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LABORATORY EVALUATION OF A CHEMICAL COUPLING AGENT TO PREVENT DEBONDING OF ASPHALTS FROM AGGREGATES

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PROJECT HPR-1-18(178)

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IN CONJUNCTION WITH FEDERAL HIGHWAY ADMINISTRATION

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ABSTRACT

Debonding of asphalt from mineral aggregates (stripping) was termed an old problem as far back as 1938, yet it continues to plague the paving industry today. Commercial anti-strip additives are available yet their long term effects are not well understood.

A silane coupling agent was compared with a well known, commercially available liquid anti-strip (amine) in the immersion-compression and double punch debonding tests on two Arizona mineral aggregate sources. The silane was used as a mineral aggregate pretreatment while the amine was added to the asphalt.

The results of this research are encouraging and indicate the silane generally performed as well as the liquid anti-strip or better. Further testing is recommended along with construction of experimental projects to evaluate field performance.

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5093

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A silane coupling agent was compared with a well known, commercially available liquid anti-strip (amine) in the immersion-compression and double punch debonding tests on two Arizona mineral aggregate sources. The silane was used as a mineral aggregate pretreatment.

The results of this research are encouraging and indicate the silane generally performed as well as the liquid anti-strip or better. Further testing is recommended along with construction of two experimental projects to evaluate field performance.

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I. INTRODUCTION

An asphalt concrete pavement is inherently dependent upon the cohesive and adhesive characteristics of the binder to hold it together. As a result, the bond between the asphalt binder and the mineral aggregate is of special importance. It is critical that a good bond is developed during construction and maintained for the life of the pavement. Any degree of loss of the asphalt-aggregate bond will result in a corresponding loss of pavement performance in one manner or another. The strength of an asphalt concrete mixture is a result of the cohesive resistance of the binder, the adhesive bond between the binder and the aggregate, aggregate interlock and frictional resistance between aggregate particles.

Several methods have been used to limit the possibility of stripping. Some of the more common methods are:

* The addition of dry lime or portland cement in small percentages to the mix or lime slurry treatment of mineral aggregate,
* Precoating aggregates with bitumen or diluents prior to asphalt concrete production,
* The addition of selected natural mineral fillers,
* Disallowance of known hydrophilic aggregates,
* Washing, wasting or blending of aggregates, and
* The addition of chemical anti-stripping agents.

All of these methods, for one reason or another, are not always acceptable or economical in every situation.

Under certain circumstances, an asphalt binder will separate from the aggregate, a complex phenomenon known as debonding (commonly referred to as stripping). Debonding is a function of the environmental conditions, traffic loading, binder and aggregate characteristics, mixture properties and more. However, it is generally agreed that the mechanism of debonding is the intrusion of water between the adherends. Even though a proper bonding of the asphalt to the aggregate may have taken place during construction, debonding is still possible. Water intrusion is the mechanism that will facilitate debonding by replacing the asphalt coating on mineral aggregates. Since water in one form or another will always be present in a pavement, stripping is always a possibility. An extensive study of debonding is available in the literature (1 through 16). The intent of this research project was to evaluate and compare an organofunctional silane as a mineral aggregate pretreatment with an amine liquid anti-strip to determine if the silane should be considered a practical anti-strip treatment. It has been reported amidoamine and imidoazoline anti-strip compounds may actually increase "emulsion" formation at the aggregate-asphalt interface (1). These additives actually enable a better coating to be placed on the aggregate particles initially, but could lead to accelerated stripping later. Emulsion formation is one mechanism by which stripping can occur; however, it is not an accurate description of the stripping mechanism. While it is true the term emulsion can be applied to any asphalt-water mixture, it may cause confusion when used to describe the stripping mechanism.

In 1976, the Arizona Department of Transportation undertook a limited in-house study to evaluate liquid anti-strip additives as well as alternate methods of preventing debonding. It was apparent then, and still is now, that the long term effects of these additives are not well understood. Many of our new pavements exhibited asphalt stripping six to twelve months after construction even though a commercial anti-strip was used. A simple but significant test program was initiated. Three aggregate materials from different sources were tested with each of two different commercial anti-strip compounds and Dow Z-6020 organofunctional silane in the immersion-compression test (AASHTO T165).

The commercial anti-strip compounds tested were Edoco and Pavebond Special. Each was added to the asphalt in the amount of 1% by weight of the asphalt. The silane was applied to the mineral aggregates as a pre-treatment and allowed an ambient cure of 24 hours before mixing. Two different silane-in-water solutions were tested: 1.5% and 2%. These solutions were applied to the dry mineral aggregate at the rate of 3% by weight of the mineral aggregate.

The results were encouraging. The silane pretreatment solutions imparted a better retained strength in the immersion-compression test in every case but one. The complete results are shown in Table 1 entitled Preliminary Test Data.

Based on these results, a second project was initiated and a consultant was hired to run further tests to confirm the effect the silane solution had on the retained strength of an asphalt concrete mix. This time two different material sources were selected for testing. Furthermore, the double punch test procedure (3) was to be used in addition to the immersion-compression test to see if the results were test dependent. It was decided Pavebond Special and Dow-Corning Z-6020 silane were to be tested. Pavebond Special was chosen because of its widespread use in Arizona.

II. THEORY

It should be noted that after considerable work by ADOT testing silane as an anti-strip, it was discovered that previous work involved the use of silane coupling agents in asphalt concrete mixes both as an

TABLE 1

IMMERSION-COMPRESSION

PRELIMINARY TEST DATA

AVERAGE OF THREE TEST REPLICATES

COMPRESSIVE STRENGTH IN psi DRY	WET	PERCENT * RETAINED STRENGTH	TREATMENT
Aggregate Source 1		PIT 8567 ZUNI	
353	118	33	None
	238	67	1% Edoco Anti-Strip
	326	92	1% Pavebond Special
	227	78	1.5% Silane
	296	84	2.0% Silane
Aggregate Source 2		PIT 8500 GLOBE	
287	119	41	None
	163	57	1% Edoco Anti-Strip
	237	83	1% Pavebond Special
	325	113	1.5% Silane
	325	113	2.0% Silane
Aggregate Source 3		UNITED METRO #11 YUMA	
375	68	18	None
	125	33	1% Edoco Anti-Strip
	190	51	1% Pavebond Special
	207	55	1.5% Silane
	264	70	2.0% Silane

* $\frac{\text{WET COMPRESSIVE STRENGTH}}{\text{DRY COMPRESSIVE STRENGTH}} \times 100\%$

anti-stripping additive and aggregate pretreatment and is documented in a patent held by Chevron. However, silanes are not presently, nor ever have been, marketed as anti-strip agents.

The patent describes dramatic asphalt retention by aggregates even when treated with as little as one part per million. Furthermore, it was reported that a tenfold increase in retained asphalt (on the surface of the aggregate) was demonstrated after a water immersion test of 180^{0}F for eight days. This work verified our early work and encouraged further testing. Significant favorable results were achieved with the silane as a mineral aggregate pretreatment as well as an asphalt additive. This report addresses the use of silanes only as a mineral aggregate pretreatment.

III. DESCRIPTION OF TESTING

In March, 1980, a proposal was submitted to the Federal Highway Administration to compare Dow Z-6020 and Pavebond Special as anti-strip agents. R. A. Jimenez of the University of Arizona was commissioned to prepare and evaluate 240 asphalt concrete specimens by two different test methods: the double punch debonding test and the immersion-compression test. A description of each test is included in the appendix.

The silane pretreatment of the mineral aggregate varied as to solution concentration as well as aggregate surface moisture condition (oven-dry or approximate saturated surface dry). The silane was applied in two different ways depending on this condition. In the oven dry state, the aggregate was treated with 3% (by weight of the aggregate) of four different silane concentrations. In the approximate saturated surface dry condition (s.s.d.) the aggregate was treated with 1% (by weight of the aggregate) of the same four silane-in-water concentrations; namely 0.25%, 0.75%, 1.00% and 1.50%. These two different aggregate surface moisture conditions were selected to determine if the silane-aggregate reactivity is dependent on this characteristic as well as to simulate field conditions. Figure 1 depicts the variables and test methods. Two different aggregate sources were tested - Salt River and Agua Fria - both from the Phoenix area. Pavebond Special was added to the asphalt binder in the amount of 1% by weight of the asphalt. This is the same way it is used in construction.

IV. MATERIALS USED FOR TESTING

Mineral Aggregates

Two aggregate sources were selected for use in the test program. Crushed Salt River and Agua Fria aggregate samples were obtained for testing from commercial stockpiles. Physical characteristics and mix design data of each source are included in Table 2. Both are stream deposits in the Phoenix valley area, with both mix gradations approaching the Fuller Maximum Density Curve. The sand equivalent values indicate the primary difference between the two sources: 32 for the Agua Fria as compared with 55 for the Salt River sources. The sand equivalent test is a very good measure of the portion of detrimental fine dust or clay-like minerals in the mineral aggregate. It is logical to conclude that a low sand equivalent number will indicate a higher potential for asphalt-aggregate debonding and, therefore, proves to be a valuable test for aggregate evaluation. A good correlation between sand equivalent value and stripping has been established (3).

Asphalt

One asphalt was chosen for use throughout the test sequence. The

FIGURE 1. TEST PROGRAM

SILANE PRETREATMENT OF AGGREGATE

Prepare Four Silane-in-Water Solutions of 0.25%, 0.75%, 1.00% and 1.50%

MINERAL AGGREGATE OVEN-DRIED

Apply 3% (by weight of aggregate) to mineral aggregate of each of the 4 solution concentrations

Allow 24 hour ambient air cure

Prepare asphalt concrete test specimens in triplicate for testing in both immersion-compression and double-punch tests

MINERAL AGGREGATE SATURATED SURFACE DRY

Apply 1% (by weight of aggregate) to mineral aggregate of each of the 4 solution concentrations

Allow 24 hour ambient air cure

Prepare asphalt concrete test specimens in triplicate for testing in both immersion-compression and double-punch tests

PAVEBOND SPECIAL

Add 1% Pavebond Special to Asphalt and thoroughly mix.

Prepare asphalt concrete test specimens in triplicate for testing in both immersion-compression and double-punch tests.

NO TREATMENT

Prepare asphalt concrete test specimens in triplicate for testing in both immersion-compression and double-punch tests.

TEST MATRIX

TEST		DOUBLE PUNCH OR IMMERSION-COMPRESSION							
TREATMENT*		SILANE 3% O.D.		SILANE 1% SSD		PAVEBOND SPECIAL		NONE	
CONDITION **		DRY	WET	DRY	WET	DRY	WET	DRY	WET
CONCENTRATION	A	3	3	3	3	3	3	3	3
	B	3	3	3	3				
	C	3	3	3	3				
	D	3	3	3	3				

* O.D = OVEN DRY AGGR., SSD = SATURATED SURFACE DRY AGGR.

** WET OR DRY CONDITIONING OF SAMPLE

PAVEBOND SPECIAL 1% BY WEIGHT OF ASPHALT

3 REPLICATES OF EACH TEST

TABLE 2

MINERAL AGGREGATE CHARACTERISTICS

GRADATION	SALT RIVER	AGUA FRIA
Sieve Size	Percent Passing	Percent Passing
1"	100	100
3/4"	94	94
1/2"	82	80
3/8"	71	66
#4	50	50
#8	40	44
#16	32	36
#30	22	25
#50	15	14
#100	8	7
#200	4	4
Sand Equivalent	55	32
CKE Oil Ratio	4.9%	4.5%
Effective Sp. Gr. 77/77F	2.67	2.69
Sp. Gr. W/ 5% Asphalt	2.47	2.49

asphalt used conforms to an aged residue grading classification of AR2000 and was obtained from Sahuaro Petroleum, Phoenix. Edgington Asphalt in Long Beach, California is the asphalt source.

Additives

Pavebond Special is a registered trade name of a product of the Carstab Corporation. It is marketed as an asphalt additive to prevent debonding.

Silane coupling agents were first introduced to improve the water resistance of reinforced plastics. It was soon observed that they also imparted significant improvement to initial properties of laminates (2). Hydrophilic mineral surfaces were used in preparing composites with organic polymers with silanes being used to improve the bond. The similarity between the polymer-glass systems and the pavement materials was noted and it was felt that silanes may have the potential to increase the bond between asphalt and mineral aggregate surfaces.

Z-6020 Silane is a registered trade name of Dow Corning. It is not marketed for the highway paving industry. It is primarily used as a coupling agent for the resin and plastic industry (2). It is a low viscosity liquid of the type: aminoalkyl functional silane with the molecular formula $(CH_3O)_3SiCH_2CH_2NHCH_2CH_2NH_2$. It is only one member of one subclass of the much larger group of organofunctional silane coupling agents. The chemical name for Z-6020 is N-(Beta-aminoethyl)-gamma-aminpropyltrimethoxysilane.

V. SUMMARY AND DISCUSSION OF RESULTS

The complete test results are included in Tables 3 through 6. The results are also plotted in Figures 2 through 5.

The retained strengths of the laboratory prepared asphalt concrete specimens were calculated two ways as shown in the tabular results.

In this manner one can compare results of a particular treatment (wet soaked) versus an untreated, unsoaked specimen or that same particular treatment versus itself in the dry state. Density, voids and the differences in compressive strength between wet and dry specimens is also reported.

The results indicate silane pretreatment of mineral aggregate is effective in preventing debonding as indicated by the two different test procedures. Furthermore, it appears to be more effective on the Agua Fria mineral aggregate which is a much "dirtier" source than the Salt River as evidenced by the low sand equivalent value of 32. Densities of the silane mixtures are consistently higher with lower voids. This may have contributed to the increased retained strengths of the silane treated mixes since it is well known low void mixes are more resistant to stripping than high void mixes.

It is significant that the silane treated specimens exhibited higher dry strengths than untreated specimens in all but three cases. Pavebond Special increased the dry strengths in every case; however, part of the increase may be a result of an increase in binder viscosity caused by the asphalt additive. It is known that amine additives facilitate better coating of aggregates and this may also contribute to higher dry strengths.

Silane concentration, amount of silane solution applied and application method all affect mix strength retention as shown in Figures 2 through 5. For example, for the same given quantity of silane treatment (75 parts per million) the retained strengths are substantially different in every case. This phenomenon indicates aggregate surface condition (specifically whether the surface is dry or approximate s.s.d.) has a definite impact on retained strength. Surface moisture may be the vehicle by which the silane is uniformly distributed over the aggregate surface area and as such, could be an important factor influencing reactivity.

In summary, it appears the silane pretreatment of mineral aggregates does improve resistance to debonding at least as well as Pavebond Special. Some retained strength values are lower, but many more silane retained strengths are higher than those with Pavebond treatment. Further work must be conducted to optimize treatment methods and silane concentrations to accomplish the most economical application that yields the best results as well as to determine long term results.

VI. CONCLUSIONS AND RECOMMENDATIONS

1. In general, the silane pretreatment of two mineral aggregates improved the resistance to debonding of asphalt from mineral aggregate in the immersion-compression and double punch tests.
2. The silane treatment appeared to have a more pronounced effect on the Agua Fria aggregate source. As a result, dirty aggregate sources (those with low sand equivalent values) may benefit most from silane pretreatment. Furthermore, marginal aggregate sources may be allowed if testing with silane verifies that minimum retained strength values can be obtained.
3. Silane concentration, application method and aggregate surface moisture condition influence retained strength values in both test methods. Therefore, a more detailed examination of these factors is the logical next step in future research endeavors.
4. Research should continue with silane chemicals as debonding preventatives. In addition, silanes should be tested as additives in

asphalts to compare with pretreatment of mineral aggregates as examined in this research effort. Preliminary tests by the Arizona Transportation Research Center have shown the chemical to be effective down to 0.05% by weight of asphalt (the equivalent of approximately 25 ppm by weight of aggregate) as an anti-stripping agent.

5. It is recommended experimental projects utilizing silane as an anti-stripping agent be constructed to determine actual field effectiveness as well as long term effects on asphalt concrete mixes.

6. Additional testing of aggregate pretreatment with silane solutions is warranted to compare the results of this research with various other aggregate types and characteristics since this research was limited to testing of two local aggregate sources. In addition, other asphalt types and sources should be tested for the same reason.

VII. REFERENCES

1. Fromm, Harold J., "The Mechanism of Asphalt Stripping from Aggregate Surfaces", Proceedings Association of Asphalt Paving Technologists, 1974.

2. Plueddemann, E. P., "Mechanism of Adhesion of Coatings through Reactive Silanes", Journal of Paint Technology, March, 1970.

3. Jimenez, R. A., "Testing for Debonding of Asphalt from Aggregates", Characteristics of and Factors Influencing Bituminous Materials and Mixtures, Transportation Research Board No. 515, Transportation Research Board, Washing n, D.C., 1974.

4. Rice, James M., "Relationship of Aggregate Characteristics to the Effect of Water on Bituminous Paving Mixtures", Symposium on Effects of Water on Bituminous Paving Mixtures, ASTM Special Technical Publication No. 240, American Society for Testing Materials, Phildelphia, PA 11958.

5. Majidzadeh, K. and Brovold, F. N., "State of the Art: Effect of Water on Bituminous Aggregate Mixtures", Highway Research Board Special Report 98, Washington, D.C., 1968.

6. Hubbard, Prevost, "Adhesion of Asphalt to Aggregates in Presence of Water", Proceedings, Highway Research Board, Washington, D.C., 1938.

7. International Symposium on Porous Asphalt, Proceedings, Amsterdam, 1976.

8. Lottman, R. P., "Predicting Moisture-Induced Damage to Asphaltic Concrete - Field Evaluation Phase", National Cooperative Highway Research Program, Moscow, Idaho, February, 1979.

9. Scott, J. A. N., "Adhesion and Disbonding Mechanisms of Asphalt Used in Highway Construction and Maintenance", Proceedings of Association of Asphalt Paving Technologists, 1978.

10. Sanderson, F. C., "Methylochlorosilanes as Anti-stripping Agents", Proceedings, Highway Research Board, Washington, D.C., 1952.

11. Clplijauskas, L., Piggot, M. R. and Woodhams, R. T., "Chemically Modified Asphalts for Improved Wet Strength Retention", American Chemical Society, I&EC Product Research and Development, June, 1979.

12. Ford, M. C., Manke, P. G. and O'Bannon, C. E., "Quantitative Evaluation of Stripping by the Surface Reaction Test", Characteristics of and Factors Influencing Bituminous Materials and Mixtures, Transportation Research Record No. 515, Transportation Research Board, Washington, D.C., 1974.

13. Lottman, R. P., Chen, R. P., Kumar, K. S. and Wolf, L. W., "A Laboratory Test System for Prediction of Asphalt Concrete Moisture Damage", Characteristics of and Factors Influencing Bituminous Materials and Mixtures, Transportation Research Record No. 515, Transportation Research Board, Washington, D.C., 1974.

14. Chu, T. Y., "Investigation of Roadway Drainage as Related to the Performance of Flexible Pavements", University of South Carolina, August, 1974.

15. Chehovits, J. G. and Anderson, D. A., "Upgrading of Marginal Aggregates for Improved Water Resistance of Asphalt Concrete", Pennsylvania State University, January, 1980.

16. Peterson, J. C., et al, "Paving Asphalts: Chemical Composition, Oxidative Weathering and Asphalt-Aggregate Interactions, Part II", Report No. FHWA-RD-74-71, June, 1974.

VIII. APPENDIX

Description of Immersion-Compression Test

A measure of resistance to debonding was obtained with the immersion-compression test, AASHTO T-165. The AASHTO procedure was followed except that enough material was mixed at one time to produce three specimens instead of one. This change was necessary to assure that all specimens of a set had received the same chemical treatment. Work in the laboratory has shown variability in density and strength measurements have met the usual requirements when mixing enough material at one time to produce these specimens. After mixing at approximately 140°C (285°F) enough mixture was taken to produce a specimen 101 mm (4 in.) by 101 mm (4 in.) after compaction at 121°C (250°F). Following compaction, the set of six specimens were placed in a 60°C (140°F) oven for 24 hours. Subsequent to the 24 hours of curing and then cooling, specimens were weighed in air and submerged in water for density calculations. The six specimens were divided into two groups of nearly equal average density. One group was submerged in hot distilled water at 60°C (140°F) for 24 hours and the second group was stored in a 25°C (77°F) room. After the 24 hour hot water exposure, the three specimens were transferred to a 25°C (77°F) water bath for two hours prior to testing under unconfined compression conditions. The other three dry specimens were then tested under similar conditions. The effect of the hot water exposure is found by dividing the strength of the "wet" specimens by the strength of the "dry" specimens and expressing this ratio as percent retained strength.

Description of Double Punch Debonding Test

The double punch debonding test was developed by Jimenez of the University of Arizona. The procedure is described and published in

Transportation Research Record No. 515 (3). The sequence of steps for this method is similar to those of the immersion-compression procedure, with the following exceptions:

1. Mixing and compaction: size of specimen is 101 mm (4 in.) by 63 mm (2.5 in) and compaction is by a vibratory kneading compactor.
2. Wet exposure: specimen is not cured for 24 hours. After density determination, specimen is submerged in 50°C (122°F) distilled water for a minimum of 45 minutes and is vacuum saturated during this time. Following saturation and submersion, the specimen is stressed by the application of a repeated pore water pressure varying from 34 to 207 kPa (5 to 30 psi) cycling at 10 Hz (580 CPM) for 10 minutes and at a temperature of 50°C (122°F).
3. Strength test: strength of the "wet" or "dry" specimen is obtained by an indirect tensile test referred to as the double punch. Two 25 mm (1 in.) diameter steel punches stress the specimen on the centers of the two flat surfaces. Load is applied at a displacement rate of 25 mm (1 in.) per minute.

TABLE 3

AGUA FRIA AGGREGATE

IMMERSION-COMPRESSION TEST

AVERAGE OF TEST REPLICATES

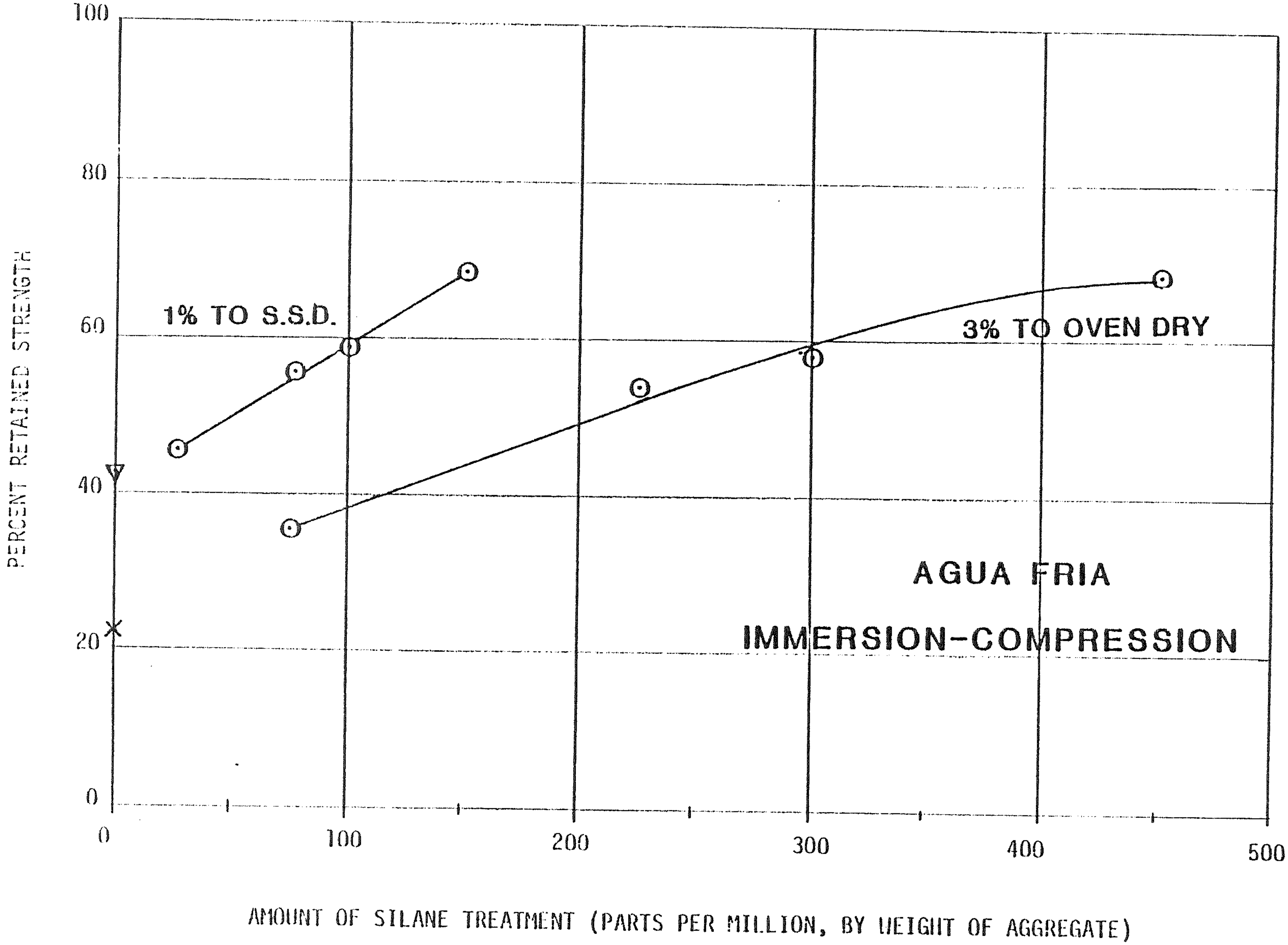
DENSITY PCF	% VOIDS	DRY PSI	WET PSI	DIFF PSI*	NOTE 1 RETAINED STRENGTH	NOTE 2 RETAINED STRENGTH	TREATMENT
142.5	8.3	391	90	301	23	23	Asphalt Only
142.0	8.4	423	182	241	43	47	1% Pavebond Special
3% APPLIED TO OVEN DRY AGGREGATE							
143.0	8.0	439	158	281	36	40	0.25% Silane Concentration
143.5	7.5	511	276	235	54	71	0.75% Silane Concentration
142.5	8.1	464	269	195	58	69	1.00% Silane Concentration
144.0	7.5	510	352	158	69	90	1.50% Silane Concentration
1% APPLIED TO SATURATED SURFACE DRY AGGREGATE							
144.5	7.0	478	220	258	46	56	0.25% Silane Concentration
144.5	6.8	514	288	226	56	74	0.75% Silane Concentration
144.5	6.8	454	268	186	59	69	1.00% Silane Concentration
144.5	6.2	477	329	148	69	84	1.50% Silane Concentration

* Dry PSI Minus Wet PSI

Note 1: $\frac{\text{Wet Strength (Treated)}}{\text{Dry Strength (Treated)}} \times 100\%$

Note 2: $\frac{\text{Wet Strength (Treated)}}{\text{Dry Strength (Untreated)}} \times 100\%$

FIGURE 2



NOTE: × DENOTES NO TREATMENT; ▽ DENOTES PAVEBOND SPECIAL TREATMENT

TABLE 4

AGUA FRIA AGGREGATE

DOUBLE PUNCH TEST

AVERAGE OF TEST REPLICATES

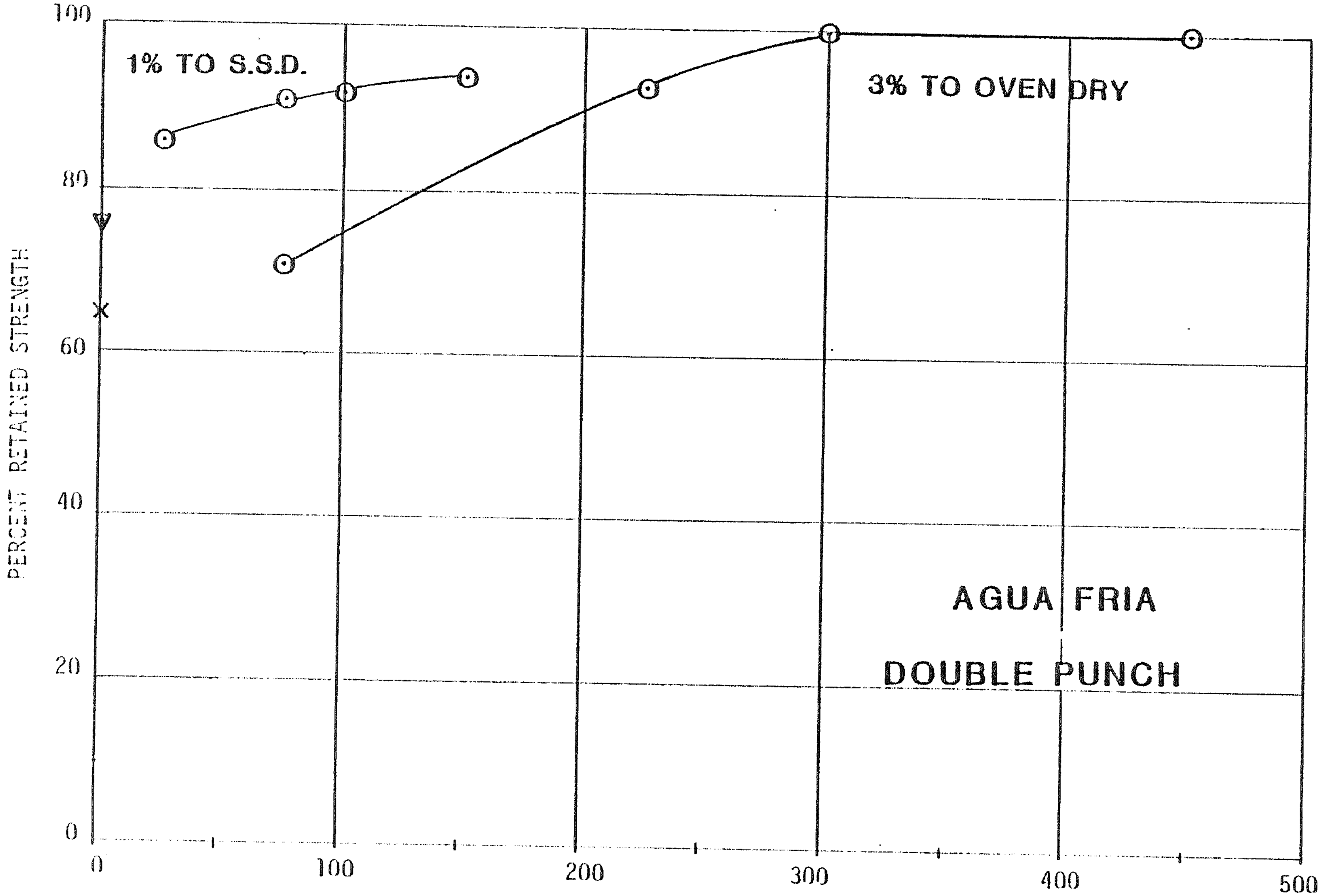
DENSITY PCF	% VOIDS	DRY PSI	WET PSI	DIFF PSI*	NOTE 1 RETAINED STRENGTH	NOTE 2 RETAINED STRENGTH	TREATMENT
149.0	3.8	185	120	65	65	65	Asphalt Only
149.5	3.5	204	155	49	76	84	1% Pavebond Special
		3% APPLIED TO OVEN DRY AGGREGATE					
150.5	3.0	204	145	59	71	78	0.25% Silane Concentration
152.5	1.9	230	214	16	93	116	0.75% Silane Concentration
152.0	2.2	238	238	0	100	129	1.00% Silane Concentration
151.5	2.4	230	230	0	100	124	1.50% Silane Concentration
		1% APPLIED TO SATURATED SURFACE DRY AGGREGATE					
151.0	2.8	158	136	22	86	74	0.25% Silane Concentration
152.0	2.1	193	176	17	91	95	0.75% Silane Concentration
150.5	3.1	151	139	12	92	75	1.00% Silane Concentration
152.0	2.2	169	159	10	94	86	1.50% Silane Concentration

* Dry PSI Minus Wet PSI

Note 1: $\frac{\text{Wet Strength (Treated)}}{\text{Dry Strength (Treated)}} \times 100\%$

Note 2: $\frac{\text{Wet Strength (Treated)}}{\text{Dry Strength (Untreated)}} \times 100\%$

FIGURE 3



AMOUNT OF SILANE TREATMENT (PARTS PER MILLION, BY WEIGHT OF AGGREGATE)

NOTE: X DENOTES NO TREATMENT; ∇ DENOTES PAVEBOND SPECIAL TREATMENT

TABLE 5

SALT RIVER AGGREGATE

19TH AVENUE

IMMERSION-COMPRESSION TEST

AVERAGE OF TEST REPLICATES

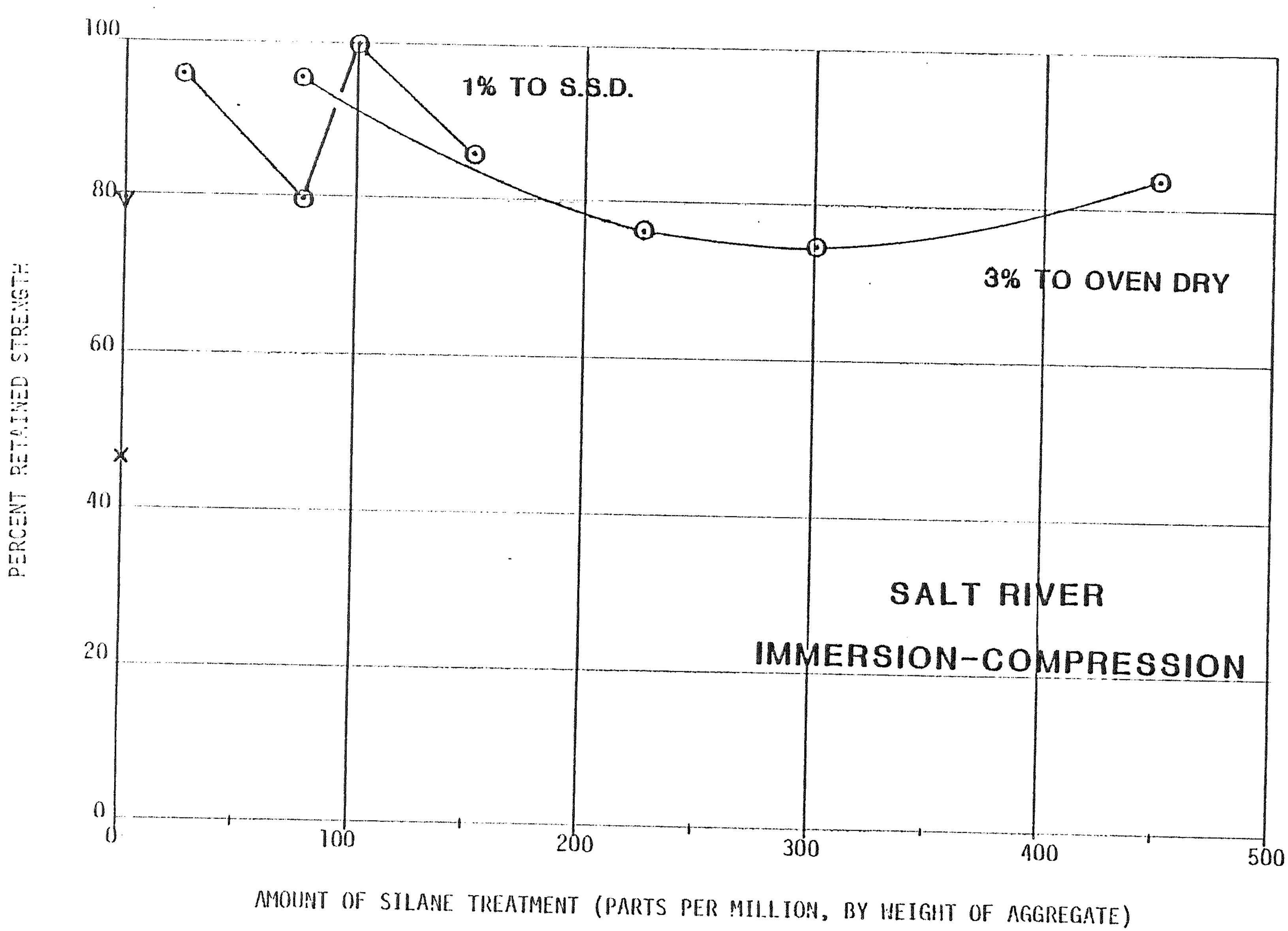
DENSITY PCF	% VOIDS	DRY PSI	WET PSI	DIFF PSI*	NOTE 1 RETAINED STRENGTH	NOTE 2 RETAINED STRENGTH	TREATMENT
142.0	8.1	321	151	170	47	47	Asphalt Only
142.0	8.1	409	327	82	80	102	1% Pavebond Special
			3% APPLIED TO OVEN DRY AGGREGATE				
142.0	8.1	325	312	13	96	97	0.25% Silane Concentration
142.5	7.8	379	292	87	77	91	0.75% Silane Concentration
142.5	7.8	428	321	107	75	100	1.00% Silane Concentration
143.0	7.2	337	283	54	84	88	1.50% Silane Concentration
			1% APPLIED TO SATURATED SURFACE DRY AGGREGATE				
144.5	6.4	498	478	20	96	149	0.25% Silane Concentration
143.0	7.5	419	335	84	80	104	0.75% Silane Concentration
145.0	5.9	537	537	0	100	167	1.00% Silane Concentration
143.5	7.1	447	384	63	86	120	1.50% Silane Concentration

* Dry PSI Minus Wet PSI

Note 1: $\frac{\text{Wet Strength (Treated)}}{\text{Dry Strength (Treated)}} \times 100\%$

Note 2: $\frac{\text{Wet Strength (Treated)}}{\text{Dry Strength (Untreated)}} \times 100\%$

FIGURE 4



NOTE: X DENOTES NO TREATMENT; ▽ DENOTES PAVEBOND SPECIAL TREATMENT

TABLE 6

SALT RIVER AGGREGATE

19TH AVENUE

DOUBLE PUNCH TEST

AVERAGE OF TEST REPLICATES

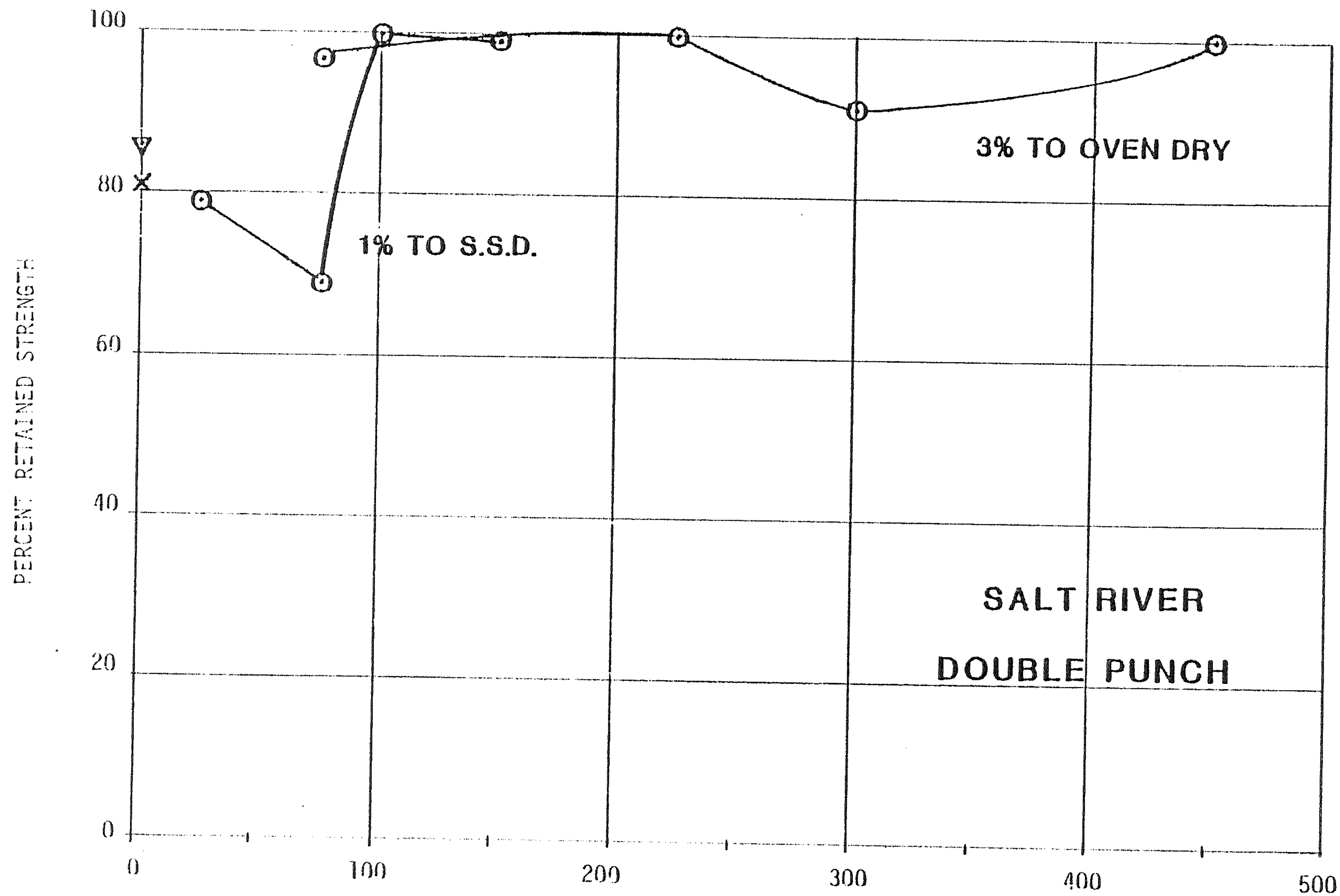
DENSITY PCF	% VOIDS	DRY PSI	WET PSI	DIFF PSI*	NOTE 1 RETAINED STRENGTH	NOTE 1 RETAINED STRENGTH	TREATMENT
149.0	3.6	140	113	27	81	81	Asphalt Only
148.5	3.9	163	140	23	86	100	1% Pavebond Special
			3% APPLIED TO OVEN DRY AGGREGATE				
151.0	2.3	165	160	5	97	114	0.25% Silane Concentration
151.5	2.0	181	181	0	100	129	0.75% Silane Concentration
151.0	2.1	157	143	14	91	102	1.00% Silane Concentration
151.5	1.7	167	167	0	100	119	1.50% Silane Concentration
			1% APPLIED TO SATURATED SURFACE DRY AGGREGATE				
151.0	2.2	172	136	36	79	97	0.25% Silane Concentration
151.5	1.9	207	143	64	69	102	0.75% Silane Concentration
151.5	2.0	200	200	0	100	143	1.00% Silane Concentration
150.5	2.4	181	179	2	99	128	1.50% Silane Concentration

* Dry PSI Minus Wet PSI

Note 1: $\frac{\text{Wet Strength (Treated)}}{\text{Dry Strength (Treated)}} \times 100\%$

Note 2: $\frac{\text{Wet Strength (Treated)}}{\text{Dry Strength (Untreated)}} \times 100\%$

FIGURE 5



NOTE: X DENOTES NO TREATMENT; ▽ DENOTES PAVEBOND SPECIAL TREATMENT