THE EFFECTS OF SEVERAL CHEMICAL SOIL CONDITIONERS AND AN ALGAL POLYMER ON COMPACTED SOIL AND GROWTH OF COOL SEASON TURFGRASSES

A Thesis Presented

By

ANTHONY MARTIN PETROVIC

Submitted to the Graduate School of the

University of Massachusetts in

partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

September 1975

Major Subject Soil Physics

THE EFFECTS OF SEVERAL CHEMICAL SOIL CONDITIONERS AND AN ALGAL POLYMER ON COMPACTED SOIL AND GROWTH OF COOL SEASON TURFGRASSES

A Thesis

By

ANTHONY MARTIN PETROVIC

Approved as to style and content by:

Robert N. Carrow

(Robert N. Carrow, Chairman of Committee)

Joseph Troll

(Joseph Troll, Member)

John M Zak

(John M. Zak, Member)

F.W. Southwick

(Franklin W. Southwick, Head,
Department of Plant and Soil Sciences)

September 1975

ACKNOWLEDGEMENTS

I wish to express my deepest gratitude and appreciation to Dr. Robert N. Carrow, Chairman of my Thesis Committee, for his advice, encouragement and assistance throughout this investigation.

Expressions of gratitude are also extended to Dr. Joseph Troll and Prof. John M. Zak, Thesis Committee members, for their advice.

To Renie, whose patience, warmth and understanding during the preparation of this thesis, is greatly appreciated.

TABLE OF CONTENTS

RESULTS

LIST OF TABLES

Page

LIST OF FIGURES

INTRODUCTION

Soil physical properties play a major role in the growth and development of plants. Soil compaction may destroy soil structure and create poor aeration, high moisture conditions and considerable mechanical resistance for root growth.

Over the past several decades, there has been an increased use of recreational areas such as sports fields and parks. The continual passing of people and machinery over the same site creates the problem of compaction on turfgrass areas. Current practices such as soil modification with soil physical amendments and periodic aerification are used on turfgrass soils to reduce the effects of compaction; however, the cost and time factors associated with such practices are considerable.

The recent development of relatively inexpensive synthetic chemical soil conditioners has caused a resurgence of interest in soil conditioning. These products have potential for improving compacted soil physical properties; however, they have not been evaluated under such conditions.

The purpose of this investigation was two-fold: first, to determine if soils treated with several chemical soil conditioners could maintain a stable structure under compaction while improving the growth of cool season grasses; second, whether an algal polymer culture of the soil algal *Chalmydomonas mexicana* had soil conditioning capability under laboratory and field conditions.

LITERATURE REVIEW

Soil Compaction

Problem

A desirable soil structure is one which will not hinder the movement of water, nutrients, and oxygen to the plant and which will allow for proper plant growth (8). Deterioration of structure by compactive forces is a common problem on heavily trafficked areas.

Harris (38) described soil compaction as a change in the volume of the soil. Forces that can change soil volume are traffic from people and machinery, and natural forces, such as rainfall impact, and wetting and drying of the soil (38). Baver *et al*. (7) defined soil compaction as an increase in soil density as a result of applied pressure. The degree to which any soil can be compacted depends on the moisture content of the soil and the magnitude of the compactive force (7).

In recent years the demand for recreational areas such as golf courses, parks, etc., has increased substantially. The repeated passing of people and machinery over the same site creates the problem of soil compaction on turfgrass areas which in turn contributes to a decline in the turfgrass quality and vigor. Madison (38) has stated, "Today, compaction is the foremost turf problem."

Soil Physical Responses to Compaction

An increase in soil density can result in the alteration of a number of soil physical properties, such as the aggregate stability of the soil. Hubbell and Gardner (45) noted that when Gila clay soil was compacted at a pressure of 2.42 bar, the water stable aggregation decreased from 65% for noncompacted soil to 32% for compacted soil.According to Vomocil and Flocker (92), an increase in bulk density from 1.5g/cc to 1.8g/cc decreased the aggregate stability from 9.4% to 1.5%, respectively. The decline in aggregate stability was attributed to the change in aggregate shape from granular to plate-like. Beacher and Stickling (9) observed a negative correlation between aggregate stability and bulk density; the more dense the aggregates became the less water stable they were.

The moisture retention properties are also influenced by soil compaction. For most soil types, Hill and Summer (42) concluded that moderate compaction increased the moisture content at a constant matric suction. Trouse *et al*. (86) and Veihmeyer *et al*. (91) noted that as compaction became more severe, the moisture content of the soil increased. However, Reeve *et al*. (71) observed that for sandy and silty soils, the retained water capacity at 0.05 bar suction declined with an increase in bulk density.

Compaction has been found to reduce water percolation substantially (80). A fourteen-fold decrease in water percolation rate on severely compacted field plots compared to noncompacted plots was observed by Cordukes (19). Infiltration rates have also been reported to decrease under compacted soil conditions (3 ,62).

Soil compaction may produce poor aeration conditions. The oxygen diffusion rate (ODR), which is a measure of soil aeration, was found to be significantly lower in compacted than in noncompacted soil (20). Letey et al. (53) observed the ODR on compacted soil to be 15 g O_2 X $10^{-8}cm^{-2}min^{-1}$ as compared to 20g O_2 X $10^{-8}cm^{-2}min^{-1}$ on noncompacted soil. As noted by Van Diest (89), ODR decreased from 32g O_2 X $10^{-8}cm^{-2}min^{-1}$ on control plots to 10g O_2 X $10^{-8}cm^{-2}min^{-1}$ where compaction was applied.

An increase in soil strength has been associated with compaction. With an increase in bulk density, Hughes et al. (46) observed an increase in soil strength, regardless of soil water pressure. Vomocil and Flocker (92) reported that field plots receiving vehicle compaction for six years exhibited a three-fold increase in modules of rupture for remodeled soil samples, compared to plots receiving no compaction.

Total and noncapillary porosity were found to be reduced by compaction (22). Grable and Siemer (35) noted that as the bulk density increased from 0.93 g/cc to 1.23 g/cc, the air porosity (at 60 cm H_2O suction) was reduced 25%. They also observed that a decrease in aggregate size from 6-3 mm to ≦.5 mm diameter resulted in a 30% reduction in air porosity. Davis (22) demonstrated that the reduction in porosity on compacted turfgrass areas was contained in the top 9 cm of the soil.

Plant Growth Responses to Compaction

The effects of soil compaction on plant growth has been reviewed by Rosenberg (75). He summarized the effects of compaction on root growth, crop yields, and seedling emergence.

Mechanical resistance to root penetration and inadequate soil aeration are thought to be the two main causes of poor root growth associated with soil compaction (43,53 ,70). Generally, an increase in mechanical resistance to root growth is observed when soil bulk density is increased. Cordukes (19) observed that bulk density increased 6%, total porosity decreased 12%, and root growth was restricted by 1/3 on compacted field plots as compared to noncompacted plots. Sunflower roots could not penetrate any soil type which had a bulk density greater than 1.9 g/cc, as noted by Veihmeyer and Hendrickson (91). It was also observed that in clay and sandy soils, root penetration was inhibited when the soil bulk density was greater than 1.6 and 1.75 g/cc, respectively. Trouse and Humbert (86) reported that sugar cane root development was restricted when the bulk density of Paia silty clay soil exceeded 1.35 g/cc. Voorhees *et al*. (93) observed the root growth of barley seedlings into 1 cm diameter soil aggregates with bulk densities of 1.4 and 1.8 g/cc. Roots penetrated aggregates with the 1.4 g/cc bulk density and were restricted to the periphery of the aggregates with a 1.8 g/cc bulk density. It was concluded that the difference in root penetration into aggregates was most likely caused by structural features such as soil strength and pore size distribution. Wilkinson and Duff (97) reported no inhibition of root growth of several turfgrass species when the bulk density of a sandy loam soil was increased from 1.1 to 1.4g/cc. Several factors were cited to explain this phenomenon: the sandy loam soil was not compacted enough to restrict root growth; this soil provided an adequate air porosity level; and the inherent ability of grasses to withstand low oxygen diffusion rates.

Root growth can also be inhibited by an increase in soil strength. Taylor et al. (84) demonstrated that less than 50% of cotton tap roots could penetrate the soil when the penetration resistance was 10.35 bar. However, when the penetration resistance exceeded 20.70 bar, very few roots could penetrate. According to Taylor and Gardner (82), a high negative correlation existed between root penetration and soil strength (measured by a static penetrometer). The ability of roots to penetrate a number of wax substrates varying in rigidity was examined by Taylor and Gardner (81). In most cases, an increase in the penetration resistance of the wax substrate reduced root penetrability.

Compacted soil conditions can create poor aeration. Letey et al. (53) observed that under compacted conditions the ODR was lowered to 15g $O_2 X 10^{-8} cm^{-2} min^{-1}$ which led to poor root growth for common bermudagrass. Waddington and Baker (95) noted that root growth of Merion Kentucky bluegrass was greatly reduced when the ODR fell below a range of 5-9g O_2 X $10^{-8} cm^{-2} min^{-1}$ while Penncross creeping bentgrass and goosegrass were found to tolerate an ODR as low as 5g O_2 X $10^{-8} cm^{-2} min^{-1}$. An ODR of 20g O_2 X $10^{-8} cm^{-2} min^{-1}$ was required for proper root growth of Newport bluegrass as reported by Letey et al. (54). Rickman et al. (73) examined the interaction between oxygen supply and physical resistance to root growth and it was concluded that low ODR's were the primary reasons for poor root growth. The effects of bulk density, aggregate size, and soil water suction on oxygen diffusion and corn root elongation were investigated by Grable and Siemer (35). They concluded that, over the range of soil water suction from 0 cm to 68 cm of H_2O suction, the rate of root elongation was primarily controlled by oxygen diffusion.

Soil compaction can have a harmful effect on crop yields (20, 28) and turf quality (22, 98, 99). Phillips and Kirkham (67) observed that corn yields decreased 18.27 hl/ha on plots receiving vehicular traffic. Optimal fertility levels were maintained throughout the three years of the experiment; thus, fertilization did not compensate for the yield reduction caused by compaction. Voloras *et al*. (87) noted that common bermudagrass clipping yields were reduced 50% under compacted conditions. Analysis of the grass clippings revealed that the top growth from the compaction treatment contained a slightly smaller amount of N and P than from the noncompaction treatment.

Seedling emergence can be drastically reduced under compacted soil conditions. Taylor *et al*. (83) noted that a slight decrease in percent seedling emergence occurred when the penetrometer measured soil strength increased to a 6 to 9 bar range. Any further increase in soil strength showed a pronounced decrease in seedling emergence for all the *Graminase* spp. investigated. No seedling emergence was observed when the soil strength reached a range of 12 to 18 bar. The effects of soil moisture content, bulk density, ODR, and crust strength on wheat seedling emergence were examined by Hanks and Thorp (37). They found that an ODR of 75 to 100 g O_2 X 10^{-8} cm^{-2} min^{-1} was required to achieve an 80% germination rate of wheat seeds. A crust strength from 200 to 500 millibars limited seedling emergence and this value decreased as the amount of available water decreased. Bulk densities greater than 1.3g/cc for a silt clay soil and 1.6g/cc for a fine sandy loam soil were found to inhibit seed germination by 20% when the soil moisture content was at field capacity (1/3 bar). Hughes et al. (46) examined the effects of bulk density and soil moisture pressure on seedling emergence of common bermudagrass and weeping lovegrass. They concluded that the soil water content was the primary factor influencing the seedling emergence of the two grasses in a clay soil. It was also observed that both grasses germinated at a low ODR of 9.7g $O_2 \times 10^{-8} cm^{-2} min^{-1}$.

Solution to Compaction

The problem of turfgrass soil compaction is quite complex and is not easily corrected. The current means of alleviating this problem on turfgrass sites is by the use of soil modification and cultivation practices.

According to Madison (59), the methods of soil modification fall into two categories, soil aggregation and dilution. Aggregating agents such as vinyl acetate-maleic acid (VAMA) can stabilize soil particles and improve the soil structure (33). Soil particles stabilized by such chemicals have not been investigated under compacted soil conditions. Soil dilution refers to the addition of materials to fine textured soils, so as to spread out or dilute the clay particles (59). Beard(10), Madison (59), and Waddington (94), have extensively reviewed the use of many soil amendments on turfgrass areas. While many soil amendments such as coarse sand, peat, calcined clay and etc. have been shown to help alleviate the harmful effects of soil compaction, the cost of renovation with soil amendments after the turf has been established is very costly and time consuming and is used only as a last resort.

The most common method of alleviating turfgrass compaction is by the use of cultivation practices such as aerification. Standard aerification equipment remove soil cores 0.65 to 1.27 cm diameter, to a 1.27 to 7.60 cm soil depth and with 5.08 to 10.18 cm centers. An aerification treatment can increase the water infiltration rate and improve aeration. However, the treatment must be repeated periodically if it is to be effective. Morgan et al. (63) evaluated the effect of deep aerification treatment on a severely compacted putting green. The deep aerification treatment consisted of 2.54 cm diameter holes, 15.3 cm deep and with 7.6 cm centers that were back-filled with various porous materials. The treatment increased water infiltration rate by 5.6 cm per hour over the standard aerification treatment. It was estimated that the cost of the deep aerification treatment was approximately ten times less than a complete renovation of the putting green.

Warkentin and La Flamme (96) demonstrated that a heat treatment of a clay soil could improve the soil structural conditions. A heat treatment of 260°C for two hours greatly improve the water permeability of a clay loam soil. In a field compaction, it was also observed that the water infiltration rate was increased due to the heat treatment.

Chemical Soil Conditioners

History

The brief history of chemical soil conditioners started in the early 1950's with the introduction of "Krilium" type conditioners. Gardner (33) and Brandt (16) have reviewed the earlier work related to these types of conditioners.

The first two "Krilium" materials introduced were vinyl acetate-maleic acid (VAMA) and hydrolyzed polyacrylonitrate (HPAN) (33). These and numerous similar materials were found to be very effective in improving the soil structure and increasing crop yields (16, 23, 33). During the period of 1950 to 1963 approximately 200 research papers were published on this type of chemical soil conditioner (33). However, widespread use of such materials was prohibited because of high cost (23,33).

New Types of Soil Conditioners

In recent years there has been a resurgence of interest in chemical soil conditioners (23, 61). DeBoodt (23) has emphasized an important shift in the basic mode of action that soil conditioners have taken. Formerly, flocculation of clay particles was considered to be the essential function of soil conditioners. With the introduction of the new chemical soil conditioners of the 1970's, however, the essential function is now placed on bond formation between sand and clay domains (23).

DeBoodt has classified the new soil conditioners by thier effect on the soil physical properties. Under this classification, materials such as polyacrylamide (PAM) and hydrophylic bitumenous emulsion make soils more hydrophylic (water-absorbing). New materials can also be classified into areas such as increasing soil temperature, increasing cation exchange capacity, and making soils more hydrophobic.

There are a number of new soil conditioners which are relatively inexpensive and have shown to be promising for large scale use(23). The most promising of these are bitumenous emulsions and solutions of PAM.

Moldenhauer and Gabriels (61) recently outlined the uses of chemical soil conditioners in the United States today. They are two-fold: first is for steep road and construction bank stabilization against erosion, second is soil stabilization for high-value crops, such as sugar beets. However, cost still prevents treatment of the entire plow layers with soil conditioners, but band treatment is feasible.

Brandt (17) concluded from his review of chemical modification of soil physical properties, "... that much effect has been directed toward synthetic organic chemicals... Yet, in almost no case is there a widespread acceptance and commercial use of synthetic organic materials that have been designed for a specific task."

Mechanism of Soil Aggregation

Harris *et al*. (38) presented a review of the mechanism of soil aggregation and the complexity of this phenomenon.

A considerable amount of research has been conducted to explain the mechanism of aggregation by bitumenous emulsions and PAM. PAM has been demonstrated to have a small contact angle and therefore has a tendency to cover the entire soil particle and also can have a thread-like linkage with soil particles (88). Emerson (26) observed that the polyacrylamide polymer formed coordination compounds with the exchangeable calcium of montmorillonite. Electrostatic bonding forces between the amide group of the PAM and the negative charge of clay particles is an important aggregating force.

It has also been shown that Van der Waals attractive forces that exist between clay surfaces and the PAM play a role in the aggregating process.

Polyacrylamide polymer absorption on minerals and soils has been reported to be related to surface area and degree of dispersion. With an increase in surface area and degree of dispersion the amount of polymer absorbed was increased (48). Schamp and Huylebroeck (76) noted that the absorption of polyacrylamide on clay minerals followed a bimodal effect. There was an immediate absorption of polymer on the external surfaces of the clay (within 15 minutes) and a much slower penetration into the cavities of the clay aggregates (within 20 hours).

Through electron microscopic technique, bitumenous emulsions have been observed to bind soil particles together at the contact points between particles (74). Electrically charged micelles of the bitumenous emulsion glide over the thin water film covering the particles and into the miniscus at the contact point between particles (88). When the soil dries, the bitumenous emulsion is fixed at the contact points and binds the soil particles together. Migration of the bitumenous emulsion to the contact points is due to capillary forces and large contact angles (74).

A major factor in the effectiveness of the bitumenous emulsion and polyacrylamide is a proper moisture content of the soil at treatment. The interaction between soil moisture content and optimal structure formation has been observed by several researchers (4, 31, 64, 74, 88). Optimal water stable aggregation for a wide range of soil types has been found to occur at the moisture content corresponding to a tension of 100 cm of H_2O on the moisture retention curve diagram for each soil (31, 88). This high moisture content is necessary for proper migration of these soil conditioners to the contact points between the particles.

For field application with these materials, it is recommended that the soil be cultivated prior to treatment. Cultivation will improve the natural soil structure which can then be stabilized by the bitumenous emulsion or polyacrylamide treatment. (31, 88).

Soil Physical and Plant Growth Responses

Most research associated with chemical soil conditioners has centered on improvement of the soil structure and the effects on plant yields. Shtatnov and Shcherbakova (78) have reported a marked increase in water stable aggregation ($>$ .25 mm) on polyacrylamide treated field plots as compared to the control areas. The rate of the polyacrylamide used was a 0.25% polymer by weight of the soil. The aggregation remained stable throughout the two years of the experiment.

Kackinskiy et al. (48) and Varnavskaya et al. (90) also obtained an increase in water stable aggregation when soils were treated with polyacrylamide at similar rates. In these experiments crop yields were improved approximately 30% in the first year, but little or no yield increase was obtained in subsequent years (48, 78, 90). The enhanced crop yield in the first year was attributed to the nitrogen content of the polyacrylamide acting as a fertilizer (48, 78). A band application of PAM has been reported to increase sugar beet seed germination (61).

Vandervelde and DeBoodt (88) found that as the clay content of a number of different soils increased, the aggregating effectiveness of bitumenous emulsion increased and polyacrylamide decreased. They determined the rate need for optimal aggregation of a number of soil types. Polyacrylamide was required at the rate of 2% polymer to the weight of the soil water for a pure sand. In soils containing clay, polyacrylamide is applied at the rate of .1 to .2% polymer. When a cross-linker was added to the polyacrylamide, maximum aggregation at aggregation at any given concentration of polyacrylamide was obtained at a much lower soil moisture content. Optimal aggregation for soils treated with bitumenous emulsions was obtained at a rate of 1 to 2% emulsion to the weight of the soil.

Gabriels (30) and Gabriels et al. (32) found increased saturated hydraulic conductivity, decreased water infiltration, and considerable soil clod erosion for soils treated with Humofina FB63 (hydrophobic bitumenous emulsion). Bitumenous emulsions and polyacrylamide have also been used to help prevent soil erosion by water impact with surface application of these materials (12, 30, 32).

Soil Algae

Occurrence

Algae are naturally occurring microorganisms found in many soils. MacEntee (56) and MacEntee *et al*. (57) have encountered as many as 42 different genera of soil algae in the Northeastern United States. The *Chlamydomonas* spp. was one of the genera most often observed. Booth (14) has observed vast acreage in the Southcentral United States covered with an algae stratum.

Soil Structure

According to Harris *et al*. (39) "Diverse bacteria, fungi, streptomycetes, yeast, and algae are capable of binding soil particles together into stable aggregates; however, the aggregating ability of these various microorganisms differs widely." There has been little research confirming the role of algae in soil aggregation. Bailey *et al*. (5) noted that when soils were incubated for a six-week period with three different algae, there was a significant increase in soil aggregation ($> 74\mu$) compared to soils without the algae. The *Oscillatoria* spp. of algae gave the greatest increase in aggregation.

Fogel *et al*. (29) found that the soil alga *Chlamydomonas mexicana* increased water stable aggregation and infiltration of water, while penetration resistance decreased as compared to untreated soil. The beneficial influence on soil structure was attributed to a polysaccharide polymer excreted by this alga into the soil during growth. The polysaccharide was found to aggregate kaolin at the ratio of 1 to 10,000 parts polysaccharide to clay. In field experiments with this algal applied at rates of 14 to 224 kg/ha acre, a significant improvement of the soil structure resulted as compared to untreated soil plots.

Algal crusts have been observed to cover large areas of badly eroded land in the Southcentral United States (14, 27, 77). This crust has been shown not to hinder water infiltration and is somewhat resistant to erosion as compared to areas without an algal crust (14,27). The moisture content of the surface inch of soil was found to be greater than that of the surrounding bare soil (14). The algal crust contained 10 to 30% more organic carbon and as much as 240 ppm more amino nitrogen in the surface inch of soil than in the underlying soil (27, 77).

MATERIALS AND METHODS

Growth Chamber Experiments

Growth Chamber Experiment 1-A

The effects of hydrophobic and hydrophylic bitumenous emulsions on the physical properties of a compacted sand and the growth of Manhattan perennial ryegrass (*Lolium perenne* L. Manhattan) were investigated.

A Windsor series sand, collected from a tobacco field in Whately, Massachusetts, was used in this investigation. The physical and chemical properties are listed in Table 1.

The bitumenous emulsions were obtained from the Petrofina Co. of Brussels, Belgium. The trade names of the materials are Humofina H.A. for the hydrophobic bitumenous emulsion and Humofina A-49 for the hydrophylic bitumenous emulsion. The rate of material applied was 1.5% undiluted emulsion to the dry weight of the soil. Prior to treatment, the emulsions were diluted three times with distilled water, bringing the total amount of liquid applied to 6% by weight. A check treatment, in which distilled water was applied to the soil at the rate of 6% by weight, was included.

The two emulsions and the check treatment were each applied separately to 11,000g air-dried soil samples, which had previously been passed through a 1.00mm sieve. The procedure for handling and treatment of the soil was similar to that used by Gabriels (30), and is as follows: first, representative soil samples

Table 1 - The physical and chemical analysis for the soils used in all Field, Growth Chamber and Laboratory Experiments

Experiment	Soil classification	Sand	Silt	Clay	pH	Total CEC	Organic matter	Moisture content Field cap.*	Moisture content 80%field cap.
		%	%	%		me/100g	%	%	%
Field 1-A	Hadley silt loam	33.5	54.8	11.7	6.49	7.3	----	24.62	----
1-B	Loamy sand	75.6	20.2	4.2	6.33	3.5	----	18.44	----
2-A	Hadley silt loam	23.5	63.8	12.7	6.58	5.6	----	23.99	----
2-B	Hadley silt loam	23.3	64.7	12.0	6.74	5.4	----	25.30	----
Growth Chamber									
1-A, 1-B	Windsor sand	90.3	5.0	4.7	5.95	3.9	2.08	4.41	3.53
1-C, 1-D	Hadley silt loam	19.3	65.7	15.0	6.27	7.3	3.37	19.60	15.68
2	Sandy loam	58.6	32.0	10.4	4.76	---	----	16.10	-----
	Clay loam	42.8	31.6	25.6	5.48	---	----	23.00	-----
	Loam	48.0	34.8	17.2	5.23	---	----	19.40	-----
Laboratory									
1	Windsor sand	90.3	5.0	4.7	5.95	3.9	2.08	4.41	3.53
2	Hadley silt loam	19.3	65.7	15.0	6.27	7.3	3.37	19.60	15.68

* Moisture content at field capacity is at a suction of 1/3 bar.

were oven-dried at 105°C for 24 hours to determine the moisture content and an approximate oven-dry weight of the whole sample; the soil was then placed in plastic containers and distilled water was added to bring the moisture content up to 80% field capacity (Table 1); the plastic containers were sealed for a 24-hour equilibration period; then the soil was mixed in a small soils mixer and sprayed with 660g of diluted emulsion (165g undiluted plus 495g distilled water) or distilled water by a small hand sprayer; finally, the treated soil was air-dried for 48 hours and then passed through a 12.75mm sieve. Soils handled in this manner will subsequently be referred to as treated soil.

Clear plexiglass cylinders, 7cm ID by 33cm long enclosed at the bottom with cheesecloth and fastened with a rubber band, were used as growth containers. This type of growth container allowed for periodic visual root counts, ODR measurements, and removal of the soil with very little disturbance.

Three methods of application with soil conditioners were investigated. The first method involved the packing of the entire cylinder with untreated soil (refers to samples that were only brought up to 80% field capacity with water and allowed to dry). Following the compaction treatment, the cylinders received surface application with the emulsions at a rate previously described. Each cylinder treated in this manner received 3.3g of undiluted emulsion plus 9.9g of distilled water sprayed on the soil surface. The amount of material applied was enough to treat the top 3cm of the soil (approximately 200g of soil). In the second method, untreated soil was packed to within 3cm of the top of the cylinder. The remaining 3cm were packed with treated soil. The third method involved the packing of the entire cylinder with treated soil. The methods of application just described will subsequently be referred to as surface, top 3 cm, and throughout treatments.

The experiment was set up in a complete randomized block 3 X 3 factorial design, in which all combinations of emulsion and check treatments and the three methods of application were investigated. Four replications of each treatment were included, making the total number of experimental units 36.

The treated and untreated soils were packed into the cylinders by the following procedure: the soil was added to the cylinders using a wide-mouthed funnel with a piece of plastic tubing attached; the soil was then packed into the cylinders at 2 cm increments, and the outside of the cylinders were tapped for a short period of time with a small hand vibrator; the packing and tapping process continued until the cylinders were filled. This procedure was followed to insure that the cylinders were uniformly packed.

The cylinders were saturated with distilled water for a 48-hour period and allowed to drain for 24 hours prior to compaction. The compaction treatment was administered by a Proctor penetrometer fitted with a wooden plug slightly smaller than the inside diameter of the cylinders. Each cylinder received three applications daily of 1.41 kg cm^{-2} compacting force for three consecutive days.

The cylinders were placed in a Percival growth chamber, model MB-60. Manhattan perennial ryegrass was seeded at the rate of 2.83 $seed/cm^2$ on 3/14/74. The seeds were mixed in with 15g of untreated soil to insure proper germination. A black plastic cover with holes cut out for the soil surface was placed on top of the cylinders. A barrier of black plastic was also placed around the outside perimeter of the cylinders to eliminate light in the root zone.

The growth chamber was maintained at a constant temperature of 18°C, a photoperiod of 14 hours, and a relative humidity of 75%. The light intensity at the soil surface was 800 foot-candles. The cylinders were lightly watered daily and at 3-day intervals were watered to field capacity by weight.

A high germination percentage was observed on 3/18/74 which was independent of any treatment. Each cylinder was clipped at a height of 9 cm on 4/2/74 and 4/10/74. All remaining top growth was clipped on 4/13/74. All clippings were oven-dried for 24 hours at 55°C prior to weighing. Visual root counts were taken around the outside of the cylinders at soil depths of 4 cm, 8 cm, 16 cm, and 24 cm on 3/26/74, 4/2/74, and 4/10/74. The plant growth section was terminated on 4/13/74.

ODR's were obtained at soil depths of 2.54 cm and 7.64 cm on 3/27/74, 4/3/74, and 4/11/74. Bulk density measurements were made prior to and following the compaction treatment. At the termination of the plant growth section, soil samples were obtained at soil depths of 0-3 cm and 7.62-10.16 cm for aggregate stability analysis.

Growth Chamber Experiment 1-B

The effects of compaction on the physical properties of a Windsor sand and growth of Manhattan perennial ryegrass were explored. This study was conducted simultaneously with Growth Chamber Experiment 1-A.

The experiment was a complete randomized block design with (+) compaction and (-) compaction treatments replicated four times. Untreated Windsor sand soil was packed into plexiglass cylinders by the procedure used in Growth Chamber Experiment 1-A. A compaction treatment (see Growth Chamber Experiment 1-A) was administered to half of the cylinders. The other half received no compaction. The cylinders were placed in the growth chamber and each was seeded with 100 Manhattan perennial ryegrass seeds (2.84 seeds/cm^2). The environmental conditions were maintained as described in the previous study. Plant growth measurements and soil physical analyses were determined as outlined in Growth Chamber Experiment 1-A.

Growth Chamber Experiment 1-C

The effects of a hydrophobic bitumenous emulsion and a solution of polyacrylamide (PAM) on the physical properties of a compacted silt loam soil and growth of Manhattan perennial ryegrass were examined.

A Hadley silt loam soil was used in this investigation. The soil was collected from the University of Massachusetts Research Farm in South Deerfield, Massachusetts. The physical and chemical characteristics of this soil are listed in Table 1.

The chemical soil conditioners used in this study were obtained from the Petrofina Co. of Brussels, Belgium. The trade names of the soil conditioners are Humofina HA for the hydrophobic bitumenous emulsion and Humofina PAM for the polyacrylamide solution. Humofina PAM is a low molecular weight polymer to which a cross linker is added. The rate of application of the emulsion was

1.5% undiluted emulsion to the oven-dry weight of the soil. The emulsion was diluted three times with distilled water prior to the soil treatment. PAM was applied at the rate of 0.5% actual PAM to the oven-dry weight of the soil. PAM was obtained as a 4% solution and was diluted three times with distilled water, resulting in a 1% solution. During the dilution process, one volume of a cross-linking additive was added to every 1000 volumes of the 1% PAM solution. The pH of the 1% PAM solution was adjusted to 8.5 with ammonium hydroxide. A check treatment in which distilled water was added to the soil at the rate of 6% water to the dry weight of the soil was included.

A complete randomized block 3 X 2 factorial experimental design was utilized. All combinations of the three soil treatments and two methods of application were included. All treatments were replicated 4 times, making the total number of experimental units 24.

The three soil treatments were each applied separately to 8581 g air-dried soil samples by the procedure outlined in Growth Chamber Experiment 1-A. Also, 8581 g of air-dried soil were brought up to an 80% field capacity moisture content and then air-dried (to be referred to as untreated soil). The amount of materials used were as follows: 118 g of undiluted bitumenous emulsion plus 354 g of distilled water; 78 g of 1% PAM solution; 475 g of distilled water (6%) for the check treatment.

Plexiglass cylinders (see Growth Chamber Experiment 1-A) were utilized as growth containers. Two methods of application investigated were the top 3 cm and throughout treatments. The soil was packed into the cylinders and compacted by the methods described previously.

The containers were placed in the growth chamber and maintained at the environmental conditions specified in the previous growth chamber studies. Each cylinder was seeded with 150 Manhattan ryegrass seeds (4.25 seeds/cm^2) on 6/7/74. The seeds were mixed in with 10 g of untreated soil and placed on the soil surface. Due to poor germination, all cylinders were reseeded on 6/21/74. A germination count was made on 7/6/74. The grass was clipped at a 9 cm height on 7/14/74. All remaining top growth was removed on 7/23/74. Visual root counts were made at soil depths of 3 cm, 10 cm, and 18 cm on 7/15/74 and 7/21/74. Root samples were collected at soil depths of 4-6 cm and 10-12 cm at the termination of the experiment (7/24/74). The root samples were washed free of any soil particles or other debris prior to drying. All clippings and root samples were dried at 55°C for 24 hours prior to weighing.

Bulk density measurements were ascertained preceeding and following the compaction treatment. ODR's were determined at soil depths of 2.5 cm and 7.6 cm on 7/7/74 and 7/22/74. Aggregate stability samples were collected at soil depths of 0-3 cm and 7-9 cm at the termination of the study for later analysis.

Growth Chamber Experiment 1-D

The effects of compaction on the physical properties of a Hadley silt loam soil and growth of Manhattan perennial ryegrass were investigated. This study was conducted in conjunction with Growth Chamber Experiment 1-C.

The experimental design used in this study was a complete randomized block which included a (+) compaction and a (-) compaction treatment. Each treatment was replicated four times, making the total number of experimental units 8.

Untreated Hadley silt loam soil was handled and packed into growth containers by the methods previously mentioned. A compaction treatment (see Growth Chamber Experiment 1-A) was applied to half the cylinders, while the other half received no compaction. The cylinders were placed in the growth chamber and each was seeded with 150 Manhattan perennial ryegrass seeds (4.25 seeds/cm^2). The environmental conditions were maintained as described in the previous experiments. The plant growth measurements and soil physical analyses were determined as outlined in Growth Chamber Experiment 1-C.

Growth Chamber Experiment 2

This study was conducted to ascertain the effects of an algal polymer culture and a solution of polyacrylamide (PAM) on water stable aggregate formation of 3 soils at 2 pH levels.

Sandy loam, loam, and clay loam soils were selected for this investigation because of their textural variation and their initially low pH levels (Table 1). The soils were collected at the following locations: the sandy loam soil in a wooded area adjacent to Puffer's Pond in North Amherst, Massachusetts; the loam soil at the University of Massachusetts farm in South Deerfield, Massachusetts; the clay loam soil from a farm south of Amherst, Massachusetts. Air-dried samples of each soil, weighing 2730 g, were placed in large plastic bags. Calcium hydroxide ($Ca(OH)_2$) was added to the sandy loam, loam, and clay loam soils at the rate of 0.40, 0.44, and 0.26 g $Ca(OH)_2$/100 g of soil, respectively. On a weekly basis, each soil sample was wetted with distilled water, mixed by hand, and air-dried. This continued for a 7-week incubation period. The pH values for the sandy loam, loam, and clay loam soils after the incubation period were 6.6, 7.2, and 7.4, respectively.

The experiment involved a three-way classification, which included all interactions of 3 soil textural classes, 3 soil treatments, and 2 pH levels, arranged in a complete randomized block experimental design. Three replications of each treatment were included. The three soil treatments refer to an application to the soil of either an algal polymer culture, a solution of PAM, or a check treatment of distilled water. The Process Research Inc. of Cambridge, Massachusetts supplied the algal polymer culture. The polymer is produced in a culture medium when the soil alga Chlamydomonas mexicana is grown under a nitrogen deficient condition. The algal culture was applied at the rate of 5 g culture to 50 g air-dried soil, or at an actual rate of 0.01% algal polymer to the dry weight of the soil. A powdered form of PAM was obtained from the American Cyanamid Co. of Linden, New Jersey. This type of PAM will be referred to as Cyanamer P-250 and is marketed under the trade name of Gelamide 250 (M.W. 5-6,000,000). A rate of 0.15% PAM to the air-dried weight of the soil (0.075 g PAM/50 g of soil) was used. A check treatment, in which distilled water was applied to the soils so as to bring the moisture content up to field capacity was included.

Each of the soils was handled and treated in the following manner. First, the soil was air-dried and passed through a 1.00 mm sieve. A 50 g sample of the soil was placed in a 14 cm diameter by 1.2 cm plastic petri dish and was then treated by one of the materials. A small hand atmoizer was used to apply the materials in the form of a fine mist on the soil surface. The algal culture and Pam were diluted with enough distilled water so as to bring the soil moisture content up to field capacity level. The petri dishes were covered and placed in the growth chamber for 48 hours. The growth chamber was kept at a temperature of 21°C and a daylength of 14 hours. No additional water was applied to the petri dishes.

Following the 48-hour incubation period, the soil was removed from the petri dishes and samples were obtained for aggregate stability analysis.

Laboratory Experiments

Two laboratory experiments were conducted during the summer of 1974. The soils used in series 1 (A-D) of the growth chamber studies, Windsor sand and Hadley silt loam, were investigated without the presence of any plant material.

Laboratory Experiment 1-A

The effects of a hydrophylic bitumenous emulsion and a polyacrylamide (PAM) solution on the physical properties of a compacted Windsor sand soil were investigated.

Five treatments were arranged in a completely random experimental design and were each replicated 10 times. The various treatments examined were as follows: a check treatment, in which untreated soil was not compacted; a check treatment, in which untreated soil received a compaction treatment; a check treatment, in which the soil received an application of 6% demineralized water to the dry soil weight, plus compaction; a treatment of the soil with the hydrophylic emulsion (Humofina A-49) at the rate of 1.5% emulsion to the dry weight of the soil, plus compaction; the soil, treated with 0.15% PAM (Cyanamer P-250), plus compaction.

Prior to the above applications, the soils were air-dried and passed through a 1.00 mm sieve. Representative samples were obtained to estimate the oven-dry weight of the soil. Five 1000 g soil samples (oven-dry estimate) were placed in plastic containers and demineralized water was added to bring the moisture content up to 3.52% by weight (80% field capacity). The containers were sealed for a 24-hour equilibration period. At this point, two samples were air-dried and set aside for the first two check treatments. The remaining three samples were treated with either the hydrophylic emulsion, the PAM, or the demineralized water by the procedure used in Growth Chamber Experiment 1-A. Fifteen grams of the hydrophylic emulsion were diluted with 45 g of demineralized water prior to the application. The amount of PAM applied was 300 g of a 0.5% PAM solution.

Following the treatment, the soils were allowed to air-dry for 24 hours and were placed through a 12.75 mm sieve. Brass cores, 5.4 cm ID by 3 cm in height and covered at the bottom with No.4 Whatman filter paper, were filled with soil. To uniformly pack each soil core, the outsides were tapped with a small hand vibrator. The packed cores were placed in a large pan containing demineralized water; they remained in this saturated state for 24 hours. After a short draining period, nine applications of a compacting force of 1.4 kg/cm^2 were administered to each core receiving the compaction treatment. The Proctor penetrometer, referred to in the previous growth chamber studies, was used to deliver the compaction treatment.

The cores were resaturated for 24 hours and placed in a pressure plate extractor apparatus. The moisture content of each core was determined at tensions of 0.06-, 1/3-, 1-, and 2-bar, at 24-hour intervals. ODR (2 values per core) and pocket penetrometer measurements (3 readings per core) were obtained when the soil was at a moisture content corresponding to a 2-bar tension. The bulk density of the soil cores was determined following the compaction treatment.

Laboratory Experiment 1-B

This study examined the effects of a hydrophobic bitumenous emulsion and a solution of polyacrylamide (PAM) on the physical properties of a compacted Hadley silt loam soil (Table 1).

The five treatments outlined in the preceeding laboratory study were also utilized in this investigation. However, one exception should be noted; the hydrophobic bitumenous emulsion (Humofina HA) replaced the hydrophylic emulsion treatment. Each of the treatments was replicated 8 times and arranged in a completely random experimental design.

Soil samples weighing 1000 g were handled, treated, packed into cores, and compacted using the procedures described in Laboratory Experiment 1-A. The amount of hydrophobic bitumenous emulsion applied was 15 g emulsion plus 75 g demineralized water (used in diluting the emulsion). As noted in the preceeding laboratory experiment, 300 g of a 0.5% PAM (Cyanamer P-250) was applied to the soil.

The moisture content of each soil core was determined at tensions of 0.06, 1/3, 1, and 2 bar at 48-hour intervals. Prior to each determination of the moisture content, the soil cores were saturated with demineralized water and allowed to equilibrate for 24 hours. Following the compaction treatment, the bulk density of each core was obtained.

Field Studies

The field studies conducted in the summer of 1974 were of two types. Experiments 1-A and 1-B were field evaluation studies of synthetic, chemical soil conditioners. Experiments 2-A and 2-B were designed to evaluate the effectiveness of an algal polymer as a soil conditioner.

Field Experiment 1-A

The purpose of this study was to evaluate the effects of several chemical soil conditioners on compacted soil physical properties and the growth of Penncross creeping bentgrass (Agrostis palustris Hud. Penncross).

A Penncross creeping bentgrass plot was established in the spring of 1973 and maintained under putting green conditions. The plot was fertilized at the rate of 145 kg/ha of nitrogen per year and mowed twice a week at a height of 0.65 cm. The soil type was a Hadley silt loam (Table 1).

The experiment was arranged in a split plot design with the main plots consting of all combinations of four soil conditioner treatments and 2 methods of application. Each of the main plots were subdivided into (+) and (-) compaction treatments. The total number of subplots was 48, which included 3 replications of each treatment. The size of the subplots was 0.91 m by 3.64 m.

The soil conditioners were applied on 7/17/74. At the time of application, soil samples were obtained from the surface 3 cm of soil. The % moisture by weight of the soil was determined to be 20.8 or 84.4% field capacity.

The soil conditioner treatments, methods of application, and amount of material applied were as follows:

Treatment number	Soil conditioner	Method of application	Amount of material applied	
			– liters/m^2 –	liters/plot –
1	Hydrophobic bitumenous emulsion (Humofina H.A.)	spray treatment after aerification	0.045	0.33
2	Hydrophobic bitumenous emulsion (Humofina H.A.)	injection	0.084	0.69
3	Hydrophylic bitumenous emulsion (Humofina A-49)	spray treatment after aerification	0.045	0.33
4	Hydrophylic bitumenous emulsion (Humofina A-49)	injection	0.038	0.28
5	Polyacrylamide (Humofina PAM)	spray treatment after aerification	0.045	0.33
6	Polyacrylamide (Humofina PAM)	injection	0.584	4.27
7	Check (water applied)	spray treatment after aerification	0.045	0.33
8	Check (water applied)	injection	0.584	4.27

A description of the chemical soil conditioners can be found in Growth Chamber Experiments 1-A, 1-C. The hydrophobic and hydrophylic bitumenous emulsions were diluted 5 times with water prior to treatment. The Humofina PAM was handled and diluted as outlined in Growth Chamber Experiment 1-C.

The two methods of applying the soil conditioners were (a) by spray treatment of the soil removed by aerification and (b) by injection of the soil conditioners into the soil. Each plot was aerified with a Ryan's Model Greens Aire II aerifier prior to the addition of the soil conditioners. The following procedure was used in the spray treatment of the soil removed by aerification: the cores were raked into a row in the center of the plot and sprayed with a soil conditioner using a small hand pesticide sprayer; the treated soil was air-dried for several hours and then broken up with a rake and dragmatted back into the core holes. The injection of the soil conditioners followed this procedure: the cores were dragmatted into the plot; the plot then received one pass with an Umbilla-Kal injection system (obtained from Agresult Inc. of Miami, Florida) which was attached to a Ryan's Greens Aire II aerifier; the soil conditioners were injected at a pressure of 10.35 bar; following the treatment each plot was lightly watered to wash off any remaining conditioner from the foliage of the turf.

The amount of the different soil conditioners injected was related to the viscosity of the material; the more viscous the soil conditioner, the less injected. The rate of soil conditioners used to spray the cores was 0.045 l per m^2. This is a very low application rate per unit area of soil. However, this is equivalent to a rate of 0.75 l per m^2 if all the soil in the plot had been treated instead of only the 6% of soil removed by aerification.

Half of each main plot received compaction treatments on 7/22/74, 7/30/74, 8/5/74, 8/12/74, 8/26/74 and 9/10/74, using a compaction device similar to that used by Goss and Roberts (34). The (+) compaction subplots were passed over one time at each date. Each pass of the compactor was equivalent to the passing of 5.6 walking men over the plot (34).

Undisturbed soil samples were obtained for moisture retention, bulk density, water stable aggregate, and dry sieving aggregate analyses. One sample per subplot, obtained at a soil depth of 0 to 3 cm and with a diameter of 5.4 cm, was obtained on 10/8/74 for moisture retention and bulk density measurements. Percent water stable aggregation was determined from 2 samples per subplot, taken on 10/30/74. The size of each sample, obtained from a soil depth of 0 to 3 cm, was 2 cm in diameter. Three samples per subplot, taken on 12/9/74, were used for dry sieving aggregate analysis. The three samples, which were 2.54 cm in diameter and taken from a soil depth of 0 to 7.62 cm, were combined and analyzed as one sample.

Root weights were determined from samples taken at two soil depths, 0 through 9 cm and 10 through 18 cm. Two samples per subplot, 4.8 cm in diameter, were taken on 9/26/74. Each root sample was washed free of all soil and any other debris, and then oven-dried at 55°C for 24 hours prior to weighing.

Field Experiment 1-B

This study was a preliminary investigation into the effects of a hydrophylic bitumenous emulsion (Humofina A-49) on the physical properties of a loamy sand soil and the growth of turfgrass.

The experiment was conducted on a loamy sand soil (Table 1) located at the home of Joseph Troll in Hadley, Massachusetts. The test site was maintained under typical home lawn conditions. The lawn was primarily composed of bluegrass, fine leaf fescue, and tall fescue.

Three treatments were replicated three times and arranged in a randomized complete-block experimental design. The treatments were as follows: (1) an untouched check treatment; (2) a check treatment in which water was injected into the soil, then followed by aerification of the plot; and (3) an injection treatment with the hydrophylic bitumenous emulsion, followed by aerification of the plot. The size of each plot was 0.9m by 1.8m with a spacing of 0.3m between plots.

The above treatments were administered on 8/6/74. One day prior to treatment, the soil was irrigated to a depth of 15 cm. Soil samples of the top 3 cm of soil were collected just prior to treatment. The moisture content of the samples indicated that the soil moisture content at application was 11.6% by weight or 65.5% of the field capacity.

The injection application was carried out with an Umbilla-Kal injection system (see Field Experiment 1-A). The plots that were injected received 2 passes with the injection apparatus. Immediately following the injection, treatment areas No. 2 and No. 3 were aerified with a Ryan's Model Greens Aire II aerifier.

The amount of hydrophylic bitumenous emulsion injected was 2.40 l/m^2 of diluted emulsion with a dilution of 1 part emulsion to 5 parts water. The amount of undiluted emulsion injected per plot was 0.40 l/m^2.

Three random undisturbed soil samples per plot were collected for moisture retention analysis on 9/20/74. The samples, 5.4 cm in diameter, were obtained at a soil depth of 0 through 3 cm. Samples of the upper 3 cm section of the thatch layer were obtained on 11/18/74 and used for moisture retention analysis. In each plot three undisturbed samples were taken with a soil sampler that extracted samples 5.4 cm in diameter. Organic matter content of these samples were determined from ash weight (550°C for 24 hours) of each sample.

The percentage of water stable aggregation was analyzed from 3 undisturbed soil samples per plot, collected on 11/18/74. Each sample was 5.4 cm in diameter and taken from the upper 3 cm of the soil.

Root weights were determined from 3 samples per plot, taken at soil depths within 0 through 9 cm and 10 through 18 cm. Prior to weighing, each sample was washed free of all soil and other debris and oven-dried for 24 hours at 55°C. The plots were visually rated on 8/27/74 for both color and density of the turf.

Field Experiment 2-A

The purpose of this experiment was to study the effects of an algal polymer culture solution on the structure of a Hadley silt loam soil in the presence of turfgrass.

The Hadley silt loam soil utilized in this experiment was similar to other soils in previous studies (Table 1). The experimental site was a two-year old stand of a mixture of 75% Baron Kentucky bluegrass and 25% creeping red fescue. An 8-6-4 lawn fertilizer was applied on 5/1/74 at the rate of 48.76 kg/ha.

The plot was mowed twice weekly at a cutting height of 3.8 cm, with clippings removed. No further care (such as water or chemicals) was given to this site.

Algal polymer cultures of two types were investigated for their potential as soil conditioners. Process Research Inc. supplied vegetative and flocculent culture types of the soil algae Chalmydomanas mexicana. The vegetative was in an immature growth stage, whereas the flocculent culture was in a mature growth stage containing a larger quantity of polysaccharide polymer. The cultures names were given by Process Research Inc.

The following is a list of treatments and rates of materials that were applied on 6/5/74:

Treatment number	Material	Rate Water	 Supplemental fertilizer	 Algal polymer*
		– l/m^2 –	g/m^2	
1	Check - water	1.14	--	--
2	Vegetative culture and $Ca(NO_3)_2$	1.13	6.64	0.01
3	Vegetative culture	1.13	--	0.01
4	Flocculent culture	0.84	--	0.21

*The rate of actual algal polymer applied, see Growth Chamber Experiment 2 for further description.

The algal polymer cultures and $Ca(NO_3)_2$ were mixed into the water and applied with a sprinkler can. The check treatment received 1.14 l of water per m^2.

The previous treatments were replicated three times and set up in a split plot design. The four treatments comprised the main plots and were subdivided into subplots, 1.82 m by 1.82 m. Half of each main plot received compaction (+) and the other half receiving no compaction (-). The (+) compaction subplots were subjected to compaction treatments (see Field Experiment 1-A) on 6/28/74, 7/5/74, 7/7/74, 7/9/74, 7/11/74, 7/15/74, 7/16/74, 7/22/74, and 7/30/74.

Two undisturbed soil samples per subplot were obtained for moisture retention, bulk density, and water stable aggregate analyses. The size of each sample was 5.2 cm in diameter by 3 cm in height. Samples obtained on 10/22/74 were utilized for moisture retention and bulk density measurements, and samples taken on 10/29/74 were used for water stable aggregate analysis.

Dry sieving aggregation was determined from soil samples obtained on 12/9/74. Three undisturbed samples per subplot were combined and analyzed as one sample. The size of each sample was 2.54 cm in diameter by 7.62 cm in height.

Field Experiment 2-B

The purpose of this experiment was to study the effects of two algal polymer solutions on the physical properties of an unvegetated Hadley silt loam soil.

Table 1 contains the physical and chemical properties of the Hadley silt loam soil. The site was free of all vegetation and was periodically hand weeded. There were no chemicals or other materials applied to this site other than the treatments. Vegetative and flocculent cultures were utilized in this investigation. Also included was a positive check treatment of a hydrophobic bitumenous emulsion

(Humofina H.A.). A description of these materials can be found in the previous sections.

The treatments were applied on 6/5/74. In addition to the initial application, the flocculent polymer culture treatment was repeated on 6/17/74 and 8/2/74. A list of the treatments and rates applied is as follows:

Treatment number	Material	Rate		
		Water	Supplemental fertilizer	Algal* polymer (emulsion)
		– l/m^2 –	g/m^2	
1	Check - water	1.14	--	--
2	Vegetative culture Ca(NO_3)	1.13	6.64	0.01
3	Vegetative culture	1.13	--	0.01
4	Flocculent culture			
	6/ 5/74	0.84	--	0.21
	6/17/74	0.35	--	0.86
	8/ 2/74	--	--	1.71
5	Hydrophobic emulsion	1.50	--	(0.5 l/m^2)

*Amount of actual algal polymer applied.

The five treatments were replicated 3 times and placed in a randomized complete-block design. The treatments were applied to 1.82m by 3.74m plots. The entire site was first cultivated to a depth of 10 cm and rolled once with a common yard roller. The algal polymer cultures were mixed with the water (and fertilizer) and applied by a small sprinkler can. The hydrophobic bitumenous emulsion was diluted 3 times with water and sprayed on the plots with a small hand pesticide sprayer. The emulsion plots were lightly raked after the application.

Undisturbed soil samples were extracted for moisture retention, bulk density, and water stable aggregate analyses. For each analysis, 3 samples per plot were obtained on 7/1/74 and 2 samples per plot on 10/22/74. Dry sieving aggregate analysis was determined as outlined in Field Experiment 2-A.

Soil Analytical Procedures

Water Stable Aggregation

The aggregate stability was determined for all studies using the procedure outlined by Kemper (49). Exceptions to this procedure were as follows: Samples from Field Experiments 1-A, 2-A, and 2-B were wetted by capillary rise instead of vacuum wetting, to cause a greater destruction of the aggregates (the level of aggregation of these soils being naturally high). Only one determination was made for each sample instead of the recommended two.

Bulk Density

The core method of determining bulk density (D_b), as described by Blake (11), was used in all field experiments. Bulk densities were calculated for all growth chamber and laboratory experiments by the following procedure: Soil samples were taken during the filling process of the cylinder or core; the moisture content was determined and an estimate of the oven-dry weight of the soil in each cylinder or core was obtained; the bulk density was then calculated by the following equation:

$$D_b = \frac{M}{V}$$

where M equals the oven-dry weight (mass) and V corresponds to the volume of the cylinder or core.

Oxygen Diffusion Rate (ODR)

ODR's were calculated utilizing the microelectrode technique (51). The electrodes used for the analysis were composed of gauge wire which had a 4 mm exposed platinum tip. A 3.5 minute equilibration period at an applied potential of -0.65 V was maintained.

In the growth chamber studies, holes were drilled in each cylinder at soil depths of 2.54 cm and 7.62 cm following the compaction treatment. The holes were slightly larger than the diameter of the microelectrode. Drilling was carefully done so as not to disturb the soil column. In Growth Chamber Experiments 1-A and 1-B, one hole per cylinder was drilled at each soil depth. Two holes per cylinder at each soil depth were drilled for Growth Chamber Experiments 1-C and 1-D. A two cm hole was also drilled near the bottom of each cylinder to provide access for the salt bridge. Following each ODR measurement, all holes were sealed with black electric tape to prevent oxygen from penetrating the soil column and to prevent drying of the soil.

In Laboratory Experiment 1-A, two electrodes per core were placed at a depth of 1.5 cm. The cores were set on a moistened soil block to which the salt bridge was attached.

Moisture Retention

The procedure described by Richards (72) with a pressure-plate extractor apparatus was used to measure the moisture retention of the soil. One exception should be noted: all undisturbed field samples were left in the brass cores in which they were extracted and placed directly on the ceramic pressure-plate for analysis. It was determined that a 24-hour equilibration period for sandy soils and a 48-hour equilibration period for heavier soils were required at each matric suction. Except where otherwise specified, the percent moisture by weight at suctions of 0.06, 1/3, 1 and 2 bar were obtained. In addition, for Laboratory Experiments 1-A and 1-B, the percent moisture by volumes (P_v) was calculated for each of the above tensions from the following equation:

$$P_v = D_b P_w$$

where D_b equals the bulk density of the soil and P_w represents the percent moisture by weight of the soil at a given matric potential.

Penetrometer

The unconfined compressive strength or penetrometer reading was determined for treated soil cores in Laboratory Experiment 1-A by the pocket penetrometer technique (21). A Soiltest model CL-700 pocket penetrometer was used to obtain the penetrometer values.

Dry Stable Aggregation

Determination of the percent dry sieving aggregation in the field experiments followed this procedure: first, the samples were passed through a 4.75mm sieve and then oven-dried at 70°C for 36 hours; the samples were then weighed and evenly distributed on the surface of a 20 mm diameter, 1.00 mm sieve; the samples were sieved for 30 seconds on a reprocative type, Ro Tap sieving machine (without the tapping apparatus in use). The samples remaining on the sieve (the aggregates) were weighed, and the percent dry sieving aggregation was calculated using the following equation:

$$\% \text{ dry sieving aggregation} = \frac{S_a}{S_t}$$

where S_a is the weight of the aggregates remaining after sieving and S_t corresponds to the total weight of the initial soil sample.

Other Measurements

The following are the procedures used to determine the chemical and physical properties of the soils listed in Table 1. The soil texture was determined by the Bouyoucos method (15). pH values were analyzed on a 1:1 soil to water mixture which was equilibrated for 30 minutes prior to the determination. The organic matter fraction of the soil was obtained by the wet-combustion technique (1). The field capacity was ascertained at a matric suction of 1/3 bar as outlined in the Moisture Retention section. The cation exchange capacities for selected soils were determined by the University of Massachusetts Soil Testing Laboratory, Amherst, Massachusetts 01002.

Plant Growth Measurements

Visible Root Counts

In the Growth Chamber Experiments root counts were obtained by the following method. The number of roots counted included all roots at a particular soil depth, which were visible around the outside of the cylinder.

Clipping Yield

The top growth was periodically collected and weighed in the Growth Chamber Experiments. Where specified, the turf was clippedat a particular height. At the termination of each study, all top growth was removed. The weights from all clipping yields and the final total yield were combined and are referred to as cumulative top growth.

Statistical Analysis

The data was subjected to analysis of variance. Standard computer programs were used to perform the analysis. When a significant difference ($P \leq 0.5$) between treatments occurred, the treatment means were subjected to a Duncan's New Multiple Range Test (25). In the case where a significant interaction existed between two or more experimental factors, it was necessary to test all treatment means, including interactions, by the Duncan's New Multiple Range Test (25). An example of such a case is found in Table 2, under the 24 cm soil depth reading on the 4/10/74 sampling date.

RESULTS

Growth Chamber Experiment 1-A

The effects of hydrophobic and hydrophylic bitumenous emulsions on the physical properties of a compacted sand and the growth of Manhattan perennial ryegrass:

The average of visible roots at different soil depths for three sampling dates is shown in Table 2. Figure 1 contains the root counts averaged over all sampling dates and methods of application for each soil conditioner. A significant improvement in root growth over all sampling dates was noted for soil receiving the hydrophylic bitumenous emulsion. Treatment with the hydrophobic emulsion resulted in a slight increase in root growth. As the experiment progressed, more extensive root growth was observed on soils receiving either a top 3 cm treatment c a througout treatment. Yields from root crops, such as radish and carrot, have increased in response to other chemical soil conditioners (41).

Results of clipping yields are found in Table 3. It is apparent that a throughout treatment of the soil column with either the hydrophylic or hydrophobic bitumenous emulsion showed a significant reduction in top growth.

Treatment of the soil with the hydrophobic or hydrophylic emulsions resulted in a significant increase in the water aggregate stability (Table 4). This is evident at both soil depths, particularly at the 7.6 to 9.2 cm depth, where aggregation was

Table 2 - Average number of visible roots at different soil depths for Growth Chamber Experiment 1-A

Soil conditioner	Method of application*	Roots by soil depth (cm)										
		Date of measurement										
		3/26			4/2				4/10			
		4	8	16	4	8	16	24	4	8	16	24
		number of roots										
Check	A	22.3	10.0	0	25.0	16.8	0.3	0	35.2	22.5	5.0	0 c
	B	18.5	5.3	0	21.3	12.8	0.3	0	27.5	21.5	2.5	0.8bc
	C	13.3	9.5	0	19.3	16.3	2.5	0	24.0	20.5	8.8	0 c
	Avg.	18.0b**	8.3b		22.8b	14.8b	1.0b		28.9b	21.1b	5.4b	
Hydrophobic Emulsion	A	28.3	10.3	0.3	37.8	18.0	3.5	0	41.3	27.0	6.8	1.0bc
	B	29.5	7.8	0	39.0	27.8	4.8	0	44.0	33.0	18.3	0.8bc
	C	13.8	8.0	0	19.8	21.8	5.8	0	22.0	26.0	15.5	2.0b
	Avg.	23.8b	8.7b		32.2ab	22.5b	4.7b		35.8ab	28.7ab	13.7ab	
Hydrophylic Emulsion	A	28.3	15.3	0	41.0	27.8	3.3	0	44.5	33.8	10.0	0.5bc
	B	36.0	15.0	0	44.8	32.3	9.8	0	50.5	41.5	25.8	0.3bc
	C	33.8	26.0	1.3	45.0	41.0	15.6	0.3	44.8	41.8	23.4	3.8a
	Avg.	32.7a	18.8a		43.6a	33.7a	9.5a		46.6a	39.0a	19.8a	
Average val. for method of application	A	26.3ab†	11.8a		35.6a	20.4a	2.3b		40.3a	27.8a	7.3b	
	B	28.0a	9.3a		35.0a	24.3a	4.9ab		40.7a	32.0a	15.7a	
	C	20.3b	14.5a		28.0a	26.3a	7.9a		30.3b	29.0a	15.9a	

* A = surface; B = top 3 cm treated; C = treated throughout.

** Values within columns followed by same letter are not significantly different at the 1% level according to Duncan's New Multiple Range Test.

† Values within columns followed by same letter are not significantly different at the 5% level according to Duncan's New Multiple Range Test.

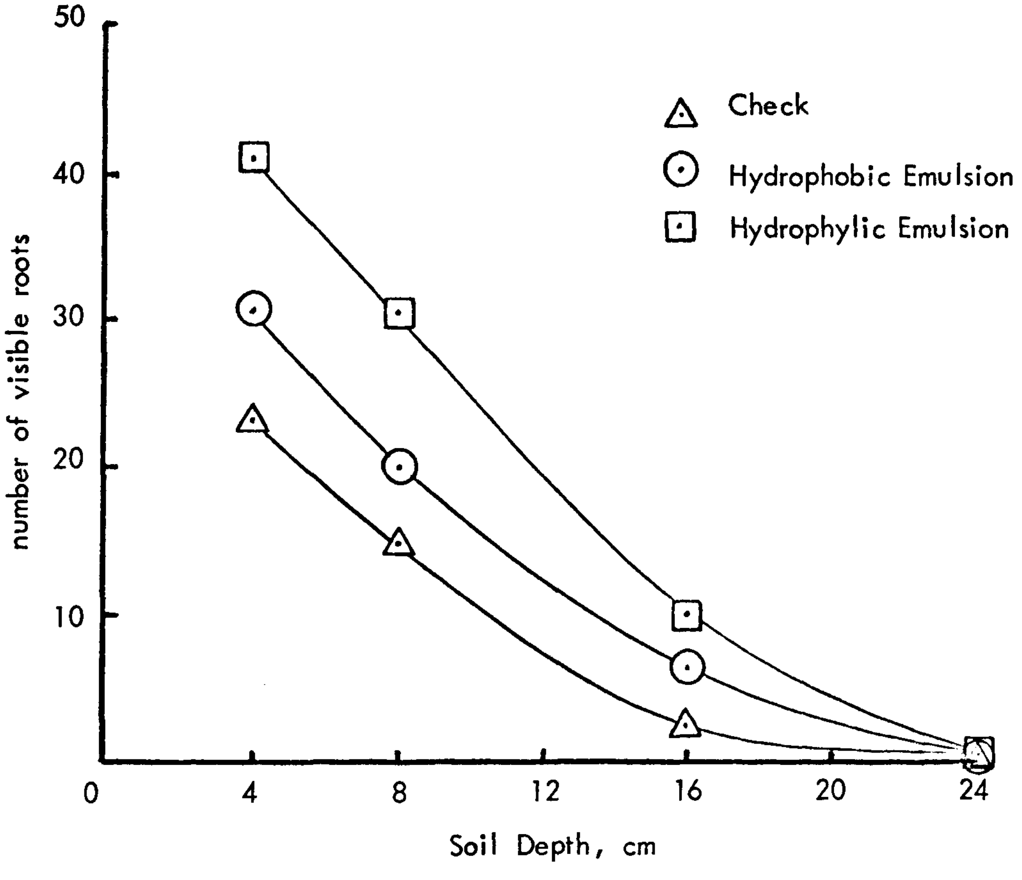

Figure 1 - Number of visible roots for each soil conditioner treatment averaged over three sampling dates and methods of application for Growth Chamber Experiment 1-A.

Table 3 - Average clipping yield data for Growth Chamber Experiment 1-A

Soil conditioner	Method of application*	Clipping yield**			Cumulative top growth
		Date			
		4/2	4/10	4/13	
		g/pot			
Check	A	0.024	0.033	0.138	0.195ab[†]
	B	0.028	0.040	0.180	0.248a
	C	0.032	0.044	0.187	0.264a
Hydrophobic Emulsion	A	0.028	0.044	0.173	0.246a
	B	0.008	0.027	0.131	0.166ab
	C	0.003	0.007	0.125	0.136cd
Hydrophylic Emulsion	A	0.036	0.040	0.167	0.236ab
	B	0.010	0.033	0.148	0.195ab
	C	0.001	0.012	0.106	0.120d

* A = Surface; B = Top 3 cm treated; C = Treated throughout.

** Clipping yields from sampling dates 4/2, 4/10 represent a cutting height of 9 cm; sampling date 4/13 represent a final clipping of all topgrowth.

† Values within columns followed by same letter are not significantly different at 5% level.

Table 4 - Average values of % water stable aggregation at different soil depths and bulk density measurements prior and following compaction for Growth Chamber Experiment 1-A

Soil conditioner	Method of application*	Aggregation – Soil depth (cm)		Bulk density – Compaction	
		0-3	7.6-9.2	prior	after
		%		g/cc	
Check	A	33.7	10.8d	1.61	1.64a
	B	33.4	12.2d	1.58	1.64a
	C	57.8	37.7c	1.42	1.50b
	Avg.	41.6b**		1.53a	
Hydrophobic Emulsion	A	62.4	20.8d	1.58	1.63a
	B	66.0	23.0d	1.54	1.61a
	C	89.3	74.6a	1.31	1.39d
	Avg.	72.6a		1.48b	
Hydrophylic Emulsion	A	51.9	11.3d	1.57	1.62a
	B	80.9	36.3c	1.56	1.62a
	C	77.7	63.1b	1.36	1.43c
	Avg.	70.2a		1.50b	
Average values for method of application	A	49.3b		1.58a	
	B	60.1a		1.56a	
	C	74.9a		1.36b	

* A = Surface; B = Top 3 cm treated; C = Treated throughout.

** Values within columns followed by same letter are not significantly different at the 5% level according to Duncan's New Multiple Range Test.

approximately doubled. The increase in aggregate stability was consistent with the findings of Vandenvelde and DeBoodt (88). Aggregate analysis of the upper 3 cm of the soil column revealed that, in general, both the top 3 cm and throughout treatment methods had a higher level of aggregation than the surface application method. Aggregate stability, with respect to any soil conditioner, was higher at the surface 3 cm of the soil column than the 7.6 to 9.2 cm soil depth section. This could be a result of the increased number of roots in the surface 3 cm section, since an actively growing root system in the presence of soil microbes can cause the formation and stabilization of aggregates (39, 44).

The bulk density was lower on soil columns treated throughout with the hydrophobic and hydrophylic emulsions (Table 4). After compaction, the bulk densities were lower than the check treatment, which indicated that the increased aggregate stability resulted in a decrease in compressibility.

Average ODR for three measurement dates and soil moisture contents at the time of sampling are shown in Table 5. Each soil column was watered to a 9% moisture content by weight 24 hours prior to the ODR measurement. The 9% moisture content for field capacity was determined by saturating the columns and allowing them to drain for 24 hours. The ODR ranged from a high of 81.1 to a low of 4.2 g of $O_2 \times 10^{-8} cm^{-2} min^{-1}$. Measurements taken at soil depths of 2.5 cm and 7.6 cm indicated that ODR increased as the soil depth increased. The difference in ODR between soil depths may be related to the degree of compaction. The magnitude of compaction applied in this study is representative of normal foot traffic which affects the top 9 cm of the soil and is most harmful on

Table 5 - Average oxygen diffusion rate (ODR) and moisture content for Growth Chamber Experiment 1-A

Soil conditioner	Method of application*	ODR by soil depth (cm)						Moisture content**		
		Date of measurement						Date of measurement		
		3/27		4/3		4/11		3/27	4/3	4/11
		2.5	7.6	2.5	7.6	2.5	7.6			
		g of O_2 X 10^{-8} cm^{-2} min^{-1}						%		
Check	A	22.3	52.0	34.8	81.1	31.2	65.0	8.40	8.30	8.08
	B	27.9	35.4	26.0	50.2	22.3	39.5	8.42	8.35	8.19
	C	15.4	41.2	25.0	56.1	23.1	41.6	8.53	8.31	8.21
Hydrophobic Emulsion	A	22.2	48.2	23.2	49.0	23.1	32.3	9.48	8.20	8.25
	B	7.1	46.7	6.1	25.8	4.2	25.6	10.83	8.58	8.19
	C	4.2	13.8	4.3	17.5	8.3	17.0	8.41	8.11	8.26
Hydrophylic Emulsion	A	21.1	28.0	20.0	41.2	20.3	36.7	9.47	8.30	8.13
	B	10.9	34.0	8.7	28.7	6.9	24.8	11.72	8.80	8.28
	C	8.6	12.2	15.2	20.4	20.3	20.8	7.72	8.39	8.32

* A = Surface; B = Top 3 cm treated; C = Treated throughout.

** % moisture by weight of soil at time ODR were taken.

the upper 2 cm section (22). It has been observed in other studies that compaction causes a reduction in ODR (20, 53). Very low levels of ODR were observed on soils treated with either bitumenous emulsion (see Laboratory Experiment 1-A for discussion).

Growth Chamber Experiment 1-B

The effects of compaction on the physical properties of a sand and growth of Manhattan perennial ryegrass:

Average root growth values for several measurement dates are found in Table 6. The deleterious effect of compaction root growth was apparent even though not significant at the 5% level. A small difference in the amount of visible roots was observed at a 4 cm soil depth; however, at a soil depth of 8 cm, compaction resulted in a greater decrease in visible roots. Similar deleterious effects of compaction on the root growth of turfgrass was observed by Cordukes (19) and Letey *et al*. (53).

Compaction had little effect on top growth of *Lolium perenne* L. (Table 7). The degree of compaction and/or the relatively short duration of the investigation may have been responsible for the noninhibitory effect of compaction on top growth in this instance.

Average aggregate stability determinations at two soil depths and bulk density measurements are shown in Table 8. While the results were not significantly different at the 5% level, compaction appeared to reduce the water stable aggregation (i.e., by 27% in the upper 3 cm of the soil column). Several other investi-

Table 6 - Average number of visible roots at different soil depths for Growth Chamber Experiment 1-B

Treatment	Roots by soil depth (cm)						
	Date of measurement						
	3/26		4/2		4/10		
	4	8	4	8	4	8	16
	number of roots						
(+) Compaction	14.8a*	1.3a	16.5a	3.8a	21.0a	5.8a	0.5a
(-) Compaction	17.0a	2.5a	18.5a	5.8a	32.0a	11.8a	0.3a

* Values within columns followed by same letter are not significantly different at the 5% level.

Table 7 - Average clipping yield data for Growth Chamber Experiment 1-B

Treatment	Clipping yield * — Date of measurement — 4/2	4/10	4/13	Cumulative top growth
	g/pot			
(+) Compaction	0.019 a**	0.030 a	0.150 a	0.199 a
(-) Compaction	0.033 a	0.024 a	0.130 a	0.187 a

* Clipping yields from sampling dates 4/2 and 4/10 represents a cutting height of 9 cm; sampling date 4/13 represents a final clipping of all topgrowth.

** Values within columns followed by same letter are not significantly different at the 5% level.

Table 8 - Average values of % water stable aggregation at different soil depths and bulk density measurements prior and following compaction for Growth Chamber Experiment 1-B

Treatment	Aggregation Soil depth (cm) 0-3	 7.6-9.2	Bulk density Compaction prior	 after
	%		g/cc	
(+) Compaction	26.6a*	16.1a	1.55a	1.61a
(-) Compaction	36.3a	17.7a	1.57a	1.57a

*Values within columns followed by same letter are not significantly different at the 5% level.

gations have shown that compaction resulted in destruction of water stable aggregates (9, 45, 92). No essential difference in aggregation existed between compacted and noncompacted soil columns at a soil depth of 7.6 to 9.2 cm. It is apparent that compaction had a minimal effect on aggregation at the 7.6 to 9.2 cm soil depth. The results obtained for aggregate analyses at both soil depths coincide with the effect of compaction from foot traffic on the top 9 cm of the soil as noted by Davis (22). Compacting the soil columns resulted in a slight increase in bulk density.

Average ODR and soil moisture contents at the time of sampling are contained in Table 9. Generally, compaction produced slightly elevated ODR levels and soil moisture contents for all measurement dates. 'The slight increase in moisture content associated with compaction may have influenced the ODR measurements. The findings of Lemon and Erickson (52) suggested that an increase in soil moisture content (reduction in suction) above a certain point (> field capacity) resulted in an increase in ODR. ODR for this study also increased with an increase in soil depth as noted in the previous experiment.

Growth Chamber Experiment 1-C

The effects of a hydrophobic bitumenous emulsion and a solution of polyacrylamide (PAM) on the physical properties of a compacted silt loam soil and growth of Manhattan perennial ryegrass:

The results obtained in Growth Chamber Experiment 1-A indicated that the surface application with the bitumenous emulsions had little or no beneficial

Table 9 - Average oxygen diffusion rates (ODR) and moisture content for Growth Chamber Experiment 1-B

Treatment	ODR by soil depth (cm)						Moisture content*		
	Date of measurement						Date		
	3/27		4/3		4/11				
	2.5	7.6	2.5	7.6	2.5	7.6	3/7	4/3	4/11
	g of $O_2 \times 10^{-8} cm^{-2} min^{-1}$						%		
(+) Compaction	31.6	74.3	43.5	65.9	15.3	52.5	9.10	8.43	8.30
(-) Compaction	21.6	43.1	27.4	74.3	30.0	37.3	8.00	8.11	8.05

* % moisture by weight of soil at time ODR were taken.

effects on all parameters measured. Thus, the surface method of application was eliminated in this study.

Results of root growth determinations are found in Table 10. Treatment of the entire soil column with the hydrophobic emulsion produced the greatest root growth as determined from root dry matter yields and visible root counts. This highly significant increase in root growth was consistent throughout the experiment and at each sampling depth. The PAM treatments had only a minimal effect on root growth.

The germination percentage was affected by different soil conditioner treatments (Table 11). Untreated soil was used to cover the grass seeds so as to eliminate any of the treatment effects on germination. However, germination on soil columns treated throughout with the hydrophobic emulsion was 15% higher than the other treatments.

Clipping yields were substantially improved by the throughout treatment with the hydrophobic emulsion (Table 11). Doyle and Hamlyn (24) and Hedrick and Mowry (41) noted increased crop yield were directly related to the structural improvement by chemical soil conditioners. Top growth and germination were not influenced by PAM.

Treatment with either the hydrophobic emulsion or PAM resulted in a highly significant increase in water stable aggregation in the upper 3 cm of the soil column (Table 12). However, at the 7 to 10 cm soil depth, aggregation was much greater for the throughout hydrophobic emulsion treatment. Regardless of treatment, bulk density increased following compaction. The hydrophobic emulsion showed a

Table 10 - Average dry matter yield of roots and visible root counts at different soil depths for Growth Chamber Experiment 1-C

Soil condtioner	Method of application*	Soil depth (cm)							
				Date of measurement					
		Root weight		7/15			7/21		
		3-7	10-14	3	10	18	3	10	18
		g		number of roots					
Check	A	0.012b**	0 b	0.8b	0 b	0 b	1.0c	0 b	0 b
	B	0.006b	0 b	0.5b	0 b	0 b	0.5c	0.5b	0 b
Hydrophobic Emulsion	A	0.005b	0.001b	2.5b	0 b	0 b	2.8bc	0 b	0 b
	B	0.041a	0.017a	14.5a	19.0a	7.3a	16.5a	24.3a	14.0a
Humafina PAM	A	0.013b	0 b	5.8b	0.3b	0 b	8.3b	0.8b	0 b
	B	0.008b	0 b	1.3b	0 b	0 b	1.8bc	0.5b	0 b

* A = Top 3 cm treated; B = Treated throughout.

** Values within columns followed by same letter are not significantly different at the 1% level according to Duncan's New Multiple Range Test.

Table 11 - Average % germination and clipping yield for Growth Chamber Experiment 1-C

Soil conditioner	Method of application*	Germination	Clipping yield†		
			Date		Cumulative topgrowth
			7/14	7/23	
		%	g/pot		
Check	A	54.2ab**	0.072b	0.168b	0.240b
	B	43.7b	0.021c	0.163b	0.184b
Hydrophobic Emulsion	A	46.3b	0.013c	0.132b	0.145b
	B	70.7a	0.098a	0.479a	0.577a
Humafina PAM	A	54.9ab	0.023c	0.183b	0.206b
	B	32.8b	0.006c	0.124b	0.130b

* A = Top 3 cm treated, B = Treated throughout.

** Values within columns followed by same letter are not significantly different at the 1% level according to Duncan's New Multiple Range Test.

† Clipping yields from sampling date 7/14 received a 10 cm cutting height; sampling date 7/23 was a final clipping of all topgrowth.

Table 12 - Average % water stable aggregation at different soil depths and bulk density measurements prior and following compaction for Growth Chamber Experiment 1-C

Soil conditioner	Method* of application	Aggregation		Bulk density	
		Soil depth (cm)		Compaction	
		0-3	7-10	prior	after
		%		g/cc	
Check	A	26.7	38.8bc	0.99d	1.24
	B	29.4	29.5c	1.10b	1.28
	Avg.	28.1c**			1.26a
Hydrophobic Emulsion	A	86.1	40.1bc	1.07bc	1.20
	B	89.3	91.1a	1.14b	1.25
	Avg.	87.7a			1.23b
Humafina PAM	A	37.1	51.6b	1.03cd	1.25
	B	48.7	51.2b	1.25a	1.30
	Avg.	42.9b			1.28a
Average values for method of application	A	50.0b			1.23b
	B	55.8a			1.28a

* A = Top 3 cm treated; B = Treated throughout.

** Values within columns followed by same letter are not significantly different at the 1% level according to Duncan's New Multiple Range Test.

slightly lower bulk density than the other soil conditioner treatments. For all soil conditioners, bulk densities and water stable aggregation analyses were considerably higher with a throughout treatment than the surface 3 cm method of application. All treatments had ODR's sufficient for normal root growth of turfgrass (Table 13). No treatment trends were apparent with respect to ODR.

Growth Chamber Experiment 1-D

The effects of compaction on the physical properties of a silt loam soil and growth of Manhattan perennial ryegrass:

Root growth in this study was very minimal with few roots penetrating further than 10 cm (Table 14). Root response to compaction treatment was not evident.

Average germination percentage and clipping yields are contained in Table 15. Compaction produced a two-fold increase in percent germination. Precautions, such as uniform watering and covering of the grass seeds with untreated soil, apparently did not diminish the treatment effects on germination. The increased germination is thought to be mainly caused by an increase in soil moisture content at the surface 3 cm of the column reflecting the moisture retention data shown in Table 20. As a result of increased number of seedlings, top growth on the compacted soil columns was significantly larger than on noncompacted soil.

Average water stable aggregate analyses and bulk density values are found in Table 16. Compaction of the soil columns reduced the water stable aggregation at both soil depths; however, the difference was only at the 10% confidence level. The aggregation results suggest that compaction adversely affects at least the top 10 cm of the Hadley silt loam soil. The bulk density, as expected, increased with compaction.

Table 13 - Average oxygen diffusion rates (ODR) and moisture content for Growth Chamber Experiment 1-C

Soil conditioner	Method of application*	ODR by soil depth (cm) Date of measurement 7/7		7/22		Moisture content ** Date 7/7	7/22
		2.5	7.6	2.5	7.6		
		g of $O_2 \times 10^{-8}$ cm^{-2} min^{-1}				%	
Check	A	53.6	53.2	40.5	66.2	14.1	13.0
	B	67.8	80.4	32.3	30.0	10.9	13.2
Hydrophobic	A	66.4	84.5	69.2	23.3	14.4	13.5
Emulsion	B	50.6	40.9	51.5	45.4	10.4	9.6
Humafina	A	75.6	79.1	47.6	51.3	13.7	13.9
PAM	B	87.1	70.4	42.3	43.3	13.9	12.6

* A = Top 3 cm; B = Treated throughout.

** % moisture by weight of soil at time ODR were taken.

Table 14 – Average dry matter yield of root and visible root counts at different soil depths for Growth Chamber Experiment 1-D

Treatment	Soil depth (cm)					
	Root weight		Date of measurement			
			7/15		7/21	
	3-7	10-14	3	10	3	10
	g/pot		number of roots			
(+) Compaction	0.004 a*	0 a	0.3 a	0 a	1.0 a	0 a
(–) Compaction	0.009 a	0.001 a	0.8 a	0 a	0.8 a	0 a

* Values within columns followed by same letter are not significantly different at the 5% level.

Table 15 - Average % germination and clipping yields for Growth Chamber Experiment 1-D

Treatment	Germination	Clipping yield* Date 7/14	Clipping yield* Date 7/23	Clipping yield* Cumulative topgrowth
	— % —	— g/pot —		
(+) Compaction	47.3a**	0.013a	0.143a	0.156a
(-) Compaction	18.7b	0.002b	0.037b	0.039b

* Clipping yield from sampling date 7/14 received a 10cm height of cut; sampling date 7/23 was a final clipping of all topgrowth.

** Values within columns followed by same letter are not significantly different at the 5% level.

Table 16 - Average values of % water stable aggregation at different soil depths and bulk density measurements prior and following compaction for Growth Chamber Experiment 1-D

Treatment	Aggregation Soil depth (cm) 0-3	 7-10	Bulk density Compaction prior	 after
	%		g/cc	
(+) Compaction	27.8a*	34.8a	0.99a	1.26a
(-) Compaction	48.0a	50.1a	1.01a	1.01b

* Values within columns with same letter are not significantly different at the 5% level.

ODR for (+) and (-) compaction treatments were at a sufficient level for normal root growth (Table 17). No consistent treatment trends were apparent due to differences in soil moisture content at the time of ODR measurements. This occurred because of separation of the soil from the cylinder side. Watering to a uniform specific moisture content by weight, therefore, was very difficult.

Growth Chamber Experiment 2

The effects of an algal polymer culture and polyacrylamide on water stable aggregate formation of three soils at two pH levels:

Average water stable aggregation values are shown in Table 18. Both the algal polymer culture and the PAM chemical soil conditioner greatly increased the percent water aggregate stability for all three soil types and pH levels. The beneficial effects of algae on aggregation have alsobeen observed by Fogal _et al._ (29) and Bailey _et al._ (5). Soil pH, in general, did not affect aggregation; however, the lower pH did enhance aggreage stabilization on the loam and clay loam soils. Independent of the soil treatment and/or pH, the level of aggregation of the silt and clay loam soil was considerably higher than the sandy loam soil.

Laboratory Experiment 1-A

The effects of a hydrophylic bitumenous emulsion and polyacrylamide (PAM) on the physical properties of a compacted sand soil:

Average measurements for moisture retention, bulk density, penetrometer, and ODR are shown in Table 19. Percent moisture by weight (P_w) and percent moisture by volume (P_v) at different matric suctions for each treatment are con-

Table 17 - Average oxygen diffusion rates (ODR) and moisture content for Growth Chamber Experiment 1-D

Treatment	ODR by soil depth (cm)				Moisture content*	
	Date of measurement				Date	
	7/7		7/22		7/7	7/22
	2.5	7.6	2.5	7.6		
	g of O_2 X 10^{-8} cm^{-2} min^{-1}				%	
(+) Compaction	69.0	56.6	37.8	41.8	11.8	13.0
(-) Compaction	44.1	53.1	69.2	41.0	16.5	16.7

* % moisture by weight of soil at time ODR were taken.

Table 18 - Average % water stable aggregation for

Growth Chamber Experiment 2

Treatment	Soil type*	pH	Aggregation	Average
			%	%
Check	SL	6.46	41.8	
		4.76	33.2 (37.5d**)	
	L	7.23	55.0	
		5.23	66.3 (60.7c)	
	CL	7.36	51.5	
		5.48	61.4 (56.5c)	51.5z***
1:10 algae culture to soil	SL	6.46	75.6	
		4.76	82.3 (78.9b)	
	L	7.23	76.7	
		5.23	85.8 (81.3ab)	
	CL	7.36	76.5	
		5.48	84.7 (80.6ab)	80.2y
0.15%PAM(Cyanamer P-250)	SL	6.46	86.5	
		4.76	84.2 (85.4ab)	
	L	7.23	84.9	
		5.23	92.8 (88.9a)	
	CL	7.36	88.4	
		5.48	90.7 (89.6a)	87.9x

*SL refers to sandy loam soil; L refers to loam soil; CL refers to clay loam soil.

**Values within column followed by same letter are not significantly different at the 5% level according to Duncan's New Multiple Range Test.

***Values within column followed by same letter are not significantly different at the 1% level according to Duncan's New Multiple Range Test.

Table 19 - Average moisture retention data, bulk density, penetrometer and oxygen diffusion rate (ODR) measurements for Laboratory Experiment 1-A

Treatment	Moisture by weight				Moisture by volume				Bulk density	Penetrometer	ODR*
	Tension (bar)				Tension (bar)						
	.06	1/3	1	2	.06	1/3	1	2			
	%								– g/cc –	– kg/cm^2 –	– $\mu g\ O_2\ cm^{-2}\ min^{-1}$ –
Check (-) compaction	17.8 ab**	13.8 a	10.5 a	9.1 a	29.2 a	22.6 a	17.2 a	14.9 a	1.64 a	1.58 a	0.135
Check (+) compaction	18.3 a	14.0 a	10.7 a	8.8 a	29.5 a	22.5 a	17.2 a	14.2 a	1.61 ab	1.32 b	0.125
Check (Treated with H_2O)	17.0 abc	13.3 a	10.9 a	9.4 a	26.5 b	20.7 ab	17.0 ab	14.7 a	1.56 b	1.07 c	0.131
Hydrophylic emulsion	7.6 d	7.0 b	6.5 b	6.3 b	10.2 d	9.4 c	8.7 c	8.4 b	1.34 c	0.65 d	0.020
PAM (Cyanamer P-250)	16.0 c	13.1 a	10.6 a	9.6 a	22.2 c	18.2 b	14.7 b	13.3 a	1.39 c	0.95 c	0.177

* ODR were taken at 2 bar tension.

** Values within columns followed by same letter are not significantly different at the 1% level according to Duncan's New Multiple Range Test.

tained in Figure 2 and Figure 3, respectively. The hydrophylic bitumenous emulsion treatment significantly reduced the moisture retentativity (P_w and P_v), bulk density, vertical penetration resistance (penetrometer), and ODR. Treatment of the soil with PAM (Cyanamer P-250) resulted in lower moisture retention (P_v), bulk density and vertical penetration resistance than that of the check treatment (demineralized water plus compaction). The soil conditioners VAMA and HPAN were found to slightly reduce the available moisture equivalent with increased aggregation (65). The moisture retentativity as affected by the hydrophylic emulsion may have been caused by the inability of the soil to be wetted by capillary action. In this study, in Growth Chamber Experiment 1-A and in another preliminary study, wetting of hydrophylic emulsion treated sand soil by capillary rise was almost impossible. This made it necessary to wet these soils by a positive hydraulic head for a short period of time. Incomplete wetting may have occurred, which could have been partially responsible for the moisture retention differences.

The hydrophylic bitumenous emulsion treatment, in this study and in Growth Chamber Experiment 1-A (Table 5), resulted in a low ODR status (0.02 μg of $O_2\, cm^{-2} min^{-1}$). The findings of other investigators (53, 54, 73) suggest that ODR as low as 0.02 μg of $O_2\, cm^{-2}$ min^{-1} would restrict normal root growth of turfgrass. The rooting data in Table 2 indicated that the low ODR did not inhibit root growth; therefore, it appeared that a true measurement of the soil aeration (ODR), with respect to the hydrophylic emulsion treatment, was not obtainable in this study and in Growth Chamber Experiment 1-A. The low ODR are thought to be a result of the effect of the hydrophylic emulsions on soil moisture content. In Experiment 1-A, soil moisture contents for the entire soil column were consistent for each treatment. However, the moisture retention data in Table 19 suggests that a difference in moisture content existed between treatments at the surface 3cm of the soil column, which is where ODR measurements were obtained. Also, Krisensen(50)noted that as the soil moisture content decreased

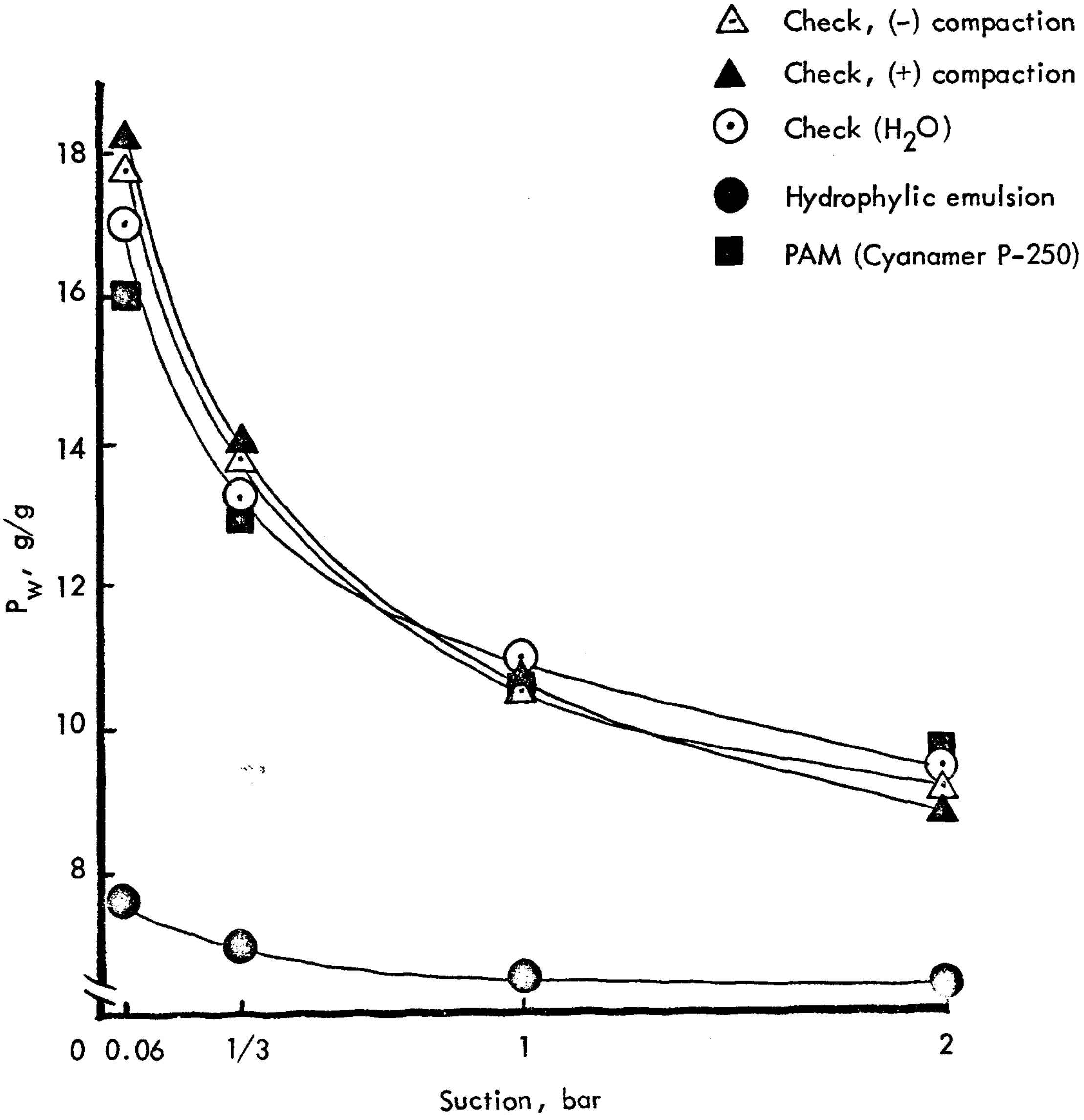

Figure 2 - Average percent moisture, by weight (P_w), at different matric suctions for each treatment in Laboratory Experiment 1-A.

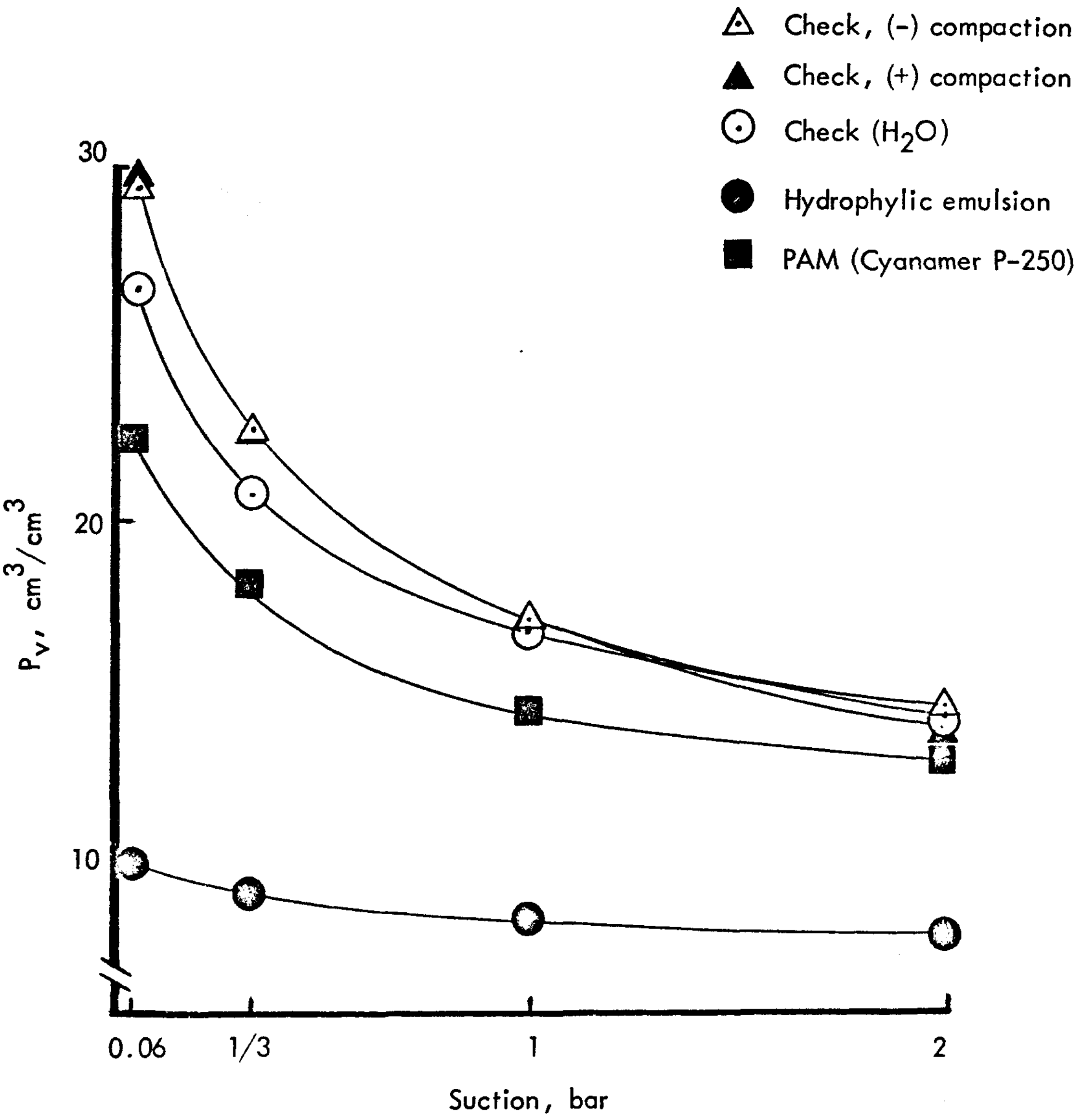

Figure 3 - Average percent moisture, by volume (P_v), at different matric suctions for each treatment in Laboratory Experiment 1-A .

(increasing soil suction) the ODR were greatly increased. The findings of Lemon and Erickson (52) revealed that for coarse textured soils, as the soil suction increases, water films surrounding the microelectrodes contract and the ODR's are reduced. Stolzy and Letey (79) also concluded that the decrease in ODR with a decrease in soil moisture is a result of incomplete wetting of electrode. This could explain the erratic nature of the ODR results.

Compaction had little effect on moisture retention or bulk density on the Windsor sand soil. However, the penetrometer and ODR parameters were reduced under compacted conditions.

Treating the soil with only demineralized water (check treatment - H_2O plus compaction) produced a lower bulk density and penetrometer value and slightly higher ODR than the untreated check plus compaction treatment. The increased level of aggregate stability of the former treatment (Tables 4 and 8) might have caused these results.

Laboratory Experiment 1-B

The effects of a hydrophobic bitumenous emulsion and a solution of polyacrylamide on the physical properties of a compacted silt loam soil:

Results of moisture retention and bulk density analyses are found in Table 20. Moisture retention curves, expressed as P_w and P_v, are shown in Figure 4 and Figure 5, respectively. The percent moisture retained by weight was substantially reduced on the hydrophobic bitumenous emulsion treated soil. In this study, no problem was encountered in wetting the soil by capillary action. The moisture

Table 20 - Average moisture retention data and bulk density measurement for Laboratory Experiment 1-B

Treatment	Moisture by weight				Moisture by volume				Bulk density
	Tension (bar)				Tension (bar)				
	.06	1/3	1	2	.06	1/3	1	2	
	%								g/cc
Check (-) compaction	35.1b*	31.1b	28.2b	24.5b	39.0b	34.5c	31.3c	27.2c	1.11b
Check (+) compaction	37.7a	34.6a	32.7a	30.0a	47.5a	43.6a	41.2a	37.8a	1.26a
Check (Treated with H_2O)	37.7a	34.9a	33.3a	31.5a	48.3a	44.7a	42.6a	40.3a	1.28a
Hydrophobic emulsion	32.3c	29.7b	27.8b	25.7b	41.0b	37.7b	35.3b	32.6b	1.27a
PAM (Cyanamer P-250)	36.5ab	34.2a	32.2a	29.4a	39.8b	37.3bc	35.1b	32.0b	1.09b

*Values within columns followed by same letter are not significantly different at the 1% level according to Duncan's New Multiple Range Test.

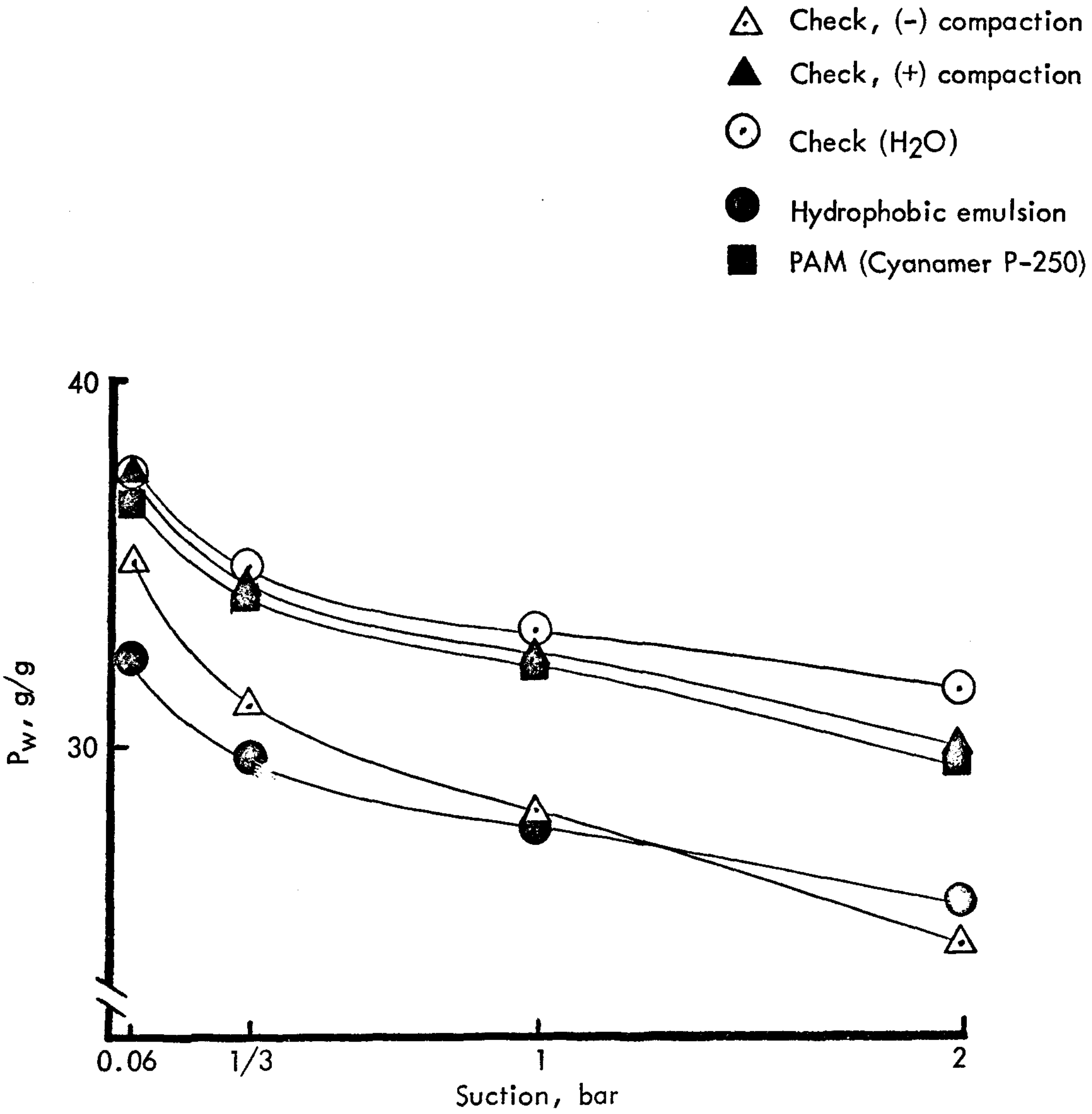

Figure 4 - Average percent moisture, by weight, at different matric suctions for each treatment in Laboratory Experiment 1-B.

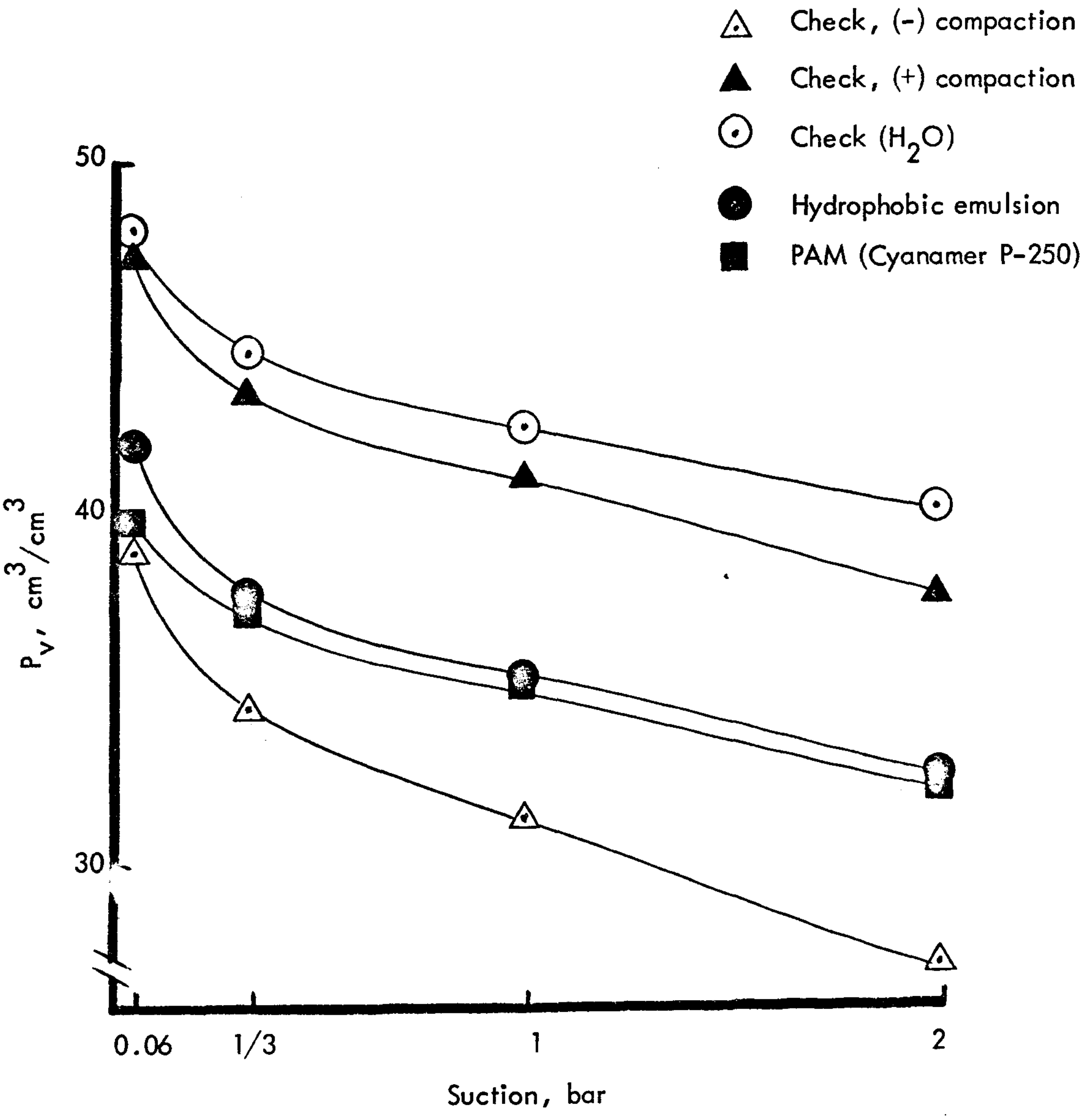

Figure 5 - Average percent moisture, by volume (P_v), at different matric suctions for each treatment in Laboratory Experiment 1-B.

release curves, represented volumetrically (Figure 5), were affected by the PAM and the hydrophobic bitumenous emulsion treatments. The lowering of the volumetric water release curve, in response to structural improvement by the hydrophobic bitumenous emulsion and PAM, represents an increase in total porosity. Improvement of soil aeration (ODR) should have accompanied the increase in total porosity; however, for the reasons stated previously, this was not observed. The PAM reduced the bulk density equivalent to that of noncompacted soil.

Compaction caused an increase in the moisture retained by weight and by volume and an increase in bulk density. The increased moisture retentativity, attributed to compaction, has been noted by others (42, 86, 91).

Field Experiment 1-A

The effects of several chemical soil conditioners on a compacted silt loam soil and the growth of Penncross creeping bentgrass;

The chemical soil conditioners showed no effect on the moisture retention property of the Hadley silt loam soil (Table 21). In Table 22, average root dry matter yields, water and dry stable aggregation, and bulk density values are shown. Root dry weight yields at a soil depth of 0 to 9 cm, water and dry stable aggregation and bulk density analysis were not affected by any soil conditioner or any method of application. The lack of improved soil physical properties and root growth by the chemical soil conditioners might have been a result of the low rates of application, the naturally well-structured soil masking the treatment effects, or the relatively few compaction applications. Treatment of the soil

Table 21 - Average moisture retention data for Field Experiment 1-A

Treatment	Method of application*	(±) Comp.	Moisture by weight			
			Tension (bar)			
			.06	1/3	1	2
			%			
Hydrophobic Emulsion	1	+	27.7	24.9	23.0	20.4
		-	27.3	24.9	22.9	20.6
	2	+	26.4	24.6	22.2	19.7
		-	27.3	25.4	23.0	20.4
		Avg.	27.2a**	24.9 a	22.8a	20.1a
Hydrophylic Emulsion	1	+	27.7	25.2	23.5	21.1
		-	28.2	25.3	23.8	21.3
	2	+	27.5	24.8	22.8	20.3
		-	27.8	25.2	23.2	20.8
		Avg.	27.8a	25.1a	23.3a	20.9a
Humafina PAM	1	+	26.8	24.7	22.5	19.9
		-	27.0	24.7	22.8	20.5
	2	+	27.3	24.9	22.7	19.9
		-	28.0	25.4	23.5	20.9
		Avg.	27.2a	24.9a	22.9a	20.3a
Che k (H_2O)	1	+	26.3	24.1	22.0	19.3
		-	27.8	25.3	23.2	20.4
	2	+	26.7	24.7	22.6	19.8
		-	27.4	25.1	23.2	21.1
		Avg.	27.0a	24.8a	22.8a	20.1a
Average for method of application	1		27.3a	24.9a	23.0a	20.4a
	2		27.3a	25.0a	22.9a	20.3a
Average for (±) compaction		+	27.0b	24.7b	22.7b	20.0b
		-	27.6a	25.1a	23.2a	20.7a

* 1 = Treatment of aerification core soil and dragmatting of soil into aerifying holes; 2 = injection of material after plots were aerified.

** Values within columns followed by same letter are not significant at the 5% level according to Duncan's New Multiple Range Test.

Table 22 - Average root yield at different soil depths, % water and dry stable aggregation and bulk density measurement for Field Experiment 1-A

Treatment	Method of application*	(±) compaction	—Root weight— Soil depth (cm) 0-9	10-18	—Aggregation— Water stable	Dry sieved	Bulk density
			g/pot		%		g/cc
Hydrophobic Emulsion	1	+	0.165	0.045	83.2	41.9	1.25
		-	0.125	0.061	79.7	45.6	1.32
	2	+	0.149	0.037	82.1	43.1	1.29
		-	0.189	0.048	83.4	43.0	1.25
		Avg.	0.157a**	0.048a	82.1a	43.4a	1.28a
Hydrophylic Emulsion	1	+	0.189	0.063	81.3	44.2	1.24
		-	0.152	0.061	81.8	47.4	1.27
	2	+	0.176	0.047	86.1	42.3	1.27
		-	0.146	0.045	81.1	47.1	1.29
		Avg.	0.166a	0.054a	82.6a	45.2a	1.26a
Humafina PAM	1	+	0.184	0.059	82.0	42.2	1.31
		-	0.153	0.052	84.6	45.2	1.32
	2	+	0.171	0.045	82.9	44.1	1.24
		-	0.154	0.045	86.0	47.0	1.33
		Avg.	0.166a	0.051a	83.8a	44.6a	1.29a
Check (H_2O)	1	+	0.166	0.047	75.6	40.0	1.33
		-	0.151	0.053	79.3	46.2	1.24
	2	+	0.165	0.048	77.1	39.8	1.30
		-	0.144	0.037	84.8	45.1	1.27
		Avg.	0.157a	0.046a	79.2a	42.8a	1.28a
Average for method of application	1		0.161a	0.055a	80.9a	44.1a	1.28a
	2		0.161a	0.044b	82.9a	44.0a	1.28a
Average for (±) compaction		+	0.171a	0.049a	81.3a	42.2b	1.29a
		-	0.152b	0.050a	82.6a	45.8a	1.27a

---

* 1 = Treatment of aerification core soil and dragmatting of soil into aerifying holes; 2 = injection of material after plots were aerified.

** Values within columns followed by same letter are not significant at the 5% level according to Duncan's New Multiple Range Test.

following aerification slightly increased the root growth at a soil depth of 10 to 18 cm. In general, compaction reduced the moisture retention and the dry stable aggregation and showed a slight increase in root growth at the 0 to 9 cm soil depth.

Field Experiment 1-B

Effects of a hydrophylic bitumenous emulsion on the physical properties of a loamy sand soil and turfgrass growth (preliminary investigation):

Determination of the moisture retentativity of the thatch layer and upper 3 cm section of the soil indicated that the hydrophylic bitumenous emulsion increased the moisture content by 3% in the thatch layer and had no effect on the soil layer (Table 23); however, this was not significant at the 5% level. The thatch layer of this turfgrass stand ranged from 3 to 10 cm in thickness. Since most of the emulsion injected remained in the thatch layer, an increase in moisture retention resulted in the thatch layer and not in the upper 3 cm of the soil.

Root dry weight yield, as shown in Table 24, appeared to be slightly lower on the hydrophylic bitumenous emulsion plots. The moisture retention data would suggest that under moisture stress conditions roots would tend to grow in the thatch layer and not penetrate the soil.

Overall grass quality, as measured by visual plot ratings (Table 24), was greater on the hydrophylic emulsion injection plots. These ratings were obtained 3 weeks after treatment and were based on color and density.

Table 23 - Average moisture retention data for Field Experiment 1-B

Treatment	Moisture by weight					
	Tension (bar)					
	Thatch		Soil sample			
	.06	2	.06	1/3	1	2
	%					
Check	23.1a*	15.8a	16.7a	15.0a	12.2a	11.0a
H_2O injected	22.4a	14.2a	17.2a	15.7a	12.7a	11.1a
Hydrophylic emulsion	25.2a	18.0a	16.2a	14.5a	11.7a	10.5a

* Values within columns followed by same letter are not significantly different at the 5% level.

Table 24 - Average root yield, visual plot rating, % water stable aggregation, % organic matter and bulk density for Field Experiment 1-B

Treatment	Root weight Soil depth (cm) 0-9	10-18	Visual plant rating*	Aggregation	Organic matter	Bulk density
	g/pot			%		g/cc
Check	0.199a**	0.085a	6.3c	38.8a	30.3a	0.98a
H_2O injected	0.192a	0.083a	7.2b	43.1a	36.0a	1.09a
Hydrophylic emulsion	0.133a	0.062a	8.5a	44.1a	32.3a	0.96a

* Scale 1-9, 1 = brown turf color and poor density; 9 = excellent color and density.

** Values within columns followed by same letter are not significantly different at the 5% level according to Duncan's New Multiple Range Test.

Water stable aggregation, organic matter content of the thatch layer, and bulk density were not affected by any treatment (Table 24). Observations of the treated soil indicated that the hydrophylic emulsion was injected into the surrounding soil and thatch layer as far as 1 cm.

Field Experiments 2-A and 2-B

The effects of an algal polymer culture on the soil physical properties of a silt loam soil and turfgrass growth:

Average moisture retention, water and dry stable aggregation, and bulk density analyses are shown in Table 25 for Field Experiment 2-A and in Table 26 for Field Experiment 2-B. No difference was observed on any parameter measured in response to any treatment in either experiment. Both the bulk density and the water stable aggregation increased as the investigation progressed (Table 26). Settling of the soil and the natural stabilization of aggregates following cultivation may have caused the increase.

Table 25 - Average moisture retention data, % water and dry stable aggregation and bulk density measurement for Field Experiment 2-A

Treatment number**	(±) compaction	Moisture by weight — Tension (bar) .06	1/3	1	2	Aggregation — Water stable	Dry sieved	Bulk density
		%						-g/cc-
1	+	28.6	26.8	24.1	21.6	79.9	45.7	1.29
	-	26.6	24.8	21.9	20.2	82.6	43.2	1.30
	Avg.	27.6 a*	25.8 a	23.0 a	20.9 a	81.2 a	44.4 a	1.30 a
2	+	24.0	21.8	19.0	17.1	79.2	44.8	1.28
	-	26.3	24.6	22.1	19.9	78.4	44.6	1.28
	Avg.	25.1 a	23.2 a	20.6 a	18.5 a	78.8 a	44.7 a	1.28 a
3	+	26.6	25.6	23.8	21.6	79.6	43.2	1.32
	-	24.4	23.7	22.1	20.3	80.2	41.9	1.29
	Avg.	25.5 a	24.6 a	22.9 a	20.9 a	79.9 a	42.5 a	1.31 a
4	+	25.4	24.2	22.2	20.5	79.2	47.0	1.23
	-	24.8	22.9	20.5	18.8	81.7	45.4	1.20
	Avg.	25.1 a	23.6 a	21.4 a	19.7 a	80.4 a	46.2 a	1.22 a
Average for (±) compaction	+	26.2 a	24.6 a	22.3 a	20.2 a	79.5 a	45.2 a	1.28 a
	-	25.5 a	24.0 a	21.6 a	19.8 a	80.7 a	43.7 a	1.27 a

* Values within columns followed by same letter are not significantly different at the 5% level according to Duncan's New Multiple Range Test.

**Treatment numbers refer to treatments listed on page 37.

Table 26 - Average moisture retention data, bulk density and % water and dry stable aggregation for Field Experiment 2-B

Treatment Number**	Moisture by weight							Date of measurement				
	Tension (bar)									Aggregation		
	Date of measurement							Bulk density		Water stable		Dry sieved
	7/8			10/22								
	1/3	1	2	.06	1/3	1	2	7/8	10/22	7/1	10/22	12/9
	%							g/cc		%		
1	25.1a*	23.7a	22.4a	30.6a	28.0a	24.4a	20.9a	1.25a	1.29a	56.0a	76.4a	44.0a
2	25.5a	24.1a	22.5a	30.4a	27.6a	24.4a	21.4a	1.17a	1.29a	55.6a	68.7a	43.6a
3	25.1a	23.6a	22.2a	29.8a	27.1a	24.2a	21.1a	1.22a	1.34a	58.0a	71.2a	41.4a
4	25.3a	23.7a	22.5a	30.3a	27.3a	24.2a	21.0a	1.24a	1.31a	55.3a	71.7a	40.9a
5	23.6a	22.3a	20.8a	29.2a	26.5a	23.3a	20.2a	1.26a	1.29a	52.4a	79.6a	44.3a

* Values within columns followed by same letter are not significantly different at the 5% level according to Duncan's New Multiple Range Test.

**Treatment numbers refer to treatments listed on page 39.

DISCUSSION

Chemical Soil Conditioners

Other investigators have shown the soil conditioning values of the hydrophobic and hydrophylic bitumenous emulsions and PAM (30, 31, 32, 68, 74, 78); however, data on the aggregate stability under mechanical stress is very scarce in the literature. This author found only one reference on the use of the three conditioners to stabilize soils under compacted conditions. Pla (68) determined that artificially stabilized soils were somewhat resistant to compaction. On heavily trafficked sites (i.e., sports fields, parks, etc.), compaction is a major problem. Thus, the emphasis of this study was on the determination of the ability of chemically stabilized soils to resist compaction.

Growth Chamber and Laboratory Experiments

The effectiveness of several chemical soil conditioners to alleviate the detrimental effects of compaction on two soils and the growth of Manhattan perennial ryegrass was our main objective. The Hadley silt loam and Windsor sand soils were chosen because of the broad difference in textural classification. Generally, fine textured soils, such as Hadley silt loam, are utilized in compaction studies primarily because of the susceptibility of these soils to compaction. On heavily traveled sandy areas, such as golf putting greens, compaction can also cause serious problems.

The Hadley silt loam soil and Windsor sand soil were affected differently by chemical soil conditioners and compaction. The hydrophylic, and to a lesser degree, the hydrophobic bitumenous emulsions enhanced root growth and reduced top growth on the Windsor sand soil. Several factors may have been responsible for the reduction in top growth associated with the maximization of root growth. First, the temperature was maintained at 18°C, which was shown to be optimal for root growth of ryegrass (60). Second, the grass plants were clipped at a relatively high height of cut (9 cm) which would favor root growth (40). Third, since the turf plants were not subjected to stress conditions, (i.e. high temperatures,low height of cut) or excessive nitrogen fertility levels, much of the plants' carbohydrates may have been utilized for root growth instead of top growth. If the study had been continued for a longer period, top growth should have been the greatest on plants with the most extensive root system.

Top and root growth and the physical properties of the Hadley silt loam soil were also dramatically improved by the hydrophobic emulsion. In addition, germination responded favorably to the hydrophobic emulsion. This may have been due to the inability of the grass seeding radicles to penetrate the treated soil surface. Results of vertical penetration resistance (penetrometer) in Laboratory Experiment 1-A (Table 19) indicate that soil strength was influenced by the different treatments. The hydrophylic emulsion had a substantially lower penetrometer value than the check treatments. Restricted root penetration and growth in response to an increase in soil strength due to compaction has been noted by several investigators (81, 82, 84).

It appeared that compaction adversely affected the water stable aggregation, moisture retention and bulk density properties far more on the Hadley silt loam than the Windsor sand. The initial structural difference between soils (i.e., the silt loam had a much greater structure as compared to the relatively structureless sand) may have influenced the effects of compaction noted here. Bodman and Constantin (13) noted similar soil textural differences in relation to the degree of compaction.

The magnitude of compaction on the Windsor sand may not have been severe enough to have an appreciable effect on the physical properties measured. Also, compaction was applied to the soil during relatively high soil moisture conditions, which has a cushioning effect against compaction (80).

The depth of treatment determined the effectiveness of the chemically improved soils to resist compaction. Results from Growth Chamber Experiment 1-A suggest that at least the top 3 cm of sand soil must be stabilized by the bitumenous emulsions before the harmful effects of compaction on root growth were diminished. Soils containing a greater portion of silt and clay (Growth Chamber Experiment 1-C) required a substantially deeper treatment with the hydrophobic bitumenous emulsion to alleviate the detrimental effects of compaction on plant growth.

The new soil conditioners, as classified by DeBoodt (23), were developed to have several beneficial qualities, such as aggregation properties and effects on moisture retention, and cation exchange capacity. Moisture retention curves from the laboratory experiments indicate that hydrophobic and hydrophylic bitumenous emulsions and PAM (Cyanamer P-250) altered the soil to a hydrophobic or "water repelling" nature. Structural improvement by VAMA and HPAN has been shown to result in a reduction in the moisture retention or available moisture equivalent (24, 65). It was not ascertained whether these soil conditioners truly affected the moisture characteristics by chemical means or whether an improvement in soil structure altered the moisture status. The hydrophylic bitumenous emulsion apparently reverted the soil to hydrophobic in nature. Rigole and De Bisschop (74) observed that in some cases organic compounds (emulsifiers) transformed hydrophylic surfaces into hydrophobic surfaces during evaporation. This phenomenon was referred to as an "autophobic characteristic of a solid-liquid system". Similar results were noted on a fine sand soil by McGuire and Carrow (unpublished data, E. McGuire and R. N. Carrow). Even though the total moisture content was initially lower, the hydrophylic emulsion treated soil retained a higher percentage of water as the soil suction increased.

Humofina PAM had a minimal effect on alleviation of compaction. The results of aggregate analyses, coupled with the rooting data, suggest that water stable aggregation had to be 80% or greater to effectively inhibit the harmful effects of compaction. The PAM treatment resulted in a much lower aggregate percentage. Destruction of PAM stabilized aggregates by compaction, and/or the ineffectiveness of PAM to aggregate the soil are two factors that could have resulted in only a slight resistance to compaction. Results from other studies (30, 31, 32, 48, 78, 90) suggest that PAM should have affected the physical properties and plant growth to a much greater extent; however, in these studies compaction effects were not determined. Vandevelde and DeBoodt (88) noted that as the clay content of the soil increased, a reduction in the effectiveness of PAM to form water stable aggregates occurred.

Improvements in the soil structure by chemical means appeared to influence root growth to a much greater extent than compaction. In Growth Chamber Experiments 1-A and 1-B the hydrophylic emulsion improved root growth by 98% on the last measurement data, whereas compaction reduced root growth by 48%. Similar results are shown in Growth Chamber Experiments 1-C and 1-D where root dry matter yield was increased 90% by the hydrophobic emulsion as compared with a 55% hindrance with compaction.

Field Experiments

The usefulness of several chemical soil conditioners and methods of application to alleviate the compaction problem on established turfgrass areas were investigated.

Compaction on a mature stand of turfgrass presents a very serious and difficult problem to solve. The two primary ways of handling turfgrass compaction are by the renovation of the existing site with soil amendments and by cultural practices such as aerifying. Complete renovation is often impractical from an economic and time standpoint. Periodic aerification will improve infiltration of water and air into the root zone, but effects tend to be of short duration.

The two application procedures, injection and treatment of soil following aerification, were developed to hopefully duplicate the aerification process and prolong the beneficial effects by stabilizing the aerifying holes from natural and mechanical destructive forces.

The three chemical soil conditioners investigated, as well as the two treatment methods, had only a minimal effect on the soil physical properties and the growth of the cool season turfgrass. Other studies (48, 78, 90) have shown that under field conditions PAM resulted in increased water stable aggregation and crop yields. However, it should be noted that a considerably higher rate of PAM (0.25% PAM to soil weight) was applied as compared to the rate used in these field studies.

Several modifications of the experimental procedures could have resulted in beneficial treatment effects. First, higher rates of application with the soil conditioners were indicated from the data of the Growth Chamber Experiments. The pumping apparatus used in the experiments limited the amount of material applied. Possibly repeated applications may have overcome this limitation. Second, the soil physical data suggest that compaction had only a slight effect on the soil structure; therefore, the number of compaction treatments should have been increased. Third, the studies were carried out for a short period of time. The usefulness of any soil conditioners should be evaluated over a considerable time period in order to determine its stability over time.

Algal Polymer

The evaluation of the effectiveness of an algal polymer culture as a soil conditioner was our primary objective. The algal culture, under controlled conditions of the growth chamber, substantially improved the water stable aggregation, independent of soil texture or pH differences.

Field experimentation showed that neither type of algal polymer culture had any beneficial influence on the physical properties of the Hadley silt loam soil. There are several possible reasons for the inability of the algal polymer culture to affect the various soil physical properties measured. First, the naturally high level of aggregation may have masked the effects of the algal polymer culture. Second, the relatively high organic matter content (Table 1) may have also inhibited the influence of the algal polymer culture, since the culture could have acted purely as an inorganic matter source. In the field study of Fogel *et al*. (29), there was a significant increase in the water stable aggregation caused by the algal polymer culture; however, the soil utilized in their study was relatively low in organic matter. Third, the algal polymer culture may have affected the physical parameters of the soil, but with time, the effects diminished. Organic compounds which are utilized as a rapidly available energy source for bacteria and fungi often affect aggregation in this manner (2, 39). Data from other preliminary growth chamber studies indicated that the algal polymer produced maximum aggregation three days after application, and with time aggregation declined. Fourth, inadequate soil moisture and sunlight may also have inhibited the algal polymer culture from influencing the physical properties. Fifth, the algal polymer may not possess aggregating capabilities under field conditions.

In Field Experiment 2-B, the hydrophobic bitumenous emulsion did not improve any of the physical parameters of the soil. It is apparent from the results obtained from the growth chamber studies that the hydrophobic emulsion required a thorough mixing, more deeply into the soil, before structural improvements would occur.

CONCLUSIONS

Compaction from foot traffic and machinery presents a serious problem on turfgrass areas as well as other agricultural land. Complete or partial modification with various soil physical amendments is extremely costly and renders the area unusable for a considerable time period. Aerification, which is the standard practice for alleviating compaction effects, is required often on heavily traveled sites and takes considerable man hours.

This investigation was initiated to ascertain if soils stabilized by synthetic, chemical soil conditioners or algal cultures could improve the compacted soil physical properties and the growth of turfgrass.

Growth chamber studies were designed to examine the effects of treatment depth and several chemical soil conditioners on alleviation of compaction and growth of Manhattan ryegrass. The results showed that under compaction the hydrophylic and to a lesser degree, the hydrophobic bitumenous emulsions improved the water stable aggregation, bulk density properties, and the root growth on Windsor sand soil. The bitumenous emulsions increased aggregation from approximately 20 to 35% over the comparable check treatments. The number of visible roots was approximately doubled by the hydrophylic emulsion in relation to the check.

Treatment of the surface 3 cm of the Windsor sand with hydrophylic bitumenous emulsion was as effective on root growth and water stable aggregation as treatment of the entire soil column. Root growth measurements did not support this relationship until the final measurement date (4/10). The level of aggregation for the top 3 cm treatment was comparable to treatment of the entire soil column.

The harmful effects of compaction on soil structure and plant growth were eliminated on the Hadley silt loam by the hydrophobic bitumenous emulsion. Treatment of the total soil column with hydrophobic emulsion resulted in an increase in root dry matter yield (9-fold), water stable aggregation (3-fold), cumulative top growth (3-fold), germination (by 27%) and a slight reduction in bulk density as compared to the check treatment. Humofina PAM had no appreciable influence on the soil physical properties or on plant growth.

Laboratory studies revealed that PAM (Cyanamer P-250) and the hydrophobic and hydrophylic bitumenous emulsions influenced the physical nature of the two soils. The hydrophylic emulsion reduced moisture retention, of the Windsor sand, from 16% to 6% (by volume), and from 9.4 to 3.1% (by weight) over the matric suction range of 0.06 to 2 bar. Moisture retentativity of the Hadley silt loam soil was substantially lowered by hydrophobic emulsion treatment in the order 5% by weight and 7% by volume at each suction. PAM caused a lowering of the moisture retention curve (P_v) and bulk density of the two soils. Reduction in moisture retention status of each soil suggests that total porosity or aeration porosity was improved by the three soil conditioners. In addition, the reduction in bulk density, associated with structural improvements by the hydrophylic emulsion and

PAM, indicated a resistance of the chemical stabilized soils to compaction (compression).

The growth chamber and laboratory studies indicated that chemical soil conditioners can alleviate the harmful effects of compaction; however, field trials were inconclusive. Improved application techniques and higher application rates were believed to be necessary in order to provide a useful field evaluation.

An algal polymer culture of the soil algae *Chalmydomonas mexicana* was investigated as to its usefulness as a soil conditioner in growth chamber and laboratory studies. Results of the growth chamber study and preliminary studies demonstrated that the algal polymer culture caused aggregate formation; however, the effects diminished with time. Under field conditions, the algal polymer culture had no measurable effect on soil structure or the growth of turfgrass.

LITERATURE CITED

1. Allison, F. E. 1965. Organic carbon. In C. A. Black (Ed.) Methods of Soil Analysis, Part II. Agronomy 9:1367-1368.

2. Allison, F. E. 1973. Soil Organic Matter and Its Role in Crop Production. American Elsevier Publishing Co., Inc., New York.

3. Alderfer, R. B. 1951. Compaction of turf soils -- some causes and effects. USGA Journal and Turf Management 4:25-28.

4. Arya, L. M. and G. R. Blake. 1972. Stabilization of newly formed soil aggregates. Agron. J. 64:177-180.

5. Bailey, D., A. P. Mazurak, and J. R. Rosowski. 1973. Aggregation of soil particles by algae. J. Phycology 9:99-101.

6. Barnes, K. K., W. M. Carleton, H. M. Taylor, R. I. Throckmorton, and G. E. Vandenberg. 1971. Compaction of agricultural soils. Am. Soc. Agr. Eng., St. Joseph, Michigan.

7. Baver, L. D., W. H. Gardner, and W. R. Gardner. 1972. Soil Physics. (4th Edition). John Wiley and Sons, Inc., New York, p 107.

8. Baver, L. D., W. H. Gardner, and W. R. Gardner. 1972. Soil Physics. (4th Edition). John Wiley and Sons, Inc., New York, p 223.

9. Beacher, B. F. and E. Strickling. 1955. Effects of puddling on water stability and bulk density of certain Maryland soils. Soil Sci. 80: 363-373.

10. Beard, J. B. 1973. Turfgrass: Science and Culture. Prentice-Hall, Inc., Englewood Cliffs, N. J., pp 348-353.

11. Blake, G. R. 1965. Bulk density. In C. A. Black (Ed.) Methods of Soil Analysis. Agronomy Monograph 9, Part I, pp 374-377.

12. Blavia, F. J., W. C. Moldenhauer, and D. E. Law. 1971. Materials for stabilizing surface clods of cropped soils. Soil Sci. Soc. Am. Proc. 35:119-122.

13. Bodman, G. B. and G. K. Constantin. 1965. Influence of particle size distribution on soil compaction. Hilgardia 36: 567-591.

14. Booth, W. E. 1941. Algae as pioneers in plant succession and their importance in erosion control. Ecology 22: 38-46.

15. Bouyoucus, G. J. 1936. Directions for making mechanical analyses of soils by the hydrometer method. Soil Sci. 42: 225-230.

16. Brandt, G. H. 1972. Soil physical property modifiers. In C. A. I. Goring and J. W. Namaker (Eds.) Organic Chemicals in the Soil Environment, Chapter 11, Part II, pp 691-729.

17. Brandt, G. H. 1972. Soil physical property modifiers. In C. A. I. Goring and J. W. Namaker (Eds.) Organic Chemicals in the Soil Environment, Chapter 11, Part II, p 719.

18. Chang, R. K. and B. P. Warkentin. 1968. Volume change of compacted clay soil aggregates. Soil Sci. 105: 106-111.

19. Cordukes, W. E. 1968. Compaction. Golf Superintendent 36(8): 20-24.

20. Dasberb, S., D. Hiller, and I. Arnon. 1966. Response of grain sorghum to seedbed compaction. Agron. J. 58: 199-203.

21. Davidson, D. T. 1965. Penetrometer measurements. In C. A. Black (Ed.) Methods of Soil Analysis. Agronomy Monograph No. 9, Part I, pp 472-484.

22. Davis, R. R. 1952. The physical condition of putting green soils and other environmental factors affecting the quality of greens. USGA Green Section and Turf Management 5(1): 25-27.

23. DeBoodt, M. 1972. Improvement of soil structure by chemical means. In D. Hillel (Ed.) Optimizing the Soil Physical Environment. Toward Greater Crop Yields, Academic Press, Inc., New York, pp 43-55.

24. Doyle, J. J. and F. G. Hamlyn. 1960. Effects of different cropping systems and of a soil conditioner (VAMA) on some soil physical properties and on growth of tomatoes. Can. J. Soil Sci. 40: 89-99.

25. Duncan, D. B. 1955. Multiple range and multiple F test. Biometrics 11: 1-42.

26. Emerson, W. W. 1960. Complexes of calcium-montmorillonite with polymers. Nature 186: 573-574.

27. Fletcher, J. E. and W. P. Martin. 1948. Some effects of algae and molds in the rain-crust of desert soils. Ecology 29: 95-100.

28. Flocker, W. J., J. C. Lingle, and J. A. Vomocil. 1959. Influence of soil compaction on phosphorus absorption by tomato plants from an applied phosphate fertilizer. Soil Sci. 88: 168-171.

29. Fogel, S., P. Foster, P. Schenck, and W. Walker. 1974. The aggregate promoting and stabilizing effect of a polysaccharide from the soil algal, Chlamydomonas mexicana. Agronomy Abstracts, p 128.

30. Gabriels, D. 1972. Response of different soil conditioners to soils. In M. DeBoodt (Ed.) Proceedings Symposium on the Fundamentals of Soil Conditioning (English Transition), pp 1014-1034.

31. Gabriels, D. and M. DeBoodt. 1972. Theoretical and practical approach for determining the optimal moisture content at the moment of soil conditioning. (English Transition), Mitteilgn. Dtsch. Boden Kundl. Gesellsch. 15: 185-203.

32. Gabriels, D., W. C. Moldenhauer, and D. Kirkham. 1973. Infiltration, hydraulic conductivity, and resistance to water-drop impact on clod beds as affected by chemical treatment. Soil Sci. Soc. Am. Proc. 37: 634-637.

33. Gardner, W. H. 1972. Use of synthetic soil conditioners in the 1950's and some implications to their further development. In M. DeBoodt (Ed.) Proceedings Symposium on the Fundamentals of Soil Conditioning. (English Translation) Mededelingen Fakulteit Landbouw-Wetenschappen Rijksuniversiteit, Gent 37: 1046-106.

34. Goss, R. L. and J. Roberts. 1964. A compaction machine for turfgrass areas. Agron. J. 56: 522-523.

35. Grable, A. R. and E. G. Siemer. 1968. Effects of bulk density, aggregate size, and soil water suction on oxygen diffusion, redox potentials, and elongation of corn roots. Soil Sci. Soc. America Proc. 32: 180-186.

36. Haise, H. R., L. R. Jensen, and J. A. Alessi. 1955. The effect of synthetic soil conditioners on soil structure and production of sugar beets. Soil Sci. Soc. Am. Proc. 19: 17-19.

37. Hanks, R. J. and F. C. Thorp. 1956. Seedling emergence of wheat as related to soil moisture content, bulk density, oxygen diffusion rate, and crust strength. Soil Sci. Soc. Am. Proc. 20: 307-310.

38. Harris, W. L. 1971. The soil compaction process. In K. K. Barnes, W. M. Carleton, H. M. Taylor, R. I. Throckmorton, and G. E. Vandenberg (Organizers) Compaction of Agricultural Soils. Am. Soc. Agr. Eng., St. Joseph, Michigan, pp 9-44.

39. Harris, R. F., G. Chesters, and O. N. Allen. 1966. Dynamics of soil aggregation. Adv. Agron. 18: 107-169.

40. Harrison, C. M. 1931. Effects of cutting and fertilizer applications on grass development. Plant Physiol. 6: 669-684.

41. Hedrick, R. M. and D. T. Mowry. 1952. Effect of synthetic polyelectrolytes on aggregation, aeration, and water relationships of soil. Soil Sci. 73: 427-441.

42. Hill, J. N. S. and M. E. Sumner. 1967. Effects of bulk density on moisture characteristics of soils. Soil Sci. 103: 234-238.

43. Hopkins, R. M. and W. H. Patrick, Jr. 1969. Combined effect of oxygen content and soil compaction on root penetration. Soil Sci. 108: 408-413.

44. Hubbell, D. S. and J. E. Chapman. 1946. The genesis of structure in two calcareous soils. Soil Sci. 62: 271-281.

45. Hubbell, D. S. and J. L. Gardner. 1948. Effects of aeration, compaction, and water-logging on soil structure and microflora. J. Am. Soc. Agron. 40: 832-844.

46. Hughes, T. D., J. F. Stone, W. W. Huffine, and J. R. Gingrich. 1966. Effect of soil bulk density and soil water pressure on emergence of grass seedling. Agron. J. 58: 549-553.

47. Jamison, V. C. 1953. Changes in air-water relationships due to structural improvement of soils. Soil Sci. 76: 143-151.

48. Kachinskiy, N. A., A. I. Mosolova, and L. K. H. Taymurazova. 1967. Use of polymers for structure formation and melioration of soils. Soviet Soil Sci.: 1660-1669.

49. Kemper, W. D. 1965. Aggregate stability. In C. A. Black (Ed.) Methods of Soil Analysis, Part I, Agronomy 9:511-519.

50. Kristensin, K. J. 1966. Factors affecting measurements of oxygen diffusion rate (ODR) with bare platinum microelectrodes. Agron. J. 58:351-354.

51. Lemon, E. R. and A. E. Erickson. 1952. The measurement of oxygen diffusion in the soil with a platinum microelectrode. Soil Sci. Soc. Am. Proc. 16: 160-163.

52. Lemon, E. R. and A. E. Erickson. 1955. Principle of platinum microelectrode as a method of characterizing soil aeration. Soil Sci. 79: 383-392.

53. Letey, J., W. C. Morgan, S. J. Richards, and N. Valoras. 1966. Physical soil amendments, soil compaction, irrigation, and wetting agents in turfgrass management. III. Effects on oxygen diffusion rate and root growth. Agron. J. 58:531-535.

54. Letey, J., L. H. Stolzy, O. R. Lunt, and V. B. Youngner. 1964. Growth and nutrient uptake of Newport bluegrass as affected by soil oxygen. Plant and Soil 20:143-148.

55. Lotspeich, F. B. 1964. Strength and bulk density of compacted mixtures of kaolinite and glass beads. Soil Sci. Soc. Am. Proc. 28:737-740.

56. MacEntee, F. J. 1970. A preliminary investigation of the soil algae of northeastern Pennsylvania. Soil Sci. 110: 313-317.

57. MacEntee, F. J., Sister G. Schreckenberg, and H. C. Bold. 1972. Some observations on the distribution of edaphic algae. Soil Sci. 114:171-179.

58. Madison, J. H. 1971. Principles of Turfgrass Culture. VanNostrand Reinhold Co., New York, p 162.

59. Madison, J. H. 1971. Principles of Turfgrass Culture. VanNostrand Reinhold Co., New York, pp 172-177.

60. Mitchell, K. J. 1954. Influence of light and temperature on growth of ryegrass (Lolium spp.) III. Pattern and rate of tissue formation. Physiologia Plantarum 7:51-65.

61. Moldenhauer, W. C., and D. M. Gabriels. 1972. Some uses of soil stabilizers in the USA. In M. DeBoodt (Ed.) Proceedings Symposium on the Fundamentals of Soil Conditioning (English Translation), Mededelingen Fakulteit Landbouw-Wetenschappen Rijksuniversiteit, Gent 37:1076-1085.

62. Morgan, W. C., J. Letey, S. J. Richards, and N. Valoras. 1966. Physical soil amendments, soil compaction, irrigation, and wetting agents in turfgrass management. I. Effects on compactability, water infiltration rates, evapotranspiration, and number of irrigations. Agron. J. 58: 525-528.

63. Morgan, W. C., J. Letey, and L. H. Stolzy. 1965. Turfgrass renovation by deep aerification. Agron. J. 57: 494-496.

64. Panabakke, C. R. and J. P. Quirk. 1957. Effects of initial water content on stability of soil aggregates in water. Soil Sci. 83: 185-195.

65. Peters, D. B., R. M. Hagan, and G. B. Bodman. 1953. Available moisture capacities of soils as affected by additions of polyelectrolyte soil conditioners. Soil Sci. 75: 467-471.

66. Phillips, R. E. and D. Kirkham. 1962. Mechanical impedance and corn seedling root growth. Soil Sci. Soc. Am. Proc. 26: 319-322.

67. Phillips, R. E. and D. Kirkham. 1962. Soil compaction in the field and corn growth. Agron. J. 54: 29-34.

68. Pla, I. 1973. Effects of bitumen emulsion and polyacrylamide on some physical properties of Venezuelan soils. Agronomy Abstracts, p 136.

69. Raney, W. A. 1953. Soil aggregate stabilizers. Soil Sci. Soc. Am.Proc. 26: 76-77.

70. Rao, E. S. 1957. Root growth in Connecticut tobacco soils. Connecticut Agricultural Experiment Station Bulletin 608, pp1-36.

71. Reeve, M. J. P., P. D. Smith, and A. J. Thomasson. 1973. The effect of density on water retention properties of field soils. J. Soil Sci. 24: 355-367.

72. Richards, L. A. 1965. Physical conditions of water in soil. In C. A. Black (Ed.) Methods of Soil Analysis, Part I, Agronomy 9:128-152.

73. Rickman, R. W., J. Letey, and L. H. Stolzy. 1966. Plant responses to oxygen supply and physical resistance in the root environment. Soil Sci. Soc. Am. Proc. 30: 304-307.

74. Rigole, W. and F. DeBisschop. 1972. The formation of adhesive links between granular particles by means of emulsions. In M.DeBoodt (Ed.) Proceeding Symposium on the Fundamentals of Soil Conditioning. Mededelingen Fakulteit Landbouw-Wetenschappen Rijksuniversiteit. Gent 37:938-954.

75. Rosenberg, N. J. 1964. Response of plants to the physical effects of soil compaction. Adv. Agron. 16: 181-196.

76. Schamp, N. and J. Huylebroeck. 1972. Physico chemical interaction of polyacrylamide on clay particles. In M.DeBoodt (Ed.) Proceedings Symposium on the Fundamentals of Soil Conditioning. Mededelingen Fakulteit Landbouw-Wetenschappen Rijksuniversiteit, Gent. 37: 923-937.

77. Shields, L. M., C. Mitchel, and F. Drovet. 1957. Alga and lichen stabilized surface crust as soil nitrogen sources. Am. J. Bot.44:489-498.

78. Shatatnov, V. I., N. I. Scherbakova. 1964. Polyacrylamide and co-polymer- B as artificial soil structure-formers and as nitrogen fertilizers (English Translation). Soviet Soil Sci.:1074-1082.

79. Stolzy, L. H. and J. Letey. 1964. Characterizing soil oxygen conditions with a platinum microelectrode. Adv. Agron. 16:249-279.

80. Swartz, W. E. and L. T. Kardos. 1963. Effects of compaction on physical properties of sand-soil-peat mixtures at various moisture contents. Agron. J. 55:7-10.

81. Taylor, H. M. and H. R. Gardner. 1960. Use of wax substrates in root penetration studies. Soil Sci. Soc. Am. Proc. 24:79-81.

82. Taylor, H. M. and H. R. Gardner. 1963. Penetration of cotton seedling taproots as influenced by bulk density, moisture content, and strength of soil. Soil Sci. 96:153-156.

83. Taylor, H. M., J. J. Parker, Jr., and G.M. Roberson. 1966. Soil strength and seedling emergence relations. II. A generalized relation for Gamineae. Agron. J. 58:393-395.

84. Taylor, H.M., G. M. Roberson, and J. J. Parker, Jr. 1966. Soil strength-root penetration relations for medium to course-texture soil materials. Soil Sci. 102:17-22.

85. Taylor, H. M. and J. A. Vomocil. 1959. Changes in soil compressibility associated with polyelectrolyte treatment. Soil Sci. Soc. Am. Proc. 23:181-183.

86. Trouse, A. C. and R. P. Humbert. 1961. Some effects of soil compaction on the development of sugar cane roots. Soil Sci. 91:208-217.

87. Valoras, N., W. C. Morgan, and J. Letey. 1966. Physical soil amendments, soil compaction, irrigation, and wetting agents in turfgrass management. II. Effects on top growth, salinity, and minerals in the tissue. Agron. J. 58:528-531.

88. Vandevelde, R. and M.DeBoodt. 1972. Reactions of soil textures on soil conditioning with an emulsion of bitumen and a solution adhesive (PAM). In M.DeBoodt (Ed.) Proceedings Symposium on the Fundamentals of Soil Conditioning (English Translation). Mededelingen Fakulteit Landbouw-Wetenschappen Rijksuniversiteit, Gent 37:993-1013.

89. VanDiest, A. 1963. Effects of soil aeration and compaction upon yield, nutrient takeup and variability in a greenhouse fertility experiment. Agron. J. 55:515-518.

90. Varnavskaya, N. V., N. N. Ilovayskaya, and K. H. Moldsvanova. 1967. Some experimental data with artificial soil structure-formers (English Translation). Soviet Soil Sci.:611-616.

91. Veihmeyer, F. J. and A. H. Hendrickson. 1948. Soil density and root penetration. Soil Sci. 65:487-493.

92. Vomocil, J. A. and W. J. Flocker. 1965. Degradation of structure of Yolo Loam by compaction. Soil Sci. Soc. Am. Proc. 29:7-12.

93. Voorhees, W. B., M. Amemiya, R. R. Allmaras, and W. E. Larson. 1971. Some effects of aggregate structure heterogeneity on root growth. Soil Sci. Soc. America Proc. 35:638-643.

94. Waddington, D. V. 1969. Soil and soil related problems. In A. A. Hanson and F. V. Juska (Eds.) Turfgrass science. Agronomy 14:119-123.

95. Waddington, D. V. and J. H. Baker. 1965. Influence of soil aeration on the growth and chemical composition of three grass species. Agron. J. 57:253-258.

96. Warkentin, B. F. and G. P. LaFlamme. 1973. Heat--a solution to soil compaction. Golf Superintendent 42(2):38-40.

97. Wilkinson, J. F. and D. T. Duff. 1972. Rooting of Poa annua L., Poa pratensis L., and Agrostis palustris Huds. at three soil bulk densities. Agron. J. 64:64-68.

98. Youngner, V. B. 1961. Accelerated wear tests on turfgrasses. Agron. J. 53:217-218.

99. Youngner, V. B. 1962. Wear resistance of cool season turfgrasses. II. Effects of previous mowing practices. Agron. J. 54:198-199.