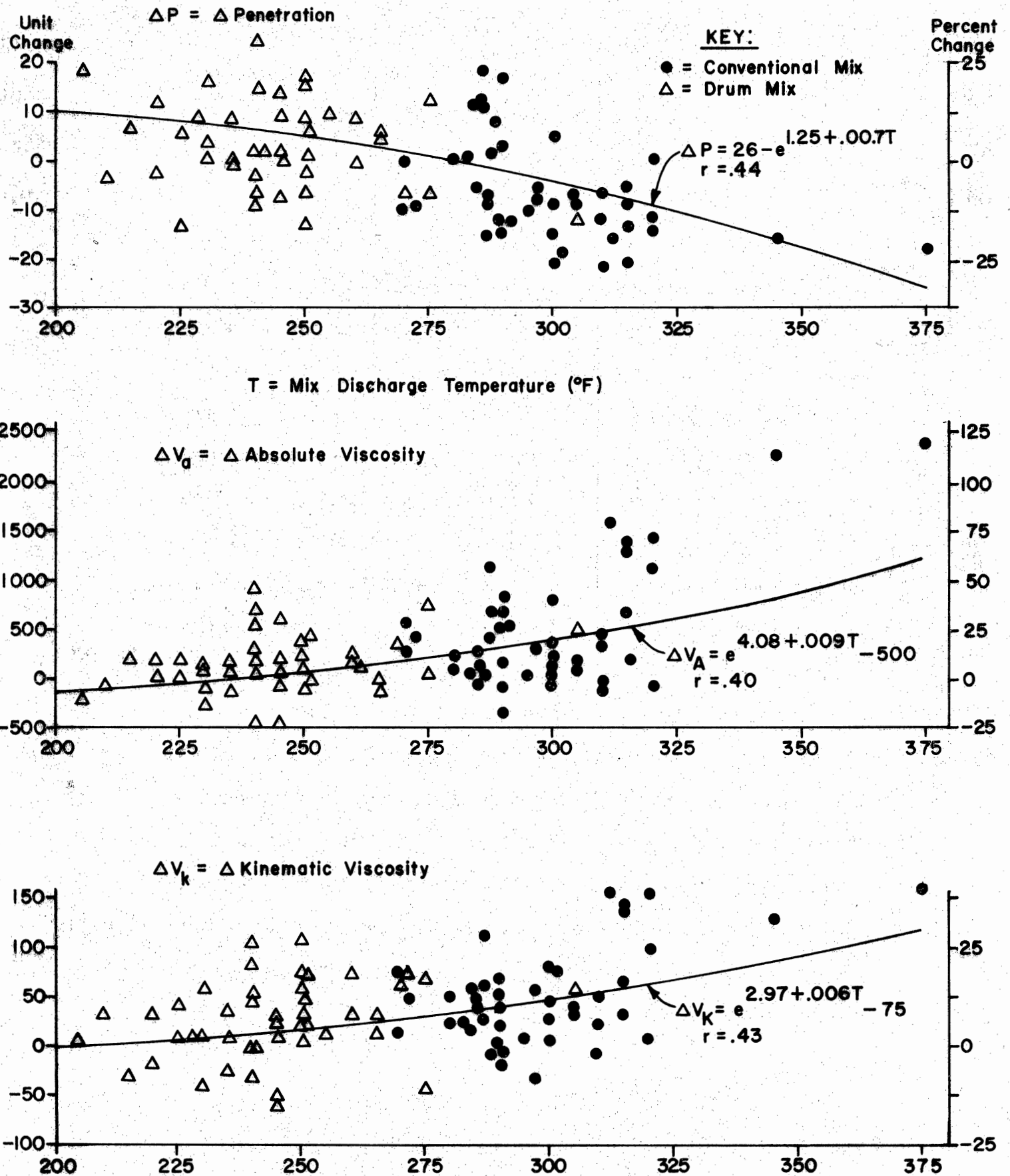
average discharge temperature for the conventional plant sample yields values which are not significantly different from those actually observed. Considering that the temperature-consistency relationships for the research and conventional plant samples are each very much only "trend lines", the observed good general agreement between the various predicted and observed values is quite remarkable.

In the writer's opinion, the above analyses provide a basis for two conclusions, one of particular significance as regards this research, and one of more general interest. First, since the predicted-observed consistency change comparisons indicate that the difference between the overall degree of hardening observed at the Sportsplex and that in the conventional plant sample are substantially (if not completely) attributable to the marked (55°F) difference in average discharge temperatures, the answer to the key research question -- is drum-mixing relatively more harmful to the asphalt than conventional processing -- seems inescapable: No. Rather, the preceding analyses indicate that if the Sportsplex drum-mix had been produced to discharge at conventional temperatures, the observed asphalt consistency change could reasonably be expected to be of the same magnitude as that from a batch plant operated at the same temperature. Secondly, as a matter of more general interest, the fact that the individual regressions for low and high temperature mixes definitely appear related (i.e., yield reasonable estimates of the expected average consistency change for

higher and lower temperatures, respectively) suggests that the best overall indication of the influence of mix discharge temperature on New Jersey consistency data may be had by combining the two data sets. The results of such a combination are depicted in Figure 34.

While the overall temperature-consistency regressions of Figure 34 are useful for a number of purposes (e.g., in providing at least some yardstick for gauging the reasonableness of future surge-silo consistency data), in the present context, perhaps their greatest utility is that they permit some further inferences to be made as to the general reliability of the present collection of New Jersey Department of Transportation consistency data. That is, returning to a point discussed earlier, the fact that for the extremely wide spectrum of discharge temperatures shown in Figure 34 the viscosity data generally display an expected type of overall behavior (being asymptotic to zero or nearly so) suggests to the writer that such data is indeed basically "reasonable". At a minimum, this characteristic of the viscosity plots would appear to rule out previous occasional observations of incomplete solvent removal as being a general deficiency. If such were the case, it seems reasonable to assume that at some point, the viscosity data would reflect this artificially induced softening by manifesting a significant "dip" below the origin (i.e., a generalized indication of viscosity loss).

**FIGURE 34: ASPHALT CONSISTENCY CHANGES FOR
LOW AND HIGH MIX DISCHARGE TEMPERATURES**



Given the fact that consistency test data provides a basis for many important decisions, it is evident that this Department should undertake a study in considerably more depth than possible here so as to determine whether the remedial measures undertaken to improve our consistency testing have in fact been effective, particularly as regards our penetration results.

4.5.4 Thin-Film Oven Tests: Each of the 14 samples of the as-supplied AC-20 was subjected to two types of thin-film oven (TFO) tests. The first of these followed the standard AASHTO procedure (conditioning at 325⁰F for five hours), while in the second procedure, the oven was maintained at 250⁰F. The purpose of the latter temperature modification was to provide a possibly better estimate of the amount of hardening which the studied asphalt might undergo if processed thru a plant operated to discharge mix at the relatively low temperatures employed at the Sportsplex (average: 245⁰F).

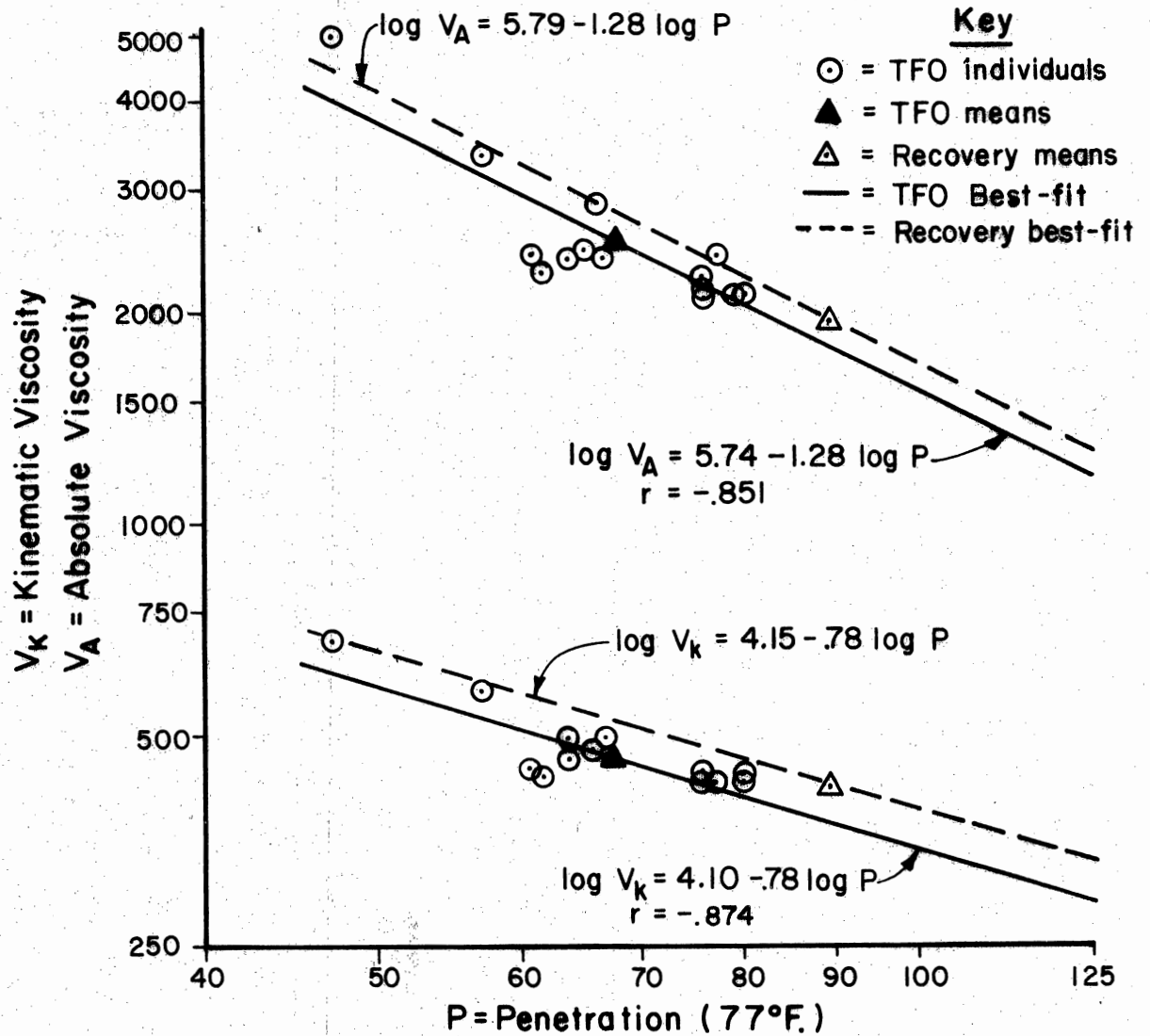
In brief, the principal significance of the thin-film oven work is that certain of the data (the 250⁰ results) strongly suggest the probable basic cause for the previously discussed characteristic penetration-viscosity anomaly of New Jersey Department of Transportation data (i.e., erroneous penetration gains). Specifically, it appears that our general underestimate of hardening based on penetration results accrues from the application of the Abson recovery technique, as contrasted to some general bias or error in the New Jersey Department of Transportation's penetration testing

procedure per se. (Note that the problem of correctly applying the Abson procedure in general is distinguishable from the earlier discussed specific problem of incomplete solvent removal.) Unfortunately, since the writer can offer no suggestion as to the particular aspect of the recovery procedure which causes the problem, the remainder of this subsection will generally be limited to a discussion of the existence and apparent magnitude of the effect. This being the case, the basic usefulness of the present collection of TF0 data is that it suggests a possible fertile area for further investigation in some future, in-depth study of the reliability of New Jersey Department of Transportation asphalt consistency sampling/testing.

The results of regression analyses designed to determine the relationship between the individual penetration and viscosity results for the low-temperature TF0 testing of the Sportsplex asphalt are presented in Figure 35. For purposes of comparison, the best-fit lines resulting from similar analyses of the Sportsplex recovery samples (previously shown in Figure 30) are also presented.

Examination of Figure 35 reveals that the best-fit lines relating the consistency results for the TF0 samples (which, of course, are not subjected to the Abson recovery process) display near-identical slope to the companion regression lines for the mixture recovery samples, but different (higher) means and (lower) intercepts.

**FIGURE 35: PENETRATION - VISCOSITY RELATIONSHIPS FOR
PROCESSED DRUM-MIX ASPHALT AND
THIN-FILM OVEN RESIDUE.**



The obvious message conveyed by the difference in means is that estimates of the amount of hardening based on laboratory conditioning of a sample at 250 degrees does not (or at least, did not) simulate the actual level of hardening for drum-mix asphalt discharged at about this same average temperature. In particular, the TFO results exceed the observed average amount of hardening by about 30% in the case of the penetration and absolute viscosity tests and by about 12% in the case of kinematic viscosity.

What significance (if any) should be attributed to this average difference between the TFO and field results? One interpretation, grounded on the proposition that the TFO test is indeed a reliable indicator of the actual amount of hardening that takes place in a conventional plant, is that compared to a conventional plant the studied drum-mix unit was significantly beneficial as regards premature hardening. However, it is here concluded that an alternate explanation is correct: Simply, the TFO results represent an overestimate of actual hardening. The basis for this conclusion is the earlier analysis of temperature-consistency relationships (Figure 34) which indicated that -- for a given discharge temperature -- no significant detrimental or beneficial effect would accrue from drum-mixing. In any event, the observation that TFO data at least occasionally represents an overestimate of actual amount of hardening occurring on processing is certainly not an uncommon one. For example, comparison of TFO

consistency data to that from (frozen) recovery samples obtained directly from the pugmill at six New Jersey conventional plants indicates that the laboratory (TF0) estimates of hardening based on absolute viscosity exceeded the actual level by an average of 53 percent.

The more important point in connection with Figure 35 is the difference in intercepts as between the penetration-viscosity regressions for the TF0 and recovery samples, which differences manifest as an apparent "offset" between the companion best-fit lines.

The significance of this feature of the regression lines is that, in contrast to the remarkably similar overall relationship between the recovery and non-recovery data classes (i.e., their near-identical slope), the specific correspondence between penetration and viscosity is distinctly different for the two classes of data. That is, for a given viscosity value observed in TF0 and recovery samples, the corresponding penetration value in the recovery samples is consistently higher (indicating softer asphalt) than that associated with the TF0 value. Since the fundamental difference between the two data sets is the application of the Abson technique, the clear implication is that the apparent general increase in penetration for the recovery samples is in fact attributable to this difference in treatment. While there are, of course, alternative explanations for the subject differences (e.g., the TF0 or viscosity data might be generally incorrect,

rather than the recovery or penetration results), since the present analysis is not performed in a vacuum, these alternatives definitely appear rejectable. Simply, the previously discussed underestimates of true penetration change appear to be due to a bias introduced by the Abson technique.

While the companion best-fit lines of Figure 35 are offset by a constant distance, it is evident that due to the logarithmic nature of the relationships, this constant difference does not equate as a constant apparent error in the recovered penetration values for varying viscosities (i.e., difference from the corresponding TF0 penetration). However, for "typical" ranges of absolute and kinematic viscosities expected in recovery samples ($V_A = 2000 - 3000$, $V_K = 400 - 500$), these penetration differences are relatively constant at about 8 and 11 units for the respective viscosity tests. The reader will recall that these estimates of the apparent bias in the level of recovered penetrations are quite similar to the previously described estimated errors in penetration change for the drum-mix and conventional plant data sets (6-10 and 5-8 units, respectively).

The key question at this point obviously is whether the described regression line offsets and the associated apparent general error in the recovered penetrations are in fact real (statistically significant). While the statistical analyses required to make this determination are something less than completely straightforward, the short answer to this question definitely appears to be "yes".

Two statistical approximations were employed to assess the different offsets. In the first of these, the assumption was made that the companion lines were truly parallel. The virtually identical slope of the line pairs suggests that this assumption is reasonable. Once this assumption was made, a significance test was made which involved comparing ordinates at a penetration value (78 units) near the overall mean of the TFO and recovery curves. This produced t-statistics which indicated that the separations for both pairs of lines were statistically significant well above the 95% confidence level. To check this first approach, another method was employed which utilized the residuals about the lines. Here again, the separations between the lines were indicated to be highly significant.

The results of the conventional (325⁰) TFO testing performed in this work provided little of significance. As expected, such results -- which supposedly approximate the level of hardening at an average discharge temperature of 300⁰ -- very much overestimated the observed hardening at the (245⁰) drum-mix plant. Further, the poor fit between the collected penetration and (absolute) viscosity data precluded meaningful comparisons to the other classes of data.

4.6 ASPHALT HARDENING: SPECIAL CHEMICAL TESTS

4.6.1 Nature and General Significance of the Testing: In order to provide an alternate basis for ascertaining the nature of any changes in the asphalt which occur on drum-mixing, a rather modest program of chemical testing was undertaken. This work involved comparisons of compositional change among drum-mix, batch plant and TFO samples.

The chemical separation technique employed -- the Rostler-Sternberg procedure^(18,19) -- has been known for nearly thirty years. However, while asphalt producers and using agencies have long employed a variety of fractionating techniques to "fingerprint" asphalt for purposes of production control and performance evaluation, this research represents the first use of any such procedure by the New Jersey Department of Transportation.

In brief, a Rostler-Sternberg analysis is a multi-step procedure entailing use of pentane and sulfuric acid to separate the exceedingly complex structure of an asphalt into five generic groups: asphaltenes (A), nitrogen bases or polar compounds (N), first acidaffins (A_1), second acidaffins (A_2) and paraffins (P). The latter four groups of constituents are collectively known as "maltenes". Broadly speaking, the asphaltenes are solid components predominantly responsible for the consistency of the asphalt, while the maltenes collectively serve to plasticize the asphaltenes and provide a homogeneous blend.

While a determination of the chemical make-up of an asphalt is useful in resolving a wide range of performance related questions, in the present research, the scope of the inquiry is relatively limited. That is, here we are basically concerned with only two issues: First, "What is the general nature and magnitude of chemical change expected during conventional processing?" and, second, "Are the observed compositional changes occurring on drum-mixing indicative of some detrimental effect?" The remainder of this introductory subsection will consist of a capsule summary of the background on the first of these questions (expected chemical changes) and the implications for associated changes in more familiar physical properties such as penetration and viscosity.

A literature review indicates that, at least in the particular case of the Rostler analysis, researchers have generally concentrated their investigative efforts on in-service (versus as-mixed) changes in asphalt composition. Consequently, while the mechanism (or at least, direction) of chemical change occurring on processing is reasonably well-defined, the magnitude of such change is apparently not definitively established.

The literature reports describing the mechanism of chemical change have variously entailed applications of the Rostler technique or other separation procedures to bituminous materials processed through a pugmill or simulated pugmill and to recovery samples from in-service pavements⁽²⁰⁻²⁵⁾. The cited literature

identifies the following broad trends: The paraffins undergo little or no change from their original levels, acidaffins convert in part to nitrogen bases, and a portion of the nitrogen bases convert to asphaltenes. Overall then, except for the paraffins, the maltenes level generally decreases, while the asphaltenes increase. As might be expected, the changes exhibited by particular asphalts have been observed to depart from this general pattern. The chemical fraction reported to display the greatest mix of net gains and losses is the nitrogen bases.

As a matter of general interest, certain of the cited studies indicate that while the vast majority of the asphalt in a finished pavement (i.e., that below the top 1/8") changes but little from its as-mixed/as-laid state*, due to exposure differences, the topmost portion may undergo marked relative changes in chemical composition and associated physical properties.

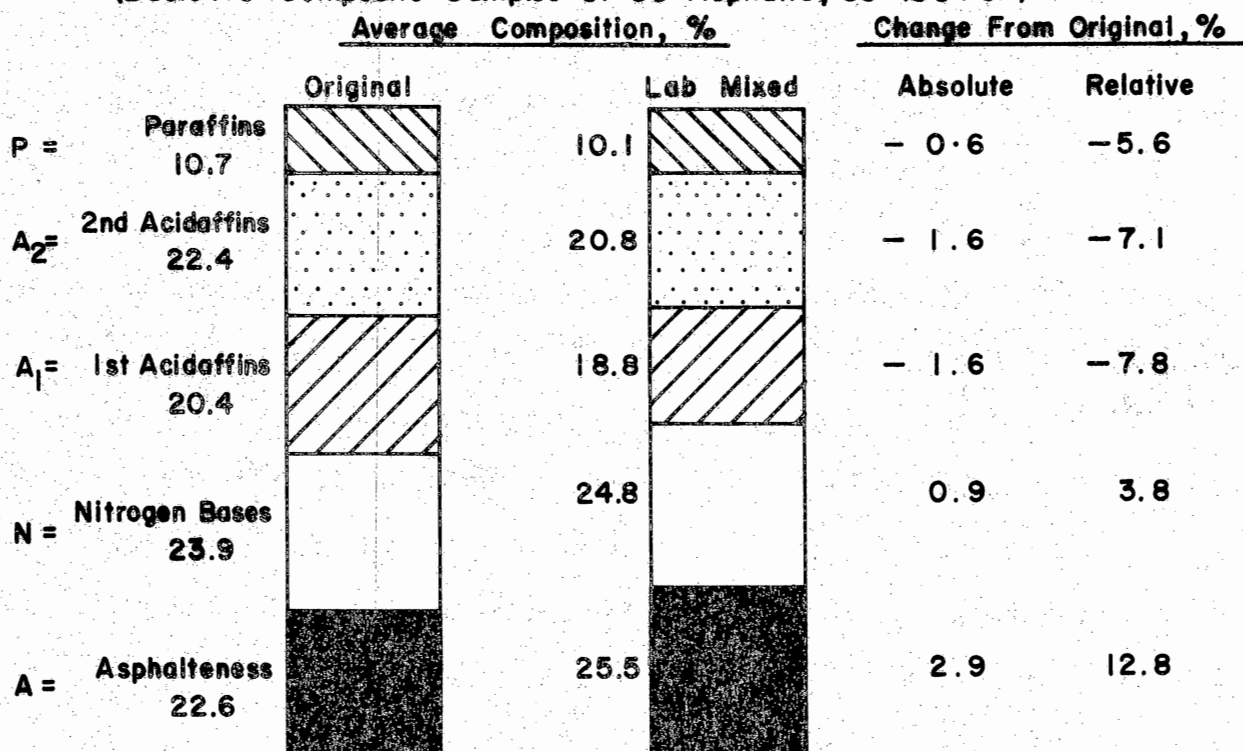
Having described the general nature of compositional change observed by others, the block diagrams of Figure 36 are presented to illustrate the magnitude of such change occurring on processing. While this figure will be commented on later in connection with the New Jersey results, in view of certain of the obvious differences between the two diagrams, a comment at this point is necessary.

*One implication of this finding is that mechanisms of chemical change postulated from in-service changes may (as here) be used to support conclusions regarding the nature of changes occurring on processing.

FIGURE 36: CHANGE IN CHEMICAL COMPOSITION OCCURRING ON PROCESSING: LITERATURE REPORTS

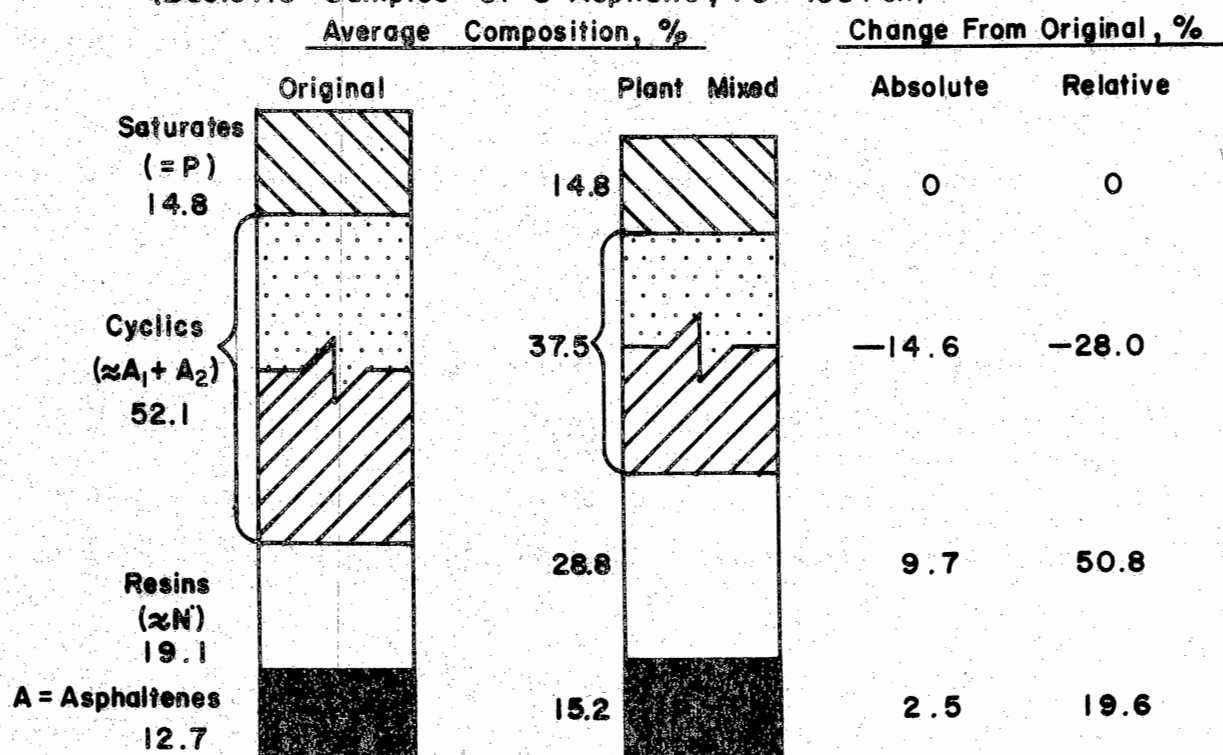
A. Holstead, Rostler, And White (Ref. 20)

(Basis: 5 Composite Samples Of 88 Asphalts, 85-100 Pen)



B. Chipperfield, Duthie, And Girdler (Ref. 22)

(Basis: 16 Samples Of 8 Asphalts, 70 - 100 Pen)



As indicated in Figure 36A, the compositional changes observed by Halstead et al were based on simulated pugmill mixing (325°F for 6 minutes). Since the application of this laboratory procedure yielded results which agreed with TFO testing, the cited authors concluded that the laboratory procedure indeed approximated the effect of mixing in a commercial hot-mix plant. The work of Chipperfield et al (Figure 36B), while based on actual plant mixing, used a different chemical separation technique. Although the resulting data compare favorably in the case of the asphaltenes and paraffins, Chipperfield observed substantially greater average changes for the chemical fractions analogous to the intermediate maltenes. Considering the well-known fact that different asphalt separation techniques or solvents can yield different boundaries for certain of the various hydrocarbon classes⁽²⁷⁾, the latter compositional differences may be due at least in part to the difference in the fractioning process. In any event, inasmuch as the present research employed the Rostler procedure, it seems evident that in comparing New Jersey results to those of others, primary reliance should be placed on the work where this same separation technique was employed (i.e., Figure 36A).

A multitude of observed correlations between asphalt chemistry and physical properties address the question of the significance of changes in chemical composition (see, e.g., reference 28). For the present introductory purpose, it is useful to reach behind those correlations and examine their fundamental

basis. Work by Corbett⁽²⁶⁾, involving a determination of the physical properties of the various individual fractions making up the asphalt blend, provides considerable insight on this point.

In the cited work, a fractionating technique different from the Rostler procedure was employed. (Indeed, since certain of the Rostler fractions are obtained as a precipitation reaction product, they are not available for further, separate investigation.) Again then, there is a potential for different boundaries for certain of the (maltene) hydrocarbon classes and their associated properties. However, since certain of the fractions isolated (asphaltenes) are the same and the others are at least similar between the Corbett and Rostler procedures, the latter's findings are useful for the present broad illustrative purposes.

Corbett observed that the chemical fractions analogous to paraffins and total acidaffins each displayed essentially unlimited penetration (300^{+} at 77°F) and absolute and kinematic viscosities whose values were in the units and tens places, respectively. In marked contrast, the separated asphaltenes displayed zero penetration and viscosity so extremely high as to be immeasurable with conventional tools. A chemical fraction apparently similar to Rostler's nitrogen bases displayed hardness only somewhat less pronounced than that of the asphaltenes. At a minimum then, Corbett's work confirms in rather dramatic fashion that the conversion of maltenes into asphaltenes expected on processing is indeed the root cause of increased hardening.

4.6.2 Comparative Compositional Changes for New Jersey Conventional and Drum-Mix Plants: In this study, the chemical composition of the processed drum-mix was based on replicate Rostler separations performed on composite recovery samples from each of three production days. These composite samples consisted of the combined Abson residue from two or three individual mixture recovery samples obtained within the particular day. Such combined samples were required since the individual samples provided insufficient material for the chemical fractionating. For each of these production days, the composition of the as-supplied asphalt was gauged by replicate Rostler determinations performed on one tank sample.

To provide a basis of comparison for the dryer-drum results, a similar program of chemical analysis was undertaken for samples from four New Jersey conventional plants and on residue from TFO testing of the Sportsplex asphalt. The conventional plant chemical testing consisted of replicate Rostler separations on one tank and recovery sample from each plant. The composition of the TFO residue was based on tests on two Sportsplex tank samples.

The average composition and change in composition observed for the conventional and drum-mix samples are shown in Figure 37. Comparative data for the TFO samples are shown in Figure 38.

Shown beneath each of the composition block diagrams of Figures 37 and 38 are the average consistency test results for the particular sample depicted. It is important to note that the sampling and testing of the conventional plant mixtures performed

FIGURE 37. COMPARISON OF CHANGES IN CHEMICAL COMPOSITION OCCURRING ON CONVENTIONAL PROCESSING AND DRUM-MIXING

A. New Jersey Conventional Plants

(Basis: Duplicate Determinations, Four Plants)

Average Composition, %		Change From Original, %	
Original	As - Mixed	Absolute	Relative
P = 12.1	11.9	-0.2	-1.6
A ₂ = 20.1	19.6	-0.5	-2.5
A ₁ = 24.3	24.6	0.3	1.2
N = 19.8	18.7	-1.1	-5.6
A = 23.7	25.2	1.5	6.3
Pen = 77	63	-14	-18.2
Consistency ($\bar{X}$ and Δ) V _A = 1974 V _K = 475	3078 *	1104	55.9
	583 *	108	22.7

*(No Test For One Sample)

B. Sportsplex Dryer-Drum Plant

(Basis: Duplicate Determinations, Three Production Days)

Average Composition, %		Change From Original, %	
Original	As - Mixed	Absolute	Relative
P = 15.3	15.1	-0.2	-1.3
A ₂ = 22.4	21.6	-0.8	-3.6
A ₁ = 21.6	21.4	-0.2	-0.9
N = 21.7	22.0	0.3	1.4
A = 19.1	20.0	0.9	4.7
Pen = 88	89	1	1.1
Consistency ($\bar{X}$ and Δ) V _A = 1749 V _K = 403	1855	106	6.1
	426	23	5.7

FIGURE 38 : CHANGE IN CHEMICAL COMPOSITION OCCURRING ON THIN-FILM OVEN PROCESSING

(Basis : Duplicate Determinations, 2 Tank Samples)

<u>Average Composition, %</u>		<u>Change From Original, %</u>	
Original	TFO Residue	Absolute	Relative
P = 15.4	14.7	- 0.7	- 4.5
A ₂ = 21.3	22.1	0.8	3.8
A ₁ = 22.9	19.4	- 3.5	-15.3
N = 22.1	21.9	- 0.2	- 0.9
A = 18.4	21.8	3.4	18.5
Consistency: ($\bar{X}$ and Δ)	Pen = 86 V _A = 1766 V _K = 410	69 2224 438	- 17 457 28
			-19.8 25.9 6.7

in this phase of the study was accomplished after the Department had undertaken steps to improve our consistency testing procedures. These remedial measures included converting from the AASHTO Abson recovery specification to the more detailed ASTM procedure. Considering this general change in procedures -- more specifically, the possible elimination/reduction of the bias in past penetration data -- it is apparent that comparisons of consistency results between the two processes is, to say the least, a delicate task.

Examination of Figure 37 reveals that the pattern of average compositional change for the present sample of conventional and dryer-drum results is basically the same as that reported in the literature. That is, the results for both processing methods are generally characterized by a reduction in maltenes and an associated net gain in asphaltenes. The obviously more important point, however, is the rather modest magnitude of chemical change indicated to occur for either type of processing. A conventional statistical test indicates that none of the indicated average changes in individual fractions for either the conventional or dryer-drum plant represent a significant change from the original value. The fact that a statistical test fails to detect a difference in means may, of course, merely reflect a limited sampling. However, here we have two bases for making inferences regarding the influence of dryer-drum processing on asphalt chemistry. That is, not only is there no detectable difference between the average composition of the as-supplied and as-processed drum-mix asphalt, but also the

average compositional changes displayed by the drum-mix are about the same if not less (e.g., with respect to asphaltenes) than those for the average conventional product. Based on the sampling of New Jersey plants then, drum-mixing clearly does not appear to effect a change in the overall chemical make-up of an asphalt which is meaningfully different from the change expected to occur during conventional processing.

Comparison of the observed compositional changes for the Sportsplex drum-mixtures to batch plant results reported by others lends support to the above conclusion. That is, compared to the conventional plant data previously shown in Figure 36, the compositional changes displayed by the New Jersey conventional and drum-mix plants are about the same for one chemical fraction (paraffins) and generally less for the other components. In the particular case of the asphaltenes fraction -- which plays a major role in the hardness of the finished blend -- the indicated changes for the New Jersey data are only about 1/3 to 2/3 of those shown in Figure 36 (i.e., at least 1 to 1.5 percent less absolute change).

In comparison to the average compositional changes indicated for both the New Jersey and literature samples of conventionally processed asphalt, the TF0 results of Figure 38 display a relatively greater net loss from the original maltenes level and a correspondingly greater net increase in asphaltenes. Indeed, the (3.4% absolute) increase in the asphaltenes level for the TF0 residue is the only change for any of the variously processed samples studied here

which is statistically distinguishable from the original value.

The significance which one assigns to this relatively greater chemical change for the TFO samples again obviously depends on what general credence is placed in the laboratory (TFO) procedure as regards its ability to provide a valid simulation of the change actually occurring in the field mixing process. Here, the results of the chemical testing performed on the TFO residue are viewed as confirming New Jersey's past observations that the TFO conditions are generally harsher than those actually encountered in the real process and thus usually provide an overestimate* of the amount of change expected on processing.

The foregoing has indicated that the chemical makeup of asphalt processed thru the dryer-drum remains relatively unchanged from its original values and that what little change does occur is generally less than that observed for either simulated (i.e., TFO conditioned) or actual conventional mixing. Therefore, it seems reasonable to view this chemical testing as confirming the previous conclusions based on consistency testing that drum-mixing does not inherently entail any detrimental effect on the asphalt cement.

*Given the benefit of hindsight -- i.e., the good penetration-viscosity fit between the Sportsplex recovery samples and the low oven temperature TFO samples previously shown in Figure 35 -- it obviously would have been preferable to perform the chemical testing on the latter (non-standard) TFO samples.

While the fundamental question of this phase of the research is considered resolved, it is useful to at least briefly address an obvious question omitted from the preceding discussions of chemical change. Namely, given the observation that conventionally processed asphalt undergoes average changes in composition which, at face, are only slightly greater than those indicated to occur on drum-mixing, to what can the marked disparity in average consistency change for these same samples (shown in Figure 37) be attributed?

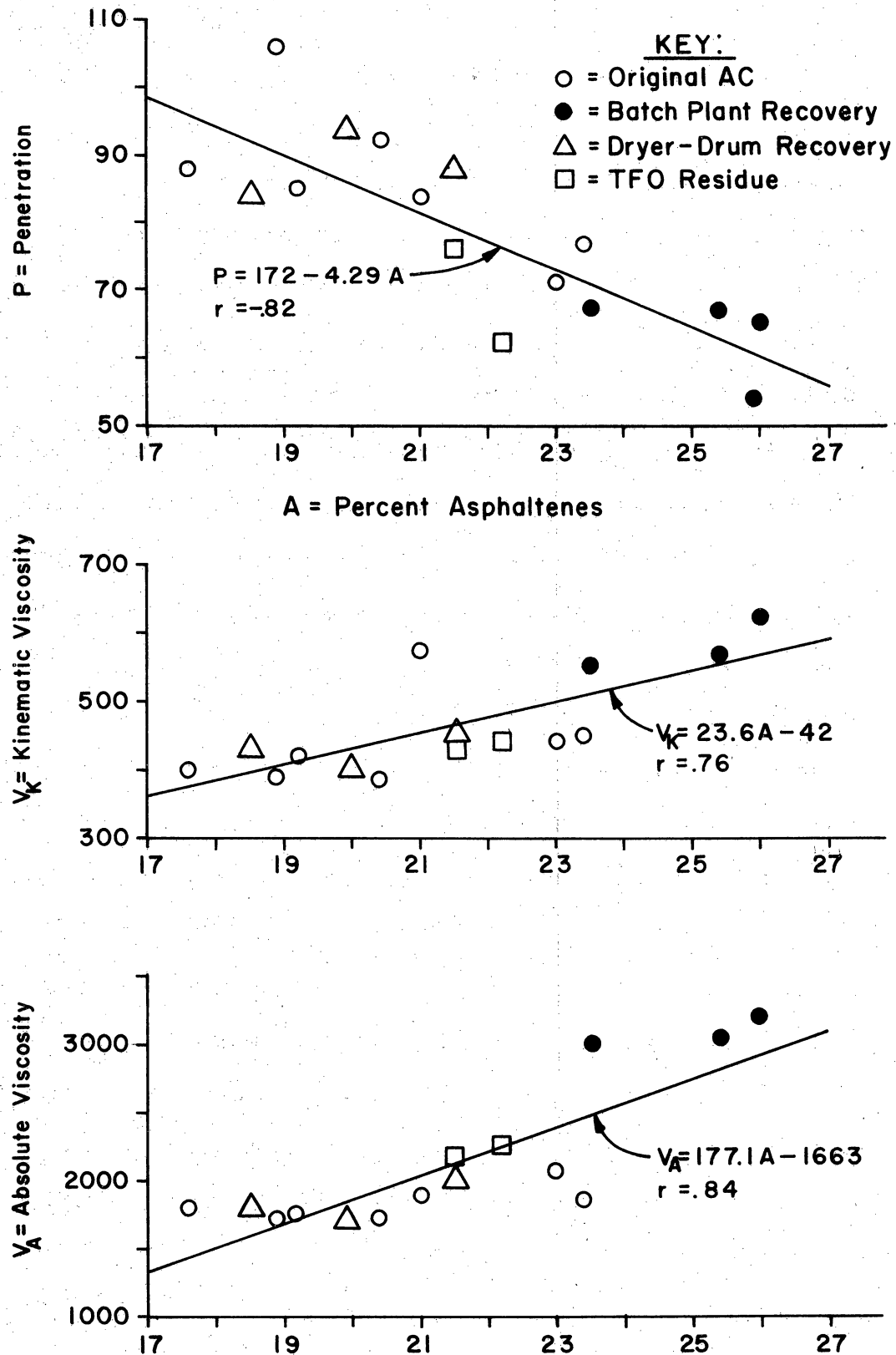
As a general proposition, the composition-consistency change anomaly evident in Figure 37 would be expected to be a function of three factors, certain of which are potentially interrelated: The chemical composition (original and processed) of the various asphalts sampled, differences in mix discharge temperature between the drum-mix and conventional plant samples, and the general change in asphalt recovery procedures.

Attempts to discover a relationship between the observed changes in particular chemical fractions and consistency proved unsuccessful. This result was undoubtedly due in part to the limited number of such comparisons possible using the present sampling. However, a number of general correlations between the level of particular chemical constituents and the physical properties of the asphalts were developed for the total sample (i.e., combined results). These gross correlations provide some insight as to the relative role that asphalt chemistry plays in

the apparent dissimilarity between the consistency and composition results of Figure 37.

For example, as shown in Figure 39, a highly significant overall relationship was found to exist between the asphaltenes content of the various asphalt samples and their consistency. In the particular case of the penetration results, a step-wise multiple regression indicates that for the present data sample, asphaltenes content is the sole significant determinant of hardness for the original and recovered samples. Specifically, the derived relationship indicates that a one percent increase in asphaltenes content can be expected to reflect as a 4 unit decrease in penetration. Since the average absolute asphaltenes content of the conventionally processed asphalt increased only 0.6 percent more during mixing than did the drum-mix, based solely on this chemical composition difference, we would expect that the conventionally processed material would harden only about 3 penetration units more than the drum-mix. As shown in Figure 37, the observed difference actually amounted to an average of 15 units; the sampled drum-mix showing a net penetration gain (softening) of one unit compared to a loss (hardening) of 14 units for the conventionally processed mix. This indication that compositional change very much provides only a partial explanation for the disparity between the penetration values observed for the data sets using the "new" and "old" Abson procedures obviously suggests that the measures undertaken to improve the Department's consistency

**FIGURE 39: RELATIONSHIP OF ASPHALT CONSISTENCY
AND ASPHALTENES CONTENT**



testing procedures may have in fact eliminated the previously discussed bias towards consistent erroneously high penetration for Abson residues. If this is indeed the case, it follows that the penetration-asphaltenes regression of Figure 39 is definitely only an estimate of the true relationship between these variables and, consequently, provides a basis for but a guess as to the magnitude of penetration change caused by the use of the new procedure.*

Use of the developed composition-consistency regression data to determine either the existence or magnitude of any possible change in the level of recovered viscosity accruing from the use of the new recovery procedure is more complex. For example, while the combined absolute viscosity data (original and processed) is significantly related to asphaltenes content, a regression analysis indicates that the absolute viscosity of the original asphalt is primarily an inverse function of paraffins content. A somewhat

*A simpler procedure for assessing the impact of the new recovery procedure would be to utilize the temperature-consistency relationships previously shown in Figure 34. Unfortunately, since the operations personnel assigned to obtain the conventional plant samples used in the chemical testing phase of the work neglected to record the requested mix discharge temperature data, the relationships of Figure 34 cannot be directly applied here.

It is interesting to note, however, that if the mix at these plants was discharged at the historical average temperature of 300°F, a difference of 4 penetration units between the drum-mix and conventional plant samples shown in Figure 37 would be expected due solely to temperature. It appears then that the indicated slightly higher asphaltenes content for the mix from conventional plants (and the associated penetration decrease) is indeed simply a reflection of relatively higher processing temperatures.

similar* effect has been observed by Utah⁽²⁴⁾. The obvious upshot of this finding is that to determine the viscosity change expected to accompany a change in asphalt chemistry, we must look to multiple chemical fractions and to both the original and recovered samples. In view of the present limited data and the availability of an alternate, more direct procedure for assessing the impact of the new recovery procedure on viscosity data (i.e., use of the relationships of Figure 34), such an exercise will not be attempted.

*In fact, based on a considerably larger sample than used here, the Utah investigators found the absolute viscosity of the as-supplied asphalt to be a function of paraffins and asphaltenes.

4.7 PAVEMENT CONSTRUCTION

4.7.1 General: The Sportsplex paving operations were observed on a number of occasions to determine if drum-mixes pose any unique construction problems. Of primary interest in this regard was the effect, if any, that the lower temperatures and higher moisture contents of the drum-mixes would have on the placement and compaction processes. Based on these observations it is concluded that the constructability of bituminous mixtures produced by the drum-mix process is essentially the same as the conventional product.

4.7.2 Compaction: Bituminous mixes for New Jersey Department of Transportation projects are generally designed at about 4 percent air voids, the center of our 2 to 6 percent design range. The design air voids for the Sportsplex surface and binder drum-mixtures were 4.0 and 4.4 percent, respectively.

The Department's current acceptance criteria for pavement density requires the average of five air voids measurements performed on pavement cores from a given (5000 $\pm$ square yard) acceptance lot be between two and eight percent. These limits were developed from research and experience and reflect consideration of the high volumes of truck traffic typically encountered on New Jersey highways.

To evaluate the compaction characteristics of the studied drum-mix, one day's production of surface coarse was monitored.

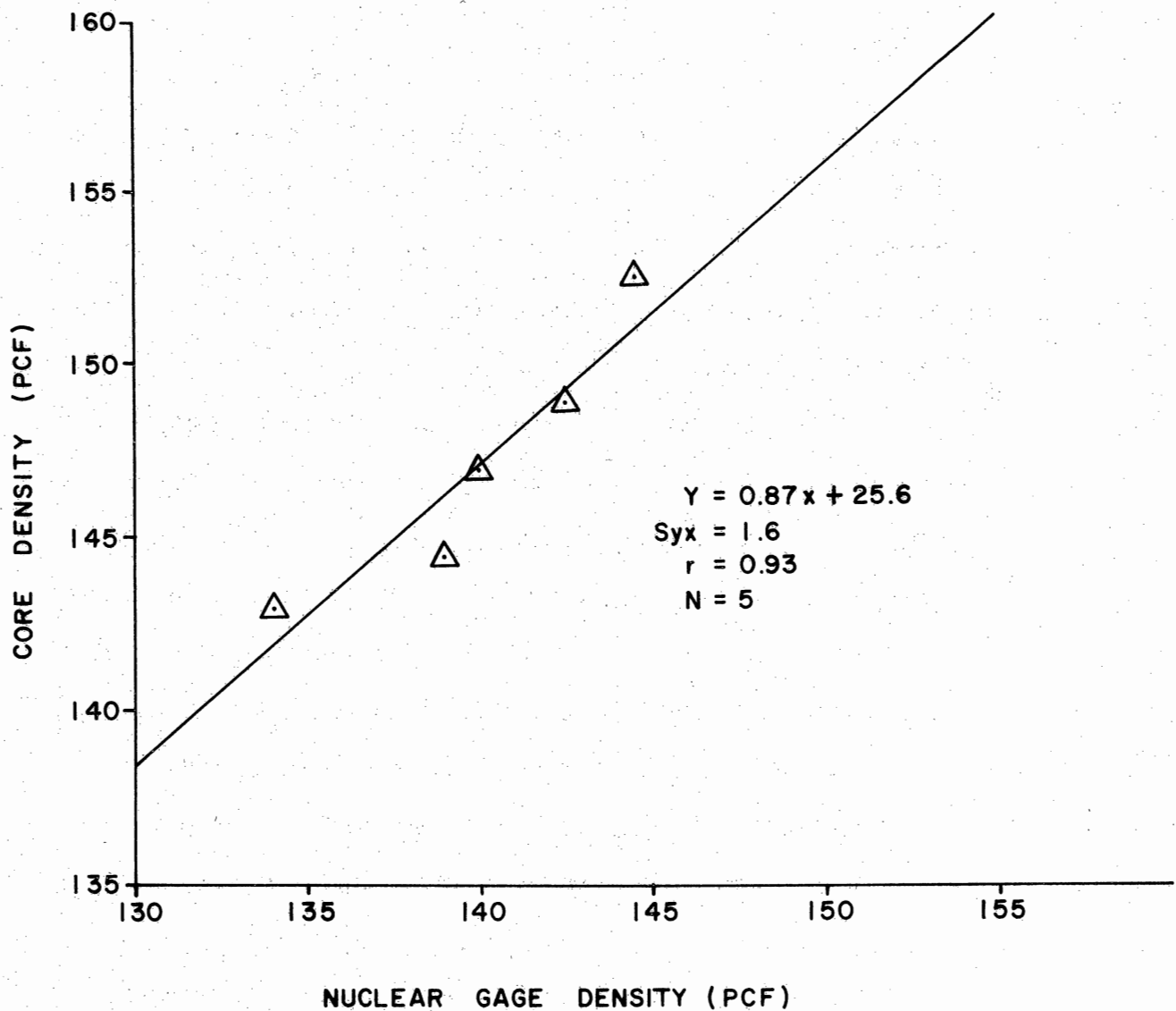
The two inch wearing surface was placed on four inches of binder/stabilized base at an average temperature of 230°F (range: 218° to 258°) and was compacted by the following rolling system:

- breakdown - 4 to 8 passes of a 16 ton vibratory roller
- intermediate - 2 to 4 passes of a pneumatic tire roller
- finish - 2 to 4 passes of a 10 ton tandem roller

The level of densification attained in each of five randomly selected areas (test sections) was evaluated during this study. To provide a valid basis of comparison for the observed in-place density and the achievable laboratory Marshall density in each test section, the respective tests were performed on identical deliveries of materials.

While the Department of Transportation normally relies exclusively on drilled core samples for pavement density acceptance, a nuclear gage was employed in the Sportsplex research in order to reduce the coring rate (standard: 5 per lot). In each test section, five nuclear density measurements (backscatter made with surface preparation) were obtained. One pavement core was subsequently cut from each test section, the location of coring being a specific nuclear density test location. The purpose of keying the core and nuclear test locations was to permit conversion of the nuclear density data to a predicted equivalent core value. The density conversions were accomplished by the equation (shown in Figure 40) derived

FIGURE 40: RELATIONSHIP BETWEEN PAVEMENT CORE DENSITY AND NUCLEAR GAGE MEASUREMENTS



thru linear regression analysis of the paired data. As shown, the relationship between pavement cores and nuclear densities is essentially one-to-one, but offset by some 26 pcf.

The results of this compaction study are presented in Table 21. As shown in the tabulation, the overall average in-place compaction in terms of Marshall density achieved was, about 96 percent, which corresponds to 9.5 percent air voids. Although this level of densification will probably be adequate for anticipated parking lot traffic at the Sportsplex, it would not comply with the previously described Department of Transportation air voids acceptance criteria.

The relatively high average voids level observed during this evaluation of drum-mix is not considered very meaningful. That is, the breakdown roller was used in the static rather than the vibratory mode of operation (the vibrating mechanism was either not turned on or was not functioning). In addition, a comparison of the design air voids for the surface mix to the Marshall test results for this study indicates the void content of the mix increased during production from 4.0 to 5.5 percent. Based on standard compaction conditions then, the achievable density for the surface mix placed during this compaction evaluation was less than at the time the mix was designed and that normally expected on Department projects. In this connection, as noted earlier, the observed average asphalt content for the surface course was lower than required

TABLE 21: SUMMARY OF COMPACTION STUDY RESULTS

Test Section	LABORATORY		FIELD		
	Marshall Density (Pcf)	Percent Marshall Voids	Mean Density (Pcf)	Percent Marshall Density	Percent Air Voids
1	155.8	3.5	149.8	96.1	7.6
2	153.8	5.7	145.2	94.4	10.9
3	154.9	4.9	146.9	94.8	9.9
4	153.5	6.2	148.1	96.5	9.5
5	151.6	7.6	147.6	97.4	9.7
Grand Averages	153.9	5.5	147.5	95.8	9.5

General Notes:

1. Marshall Density and voids are based on the average of two specimens.
2. Mean density is average of five measurements; one pavement core and four predicted core density values, based on nuclear density measurements.

$$3. \% \text{ Air Voids} = 100 - \frac{\text{Mean Density}}{D_M} \times 100$$

Where: D_M = Average of three maximum density values obtained from two Marshall specimens and one pavement core.

by the job mix formula (5.1 versus 5.5%). A review of the Marshall design curves for the surface mix revealed that at this observed asphalt content, the air voids would increase from the 4.0 percent design value to the 5.6 percent level or surprisingly close to the average Marshall voids (5.5%) actually attained. Tighter control of the mixtures asphalt content would most likely have resulted in Marshall voids closer to the 4 percent design value. In any event, if a decision is made to permit use of the dryer-drum process on a future Department of Transportation project, more realistic data relative to the compactability of drum-mixes should be obtained.

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A P P E N D I C E S

	<u>Page</u>
Appendix A: Mix Designs for Sportsplex Project	201
Appendix B: Comparison of Tonnage of Mix Constituents: Scale House versus Control Room	202
Appendix C: Relative Effects of Individual Proportioning System Errors on Drum-Mix Asphalt Content Acceptability	203
Appendix D: Proposed Dryer-Drum Specifications	204

Appendix A: Mix Designs for Sportsplex Project
Theoretical Gradation

Sieve	Total % Passing	
	Mix I-3 Binder	Mix I-5 Surface
1 1/2"	100	--
1"	100	--
1/2"	68	100
3/8"	--	92
#4	44	60
#8	37	49
#50	12	16
#200	4.9	6.7

	Mix I-3	Mix I-5
Asphalt Content, %	4.7	5.5
Air Voids, %	4.4	4.0
Stability, lbs.	2,000	1,960
Flow, inches	0.11	0.10
Weight, PCF	154	151

APPENDIX B: Comparison of Tonnage of Mix Constituents: Scale House versus Control Room

		SCALE HOUSE DATA						CONTROL ROOM DATA						COMPARISON OF DIFFERENCES: SCALE HOUSE VS CONTROL ROOM							
		Daily Mix Tonnage, M_{wet}	Mix Moisture Content, M_{cl}	Dry Mix Tonnage, M_{dry}	AC Content, M_{ac}		Stone Content, Tons	Wet Aggregate Supplied, Tons	Blended Aggregate Moisture, M_{c2}	Dry Aggregate Supplied, Tons	AC Supplied, Tons	Total Daily Mix Tonnage Supplied		Δ Daily Mix (Scale House) - (Control Room)				Δ AC (Scale House) - (Control Room)		Δ Aggregate (Scale House) - (Control Room)	
					%	TONS								Tons By Difference (Wet)	% of Scale-House Mix Tonnage (Wet)	Tons By Difference (Dry)	% of Scale-House Mix Tonnage (Dry)	Tons By Difference	% of Scale-House AC Tonnage	Tons By Difference	% of Scale-House Stone Content, Tons
Test Day	Mix	Directly from Scale Mts	Directly from Test Data	$M_{wet} \times 100$ $100 + M_{cl}$	Directly from Test Data (Extractions)	$M_{dry} \times AC\%$	$M_{dry} - M_{ac}$	Directly from Totalizer	Directly from Test Data	$M_{wet} \times 100$ $100 + M_{c2}$	Calculated from Totalizer	Wet Agg. + AC Supplied, Tons	Dry Agg. + AC Supplied, Tons								
1	Binder	1,553.0	1.1* (N=7)	1,536.1	4.51 (N=7)	69.3	1,466.8	1,457.6	3.4 (N=7)	1,409.7	68.7	1,526.3	1,478.4	26.7	1.7	57.7	3.8	0.6	0.9	57.1	3.9
2	Top	2,380.0	0.8* (6)	2,361.1	5.18 (6)	122.3	2,238.8	2,308.8	4.9 (6)	2,201.0	127.7	2,436.5	2,328.7	-56.5	-2.4	32.4	1.4	-5.4	-4.4	37.8	1.7
3	Top	2,954.9	0.9* (8)	2,928.5	4.99 (8)	146.1	2,782.4	2,756.9	5.3 (8)	2,618.1	152.6	2,909.5	2,770.7	45.4	1.5	157.8	5.4	-6.5	-4.4	164.3	5.9
4	Binder	3,388.0	0.6 (8)	3,367.8	4.27 (16)	143.8	3,224.0	2,982.1	2.5 (7)	2,909.4	140.1	3,122.2	3,049.5	265.8	7.8	318.3	9.5	3.7	2.6	314.6	9.8
5	Top	2,637.0	1.0 (6)	2,610.9	4.94 (12)	129.0	2,481.9	2,440.5	4.1 (6)	2,344.4	133.9	2,574.4	2,478.3	62.6	2.4	132.6	5.1	-4.9	-3.8	137.5	5.5
6	Top	564.4	0.9 (1)	579.2	5.16 (4)	29.3	549.3	550.1	3.3 (2)	532.5	31.8	581.9	564.3	2.5	0.4	14.9	2.6	-1.9	-6.4	16.8	3.1
7	Top	973.1	0.9 (9)	964.4	5.18 (6)	50.3	914.4	931.9	4.5 (3)	891.8	52.9	984.6	944.7	-11.7	-1.2	19.7	2.0	-2.9	-5.8	22.6	2.5
8	Binder	3,680.1	0.7 (9)	3,654.5	4.13 (18)	150.9	3,503.6	3,388.5	2.7 (9)	3,299.4	160.7	3,549.2	3,460.1	130.9	3.6	194.4	5.3	-9.8	-6.5	204.2	5.8

*For days 1 thru 3, only mix moisture exiting drum was obtained. For other days Δ mix moisture between truck and drum samples ranged from 0.04 to 0.25% and averaged 0.17%. Values used for days 1 thru 3 are drum moisture -- ave. difference of $\pm 0.2\%$.

**The volume of AC used is determined from the AC totalizer and is converted into tons as follows: $TONS\ AC\ USED @ 60^\circ F = \frac{(A)(V_{cf})(B)}{C}$

Where: A = Vol. AC used @ 300°F equal to counts on AC totalizer/2 counts rev. times 0.63 gal/rev.
 V_{cf} = Temp correction factor for 300°F equal to 0.9187.
 B = Weight AC having sp. gr. of 1.02 @ 60°F equal to: 8.495 lb/gal.
 C = Conversion factor equal to 2000 lb/ton.

Appendix C: Relative Effects of Individual Proportioning System Errors on Drum-Mix Asphalt Content Acceptability

Mix	Test Day	Tonnage of Mix Constituents (Scale House)		Asphalt Content, %			Eliminate Asphalt Pump Inaccuracy			Eliminate Weigh Belt Inaccuracy			Use True Moisture in Blended Aggregates		
		AC	AGG.	Design	Actual	N	ΔAC_1^a , TONS	NEW AC %	ΔAC_1 %	ΔAC_2^b , TONS	NEW AC %	ΔAC_2 %	ΔAC_3^c , TONS	NEW AC %	ΔAC_3 %
Binder	1	69.3	1466.8		4.51	7	- 0.2	4.50	-0.01	+ 2.8	4.69	+0.18	+0.4	4.54	+0.03
	4	143.8	3224.0	4.7	4.27	16	- 1.0	4.24	-0.03	+15.5	4.71	+0.44	+0.7	4.29	+0.02
	8	150.9	3503.6		4.13	18	+11.3	4.42	+0.29	+10.1	4.39	+0.26	+0.5	4.14	+0.01
	Weighted Average % AC				4.25			4.36			4.57			4.27	
	Estimated Effect on % AC:						Increased by 0.11%			Increased by 0.32%			Increased by 0.02%		
Top	2	122.3	2238.8		5.18	6	+ 6.9	5.46	+0.28	+ 2.2	5.27	+0.09	-1.1	5.14	-0.04
	3	146.1	2782.4		4.99	8	+ 6.7	5.21	+0.22	+ 9.6	5.30	+0.31	-0.4	4.98	-0.01
	5	129.0	2481.9	5.5	4.94	12	+ 8.9	5.26	+0.32	+ 8.0	5.23	+0.29	-1.5	4.89	-0.05
	6	29.9	549.3		5.16	4	+ 1.5	5.41	+0.25	+ 1.0	5.33	+0.17	-0.4	5.10	-0.06
	7	50.0	914.4		5.18	6	+ 3.2	5.50	+0.32	+ 1.3	5.31	+0.13	-1.3	5.06	-0.12
	Weighted Average % AC				5.06			5.34			5.28			5.00	
Estimated Effect on % AC:							Increased by 0.28%			Increased by 0.22%			Decreased by 0.06%		

General Notes on Calculation Procedure:

- ^a Difference between actual (Scale House) AC and required AC for indicated (Control Room) tons dry aggregate (from Table 7, Col. 9).
- ^b Estimated additional AC required for difference in actual tons dry aggregate (Scale House) and indicated tons of dry aggregate (Control Room).

$$\text{Additional AC} = \frac{(\text{AC}\%) (\Delta \text{Wt. Aggr.})}{100 - \text{AC}\%}$$
 where Δ Weight Aggregate is difference in columns 6 and 8 of Table 6.
- ^c Estimated change in actual AC (Scale House) tonnage due to difference in true aggregate moisture and console dial setting (from Table 8, col. 7).

Appendix D: Proposed Dryer-Drum Specifications

ADDENDUM _____

NJDOT SPECIAL PROVISIONS FOR DRYER-DRUM
MIXING OF HOT-MIX BITUMINOUS CONCRETE

For Project I - _____, the Sections "Bituminous Stabilized Base" and "Hot-Mix Bituminous Concrete" of the Standard Specifications are hereby amended with respect to the clauses cited below. No other clauses or requirements for these items are waived, relaxed or otherwise changed hereby.

ARTICLE 3.10.3, METHODS OF CONSTRUCTION

The following is added to this article of the Specifications:

Dryer-Drum Mixing Plant. The Contractor may, at his option, elect to use the dryer-drum mixing process in the production of bituminous stabilized base and bituminous concrete. If the Contractor elects to use this alternate process, the heating, coating, and mixing of the bituminous mixture shall be accomplished in an approved parallel flow dryer-mixer. The plant shall be designed, equipped, calibrated and operated to deliver a well-coated homogeneous bituminous mixture meeting the requirements of Article 3.10.2. The plant shall consist of the following items of equipment:

(1) Aggregate Bin System. The plant shall have cold feed aggregate storage bins of sufficient number and capacity to store the amount of aggregate required to keep the plant in continuous operation and of proper design to prevent overflow of material from

one bin compartment to that of another compartment. The number of cold feed aggregate bins shall be equal to or greater than the number of stockpiles of individual materials to be used.

The fine aggregate bin compartment(s) shall be equipped with an appropriate type and size vibrator which is automatically actuated when "bridging" of the material occurs and which shuts off automatically with the onset of continuous material flow.

Each bin compartment shall be equipped with a device that visually and/or audibly signals when the level of aggregate is below the quarter point. Indicators shall also be provided on each bin to show the respective gate opening.

Each aggregate feeder shall be interlocked in such a manner that production is interrupted if one or more cold bins becomes empty or obstructed.

(2) Mineral Filler System: When mineral filler is to be added, it shall be from a bin and feeder separate from the aggregate cold bins. The system shall have a device to feed the mineral filler at adjustable rates accurately and uniformly.

The feeder shall be interlocked in such a manner that production is interrupted if the bin becomes empty or the flow is obstructed.

(3) Aggregate Feed System: The plant shall be provided with a mechanical system for uniformly and continuously feeding each aggregate in its proper proportion onto a collecting belt and then into the dryer-drum mixer. Prior to entering the mixer, the aggregates on the collector belt shall pass through a two inch scalping screen or other device that will remove oversize or debris. The control of the quantity of aggregate

fed to the dryer-drum shall be by variable speed system which provides for total and proportional control. One feeder shall be provided for each bin compartment.

The individual bin feeder belts or the intermediate collecting belt that delivers the aggregate to the main feed for the dryer shall be equipped with belt type scales (load cells) capable of continuously displaying, at the operator's station, the weight of aggregate flow in tons per hour from each individual bin and the accumulated total from each bin in tons. Belt scales shall be accurate within 1.0 percent of the indicated weight throughout the full range of the plant's production capacity.

Means shall be provided for conveniently diverting the aggregate cold feed delivery into trucks or other suitably large containers for checking the accuracy of the aggregate feed system. A method and facilities shall be provided for obtaining representative samples of the composite or total cold aggregate from the main feed to the dryer-drum at any time during production operations.

(4) Asphalt Metering System. A satisfactory system shall be provided to introduce the proper amount of asphalt into the mix.

The asphalt pump shall be a positive displacement type pump with a circulating asphalt system. The asphalt pump shall be equipped with a revolution counter or flow meter and a pyrometer or thermometer probe of suitable range and accuracy to record the asphalt temperature, with the data being transmitted to the operator's station. A flow switch designed to interrupt production if the bitumen flow is discontinued shall be installed in the delivery line between the meter and the mixer.

A temperature compensating device shall be installed in conjunction with the meter to correct the quantity of asphalt to 60°F.

The flow of asphalt to the dryer-drum mixer shall be displayed in appropriate units of weight and time shall be totaled. The asphalt delivery system shall be accurate within 1.0 percent of the indicated quantity at any given production rate.

Convenient means shall be provided for diverting the asphalt into distributor trucks or other suitably large containers for checking the accuracy of the asphalt delivery system.

(5) Proportioning Control System. The combined aggregates shall pass over a weigh belt or belt scale that is electronically interlocked with the asphalt pump in such a manner as to automatically vary the asphalt feed rate as required to maintain the required proportion at the point where the aggregate and asphalt are being combined in the dryer-drum mixer.

The composite aggregate weigh belt shall have an electronic readout or display at the operator's station that continuously shows the tons per hour passing over the belt. The composite aggregate weighing system shall be accurate within 0.5 percent of the indicated weight at any given production rate. To prevent adherence or other loss of the weighed cold feed aggregate, belt conveyors shall be equipped with scrapers or other suitable devices.

Provisions shall be made for introducing the moisture content of the cold feed aggregates into the belt weighing signal and correcting wet aggregate weight to dry aggregate weight. The dry weight of the composite aggregate flow shall be displayed in units of tons per hour and shall be totaled.

An automatic cold feed shut-off shall be provided to operate or actuate when the flow from any individual aggregate feeder is interrupted or when the pressure falls in the bituminous supply lines.

Prior to the start of production, the plant proportioning controls must be calibrated using the project materials. At least ten days prior to such initial calibration, the Contractor shall submit to the Engineer two complete sets of plant drawings, a plant operator's manual, and a plan detailing the intended method of calibration. Submission of plant drawings and operator's manual will not be required for any subsequent calibrations.

The Engineer shall witness the calibration of the individual cold feeders at various gate openings and control console dial settings. A copy of the Contractor's computations for the combined rate of flow and a plot of calibration charts shall be submitted to the Engineer. Such charts shall indicate the rate of aggregate delivery in tons per hour from each cold feeder for particular dial settings and gate openings at production rates throughout the range of the plant's capacity. Calibration points will be determined by independently diverting each cold feed into trucks (or running each feed through the plant) and determining the proper console dial setting corresponding to the measured rate of delivery. Such calibration points shall be determined in increments of approximately 100 tons per hour of total aggregate flow throughout the range of the plant's capacity.

The Engineer shall witness a check on the asphalt feed at several production rate increments throughout the range of the plant's capacity. Calibration of the asphalt metering controls and subsequent checks thereof shall be accomplished by diverting the asphalt into a suitably large container for weight or volumetric measurement. The procedure shall be sufficient to assure the Engineer that the asphalt controls are properly marked to correspond to positive calibration of the asphalt feed.

Any changes or modifications to the dryer-drum system equipment and/or operation subsequent to initial calibration shall be reported to the Engineer who, depending on the nature and extent of the modifications made, reserves the right to direct calibration checks and/or a new plant calibration in accordance with the procedures contained herein.

(6) Dryer-drum mixer. A drum mixer of satisfactory design shall be provided. The dryer-drum mixer shall be of the type that continually agitates the mixture of aggregate and asphalt during heating and in which the temperature can be so controlled that the aggregate or asphalt will not be injured in the necessary drying and heating operations required to obtain a mixture of the specified temperature. A continuous recording pyrometer or thermometer shall be provided which will indicate the temperature of the mixture as it leaves the dryer-drum mixer.

An approved method and facilities shall be provided for safely and conveniently obtaining representative mixture samples at the discharge end of the drum-mixer.

(7) Surge Bin System. The plant shall be provided with a surge bin system of adequate capacity to minimize the production interruptions during the normal day's operation. The surge bin shall be designed and operated to prevent hardening of the asphalt, mix segregation and loss of mix temperature.

The Contractor's attention is directed to the fact that such surge-storage systems must be prequalified in accordance with the supplemental requirements of Article 3.10.2 cited elsewhere herein.

(8) Truck Scale System. An approved weighing system, conforming to the requirements of Article 3.10.4, shall be furnished at a location approved by the Engineer.

(9) Emission Control System. The plant shall be equipped so as to meet all applicable limitations on emissions.

(10) Control Console. The following items will be part of a control console furnished in the operator's station:

(a) Cold Aggregate Feed Controls capable of both total and proportional control of the aggregates.

(b) Dryer Burner Controls that automatically control the temperature of the mix and record the mix temperature at the dryer discharge.

(c) Weigh Belt Readouts displaying the weight, in tons per hour, of material being proportioned from each aggregate bin and the total flow over the main feeder to the dryer, together with an accumulative total in tons for each.

(d) Mineral Filler Readouts displaying the weight of material, in tons per hour, of material being proportioned from the mineral filler bin, together with an accumulative total.

(e) Asphalt Pump Meter Readout indicating the quantity of asphalt being proportioned into the mix and a recording pyrometer or thermometer that records the temperature of the asphalt at the pump.

(f) Proportioning Control dials that set the asphalt content as well as the aggregate moisture adjustment shall be capable of being key locked.

(11) Incidental Equipment. The Contractor shall furnish power units, conveyors, aggregate handling equipment and all else necessary for the proper and continuous operation of the plant.

If the Contractor elects to use the dryer-drum process, ARTICLE 3.10.2 MATERIALS shall be supplemented by the addition of the following:

(1) Sampling Rate. Five random samples will be taken from each lot of approximately 1750 tons of each type of mix. When a lot of bituminous concrete is necessarily less than 1750 tons, samples will be taken at random for each type of mix at the rate of one sample for each 350 tons or fraction thereof.

(2) Sampling and Testing. The bituminous mixture will be sampled in accordance with Article 9.1.22.

To determine the quantity of bitumen and the gradation of the aggregate in bituminous concrete mixtures for acceptance testing purposes, extractions at the sampling rate specified shall be performed each day for each type mixture in accordance with Article 9.1.23.

Acceptance testing of bituminous concrete shall be performed by the Department's technician at the plant laboratory.

Under no circumstances will an employee of the Department do the composition control testing or other routine test functions in the absence of, or in lieu of the plant laboratory technician.

(3) Gradation Control of Mineral Aggregates. Prior to the start of production, the Contractor shall assure that the cold feed aggregates are of known and uniform gradations so that they may be metered in the prescribed proportions and consistently produce a mixture within specification limits. Control of the individual stockpile gradations and proportioning from those stockpiles shall be the Contractor's responsibility.

(4) Mix Moisture Content. The moisture content of finished bituminous mixtures shall not exceed 1.5 percent. Moisture content determinations shall be based on the weight loss on heating for three hours at $280^{\circ} \pm 5^{\circ}\text{F}$ of an approximately 1500 gram sample of finished bituminous mixture.

(5) Asphalt Hardening. As part of the prequalification process for the plant surge bin system, bituminous mixtures shall be evaluated for gradation, temperature, and asphalt hardening. The method of sampling, rate of sampling, and testing and analysis procedures shall be in accordance with the requirements of "Appendix A: Evaluation Procedure" of the report "Storage of Hot Bituminous Concrete Mixes", NJDOT Research Report No. 74-007-7733 (October 1973).

The analysis of asphalt hardening performed as a part of the prequalification of the surge bin system shall consist of a comparison of the penetration of the asphalt cement from mixture recovery samples obtained at the dryer-drum discharge and the surge silo discharge. The penetration of the asphalt cement recovered from the stored surge silo mixture samples will be acceptable if the average penetration is no more than 15 percent less than the average penetration of the asphalt cement recovered from mixture samples from the dryer-drum discharge. Recovery of asphalt from mixture samples shall be performed in accordance with ASTM D 1856.

In addition to comparison of penetration test results performed on the finished mixture, the Engineer reserves the right to perform test comparisons between the penetration of the asphalt cement in its original form from plant tank samples and in processed form from mixture recovery samples obtained at the dryer-drum discharge. The purpose of such comparisons of test results is to ensure that the asphalt is not injured in the drying and heating operation. The results of such penetration tests shall be used solely to gauge whether a processing improvement is necessary to eliminate excessive volitization, oxidation or other causes of premature penetration loss.

(6) Production Experimentation. The Engineer reserves the right to require that for research purposes, a selected quantity of one or more of the specified bituminous mixtures be produced at a temperature lower than the specified discharge temperature contained in the standard specifications.

If such experimentation with low mix temperatures is in fact ordered by the Engineer, it is expected that approximately _____ tons of each of the specified bituminous mixtures will be involved. When low discharge temperature mix is ordered by the Engineer, the specified moisture content, Marshall stability and air voids requirements will be waived for the affected quantity of material. The specified thickness, gradation or asphalt content requirements shall not be waived for any low temperature mix ordered by the Engineer.

The Contractor's attention is directed to the fact that the decision to undertake any experimentation with low temperature mix is completely discretionary with the Engineer. The Contractor will not be granted additional compensation or other concession as a result of the Engineer electing not to undertake experimentation with low mixture temperature.

If the Contractor elects to use the dryer-drum process, ARTICLE 8.5.4 COARSE AGGREGATE shall be supplemented by the addition of the following:

(1) Adherent Fines: Coarse aggregate shall contain a maximum of 1.5 percent adherent fines of clay, caked stone dust, or other coatings or material as determined by Article 9.1.26 of the standard specifications.

