EFFECT OF MICROBIAL DEGRADATION ON BOND BETWEEN ASPHALTIC CONCRETE LAYERS

by

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ABSTRACT

Rutting, cracking, raveling, shoving, stripping and disintegration are responsible for asphalt pavement failures costing this country millions of dollars every year. Traffic loadings are directly responsible for these failures but there are a variety of extenuating and contributing factors. Physical and chemical activity are regarded as the primary causative agents even though numerous studies have shown that a diverse group of microorganisms are capable of degrading asphalt and related hydrocarbons. Thus, it is possible that microorganisms may be responsible for far more asphalt pavement failures than the engineering community currently realize. The primary objective of the research described in this proposal was to determine if, under the proper environmental conditions, microbial degradation could play a role in bond loss and deterioration between two asphaltic concrete layers. Bond loss can be a major contributor to thin overlay failure and stripping in multilayer pavements is often concentrated along layer interfaces.

In this study composite specimens (simulating an overlay situation) were fabricated and tested for interfacial shear strength. The test specimens were divided into groups of eight specimens per group. These groups were treated with different saturation solutions, containing varying amounts of nitrogen, phosphorus, glucose, lime and mercuric chloride. Activated sludge taken from AU's waste oil reprocessing plant was added to some of the saturation solutions. Each eight specimen group was subdivided into four specimen sets. One set (anaerobic) of each group was placed in zip-lock bags and stored for seven months in an environmental chamber controlled to a temperature of 20°C and a relative humidity of approximately 90%. The other set (aerobic) was left uncovered and stored adjacent to the covered group.

Data indicate that microbial degradation can reduce the interfacial shear strength between asphalt layers to a level significantly below that which results from bond loss due only to the presence of water. It was found that the interfacial shear strength of anaerobic specimens was, in general, lower than that for aerobic specimens.

The smallest average ratio interfacial shear strength ratio computed for any group of specimens to the interfacial shear strength of the control group of specimens was 0.16. This value was measured for the water, nitrogen, phosphorus, and microorganisms saturation solution, anaerobic specimen group. It is 0.29 units less than the ratio of 0.45 measured for the water saturated group.

Pictures taken with a scanning microscope indicates the presence of microorganisms, which appeared to be the fungus Geotrichum, at the layer interface.

CONTENTS

INTRODUCTION

Rutting, cracking, raveling, shoving, stripping, and disintegration are responsible for asphalt pavement failure costing this country millions of dollars every year. Traffic loadings are directly responsible for these failures but there are a variety of extenuating and contributing factors. Physical and chemical activity are generally regarded as the primary causative agents. However, given the fact that a number of studies have shown that a diverse group of microorganisms are capable of degrading asphalt and related hydrocarbons, it is possible that microorganisms may contribute to far more asphalt pavement failures than the engineering community currently realize (1).

The primary objective of the work described in this report was to determine if microbial degradation could play a role in bond loss and deterioration at the interface between two asphaltic concrete layers. Bond loss can be a major contributor to thin overlay failure amd stripping in multilayer pavements is often concentrated along layer interfaces.

LITERATURE REVIEW

There is virtually no concern among pavement engineers that microbial activity contributes in any way to asphalt pavement deterioration. Such an attitude has greatly restricted research in this area and effort has been focused on physical and chemical causes. Still, a small number of research projects have been conducted on this subject and results from these studies indicate that even though microbial activity may not be the sole cause of failure in asphalt pavements, in many situations it can be a contributing factor and in certain situations it may be a major contributing factor. As a

contributing factor, microbial activity may weaken asphalt-aggregate bond making it more susceptible to the detrimental effects of water.

The literature review by Ramamurti, Jayaprakash, and Crumpton (1) contains a concise and complete review of past research related to microbial biodeterioration of asphalt and related hydrocarbons up to 1984. They summarize their effort by stating that, "many studies indicate that microorganisms prefer low molecular paraffinic hydrocarbons for their growth and activity. Most of the asphalt used in the U.S. is of petroleum origin with greater amounts of paraffins, than natural asphalts. This increases their vulnerability to microbial attack. The intensity of microbial attack depends on the types of microorganisms, moisture, temperature, oxygen, pH, composition of asphalt, etc. Under favorable conditions, microbial activity could cause rapid oxidation of hydrocarbons but usually any effect on road would take decades".

In 1987 Brown and Darnell (2) published a report dealing with the relationship between microbial activity and blistering of asphalt overlays. Their study was initiated when it was observed that a portion of Mississippi Highway 16, which had been recently overlaid, along with a number of other Mississippi highways which had been recently overlaid, were experiencing a blistering problem. Gas samples from the blisters were found to contain both carbon dioxide and methane which are produced by microbial activity under anaerobic conditions. The original asphalt below the blistered asphalt overlay was deteriorated and a microbial bioassay revealed that it contained 1,000 - 10,000 anaerobic bacteria per gram.

A core drill was used to obtain samples from the overlay and the degraded asphalt layer underneath the overlay. A number of laboratory tests

were conducted to establish the potential detrimental effect of microbial activity on asphaltic concrete material. These included a test to determine the ability of asphalt to support microbial growth.

To make this determination, specimens consisting of old degraded asphalt roadway mixed with a small amount of pure asphalt were prepared. This mixture was placed in the bottom of a 100 ml serum bottle and covered with 50 ml of a nutrient solution prepared from distilled water that had been passed over degraded asphalt. Controls were prepared by adding 1 ml of $HgCl_2$ solution (5.1 g/100 ml H_2O) to identical samples. All serum bottles were incubated for one week at 30°C.

Findings from this test are presented in Table 1. Data presented in this table indicate that a fairly large population of microorganisms can be supported from only the carbon contained in an asphalt mix. This population will increase in size when a supplemental carbon source is provided. On the basis of this information and other similar information obtained during the course of their study, Brown and Darnell (2) concluded that adequate nutrients were present in asphalt mixes to support good microbial growth and that the blisters observed in asphalt overlays were the result of gases produced by anaerobic microorganisms.

In a 1988 study Brown and Pabst (3) investigated the contribution of microorganisms to stripping of asphalt pavements. The basic premise of this work was that since microorganism produce surfactants and emulsifiers, they could play a role in accelerating the stripping process where water replaces the asphalt as the aggregate's coating. In their work, asphalt was applied to gravel by immersion of individual pieces of gravel in hot asphalt cement. The pieces were air dried overnight. Some of the pieces of gravel were treated

with silane before coating with asphalt. Their testing procedure was to place ten appropriately treated pieced of gravel into 6 oz prescription bottles containing nutrient solution and other additives (such as $HgCl_2$ to prevent microbial growth) and to incubate under various conditions. Results from their work are presented in Tables 2-4. Some important observations which can be derived from these data are:

1. Significant stripping was demonstrated in a short period of time (5 to 14 days) under the test conditions employed.

2. Treating the gravel with silane prior to coating with asphalt appeared to reduce the stripping process. Still, even with the silane coating, the contribution of microbial activity to the stripping process was significant.

3. Anaerobic conditions appear to be more conducive to stripping than aerobic conditions.

4. The addition of lime has essentially the same effect on reducing the stripping process as adding $HgCl_2$.

On the basis of their work, Brown and Pabst (3) concluded that microorganisms significantly contribute to the stripping process.

Benefield and Parker (4) investigated the effects of microbial degradation on the tensile strength of asphaltic concrete. In their study, Marshall specimens were fabricated and tested for indirect tensile strength. The test specimens were divided into groups of eight specimens per group. These groups were saturated to 60-80% with solutions, containing varying amounts of nitrogen, phosphorus, glucose, and chlorox (see Table 5). Activated sludge taken from a waste oil reprocessing plant was added to some of the saturation solutions. Each eight specimen group was subdivided into four specimen sets. One set of each group was placed in zip-lock bags and stored for seven months in an environmental chamber controlled to a

temperature of 23°C and a relative humidity of approximately 100%. The other set was left uncovered and stored adjacent to the covered group.

Average tensile strength values were used to compute the tensile strength ratios shown in Figure 1. For the Tunnicliff and Root (5) procedure conditioned specimens are saturated (60-80%) with distilled water and then soaked for 24 hours in distilled water at 140°F. Control specimens are kept dry and tested with condioned specimens. The Tunnicliff and Root ratio is computed by dividing the average tensile strength of the conditioned specimens by the average tensile strength of the control specimens. For specimens conditioned for seven months, ratios were computed by dividing the average tensile strength of specimens saturated with various solutions by the average tensile strength of dry specimens. Dry specimens were stored under the same conditions, i.e., aerobic or anaerobic.

Data presented in Figure 1 indicate that microbial degradation can reduce the tensile strength of asphaltic concrete to a level significantly below that which results from bond loss and stripping due only to the presence of water. It was found that the tensile strength of anaerobic specimens was, in general, lower than that for aerobic specimens. The smallest average tensile strength ratio computed for any group of specimens was 0.502. This value was computed for the water, nitrogen, phosphorus, and microorganism saturation solution, anaerobic specimen. It was 0.338 units or 40% less than the Tunnicliff and Root tensile strength ratio of 0.84 measured for the same asphaltic concrete mixture.

In both the works of Brown and Pabst (3) and Benefield and Parker (4) it was observed that microbial activity could contribute to the stripping process and that anaerobic conditions resulted in a greater coating and strength loss

than aerobic conditions. Saturation conditions also appear to play a major role. In the work of Brown and Pabst (3) all test specimens were submerged in an aqueous solution. In the work of Benefield and Parker (4) the specimens which showed the lowest tensile strength were those inside zip-lock bags. These bags prevent moisture loss and maintain as saturated conditions.

The research described in the proesent report examined the effects of microbial activity on bond loss at the interface between two asphaltic concrete layers. This is a location where pavement deterioration often occurs.

METHODOLOGY

The experimental protocol for this research was essentially the same as that used by Benefield and Parker (4), except that in this work an overlay situation was simulated and bond strength degradation measured. Mix was compacted on top of cores taken from an existing pavement near Dadeville, Alabama. The cores were trimmed and placed in Marshall compaction molds. The asphalt concrete mix used to form the simulated overlays for the tests was a 1 1/2 inch top size base/binder mix that had been used in earlier research (6). The mix is considered by field personnel to be particularly susceptible to stripping although laboratory tests in the earlier research indicated that it should be very resistant to stripping. Aggregate was comprised of 35% uncrushed gravel, 50% coarse washed sand and 15% natural fine sand. The gravel is a "cherty" material (specific gravity≈2.5) with highly variable material types including light and porous particles. Adsorption is relatively high at about 2.5%. The washed sand is from the same source as the gravel and is primarily quartz but the coarser particles tend to be similar to the gravel.

The asphalt content of 4.9% was selected by the Alabama Highway Department with the 50 blow Marshall mix design procedure. A viscosity grade AC-20 asphalt cement was used.

Each composite specimen was formed by compacting the asphalt mix with a manual compactor for 25 blows in a 4-inch Marshall compaction mold containing a 2-inch thick core section. Each core section was positioned with the surface side up, i.e., the side originally forming the pavement surface was interfaced with the asphalt mix. Before placing the core in the mold the surface was cleaned with a steel brush to remove loose material.

After cooling to room temperature the composite specimens were removed from the molds and specific gravity and percent air voids determined in accordance with ASTM D 2726 and ASTM D 3203, respectively. The composite specimens were divided into 14 groups (which included one set of controls) with each group containing 8 composite specimens. The control sets were kept dry but one set each stored in aerobic and anaerobic conditions.

A variety of conditions were simulated by submerging each group of composite specimens in a different solution and vacuum saturating to 60-80%. The degree of saturation was calculated using the relationship:

$$S = \frac{(B-A)}{V(B-C)} \times 100$$

where

S = degree of saturation, %

A = dry weight of composite specimen in air, g

B = weight of surface-dried composite specimen after saturation, g

C = weight of saturated composite specimen in test solution, g

V = percent air voids expressed as a decimal

The different saturation solutions utilized in this research are given in Table 6. Nitrogen (1 mg/L) and phosphorus (0.1 mg/L) are shown as additives to certain of the solution because asphalts are deficient in these nutrients which are required in microbial growth. Glucose (10 mg/L) was also added in some cases to insure the presence of a carbon and energy source. A small concentration of microorganisms from the wastewater treatment plant for Auburn University's waste-oil reprocessing plant was added to a number of the solutions to insure the presence of organisms that have the ability to degrade hydrocarbons. Control units were established by adding Mercuric chloride to kill any microoganisms that were present in the system. The effects of lime addition to the aggregate mix was evaluated by adding lime to the mix of four composite specimens and not saturating the specimens before storage. Four composite specimens were also prepared with lime in the mix and saturated in water before storage.

Eight composite specimens were prepared from each solution shown in Table 6. Four of these composite specimens were sealed in zip-lock bags to develop an anaerobic environment while the other four composite specimens were left exposed, i.e., maintained under aerobic conditions. All composite specimens were placed in storage for seven months in an environmental chamber controlled to a temperature of 20°C and relative humidity of approximately 90%.

After seven months of storage, composite specimens were removed from the environmental chamber. The bulk specific gravity of each composite specimen was measured. The bond between the simulated overlay and the core base was tested for shear strength by modifying a Marshall stability testing machine as shown in Figure 2. A loading head for holding and shearing the specimens was

fabricated from two molds. The composite specimen was first inserted into the loading head and secured. The interface of the simulated overlay and the core base was positioned at the edge of the holding molds. The reaction bar attached to the loading ram on the tester was then moved up to the molds and positioned as close as possible to the interface so that any moment created during loading would be minimized. At initial contact the recorder was zeroed. The load was then applied at a controlled rate of deformation of 2 inches per minute until shear failure along the interface occurred. The interfacial strength was then calculated from the relationship:

$$SS = \frac{P}{IA}$$

where

SS = shear strength, psi

P = maximum load before failure, lb

IA = interface area, in^2

The average interfacial shear strength ratio of each group of conditioned composite specimens was calculated from the relationship:

$$ASSR = \frac{\text{Average interfacial shear strength of saturated group}}{\text{Average interfacial shear strength of dry group}} \times 100$$

Asphalt fragments were taken from the interface of specimens from each group after the direct shear test had been completed. These fragments were prepared and viewed under a scanning electron microscope to confirm the presence of microbial growth and to compare with the fungus type growth observed in the previous study by Benefield and Parker (4).

RESULTS AND DISCUSSION

Values for percent void, percent saturation, initial specific gravity, final specific gravity, and interfacial shear strength for each composite specimen are presented in Table 7. Also included in this table are the average interfacial shear strength for a particular group of four composite specimens, and the average interfacial strength ratio for each group of four composite specimens which was based on the average interfacial shear strength of the appropriate air cured group.

Average interfacial shear strength ratio values presented in Table 7 were used to develop Figure 3 which is a histogram illustrating the relationship between average interfacial shear strength ratio, type of saturation solution, and type of storage environment, i.e., aerobic or anaerobic. The dashed line shown on each histogram represents the average interfacial shear strength ratio for stored composite specimens where only water was used to saturate the composite specimens.

The interfacial shear strength data obtained for the unsaturated, anaerobically stored composite specimens were highly variable and taking the average of such values is not realistic. The values, in Table 7, range from 1.91 to 81.33 psi and it was impossible to determine of the lower two or higher two were more representative. Thus, the average interfacial shear strength from the unsaturated, aerobic stored composite specimens were also used as the control in computing the average interfacial shear strength ratio. In addition, outliers, which were 30 units or more larger than the next closest value, were not used in computing the average interfacial shear strength for the group. This eliminated three data points from Table 7. These were the 89.13 value for the aerobic WG specimen, the 79.88 value for

the aerobic MG specimen, and the 121.36 value for the aerobic MNPG specimen. With these modifications, a modified graphical presentation of the data is given in Figure 4. Data presented in Figure 4 indicate that:

1) The interfacial shear strengths of composite specimens stored in anaerobic conditions are, in general, lower than interfacial strengths for comparable specimens stored in aerobic conditions. The moist anaerobic environment created inside the sealed zip-lock bag provides an ideal environment for biological growth. There is enough moisture to keep chemicals mobile and readily available for utilization by microorganisms.

2) With few exceptions the composite specimens saturated in solutions containing microorganisms from the wastewater treatment plant for Auburn University's waste-oil reprocessing facility showed the lowest average interfacial shear strength ratio values. Such an observation suggests that the presence of a high population of microorganisms capable of hydrocarbon degradation can have a detrimental effect on the bond strength at the interface of the two asphalt layers of an overlay or at the base of an asphalt layer over a base course.

3) The smallest average interfacial shear strength ratio computed (modified data) for a specimen group was 0.16. This was computed for the water, nitrogen, phosphorus, and microorganism saturation solution stored under anaerobic conditions. It is interesting to note that the same specimen group and storage condition gave the smallest average tensile strength ratio for the stripping study reported by Benefield and Parker (4).

4) The four composite specimens stored under anaerobic conditions in the presence of mercuric chloride and with no nutrient addition, gave a higher average interfacial shear strength ratio than did the four specimens saturated with water and stored under anaerobic conditions (0.56 compared to 0.36). This indicates that under high moisture conditions, microbial activity can be quite detrimental to the adhesion bond between two asphalt layers. The same agreement cannot be presented for similar specimens stored outside zip-lock bags where high moisture conditions were not sustained. Under these conditions the presence of mercury actual caused a decrease in the average interfacial shear strength ratio (0.92 with water compared to 0.48 with water and mercury). No explanation can be given for this observation but it probably is a result of the loss in mobility of chemical species within the specimens as the moisture level within the specimens decreases which also changes the chemical characteristics of surfaces. In fact, with the exception of the aerobic WNP specimen group, all other specimen groups stored under aerobic conditions have similar average interfacial shear strength ratios.

5) The addition of lime to the aggregate mix serves to increase the strength of the adhesion bond (average interfacial shear strength ratio 0.44 for lime + W saturated specimens under anaerobic conditions as compared to a value of 0.36 for plain water saturated specimens stored under anaerobic conditions). Still, for the lime and mercuric chloride dosages used in this research,

mercuric chloride seem to be more effective at maintaining adhesion bond strength.

A review of the data presented in Figure 4 shows that the presence of a supplemented population of microorganisms capable of hydrocarbon degradation will reduce the shear strength of the adhesion bond between two asphalt layers to a level significantly below that which results from bond loss due only to the presence of water when high moisture levels are maintained. However, one should not be mislead into thinking that because a supplemented population of microorganisms was required to generate the observed reductions in interfacial shear strength, asphaltic concrete in a natural setting would be immune to microbial attack. Pictures of specimen fragments showed microorganisms growing at the interface of composite specimens where microorganisms had not been added to the saturation solution.

Figure 5-a is a picture of what appears to be the fruiting bodies of the fungus Geotrichum. This picture was taken from a fragment obtained from a water only saturation solution, anaerobic stored specimen. Figure 5-b is a picture of the same microorganisms shown in Figure 5-a except it is at a lower magnification. These photomicrographs were taken from a fragment obtained at the interface of the composite specimen. Figure 6-a, b, c and d are from different fragments of the same specimen used for Figures 5-a and b. Figures 7-a and b are pictures taken from a fragment obtained from the interface of a composite specimen saturated in a water, nitrogen and phosphorus solution and stored in a zip-lock bag. The microorganism shown in Figutres 7-a and 7-b appears to be a fungus, however, it is different from the microorganism shown in the previous photomicrographs.

Figures 8-a and 8-b are pictures taken from an interfacial fragment of a specimen saturated in a mercuric chloride solution and stored in a zip-lock bag. These pictures show that even in the presence of mercury microoganisms will still proliferate on asphalt surfaces. In this case the microorghanism again appears to be the fungus Geotrichum.

Figures 9-a, b, and c are photomicrographs taken from a fragment obtained from the interface of a composite specimen saturated in a water, microorganism, nitrogen, and phosphorus solution and stored under anaerobic conditions. The microorganism shown in these figures appears to be a fungus which is different from the forms previously presented. In this case it appears to be the fungus Mucor.

Microorganisms were present in specimens treated with saturation solutions supplemented with activated sludge, as well as, in specimens treated with saturation solutions which were not supplemented with activated sludge. The primary difference between these specimens was the microbial population density. The microbial population density was much higher in the specimens treated with the saturation solution supplemented with activated sludge. Hence, the effects of microbial activity should be observed much sooner in these samples. However, one would expect to observe a similar effect in the specimens treated with a saturation solution not supplemented with activated sludge after enough time had passed to allow an adequate microbial population density to develop.

SUMMARY

In this study composite specimens were fabricated and tested for interfacial shear strength. The test specimens were divided into groups of eight specimens per group. These groups were treated with different

saturation solutions containing varying amounts of nitrogen, phosphorus, glucose and mercuric chloride. Activated sludge taken from Auburn University's waste oil reprocessing plant was added to some of the saturation solutions. Each eight specimen group was subdivided into 2-four specimen sets. One set of four specimens was placed in zip-lock bags (anaerobic) and stored for seven months in an environmental chamber controlled to a temperature of 20°C and a relative humidity of approximately 90%. The other four specimen group was left uncovered (aerobic) and stored adjacent to the covered group.

It was found that the interfacial shear strength of anaerobic specimens was, in general, lower than that for aerobnic specimens. Data from this study indicate that microbial degradation can reduce the shear strength of the adhesion bond between two asphalt layers to a level significantly below that which results from bond loss due only to the presence of water.

The smallest average interfacial shear strength ratio computed for any group of specimens was 0.16. This value was computed for the water, nitrogen, phosphorus, and microorganisms saturation solution specimens stored under anaerobic conditions.

Pictures taken with a scanning electron microscope indicated the presence of at least three different type of fungi. One appears to be the fungus Geotrichum, another appears to be the fungus Nucor while the third type is unknown at this time.

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Table 1. Analysis of Microbial Activity on Asphalt Material Using Varying Amounts of Carbonaceous, Nitrogenous, and Phosphorus-Containing Nutrients (2).

Sample Mix	CO_2 Produced (μl)	H_2 Produced (μl)	pH (units)	Anaerobes (No./ml)
Asphalt mix control	23 ± 1.41	0	7.05±0.00	<63.00
Asphalt mix	239 ± 12.35	0	6.87±0.01	$3.43\pm0.32 \times 10^3$
ANC	1443 ± 46.81	0	5.93±0.03	$6.0\pm0.56 \times 10^4$
ANC + 500 μg/ml P	2179 ± 34.86	0	5.60±0.02	$3.4\pm0.27 \times 10^5$
APC	2049 ± 5.35	516 ± 8.20	5.13±0.02	$5.8\pm0.22 \times 10^5$
APC + 500 μg/ml N	2422 ± 26.88	124 ± 68.05	4.85±0.02	$7.4\pm0.41 \times 10^5$
APN	169 ± 3.41	0	6.79±0.51	$6.4\pm0.38 \times 10^3$
APN + 500 μg/ml C	363 ± 16.43	0	6.76±0.01	$4.2\pm0.71 \times 10^4$

The asphalt mix control contained 1 ml $HgCl_2$ solution (5.1 g/100 ml H_2))

All values are the average of four determinations

A = asphalt overlay

P = K_2HPO_4 added (final concentration 50 μg P/ml)

N = NH_4NO_3 added (final concentration 100 μg N/ml)

C = glucose added (final concentration 2 mg glucose/ml)

Table 2. Asphalt Loss in Test Systems Evaluating the Impact of Silane on Stripping (3).

System	Treatment	Number of Pieces of Gravel Showing Asphalt Losses of None	<25%	25-50%	50-75%	75-100%	Loss Index*	% Showing 25% or Less Loss	% Showing More Than 25% Loss
1	$HgCl_2$, aerobic	8	10	9	9	4	1.8	45	55
2	Aerobic	0	15	13	12	0	1.9	38	62
3	$HgCl_2$, aerobic, 1/25 silane	23	9	7	1	0	0.7	80	20
4	Aerobic, 1/25 silane	14	14	10	2	0	1.0	70	30
5	$HgCl_2$, aerobic, 1/100 silane	13	24	3	0	0	0.8	93	7
6	Aerobic, 1/100 silane	17	21	2	0	0	0.6	96	4
7	$HgCl_2$, aerobic, 1/250 silane	13	15	12	0	0	1.0	70	30
8	Aerobic, 1/250 silane	5	24	11	0	0	1.2	73	27

* Loss Index = $\frac{[(\text{No. showing } <25\%)(1)] + [(\text{No. showing } 25\text{-}50\%)(2)] + [(\text{No. showing } 50\text{-}75\% (3)] + [(\text{No. showing } 75\text{-}100\%)(4)]}{\text{No. tested}}$

1/25, 1/100, 1/250 represent dilution of silane in water

Table 3. Asphalt Loss in Test Systems Evaluating the Effect of Oxygen and an Added Carbon Source on Stripping (3).

System	Treatment	Number of Pieces of Gravel Showing Asphalt Losses of None	<25%	25-50%	50-75%	75-100%	Loss Index*	% Showing 25% or Less Loss	% Showing More Than 25% Loss
1	$HgCl_2$, aerobic	8	10	9	9	4	1.8	45	55
2	Aerobic	0	15	13	12	0	1.9	38	62
3	$HgCl_2$, anaerobic	4	10	18	8	0	1.8	35	65
4	Anaerobic	0	10	18	8	0	2.3	8	92
5	$HgCl_2$, aerobic, 1% SLS	7	6	10	10	7	2.1	33	67
6	Aerobic, 1% SLS	0	14	15	9	1	1.9	36	64
7	$HgCl_2$, anaerobic, 1% SLS	1	21	13	5	0	1.6	55	45
8	Anaerobic, 1% SLS	0	0	13	21	5	2.8	0	100
9	$HgCl_2$, aerobic, 1% glucose	0	4	12	19	5	2.6	10	90
10	Aerobic, 1% glucose	0	1	3	25	11	3.2	3	97
11	$HgCl_2$, anaerobic, 1% glucose	0	1	7	29	3	2.9	3	97
12	Anaerobic, 1% glucose	0	1	9	20	10	3.0	3	97

* Loss Index = $\dfrac{[(\text{No. showing } <25\%)(1))] + [(\text{No. showing } 25\text{-}50\%)(2)] + [(\text{No. showing } 50\text{-}75\%)(3)] + [(\text{No. showing } 75\text{-}100\%)(4)]}{\text{No. tested}}$

SLS represents the addition of the biodegradable surfactant sodium lauryl sulfate.

Table 4. Asphalt Loss in Test Systems Where Lime is Added (3).

System	Number of Pieces of Gravel Showing Asphalt Losses of None	<25%	25-50%	50-75%	75-100%	Loss Index	% Showing 25% or Less Loss	% Showing More Than 25% Loss
Asphalt	5	16	11	12	5	1.92	43	57
Asphalt + $HgCl_2$	21	24	5	0	0	0.68	90	10
Asphalt + Glucose	5	22	15	6	2	1.30	54	46
Asphalt + Lime	10	36	4	0	0	0.88	92	8
Asphalt + Glucose + Lime	19	26	4	1	0	0.74	90	10

Lime concentration was 1g per 100ml.

$$\text{Loss Index} = \frac{[(\text{No. showing } <25\%)(1)] + [(\text{No. showing } 25\text{-}50\%)(2)] + [(\text{No. showing } 50\text{-}75\%)(3)] + [(\text{No. showing } 75\text{-}100\%)(4)]}{\text{No. tested}}$$

Table 5. Composition of Saturation Solutions Used to Condition Specimens (4).

Solution Number	Solution Composition*
1	W
2	WNP
3	WG
4	WNPG
5	WM
6	WNPM
7	WMG
8	WNPGM
9	WC
10	WNPC
11	WGC
12	WNPGC

*W: Distilled water with KCl, $NaHCO_3$ and $CaSO_4$ (Ionic strength of 0.001 M) to simulate ground water
N: 10 mg/L ammonia nitrogen
P: 1.0 mg/L orthophosphate
G: 10 mg/L glucose
M: 10 ML of microbial suspension from waste oil wastewater treatment plant
C: 0.1% chlorox solution

Table 6. Composition of Saturation Solutions Used to Condition Specimens

Solution Number	Solution Composition*
1	W
2	WNP
3	WG
4	WNPG
5	H
6	HNP
7	HG
8	HNPG
9	M
10	MNP
11	MG
12	MNPG
13	Lime (4 Specimens) Lime + W (4 Specimens)

*W: Distilled water with KCl, $NaHCO_3$ and $CaSO_4$ (Ionic strength of 0.001 M) to simulate ground water
N: 10 mg/L ammonia nitrogen
P: 1.0 mg/L orthophosphate
G: 10 mg/L glucose
M: 10 ML of microbial suspension from waste oil wastewater treatment plant
H: Mercuric Chloride (10 mg/L as Hg)
Lime: 10 g/specimen

Table 7. Experimental Data Obtained During Research Period.

Specimen Number	Type of Saturation Solution	Storage Environment		Percent Voids	Percent Saturation	Specific Gravity		Shear Strength (psi)	Average Shear Strength (psi)	Average Shear Strength Ratio
		Anaerobic	Aerobic			Initial	Final			
1	None	X		5.23	-0-	2.24	2.28	47.75		
2	None	X		4.78	-0-	2.25	2.25	81.33		35.22
3	None	X		6.26	-0-	2.21	2.21	1.91		
4	None	X		8.27	-0-	2.17	2.22	9.87		
1	None		X	5.13	-0-	2.24	2.25	66.37		
2	None		X	4.87	-0-	2.24	2.24	44.56	43.81	
3	None		X	6.30	-0-	2.21	2.24	35.81		
4	None		X	8.19	-0-	2.17	2.22	28.49		
1	W	X		5.79	77.7	2.22	2.27	27.85		
2	W	X		7.98	76.3	2.17	2.29	17.35		15.98
0.45										
3	W	X		4.82	82.5	2.25	2.29	3.18		
4	W	X		5.92	74.7	2.22	2.27	15.52		
1	W		X	5.68	77.2	2.23	2.25	31.91		
2	W		X	5.24	75.2	2.24	2.27	42.18		40.11
0.92										
3	W		X	7.81	78.4	2.18	2.23	46.15		
4	W		X	5.87	76.3	2.22	2.24	40.19		
1	WNP	X		5.10	67.9	2.24	2.26	19.26		
2	WNP	X		5.58	70.2	2.23	2.25	16.79		13.89
0.39										
3	WNP	X		7.49	79.3	2.18	2.27	17.19		
4	WNP	X		6.31	67.9	2.21	2.27	2.31		
1	WNP		X	5.98	79.7	2.22	2.24	53.95		
2	WNP		X	6.96	76.8	2.20	2.24	26.10		35.61
0.81										
3	WNP		X	6.31	78.7	2.21	2.25	44.88		
4	WNP		X	5.32	72.2	2.23	2.25	17.51		

Table 7. Experimental Data Obtained During Research Period (continued).

Specimen Number	Type of Saturation Solution	Storage Environment		Percent Voids	Percent Saturation	Specific Gravity		Shear Strength (psi)	Average Shear Strength (psi)	Average Shear Strength Ratio
		Anaerobic	Aerobic			Initial	Final			
1	WG	X		6.85	70.6	2.20	2.24	37.32		
2	WG	X		5.33	66.1	2.23	2.30	12.72	8.99	0.26
3	WG	X		5.87	81.7	2.22	2.25	1.91		
4	WG	X		8.27	73.0	2.17	2.22	10.19		
1	WG		X	5.45	79.1	2.23	2.27	32.23		
2	WG		X	6.32	65.6	2.21	2.26	4.77	38.87	0.89
3	WG		X	6.30	63.9	2.21	2.25	89.13		
4	WG		X	6.29	60.6	2.21	2.26	29.36		
1	WNPG	X		4.80	71.5	2.25	2.29	17.51		
2	WNPG	X		5.64	80.1	2.23	2.25	17.51	17.39	0.49
3	WNPG	X		7.31	71.7	2.19	2.25	28.25		
4	WNPG	X		6.93	74.1	2.20	2.26	6.29		
1	WNPG		X	7.30	66.0	2.19	2.23	14.64		
2	WNPG		X	4.96	77.1	2.24	2.25	18.38	23.18	0.53
3	WNPG		X	5.96	62.9	2.22	2.25	34.22		
4	WNPG		X	6.54	69.6	2.21	2.24	25.64		
1	H	X		4.25	76.6	2.26	2.30	33.82		
2	H	X		6.27	64.8	2.21	2.26	16.15	24.77	0.70
3	H	X		10.86	68.2	2.10	2.26	8.36		
4	H	X		4.01	78.8	2.27	2.28	40.74		
1	H		X	10.34	73.6	2.12	2.24	22.28		
2	H		X	6.46	64.2	2.21	2.26	0.00	24.77	0.70
3	H		X	4.44	68.7	2.26	2.27	28.65		
4	H		X	4.16	68.1	2.26	2.27	12.03		

Table 7. Experimental Data Obtained During Research Period (continued).

Specimen Number	Type of Saturation Solution	Storage Environment		Percent Voids	Percent Saturation	Specific Gravity		Shear Strength (psi)	Average Shear Strength (psi)	Average Shear Strength Ratio
		Anaerobic	Aerobic			Initial	Final			
1	HNP	X		6.53	63.1	2.21	2.27	6.45		
2	HNP	X		9.45	63.7	2.14	2.24	5.65	12.38	0.35
3	HNP	X		4.43	69.5	2.26	2.28	19.50		
4	HNP	X		5.00	80.0	2.24	2.27	17.90		
1	HNP		X	4.58	74.1	2.25	2.25	3.58		
2	HNP		X	4.80	77.5	2.25	2.26	9.55	11.88	0.27
3	HNP		X	6.60	65.2	2.20	2.24	16.71		
4	HNP		X	9.49	75.5	2.14	2.24	17.67		
1	HG	X		9.15	70.8	2.14	2.27	12.73		
2	HG	X		5.84	80.7	2.22	2.29	15.12	17.21	0.49
3	HG	X		4.61	60.9	2.51	2.28	24.27		
4	HG	X		5.87	60.6	2.22	2.25	16.71		
1	HG		X	8.68	60.6	2.15	2.23	15.92		
2	HG		X	5.68	79.0	2.23	2.26	27.06	24.33	0.56
3	HG		X	4.83	77.4	2.25	2.25	25.86		
4	HG		X	6.29	80.2	2.21	2.24	28.49		
1	HNPG	X		5.12	79.9	2.24	2.27	13.53		
2	HNPG	X		6.64	68.6	2.20	2.27	16.31	16.63	0.47
3	HNPG	X		5.52	80.4	2.23	2.29	17.90		
4	HNPG	X		8.42	74.5	2.16	2.28	18.78		
1	HNPG		X	5.24	70.4	2.24	2.31	15.92		
2	HNPG		X	5.15	74.6	2.24	2.27	36.61	19.52	0.45
3	HNPG		X	7.94	68.9	2.17	2.24	7.96		
4	HNPG		X	7.13	65.2	2.19	2.25	17.59		

Table 7. Experimental Data Obtained During Research Period (continued).

Specimen Number	Type of Saturation Solution	Storage Environment		Percent Voids	Percent Saturation	Specific Gravity		Shear Strength (psi)	Average Shear Strength (psi)	Average Shear Strength Ratio
		Anaerobic	Aerobic			Initial	Final			
1	M	X		5.74	80.1	2.23	2.28	15.28		
2	M	X		7.79	77.5	2.18	2.26	10.74	12.89	0.37
3	M	X		5.34	59.4	2.23	2.28	13.13		
4	M	X		6.58	61.5	2.21	2.24	12.41		
1	M		X	7.20	62.5	2.19	2.24	27.93		
2	M		X	6.99	68.2	2.20	2.23	15.04	18.18	0.42
3	M		X	5.96	70.1	2.22	2.23	13.05		
4	M		X	5.27	62.7	2.24	2.23	16.71		
1	MNP	X		6.59	78.3	2.21	2.28	2.79		
2	MNP	X		5.71	79.4	2.23	2.27	15.84	12.04	0.34
3	MNP	X		7.03	79.4	2.19	2.27	12.02		
4	MNP	X		6.14	74.6	2.21	2.28	17.51		
1	MNP		X	5.71	59.4	2.23	2.27	19.10		
2	MNP		X	6.88	60.7	2.20	2.25	21.65	19.18	0.44
3	MNP		X	5.95	67.0	2.22	2.26	22.04		
4	MNP		X	6.87	62.3	2.20	2.24	13.93		
1	MG	X		6.63	76.4	2.20	2.27	16.00		
2	MG	X		6.67	72.9	2.20	2.28	7.32	7.86	0.22
3	MG	X		4.21	76.7	2.26	2.32	6.37		
4	MG	X		8.38	75.1	2.16	2.21	1.57		
1	MG		X	5.94	71.8	2.22	2.25	20.69		
2	MG		X	5.72	75.1	2.23	2.25	46.47	42.42	0.97
3	MG		X	8.51	63.7	2.16	2.25	22.68		
4	MG		X	5.68	76.7	2.23	2.23	79.58		

Table 7. Experimental Data Obtained During Research Period (continued).

Specimen Number	Type of Saturation Solution	Storage Environment		Percent Voids	Percent Saturation	Specific Gravity		Shear Strength (psi)	Average Shear Strength (psi)	Average Shear Strength Ratio
		Anaerobic	Aerobic			Initial	Final			
1	MNPG	X		6.63	77.1	2.20	2.26	1.19		
2	MNPG	X		5.75	69.7	2.22	2.25	17.59	7.12	0.20
3	MNPG	X		7.11	64.0	2.19	2.30	6.05		
4	MNPG	X		6.45	69.1	2.21	2.27	3.66		
1	MNPG		X	6.84	76.8	2.20	2.23	9.95		
2	MNPG		X	5.92	81.0	2.22	2.26	13.69	43.27	0.99
3	MNPG		X	6.81	71.8	2.20	2.25	28.09		
4	MNPG		X	6.17	79.4	2.21	2.24	121.36		
1	Lime	X		5.19	-0-	2.24	2.23	23.55		
2	Lime	X		4.04	-0-	2.27	2.25	28.97	30.72	0.87
3	Lime	X		4.91	-0-	2.24	2.25	21.96		
4	Lime	X		6.36	-0-	2.21	2.23	48.38		
1	Lime + W	X		4.95	76.4	2.24	2.28	19.89		
2	Lime + W	X		5.42	67.9	2.23	2.27	14.16	19.26	0.44
3	Lime + W	X		4.90	81.4	2.24	2.26	29.05		
4	Lime + W	X		5.11	74.6	2.24	2.27	13.93		

Solid Line: Tunnicliff and Root tensile strength ratio

Dashed Line: Water only saturation solution tensile strength ratio

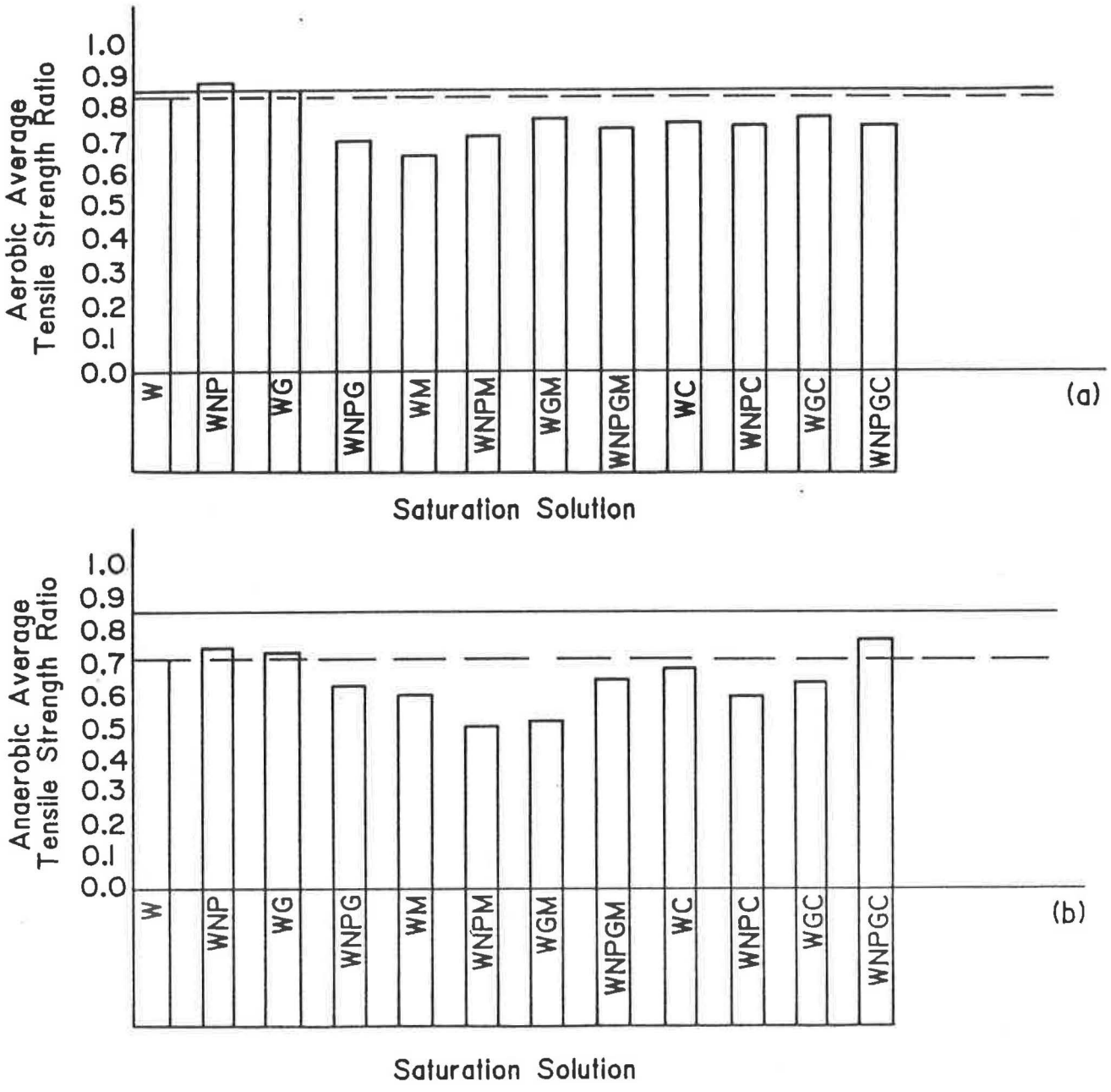
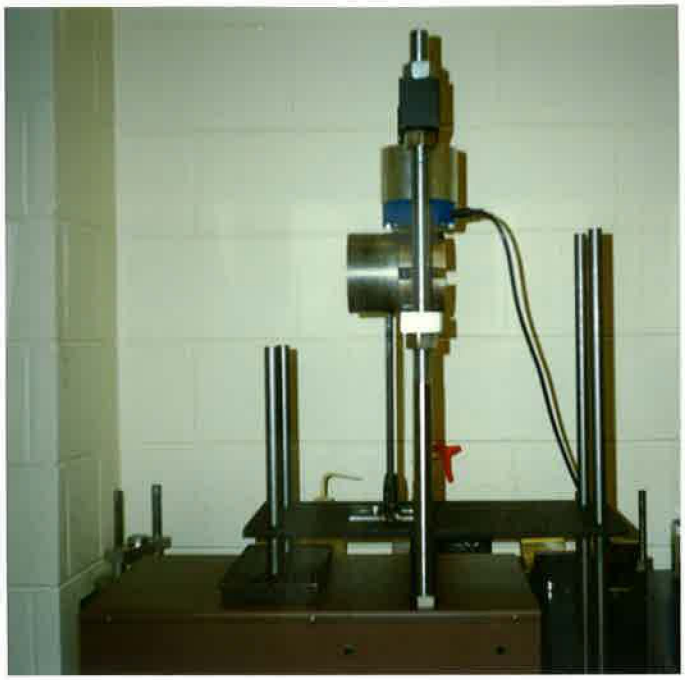


Figure 1: Histogram illustrating the Relationship Between Tensile Strength Ratio, Type of Saturation Solution, and of Storage Environment.

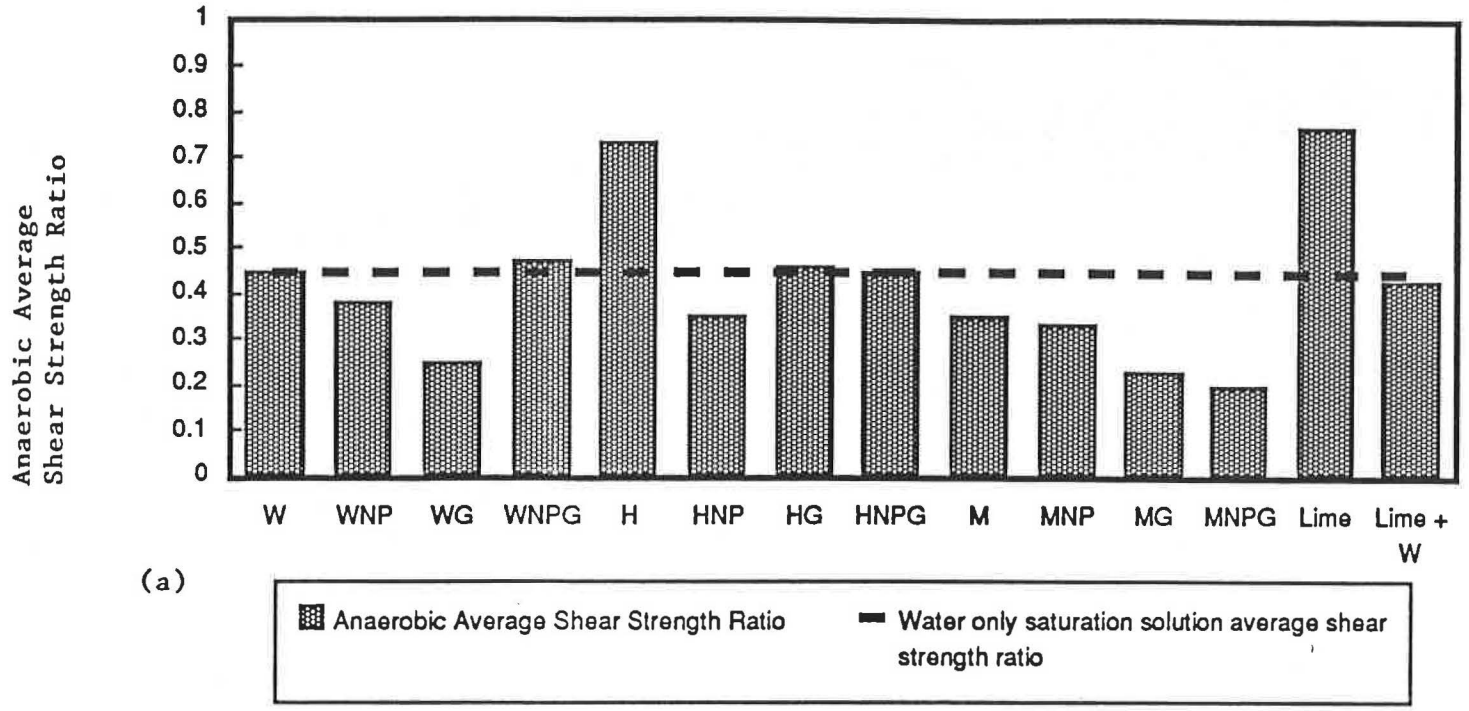


a. side view of apparatus

b. end view of apparatus

Figure 2. Apparatus Used for Measuring Shear Strength of Composite Specimens.

Dashed Line: Water only saturation solution average shear strength ratio.



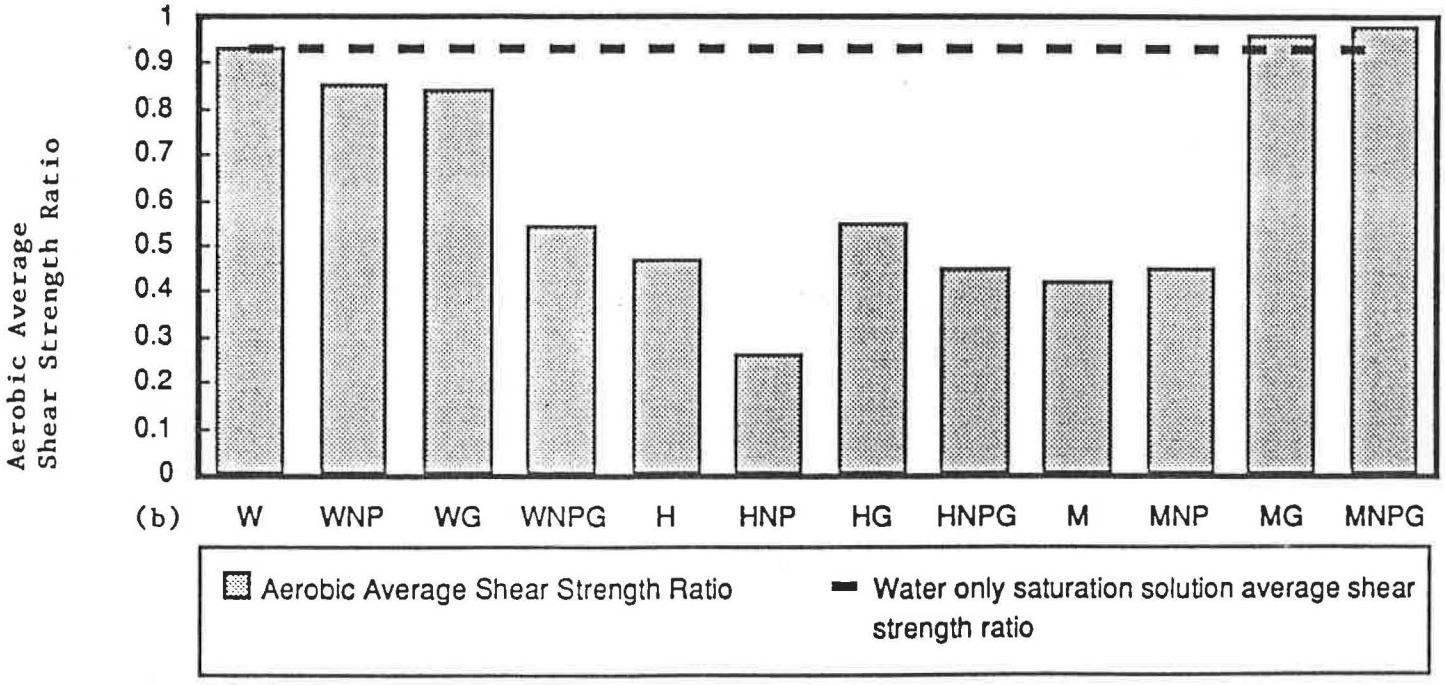


Figure 3: Histogram Illustrating the Relationship Between Average Shear Strength Ratio, Type of Preconditioning of Specimen, and Specimen Storage Environment.

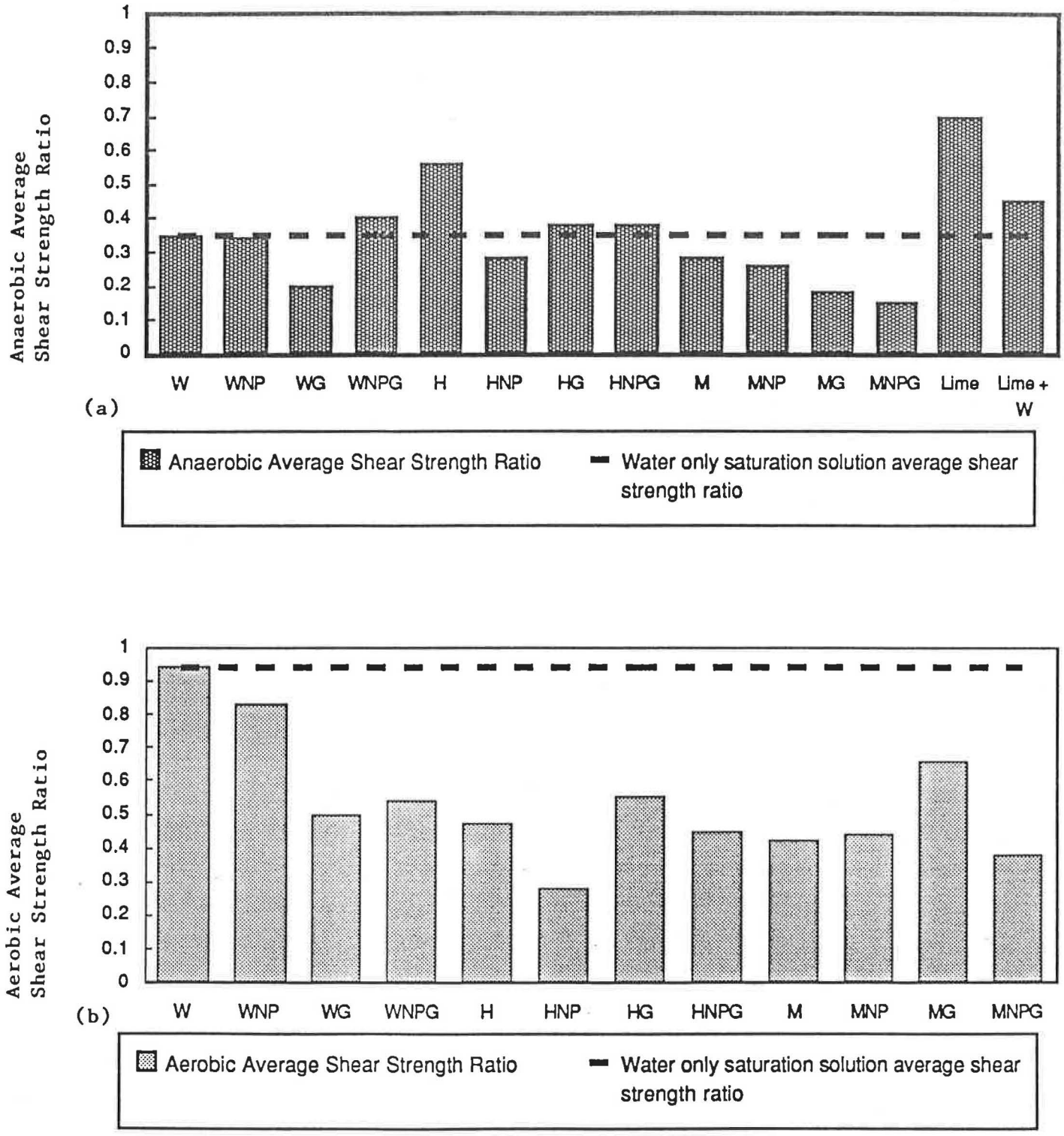
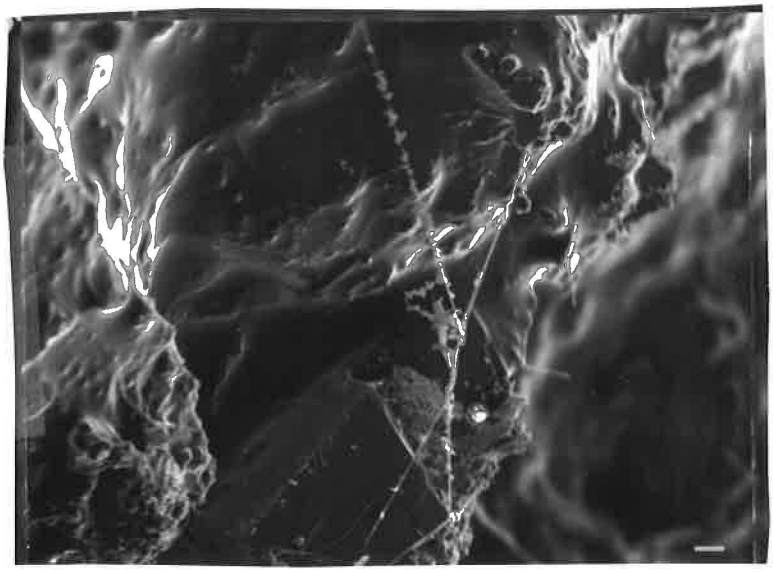


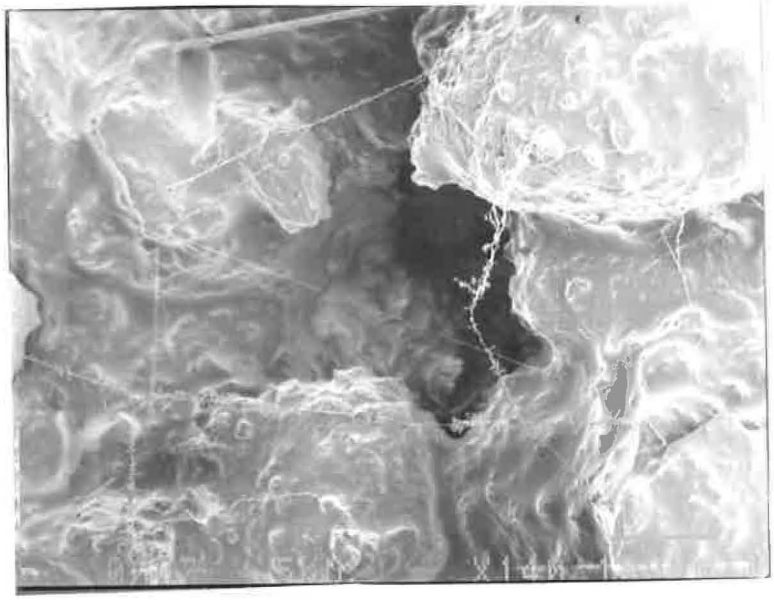
Figure 4: Modified Data Histogram Illustrating the Relationship Between Average Shear Strength Ratio, Type of Preconditioning of Specimen, and Specimen Storage Environment.

a)

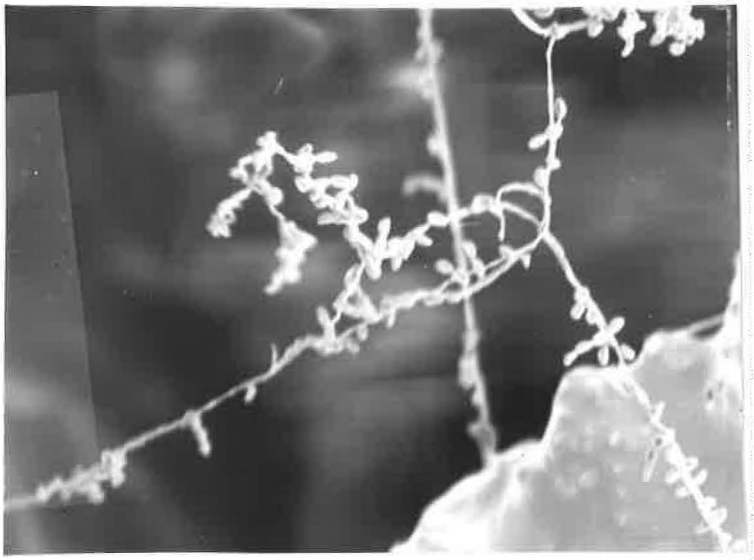


b)

Figure 5: Photomicrographs Taken from an Interfacial Fragment of a Composite Specimen Saturated in a Water Only Solution and Stored in a Zip-Lock Bag.



a)



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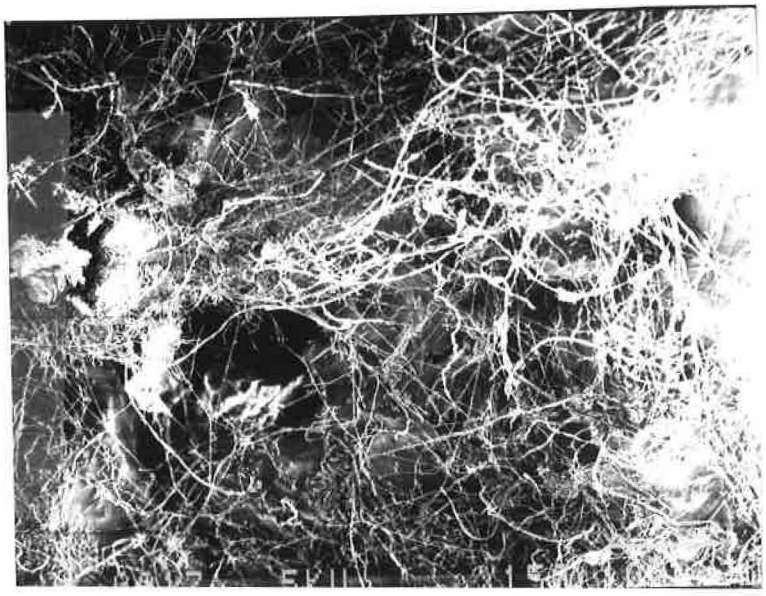
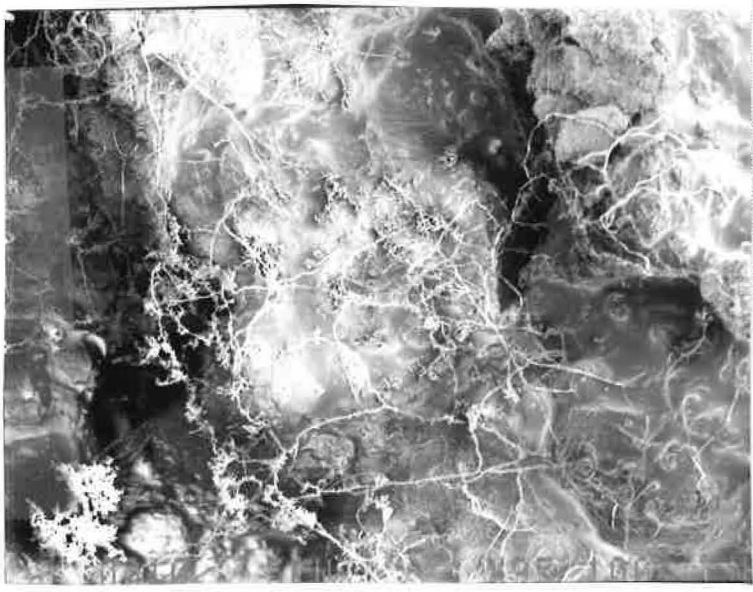


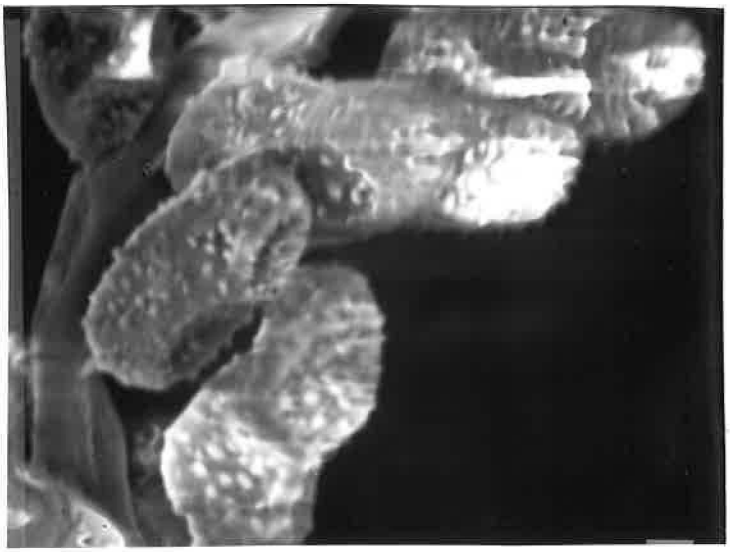
c)



d)

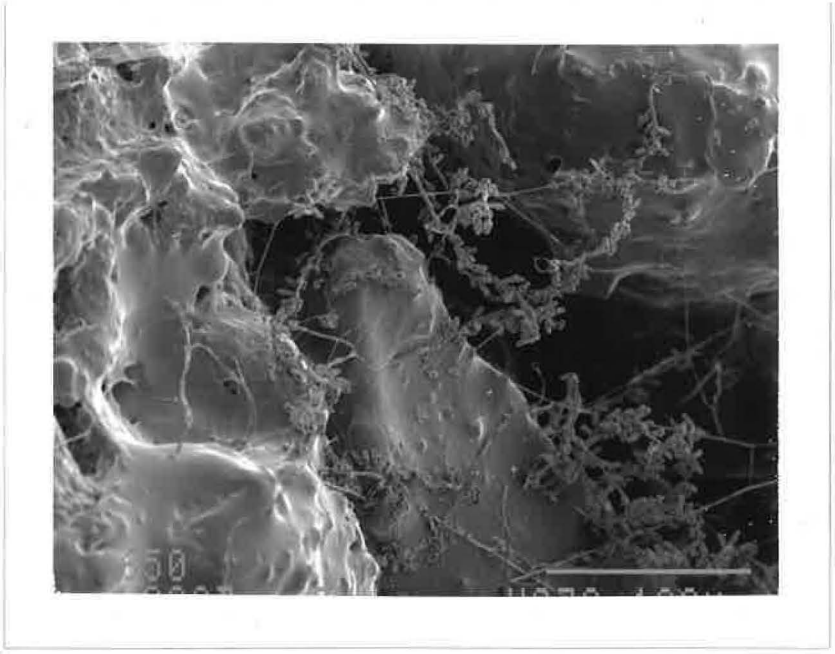
Figure 6: Photomicrographs Taken from an Interfacial Fragment of a Composite Speicmen Saturated in a Water Only Solution and Stored in a Zip-Lock Bag.

a)

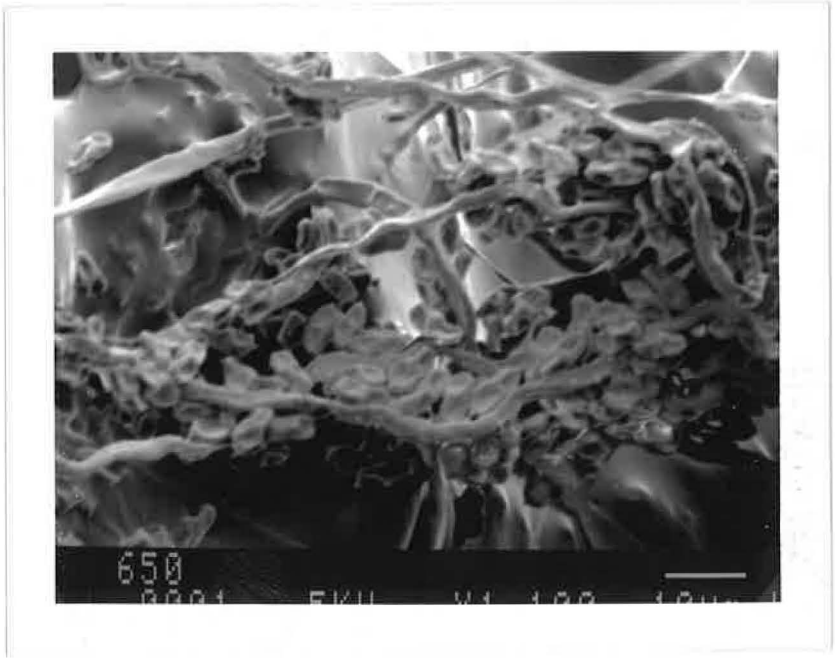


b)

Figure 7: Photomicrographs Taken from an Interfacial Fragment of a Composite Specimen Saturated in a Water, Nitrogen, and Phosphorus Solution and Stored in a Zip-Lock Bag.

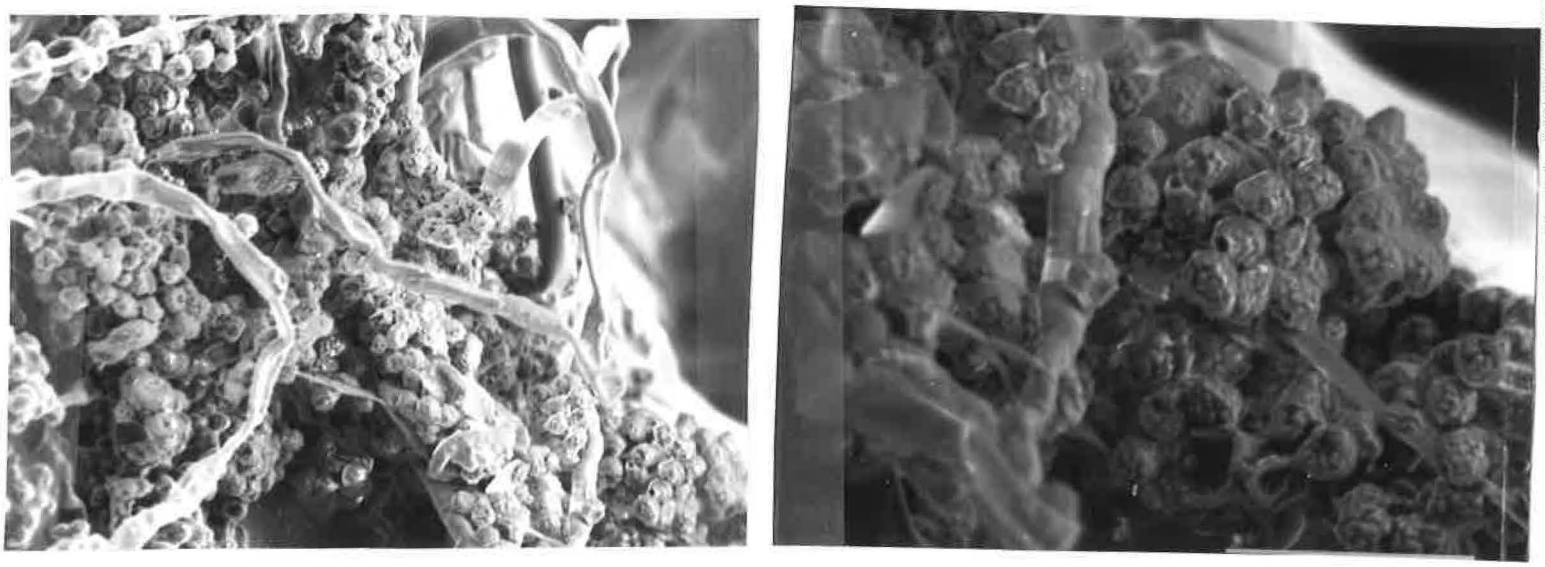


a)

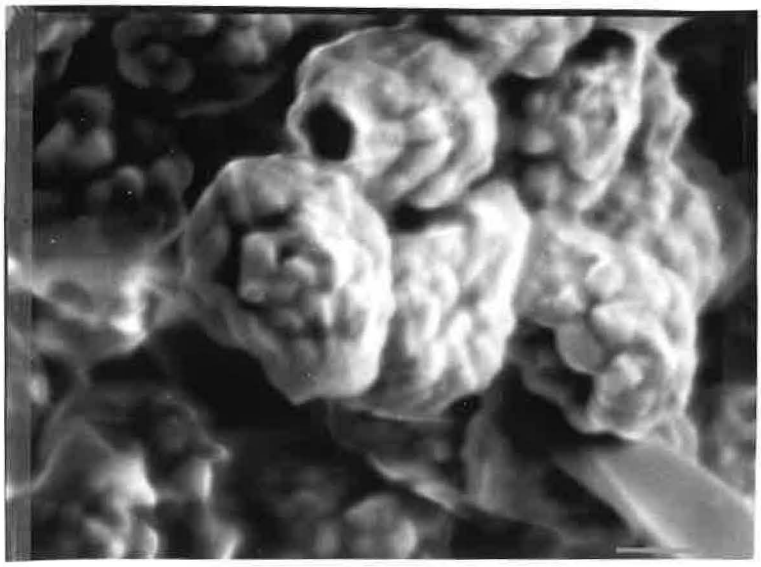


b)

Figure 8: Photomicrographs Taken from an Interfacial Fragment of a Composite Specimen Saturated in a Water and Mercuric Chloride Solution and Stored in a Zip-Lock Bag.



a) b)



c)

Figure 9: Photomicrographs Taken from an Interfacial Fragment of a Composite Specimen Saturated in a Water Microorganism, Nitrogen, and Phosphorus Solution and Stored in a Zip-Lock Bag.