THESIS

PHYSICAL PROPERTIES OF GREENHOUSE CONTAINER MEDIA

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY GARY CHARLES NELSON ENTITLED PHYSICAL PROPERTIES OF GREENHOUSE CONTAINER MEDIA BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

PHYSICAL PROPERTIES OF GREENHOUSE CONTAINER MEDIA

Combinations of Canadian peat, vermiculite, perlite, Colorado peat, sand and soil were used to prepare 50 greenhouse container media. These media were placed in six-inch plastic pots in a greenhouse environment. Physical properties were determined on undisturbed core samples taken from these pots at 0, 30, 60 and 90 days after potting.

There were no changes in bulk density or total porosity over a 90-day period and only slight changes in aeration porosity and available water. Aeration porosities of the media ranged from 18-54%, all values being above the 10-15% minimum recommended by most researchers. Fresh and dry weights of chrysanthemums grown in 10 widely varying media increased with increasing aeration porosity. Available water ranged from 16-57%. Media with a high percentage of Canadian peat, Colorado peat, or vermiculite held the greatest amounts of available water and those high in soil or sand held the least. Bulk densities ranged from 0.10-1.55 g/cc. If densities less than 1.0 g/cc are desired, less than 80% soil or 60% sand should be used. Total porosities ranged from 43-97% and were correlated with all other physical properties. Bulk density values can be used to predict the total porosity of media. Total porosity values may be used to approximate available water and give a general idea of aeration porosity.

In general, soilless media possessed the most desirable physical properties. Media containing only soil and/or sand consistently had the least desirable properties. Adding sand to soil produces few, if any, physical improvements. Colorado peat appears satisfactory as a substitute for Canadian peat. Physical properties of Colorado peat are more desirable when mixed with perlite or vermiculite, rather than soil or sand.

The threshold proportion concept did not apply to any of the physical properties for most of the media tested.

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INTRODUCTION

A plant root environment is determined by the chemical, physical, and biological properties of the medium in which it grows. Many researchers believe the physical properties may influence media productivity as much as the chemical properties, since changes in the moisture and air relationships not only modify plant growth directly, but affect chemical and biological reactions which affect the plant indirectly (121). The chemical composition of the medium can be altered after plant growth begins, but physical properties must be optimized during preparation of the medium. There are many ways physical conditions can be worsened after planting, but few ways to improve them.

Almost any plant can be grown in almost any medium provided it is properly managed (47, 61). Many researchers have shown that satisfactory plant growth can occur in a wide range of media. However, some media are more easily managed than others, which can often be predicted by their chemical and physical properties (47). Greenhouse plants are often produced in shallow containers less than 8 inches deep. Placing a soil in such a container greatly limits its volume and creates a "perched" water table which increases the soil's water holding capacity at the expense of aeration porosity (47, 79, 108, 115, 116, 132). Containerized soil is difficult to manage and is seldom used unamended because of its very specific cultural requirements (47). Modification of such a soil provides a root environment more suitable for optimum plant growth (47, 61, 69).

Choice of a medium depends on its physical and chemical characteristics and cost. Correlation of physical and chemical properties with plant growth provides standards for comparing media(70). Considerable research has been conducted on chemical properties, especially pH and soluble salts. Less is known about physical properties. Feustel (43) pointed out a need for more information on physical amendments in 1939. Hanah (55), Bunt (19-23), Richards et al. (108), White (132), Joiner et al. (70), and Waters et al. (131) responded with valuable information, especially pertaining to the "perched" water table effect and the effect of media depth on water holding capacity. Physical properties considered important by these workers include bulk density, available water holding capacity, total and aeration porosity, structural stability, and infiltration rate. Most other research on container media has been centered on correlating various media combinations with plant growth instead of correlating physical properties with plant growth (131). Optimum ranges for the above mentioned properties have not been determined. It is evident that much more needs to be understood about plant growth in various media, and the study of physical properties is a first step in that direction.

Structural stability is a desirable characteristic of greenhouse media (47, 102). Same media tend to settle or compact with time and are not suitable for long term use (115). Furuta (47) states that it is impossible to use a medium whose properties would remain constant, because even growing roots create a measurable change. Hanan (55) found that the bulk density of soil:sand mixtures increased with time. This increased the capillary pores at the expense of noncapillary pores. Adding peat reduced this effect, whereas no changes occurred over time with peat:perlite media. Mazur et al. (88) tested media containing bark over a 13-month period and found that media containing finely ground bark lost their desirable structure to a greater extent than those containing coarse bark. Pokorny (100) measured media water holding capacities over a two-year period. Soiless media contained higher available water initially, but media containing soil held more water after two years.

Biological decomposition reduces porosity and increases bulk density and non-wettability of organic amendments (133). Imported peats are the organic amendments most widely used in container production (92, 102, 103). Native peats are promising (131), but little is known about their physical properties, especially their structural stability over time. Imported peats usually contain desirable levels of organic matter within the optimum range of 90-100% (31, 92), but native peats may contain as little as 50% organic matter. Native peats may have lower water holding capacities and higher bulk densities than imported peats (78). The main objection to the use of native peat is its non-uniformity and the lack of information on its properties (78). Peats decompose fastest when well aerated, moist, and well provided with nutrients--conditions similar to those in container culture (32). Although stability over time is an important requirement of greenhouse media, very little information exists on the subject.

Media physical properties are influenced by the size and shape of their particles. Whenever particles of different sizes are mixed together the final volume is usually less than the sum of the original volumes. The greater the difference in particle sizes, the greater will be the reduction in volume from mixing. This decrease in bulk volume usually increases bulk density and decreases aeration porosity (47). For this reason Spomer (115) concluded that materials made up of a wide range of particle sizes are poor amendments. However, Mazur's (88) work with bark showed that a wide range of particle sizes improved the physical properties of a silty clay loam better than bark screened to uniform sizes. The effect of particle size evidently depends on other factors, especially the type of components used in the media. Aggregation of small particles usually improves physical properties and depends on the method of mixing and the moisture content during mixing. Mastalerz et al. (85) found that mixing moist components in a concrete mixer produced excellent aggregation. Richards et al. (108) felt that particle size distribution was not as good a criterion as other physical properties as a basis for recommending media.

Most investigators agree that the quantity of amendment needed to improve a field soil depends on the texture of the soil (47, 73, 77, 95). A direct correlation generally exists between the clay content and the amount of amendment needed (47, 95). Hanan (61) recommended at least 33% organic matter or 50% sand. Conover (30) recommended at least 50% organic matter for foliage plants, and Waters et al. (131) advised at least 33% peat or peat-like material. Pearson (95) recommended 40-50% amendment for sandy soils, but 66% if the soil is silty or clayer. He advised 50% amendment for best results (96). According to Spomer (115), amendments having high porosity are required in lower amounts.

The optimum quantity of amendment is usually determined by the trial and error method of comparing plant growth in various mixtures (70, 116). Spomer (116) felt that this was a time consuming, inaccurate procedure and agreed with Joiner (70) that further studies should attempt to correlate growth with media physical properties. His findings with soil:sand mixtures agreed with the ideas of other workers (16, 47, 61, 86, 87) who found that combining materials of large and small particle sizes could actually make physical properties worse than the properties of either amendment used alone. He proposed the "threshold proportion" concept which stated that addition of increasing amounts of sand to a soil actually reduced total porosity until 70% sand was added. The proportion of amendment at which total porosity was minimum was termed the threshold proportion. Addition of sand above 70% increased the mixture's total porosity. When 70% or less sand was used soil particles filled the large pores between the sand grains. Only when 70% or more is used will there be too little soil to fill the sand's pores, and total porosity will begin to increase. Amendment particles must be many times larger than soil particles for the threshold effect to occur, and is most critical when the particles within each component are of uniform size. The threshold proportion is the least desirable proportion of soil and sand. White (132, 133) added peat to a soil and found corresponding increases in total porosity. In other words, no threshold proportion existed.

The limited information available on media physical properties is further confounded because of the lack of reference methods for determining these properties (133). Various methods are used to determine the same physical parameter. Results from these may or may not be comparable. Some investigators determine media characteristics on disturbed samples artificially compacted into laboratory containers (115, 132). Others believe only undisturbed media preconditioned under growing conditions should be used (19, 131). Many do not describe their methods in great enough detail for others to understand.

Because of the general lack of knowledge about physical properties of media and the conflicting findings on the important concept of threshold proportion, the following research was initiated to look into the problem in more detail. Some of the questions to be answered are:

1. Does a threshold proportion exist for commonly used greenhouse container media?
2. If so, what proportion of amendment is optimum?
3. Does the threshold concept apply to aeration porosity, bulk density, and water holding capacity as well as to total porosity?
4. How does Colorado native peat compare to imported peat when used as an amendment?
5. What is the effect of time on the physical properties of media under normal greenhouse conditions?
6. How does plant growth compare among media of known physical properties?

LITERATURE REVIEW

Plant Responses to Water

The amount of water used by plants in a given time depends upon the plant size and specie, rate of root and shoot growth, root surface area, rate of absorption by roots, rate of moisture movement to roots, temperature of the medium, and the climatic conditions, especially light intensity (11, 34, 37, 47, 51, 64, 79, 107, 117, 132, 133). It also depends on container size and type and the characteristics of the medium.

Not all the water in a medium is available to the plant. Water is held at various tensions in a mixture and its tension greatly determines its availability. There is no unique relationship between the water tension and the amount of water contained by media as a whole (110). Richards et al. (108) and White (132) concluded that most media contain much of their available water at tensions less than 0.3 atm. White (132) found that media containing 50% or more peat or perlite held much of their available water at tensions below 0.03 atm, whereas mixtures with 50% or more soil released water more uniformly over the desorption range. Tensions at container capacity were similar for a wide range of media and averaged 0.013 atm.

Stanhill (122) reviewed many papers concerning moisture regime studies and concluded that plant growth was usually reduced as the available water was depleted. Hagan (51) and Denmead (35) found that plants with dense root systems and/or under low transpiration conditions could use more of the soil water without suffering reduced growth.

Wiggin (137) found decreasing quality of chrysanthemums with decreasing moisture levels. Bunt (23) stated that plants grown in containers are more sensitive to water stress than those grown in the ground.

Limited moisture influences plant physiological functions. Accumulation of fresh and dry weight, elongation of plant organs, photosynthesis, respiration, and transpiration are adversely affected by water stress (11, 51). Hanan (64) stated that soil moisture stress can reduce the rate of photosynthesis before actual wilting occurs. Hagan (51) found that as transpiration rate increases plants probably suffer reduced growth at higher moisture levels. Danielson (33) found a sharp decrease in ion uptake with decreasing moisture levels. Stanhill (122) stated that growth, photosynthesis, and other physiological functions are generally reduced before soil moisture reaches the wilting point. White (132) found that the irrigation frequency and fertility level had a greater effect on growth than aeration porosity.

Moisture content affects resistance to root penetration. As a soil dries out the resistance increases rapidly because the particles become closer together and the lubrication effect of the moisture decreases (11, 38).

Crown and root rots may be aggravated by a medium kept too moist (47). Hanan (54, 63) stated that good bench crops could be grown under very moist conditions if careful cultural and sanitation programs were carried out. Otherwise, drier media would usually give superior results if pathogens could not be completely eliminated.

Moisture stress may adversely affect plant growth, but it also appears that high moisture levels may do the same, even when aeration is sufficient (56), According to Bachman (5) a high moisture content can adversely affect crop quality. Information on this subject is very scarce in the literature.

Much information is available on specific values for optimum moisture tension ranges. Growers often water at tensions of 0.5 atm or less to avoid stress (79). White (132) reviewed several container experiments and found that increases in dry weight or crop yield were restricted by tensions of 0.5 atm or greater. Holley (67, 68) watered carnations at tensions of 0.1, 0.3, 0.5 and 0.7 atm and found yield and quality were similar in all treatments. He recommended watering at 0.3-0.5 atm. Ball (7) recommended 0.15-0.20 atm for standard chrysanthemums and Feaster (41) recommended 0.20-0.30 atm for snapdragons and 0.1 atm for carnations. Mastalerz et al. (85) advised watering potted mums when one-half the available water has been used. Richards (108) recommended watering most pot plants at 0.3 atm. White (133) and Furuta (47) agreed that most of the readily available water is held below 0.3 atm tension, but White indicated some greenhouse crops suffer water deficits at less than that tension. Milthorpe (90) and Salter et al. (111) stated that water below 1 atm tension may be the only water freely available to plants; higher tensions might limit growth. Richards (104) found that 50% of the available water in fine soils may be held below 0.85 atm, 90% in sandy soils. Hanan (62) determined that most of the water in greenhouse media is held at tensions under 0.1 atm.

Less information is available concerning the optimum container capacity range for greenhouse media. Hanan (58, 63) recommended 15-40% and Poole et al. (102) 30-60%. Conover (28) recommended 35-50%, and Furuta (47) 40%. White (132) found the most practical method of insuring optimum water was to use well-drained media to provide a buffering effect against over-watering, and then water frequently.

Water Holding Capacity

The amount of water in a medium determines its suitability for plant growth (114). The amount and energy status of the water influence the mixture's physical properties more than any other factor (11). Almost any containerized soil, amended or not, holds more water than the same soil in the field (79). Most greenhouse media hold between 25 and 50% water (79).

Richard's "outflow law" (106) states that "the outflow of free water from the bottom of a soil column occurs only if the pressure in the soil water exceeds atmospheric pressure." Thus, the soil-container interface acts as a barrier to drainage, creating a "perched" water table (132).

Water content is a function of depth in shallow media. Increased depth results in a lower moisture content at a given distance below the surface (52, 59, 105, 131). Hanan (60) found small increases in depth resulted in small decreases in water retention for media containing many small particles, such as a soil mixture. However, a 5 cm increase in depth of some soilless media could result in up to a 50% loss in water retention.

The particle surface area and the amount and size of the pores also affect the amount of water retained. These depend on the texture and structure of the medium (114). However, the effect of texture on water retention may be overshadowed by the effect of depth when media are placed in shallow containers (79). Lunt (79) and Matkin et al. (87)

found little difference in water holding capacity of various media in containers. Structure has a greater effect on water held at low tensions than high tensions because the large pores which hold water at low tensions are more affected by structure (111). Compaction reduces the size of these large pores and may result in reduced water holding capacity (119).

White (132) defined "container capacity" as the total volume of water held by a given depth of medium at equilibrium after drainage, in the absence of evapotranspiration. Richard's outflow law states that the moisture tension in cm of water at a given point will be equal to the distance of the point above the container bottom in cm (105). White (132) found that the outflow low underestimated the actual tension at container capacity (overestimated the water retained) for most media. He concluded that the container capacity for a given medium at a given depth could not be predicted by use of the outflow law.

The effect of an amendment on water retention depends on the type of amendment, its internal porosity and its particle size. Most organic and synthetic amendments absorb as well as adsorb water (114). Adding organic matter to a soil usually increases water retention (19, 47, 108) but the extent of increase may be exaggerated if retention is determined on a weight basis (42, 43). Feustel (43) determined that the increased retention from peat could be offset by increased unavailable water. Hanan (56) felt claims of water retention improvement from peat were exaggerated. Addition of mineral amendments such as perlite, calcined clay or sand may reduce the water holding capacity (47, 86). Matkin et al. (87) and Mazur et al. (88) found that finely ground materials increased retention better than the same material coarsely ground.

Pokorny (101) could control media water holding capacity by grinding bark to different sizes. The best particle size depended on the particle sizes of the other components. Some media may be difficult to wet thoroughly of their infiltration rate is high or if excess organic matter is added. From a cultural standpoint special irrigation methods may be necessary (47, 81).

Bulk Density and Compaction

Bulk density is defined as the mass of a given volume of dry medium and depends on the amount of solids in the volume and their particle density. Compaction is defined as an increase in media density caused by an applied pressure (11). Compaction and bulk density are closely correlated and the two words are often used synonymously in the literature.

Low weight is desirable in container production because it reduces shipping and handling costs and is less restrictive to root growth. However, heavier media give better stability to the container, so a compromise weight is usually sought (47, 102). Hanan (56, 61) pointed out that increases in bulk density generally result in decreased infiltration rate and total and aeration porosities. Accordingly, soils not properly amended will increase in bulk density rapidly with successive crops. Furuta (47) stated that mixing components of widely differing particle sizes results in reduced final volume which increases the bulk density. Matkin et al. (87) found that finely ground amendments reduced the bulk density of a loam soil more than the same amendment coarsely ground. Addition of light weight amendments to soil reduces bulk density while addition of sand or calcined clay increases it.

Nearly all the desirable physical characteristics of soils vanish when severely compacted (14). Compaction of a given mixture depends on the handling methods, water content, and the method of planting and watering. Many growers compact the medium around the plants as they pot them (29). Henley (66) found that this reduced root penetration by four times compared to uncompacted media, and advised against it. Ecke (40) warned that light weight media are easily compacted. Aubertin (4) found excessive handling compacts media and Boodley (15) pointed out that forceful watering disperses and compacts the upper surface of the medium. Baver et al. (11) concluded that an application of an increasing force to a soil with a given moisture content will cause an exponential increase in its density. The more moist a soil the less force is required to compact it. Increased moisture lubricates the particles and allows them to slide over each other and fit closer together. Compaction generally reduces the infiltration rate, total porosity, and aeration porosity. The percentage of solids increases at the expense of the large pores. Density, soil strength, bulk density, mechanical impedance, percent solids, and ratio of small to large pores increase with increased compaction (4, 9, 11, 14, 15, 38, 45, 48, 109, 123).

Bulk density and compaction limit plant growth by restricting root growth. Active root growth is necessary to maintain normal growth of the entire plant (120). As a general rule, increased bulk density results in increased resistance to root growth (61). The reduced pore size in high bulk density and compacted media may restrict root penetration (48, 129, 136) and absorption of water and nutrients (14, 45). The interaction of deficient aeration, water stress, and mechanical impedance to roots is the main cause of root restriction (4, 11, 24, 38, 48, 91, 109). Eavis (38, 39) studied this in detail and found it difficult to isolate the effects of any one factor. He concluded that resistance to penetration increases with bulk density and increasing moisture tension, and penetration is approximately inversely proportional to the level of mechanical impedance. Elongation increases with increasing moisture tension to a maximum, due to increased aeration. Increasing tensions then inhibit elongation due to increasing mechanical impedance. Mechanical impedance failed to restrict root growth at a bulk density of 1.0 g/cc. At 1.1 it restricted growth only at tensions above 0.1 atm. But a bulk density of 1.4-1.6 restricted growth over the entire moisture range. It appears that media with bulk densities below 1.0 must be used to avoid mechanical impedance to root growth. Symptoms of high bulk density or compaction include delayed maturity, nutritional deficiencies, reduction in growth, quality, and yields, and distorted roots (14, 24, 38, 45, 48, 109, 128). Plant species respond differently to dense media (45, 109).

Little agreement exists in the literature concerning desirable bulk density ranges. Conover (28) recommended 1.3 or less for container media, but Poole et al. (102) suggested 0.15-0.50. Hanan (61) stated that 1.0-1.2 resulted in acceptable levels of total porosity. Wittsel et al. (138) found bulk densities from 0.72-1.45 had no effect on stem or spike length or dry weight of snapdragons, but these were greatly reduced at 1.45-1.60. Veihmeyer et al. (129) and Camp et al. (24) suggested that the level of bulk density which limits root growth depends on the soil texture and structure. They found that 1.5-1.7 could limit growth in clays, while 1.75 was the upper limit in sands. Warnaars et al. (130) found that mechanical impedance was the same at all moisture levels in coarse sands, but increased with decreasing moisture in fine sands. Phillips et al. (97) showed that corn root elongation decreased linearly as bulk density increased from 0.94-1.30 in clay soils compacted to different levels. Bertrand et al. (12) found that corn roots grew well in a silty clay loam at 1.2 but would not penetrate it when compacted to 1.5. Camp et al. (24) found no penetration into soils at 1.7-1.8 at any moisture level. Forristall et al. (46) found that tree roots of some species could penetrate a soil with a bulk density of 1.8 while other species could not penetrate the same soil at 1.3. Flocker et al. (44) grew tomatoes in a sandy loam compacted to 1.1, 1.4 and 1.7 g/cc in six-inch pots. Root growth at 1.1 was good throughout the pot, at 1.4 roots grew mostly in the surface 2-4 inches with sparce growth below, and at 1.7 roots were concentrated in the upper one inch of soil. Lunt et al. (80) found no difference in carnation growth between a soil: pine shaving mix of bulk density 1.07 and a silt loam compacted to 1.52.

Infiltration Rate

Infiltration is defined as the downward movement of water into a medium. It is affected by matric and gravitational forces, resulting in horizontal as well as vertical movement. As the medium becomes wetter the matric forces decrease, resulting in decreasing infiltration rate over time (11). Many factors affect infiltration, but the effect is usually an interaction between them. Browning (17) pointed out that no single factor could serve as an index for infiltration rates.

The infiltration rate generally depends on the particle size distribution (82), pore size distribution (47, 94, 110, 113), degree of compaction (65, 87, 94, 124), degree of shrinking and swelling (6, 82, 110), initial wettness (1), water application force (110), presence of a surface crust (11, 36, 47, 125), bulk density (132), and aeration porosity (9, 10, 15, 17, 40, 87, 94, 110, 124, 132). White (132) found the infiltration rate negatively correlated with bulk density. Media with more than 70% soil had lower rates (5-8 cm/hr), whereas those with less than 70% soil had high rates (25 cm/hr or greater).

The infiltration rate is severely reduced by the formation of a dense crust on the medium's surface. Forceful watering or saturation of the surface allows particles to rearrange and become closer (11). Water should be applied as gently as possible to prevent this (47). This problem is most common in media containing high amounts of soil, and addition of amendments can prevent it (125). Alway (1) tested the infiltration rate of many different types of soil and found that it did not depend on texture. According to Russell (110) the rate depends mostly on the volume of pores drained at 0.01 atm tension, but pores draining at tensions up to 0.1 atm may also contribute. Less than half of the noncapillary pores carry water into and through soils (113). It appears that the shape of the desorption curve at low tensions might furnish information about the infiltration rate. Amendments are often used to increase infiltration (47, 87) but notable effects may only be seen when additions exceed about 40% by volume in many cases (94).

A high infiltration rate is a desirable property of container media, but it only affects plant growth indirectly. High rates are strongly associated with adequate aeration porosity. In fact, the infiltration rate can give a rough estimate of the desirability of media for container use (40, 47). Rates above 1.5-5 cm/hr usually give desirable results (47, 87). Brown (16) found that media with rates above

25 cm/hr still held enough water for good growth. High rates allow proper leaching, which is necessary with modern cultural practices. They also allow application of the correct amount of water in a minimum of time, thus minimizing labor costs.

Porosity and Aeration

One of the basic requirements of a greenhouse growing medium is adequate aeration, because media are usually kept at moisture contents near container capacity (69, 108). Aeration is the exchange of O_2, CO_2 and other gases between the air-filled pores and the aerial atmosphere caused by mass flow and diffusion. Mass flow is caused by the effects of wind, temperature, barometric pressure, and irrigation on gaseous exchange. It probably contributes little to the total aeration potential (11). Diffusion is mainly responsible for aeration and depends upon the porosity between the particles, porosity within the particles, shape of the aggregates and the particles composing them, and the fraction of the pore space filled with water (11, 52). Rate of diffusion to the actual root surface depends on the thickness of the surrounding water films and the gaseous concentration gradient between the root and its surroundings. Diffusion evidently is not inhibited by a surface crust as is infiltration rate (11).

It is evident, then, that the diffusion rate, thus aeration, depends largely upon the volume of air spaces in the medium (15, 50, 52,, 87, 108, 114, 119, 127, 128, 133, 135). This volume of air-filled pores is referred to as aeration porosity and aeration pores do not hold water against the force of gravity. If all the water was removed from the small pores, the resulting pore volume would be called the total porosity. Because aeration porosity is correlated with aeration and is easily measured it is often used as a criterion for evaluating container media.

Factors which determine the volume and size of the pores, thus aeration porosity, are the degree of shrinking and swelling (17), aggregation (11, 15, 114, 118), compaction (9, 38, 50, 74, 114, 118, 119, 124), depth (49, 52, 53, 58, 131), moisture content (2, 3, 15, 74, 114, 119), and size of the particles (3, 11, 15, 18, 47, 86, 87, 101, 114, 115).

The container depth is very important because of its effect on aeration. Grable (50) stated that lower diffusion rates may be adequate in deeper containers but higher rates are required for shallow ones. This is probably due to the increased root proliferation and oxygen consumption of plants confined in smaller containers. Hanan (52, 59) pointed out that adding gravel to the bottom of a pot reduces the effective depth of the medium, resulting in increased moisture holding capacity and reduced aeration porosity at a given distance below the surface. He compared the properties of various media at depths ranging from 8-45 cm and found optimum levels of aeration porosity and oxygen diffusion in all cases (53). However, Waters (131) found that aeration porosities of various media at 6 cm depths were extremely low. He recommended using extremely well drained media when shallow containers are used.

Compaction generally increases the amount of small, capillary pores at the expense of the large, aeration pores (9, 38, 50, 124). Sudds et al. (123) found that as bulk density increased in soils, the aeration porosity decreased. White (132) found as bulk density increased for soil:perlite:peat mixtures total porosity generally decreased. Aeration porosity also decreased, but not consistently. Swartz (124) found a strong correlation between aeration porosity and infiltration rate.

Particle size determines the aeration porosity to a large degree. Rounded materials tend to pack more tightly than angular ones (115). Buehrer (18) found that total porosity increased with increasing particle size. Data from Matkin (86, 87), Furuta (47) and Brown et al. (16) suggested a threshold proportion for total and aeration porosity when mixing materials varying widely in particle size. Matkin (87) reported that finely ground amendments usually increased the total and aeration porosities more than the same amendment coarsely ground.

Total porosities of average soils usually are near 50%, with sands being lower and clays and organic soils somewhat higher (11). Aeration porosities in average, well tilled soils are near 20% (99). Spomer (118) stated that total porosities of soils mixed with sand, perlite, calcined clay, vermiculite, bark, or other coarse amendments were usually in the 10-30% range depending on the amount of amendment added. Blake et al. (13) and Grable (50) found that diffusion was nearly zero in soils and sands with aeration porosities as high as 10%. They attributed this to blocked or dead end pores.

Most higher plants require adequately aerated media for proper development of their root systems. Poor aeration inhibits root growth through lack of O_2, toxic levels of CO_2, and/or production of toxic substances. O_2 requirements for maximum growth rate generally increase as media temperature, moisture content, and resistance to penetration increase (48, 128). Whether a period of poor aeration will be long enough to cause observable reduction in growth depends on how fast the plant removes water (61). Plant species respond differently to poor aeration; some are tolerant, some are sensitive (99, 126, 128, 135). Some tolerant plants are capable of internal O_2 transport and obtain significant amounts from the shoot (75, 84, 99). Roots undergo morphological and physiological changes in response to poor aeration which permit a degree of adaptation. However, quality and yield are adversely affected before complete recovery occurs (25, 75, 89, 128).

Plants develop many symptoms in response to poor aeration, but the extent to which symptoms develop depends on the type of plant and the length of time poor aeration exists. Moderately poor aeration can result in lower yields and quality without producing other visible symptoms (15, 89). Poor aeration can cause the death of roots, and the subsequent loss of permeability and absorbing surfaces reduces respiration (50), water absorption (11, 15, 50, 128), translocation (15), and nutrient absorption (8, 11, 15, 50, 128). This results in reduced shoot size (15, 61, 76, 128), vigor (15, 48), yields (15, 89), and root branching and growth (15, 27, 76). The extent of disease and chlorosis may also be increased (11, 61, 76, 89, 99). Extremely poor aeration for long periods of time may result in wilting of leaves and their eventual death (15, 74, 76, 89). Grable (50) stated that additions of fertilizer could alleviate almost any conceivable situation of deficient aeration, except under conditions of complete moisture saturation. Baver et al. (11) disagreed and concluded that poorly aerated media are not productive regardless of the fertility level.

Information concerning optimum aeration porosity levels is limited in the literature. Many authors believe at least 10% is needed for best growth, but that many exceptions exist. Others believe that an optimum level exists for each type of medium. Others believe that no single level can be considered optimum, or even minimum, for all situations (50). White (133) stated that aeration porosity should be higher than the minimum level because it tends to decrease with time in most media. Baver et al. (11) concluded that root growth is restricted below 10%. According to Blake (14) diffusion becomes extremely limited below 10-15%. Conover (28), Furuta (47), and Richards et al. (108) recommended 10-20%, 5% and 5%, respectively, as minimum for container media. Kerbo (71) recommended 10-20% minimum for foliage plants. Widmer (134) felt that aeration porosities below 10% were undesirable. Baver (10) found that 8-10% was necessary for good growth of sugar beets in field soils. Eavis (38) showed that poor aeration inhibited root growth below 30% aeration porosity in soils of low bulk density (1.1 g/cc), below 22% in soils of medium bulk density (1.4 g/cc), and below 11% in high bulk density soils (1.6 g/cc). Mechanical impedance overshadowed the effects of poor aeration at the higher densities.

The literature contains many conflicting reports as to the extent of the aeration problem in greenhouses. Lunt (79, 80), Hanan (55), and White (132) questioned the idea that deficient aeration was a significant problem. Taylor (128) stated that poor growth resulting from undesirable water relations, unfavorable temperature, etc., was often attributed to poor aeration because researchers failed to determine the true cause of the problem. Hanan et al. (57) found that problems thought to be caused by poor aeration were actually caused by pathogens.

MATERIALS AND METHODS

Preparation of Media

Every effort was made to treat the media as they would be treated under commercial greenhouse practices. The main exception was that no plants were grown in the media. Many researchers have used artificially compacted samples, but it is questionable if these are representative of media subjected to typical greenhouse conditions. Media in this study were mixed, handled, and aged just as if they contained growing plants. Physical properties were determined on core samples, undisturbed as far as possible.

The components of the media were those commonly used by Colorado potted plant growers and consisted of:

1) shredded and baled Canadian moss peat, 90% organic matter (Western Peat Moss Ltd., Vancouver, B.C., Canada)
2) horticultural grade vermiculite (W. R. Grace and Co., Cambridge, Mass.)
3) #8 perlite (Persolite Products, Inc., Florence, Colo.)
4) native Colorado peat from Fairplay, Colo., 56% organic matter
5) coarse river sand
6) sandy clay loam from an Arvada, Colo., alfalfa field, 3% organic matter

Detailed textural information describing the soil and sand components is shown in Table 1. The native peat closely resembled the peat humus described by Lucas et al. (78).

Table 1. Textural analysis of the sand and soil components by weight.

Sand	Soil
42% >1.0 mm	62% sand
27% 0.5 -1.0 mm	16% silt
14% 0.25-0.5 mm	22% clay
13% 0.10-0.25 mm	
3% 0.05-0.10 mm	
1% <0.05 mm	

Soil and native peat were run through a shredder before mixing. Canadian peat, perlite, and vermiculite were mixed at their packaged moisture content; soil, native peat, and sand were slightly moist when mixed. An electric concrete mixer was rotated for three minutes to thoroughly mix the components. Media containing perlite required further wetting to insure adequate mixing by spraying the revolving mixtures with a fine mist. The soil:perlite mixtures became very well aggregated due to this extra wetting. All two-way combinations of the six components were prepared except sand:perlite, sand:vermiculite, perlite:vermiculite, and Canadian peat:native peat. This resulted in 11 combinations, each combination made up at the following ratios:

100%:0%
80%:20%
60%:40%
40%:60%
20%:80%
0%:100%

Mixtures were poured into six-inch standard plastic pots and settled by gently tapping the pot until settling ceased. Plastic mesh (540 mesh per square inch) was used in the bottom of the 100% sand pots to keep it from sifting out. The pots were placed on snow-fence-covered benches in a greenhouse which was kept at 52°F night temperature. Enough of each ratio was prepared to fill 25 pots. Five pots of each ratio were tested at 0, 30, 60 and 90 days from the initial watering to determine changes in physical properties over time. The remaining five pots were planted with tomatoes, to determine percentage unavailable water at the end of the experiment. The 1525 pots were watered approximately every other day to simulate natural greenhouse settling processes. Watering was done by means of a water breaker held about 50 cm above the pots. Media was added after each watering to bring the level to within 1 cm of the top.

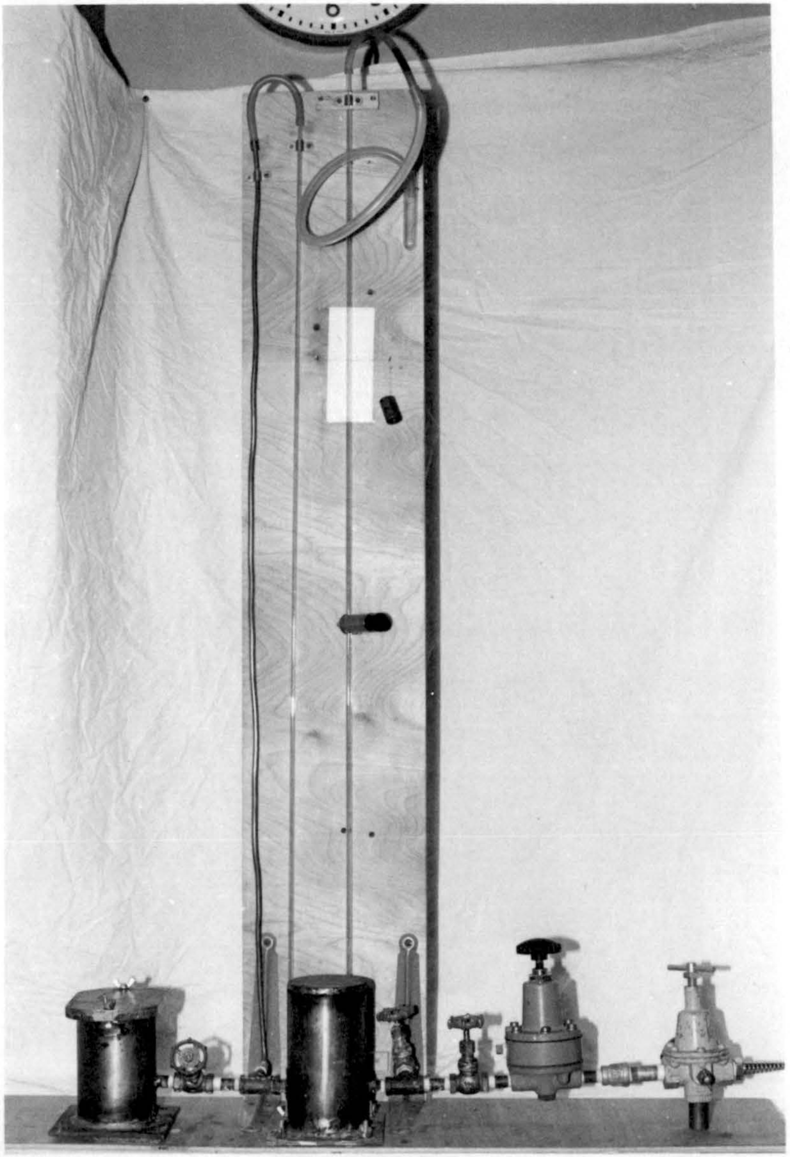
Preparation of Undisturbed Samples

All physical properties were determined on undisturbed samples taken from the potted media. A commercially available core sampler was used (Figure 1) which is similar to the ones described by Baver (11) and Lutz (83). The removable inner liner and spacer were constructed from 5.4 cm ID aluminum conduit. Twenty-five extra liners were made from similar conduit in order that many samples could be taken in a short time. The sampler was inserted into the medium with a twisting motion, then withdrawn. The inner liner was removed and all excess soil trimmed from each end. Depth of the medium in each pot was 14 cm, and length of the liner 11.5 cm. The extracted sample consisted of the entire 14-cm core less the bottom 1/2 cm and the top 2 cm. The samples were taken 30 minutes after a thorough watering. White (133) stated that container capacity should be determined at an arbitrarily set time after watering, usually less than 24 hours. It

Figure 1.

Photograph of the air picnometer used in determining aeration porosities of greenhouse media.

Apparatus used for extracting undisturbed core samples from pots of greenhouse media. #20 is a removable liner for the main cutting tube, #4 is a spacing ring.




4.
20.

was decided that examining the properties 30 minutes after watering would show which media provided adequate aeration porosity. As soon as the samples were taken, the bottom end of each tube was covered with plastic film held with a rubber band (Figure 2). These were placed in the laboratory, covered with a plastic sheet, and allowed to equilibrate with the laboratory temperature for 3 to 4 hours.

Determination of Aeration Porosity

Aeration porosity is defined in this study as the percentage volume of air spaces 30 minutes after a thorough irrigation. It is usually obtained in three ways: by calculation based on specific gravity and water holding capacity, by air picnometer, or by the "saturate and drain" method whereby a sample of given volume is saturated with water and drained. The volume of water removed supposedly equals the volume of the aeration pores. However, many researchers have shown that these "saturated" samples still contain considerable air (1, 26, 72, 98, 112, 113), thus the aeration porosity would be underestimated by this method.

Baver (11), Kummer et al. (72), Page (93) and Taylor et al. (128) recommended the air picnometer for porosity measurements. They pointed out that it was accurate, fast, and easy to use. An air picnometer was used in this study and built according to Kummer's suggestions, with certain modifications (Figures 1, 2). Pressure chambers (a) and (b) (Figure 3) were constructed from 8-cm ID steel pipe. The upper lip of chamber (a) and its lid (c) were machined to accept an O-ring. Valves (j), (k) and (l) are 1/4-inch globe valves. Regulator (e), the fine

Figure 2. Photograph of the air picnometer constructed for use in this study, showing an undisturbed sample ready to be tested.

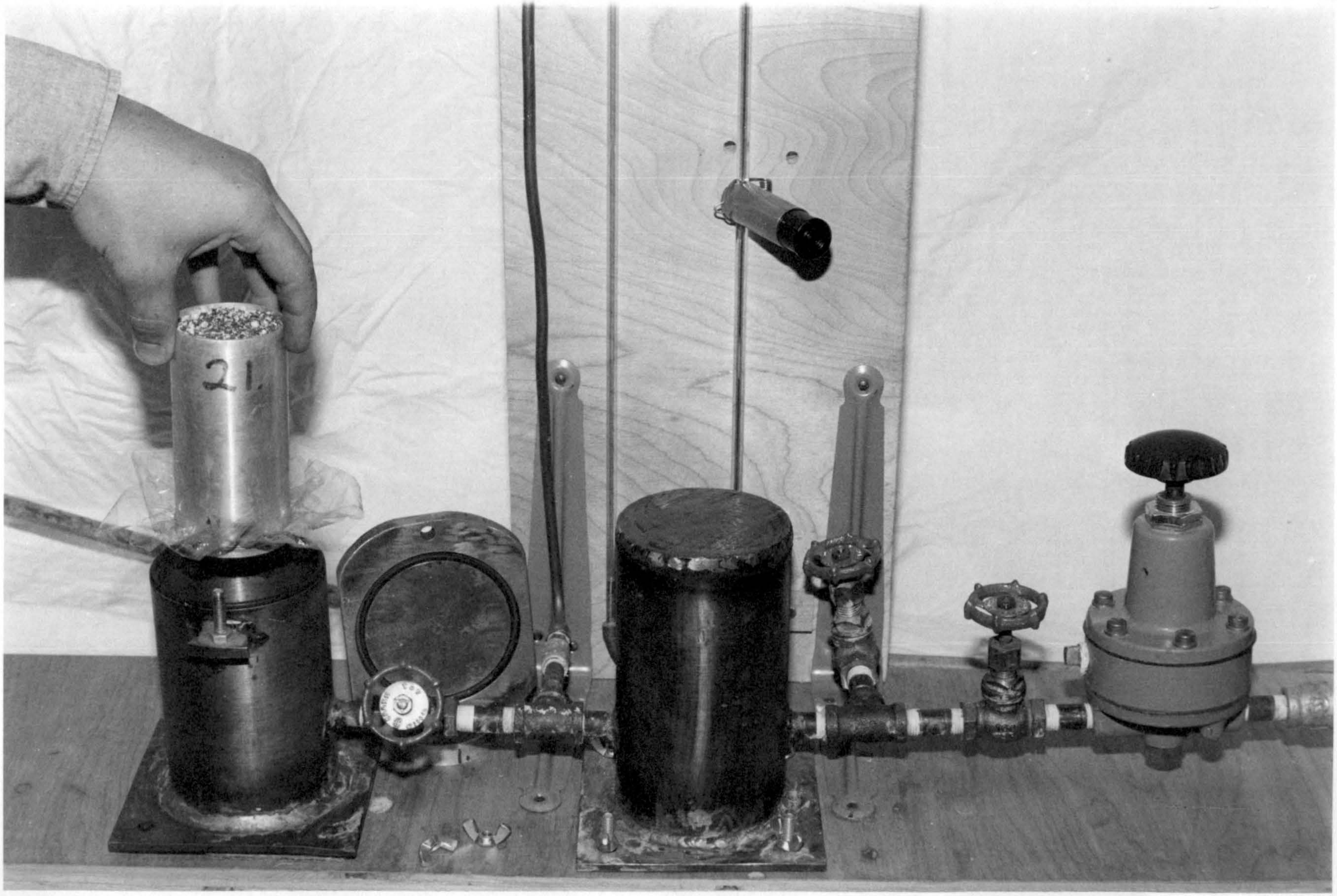

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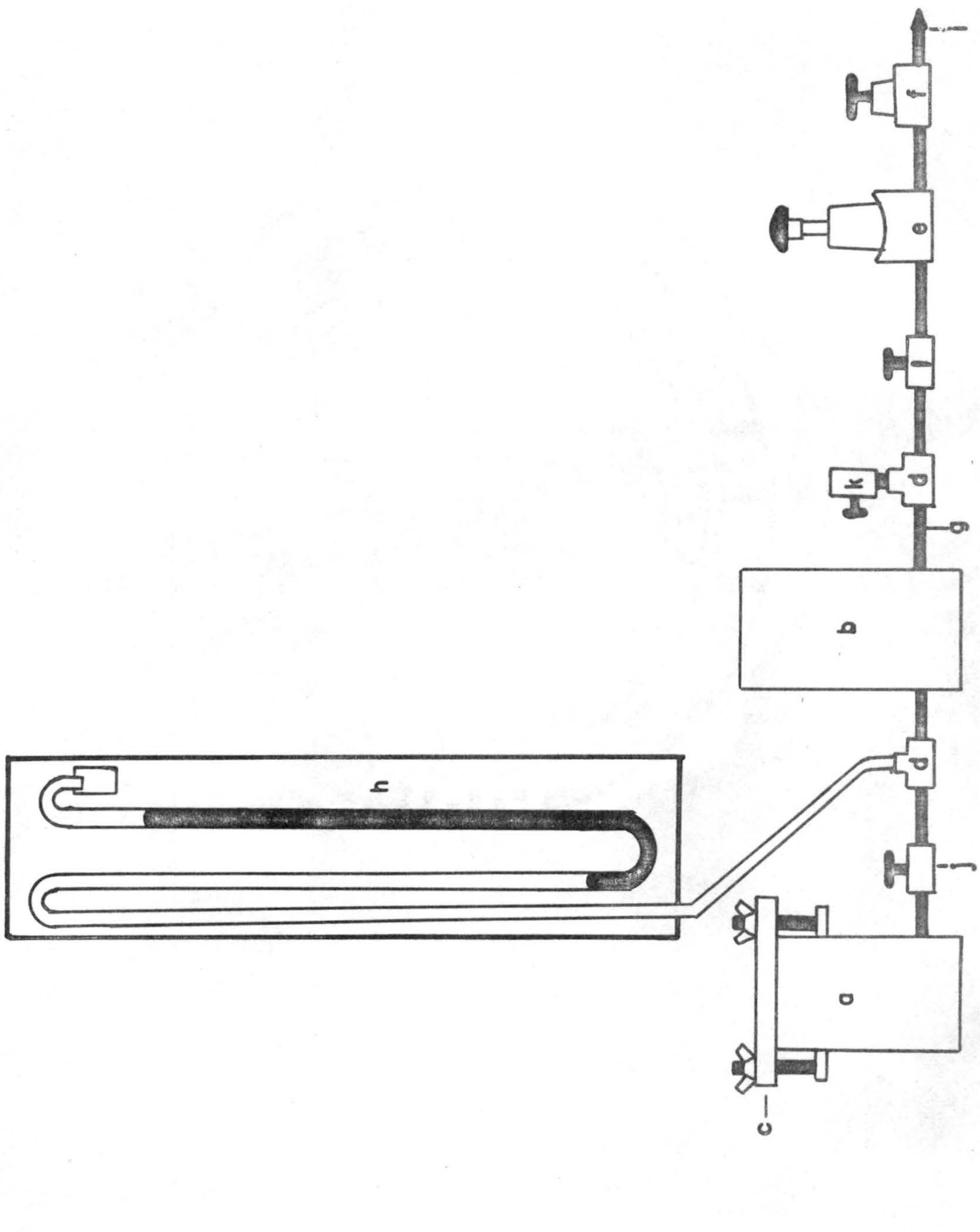
Figure 3. Diagram and list of parts for the air picnometer used in determining the aeration porosity of greenhouse media.

(a) sample chamber
(b) pressure chamber
(c) lid sealed with an "O" ring
(d) 1/4 inch "T" fitting
(e) fine pressure adjustment regulator
(f) coarse pressure adjustment regulator
(g) 1/4 inch galvanized pipe
(h) mercury manometer
(i) air hose adapter
(j)
(k) 1/4 inch globe valves
(l)


a
b
c
d
d
e
f
g
h
i
j
k
l

pressure adjustment, is a Nullmatic Pressure Regulator.[1] This regulator must be capable of giving very sensitive pressure adjustments. Regulator (f) is the coarse pressure adjustment. Part (d) is a 1/4-inch "T", and (g) is 1/4-inch galvanized pipe. Part (h) is a mercury manometer and (i) is the air hose connector.

To operate the picnometer regulator (e) is closed, an airline is connected to part (i), and regulator (f) is adjusted to approximately 1.3 atm pressure. With valves (j) and (k) closed and (l) opened, regulator (e) is adjusted to an arbitrary pressure, in our case 1 atm. A mark should be placed on the manometer at this mercury level so that the same initial pressure can be used each time. Valve (l) is then closed and valves (j) and (k) opened to release the pressure. The media sample is then placed into chamber (a) (Figure 3) and the lid closed. With valves (j) and (k) closed, valve (l) is opened slowly, the mercury column is adjusted to the original mark with regulator (e), and valve (l) is closed. Valve (j) is then opened and the pressure is read on the manometer with a buret reader or cathetometer.

Since the same initial pressure and sample tube volume were used each time in our procedures, it was possible to set up a calibration curve of height of mercury versus aeration porosity. This was done by placing known volumes of water in the sample tubes (thus, known percentages of air) and noting the height of the mercury column. Our curve consisted of 11 values of aeration porosity, from 0-100% of the sample tube volume, versus the mean of 10 heights of mercury at each volume (Figure 6).

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[1] Model 40-50, Moore Products Co., Spring House, Pa.

Temperature and atmospheric pressure have a large influence on the results obtained. It was extremely important that the media samples be at the same temperature as the laboratory air temperature. The picnometer was calibrated each day by inserting an empty sample tube (100% aeration porosity) and adjusting the cathetometer so that this porosity corresponded to height 0. Approximately 20 samples could be tested per hour with the picnometer.

Determination of Container Capacity and Bulk Density

Immediately after the sample tube was removed from the picnometer it was weighed to the nearest gram. It was then dried in a forced air oven for 24 hours at 100-105°C as recommended by Taylor et al. (128), reweighed, and the results used to determine the bulk density and percentage volume of water at container capacity.

Determination of Available Water

Tomatoes were grown one plant per pot until the roots extended completely through the media. The pot and soil were then covered with aluminum foil to prevent evaporation from the soil surface and the plants were allowed to wilt. When the plants failed to recover from wilting overnight, they were removed from the pot and as much media as possible was removed from the roots by shaking. This was weighed, dried, and reweighed to determine the volume of water held at the wilting point. Since the bulk density was known, the following formulae were used to determine percent available water.

(1) wt. soil at wilting point (g) - wt. dry soil (g)

= volume water at wilting point (cc)

$$\frac{\text{wt. dry soil (g)}}{\text{bulk density dry soil (g/cc)}} = \text{volume dry soil (cc)} \tag{2}$$

$$\frac{\text{vol. water at wilting point}}{\text{vol. dry soil}} \times 100 \tag{3}$$

$$= \text{\% water at wilting point, by vol.}$$

$$\text{\% water at container capacity} - \text{\% water at wilting point} \tag{4}$$

$$= \text{\% available water}$$

Russell (110) pointed out that most plants extract approximately the same amount of water from a medium between container capacity and wilting point, so the results obtained with tomatoes should also apply to other crops.

Determination of Infiltration Rates

Several methods of determining infiltration rates were tried before an acceptable method was found. One method gave satisfactory results but was rather crude. It could, however, be used by the commercial grower as a basis of evaluating media since no special apparatus is required. Six-inch standard plastic pots were filled with soil to a depth of three inches, covered with a circular piece of screen, and settled by watering with a water breaker. The screen was placed on the medium to prevent excessive compaction during watering. Additional medium was added until it failed to settle below the three-inch depth. The pot was then filled with water with the water breaker, and the time required for the three-inch falling head to infiltrate the medium was recorded.

Some media required hours to drain. Since periods longer than 10 minutes (600 sec) were considered undesirable, the time value for these media was recorded as >600 seconds. This presented problems when the mean was determined for the five replicates. Therefore, rates above 600 sec were assigned the value of 600 sec, and the number of these per treatment was noted.

Determination of Desorption Curves

Moisture release values were determined on a 0-1 atm pressure plate (128). Moist samples of each type of media were stored in closed plastic containers to prevent drying. Samples were poured into 1.5-cm deep rings (Figure 1, #4) and wetted with a small stream of water from a wash bottle until settling ceased. It was assumed that this settling method would make the samples structurally similar to their counterparts from which the core samples were taken. These were allowed to soak for approximately one hour before pressure was applied. Three replicates of each media ratio were tested. The samples were allowed to equilibrate under pressure for 24 hours, after which they were weighed, dried, and weighed again. Bulk density values from the core samples were used to determine the percent water, by volume, in the pressure plate samples. Pressures used were those recommended by White (133): 0.01, 0.05, 0.20, 0.33, 0.50 and 1.00 atm.

Correlation of Plant Growth with Media Physical Properties

A study was undertaken with chrysanthemums on January 27, 1976, to determine how plant growth is affected by media of known physical properties. Ten media were chosen which represented a wide range of physical properties. In order to insure that nutrients were not the growth limiting factor, superphosphate and agricultural gypsum were added at 114 and 227 grams per bushel, respectively, during mixing. The plants were fertilized at each watering with 200 ppm nitrogen, 250 ppm potassium, 16 ppm phosphorous, 140 ppm calcium, 15 ppm magnesium, plus boron and zinc. The plants in pine bark:Canadian peat soon developed nitrogen deficiency symptoms, so one teaspoon of slow-release fertilizer containing 19% N, P and K was applied to each of these plants.

Ten six-inch standard plastic pots of each medium were prepared. Half were potted with <u>Chrysanthemum</u> <u>morifolium</u> Ram. c.v. 'Paragon', half with c.v. 'Dramatic'. Five rooted cuttings were placed around the perimeter of each pot. The medium was settled around the cuttings by watering with a water breaker. No other pressure was applied to the media. A trickle irrigation system was used to prevent compaction from water pressure. The entire group of plants was watered when the first signs of wilting were observed.

The mums were grown as a pinched crop under standard cultural conditions. B-Nine[2] growth regulator was applied at 0.25% on February 4, and at 0.5% on February 28 and March 10. The center buds were removed from 'Dramatic' and the lateral buds from 'Paragon' on March 18 and 25, respectively. The height and number of flowers were determined on April 20 when all plants were in full bloom. On April 24 all plants were excised at the soil surface and the fresh and dry weights were determined.

Correlations between physical properties and plant growth, and among the various physical properties were determined. Infiltration

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[2] B-Nine, Uniroyal Chemicals, Inc., Naugatuck, Conn. 06770.

rates were determined on each pot after the plants were removed. The depth of the medium in each six-inch pot was 5.5 inches. The media were thoroughly soaked, the pots filled with water, and the time required for the 1/2-inch head to infiltrate each medium was determined.

RESULTS AND DISCUSSION

Effect of Time on Physical Properties

The physical measurements of each of the 11 media were subjected to a two-way analysis of variance to determine the effect of amendment proportion and time on the physical properties. Changes in bulk density and total porosity over time were almost unnoticeable, and were certainly unimportant. The only exceptions were soil:sand mixtures whose bulk density increased slightly from 0 to 30 days, then remained fairly constant. Total porosity decreased slightly over the first 30 days for soil:sand mixtures containing less than 60% sand.

Aeration porosity and available water percentage changed more significantly over time than total porosity or bulk density. The major changes occurred during the first 30 days, with properties at 30, 60 and 90 days being very similar. No consistent increase or decrease occurred for either property, the change depending on the type of medium and the particular proportion in question. The changes in aeration porosity occurred mostly at the expense of the water holding capacity, and vice versa, since total porosity changed very little. It appears that a wide range of media can be used over a period of at least 90 days without concern for significant compaction, decomposition or other changes in physical properties.

The large soil aggregates in the soil:perlite mixtures were remarkedly stable over a 90-day period. This method of mixing is recommended when soil is used, as it provides excellent aeration and infiltration rates.

Figure 4 shows the effect of increasing amendment proportion on aeration porosity, available water holding capacity, total porosity, and bulk density. Since these properties changed very little after 30 days, the values from day 30 were selected for Figure 4, rather than using the means of day 0, 30, 50 and 90. Values for all the physical properties, averaged over 90 days, are given in Tables 5-10 in the Appendix.

Media Physical Properties

The precision of the air picnometer was high (±1% of the aeration porosity). This instrument was also accurate to within ±1% when properly calibrated. Total porosity values for a given medium at a given sampling date were within ±2% of total porosity. Aeration porosity and container capacity generally were more variable and were within ±5%, while bulk density varied within ±0.03 g/cc.

Aeration porosity ranged from 18 to 54%, all values being above the 10-15% minimum recommended by most researchers. If these minimum values are correct, then poor aeration should not be a significant problem with most container media at depths of six inches or greater. However, these media were not subjected to the compacting effects of high water pressure or hand firming. Practices such as these might easily reduce the aeration porosities to below minimum.

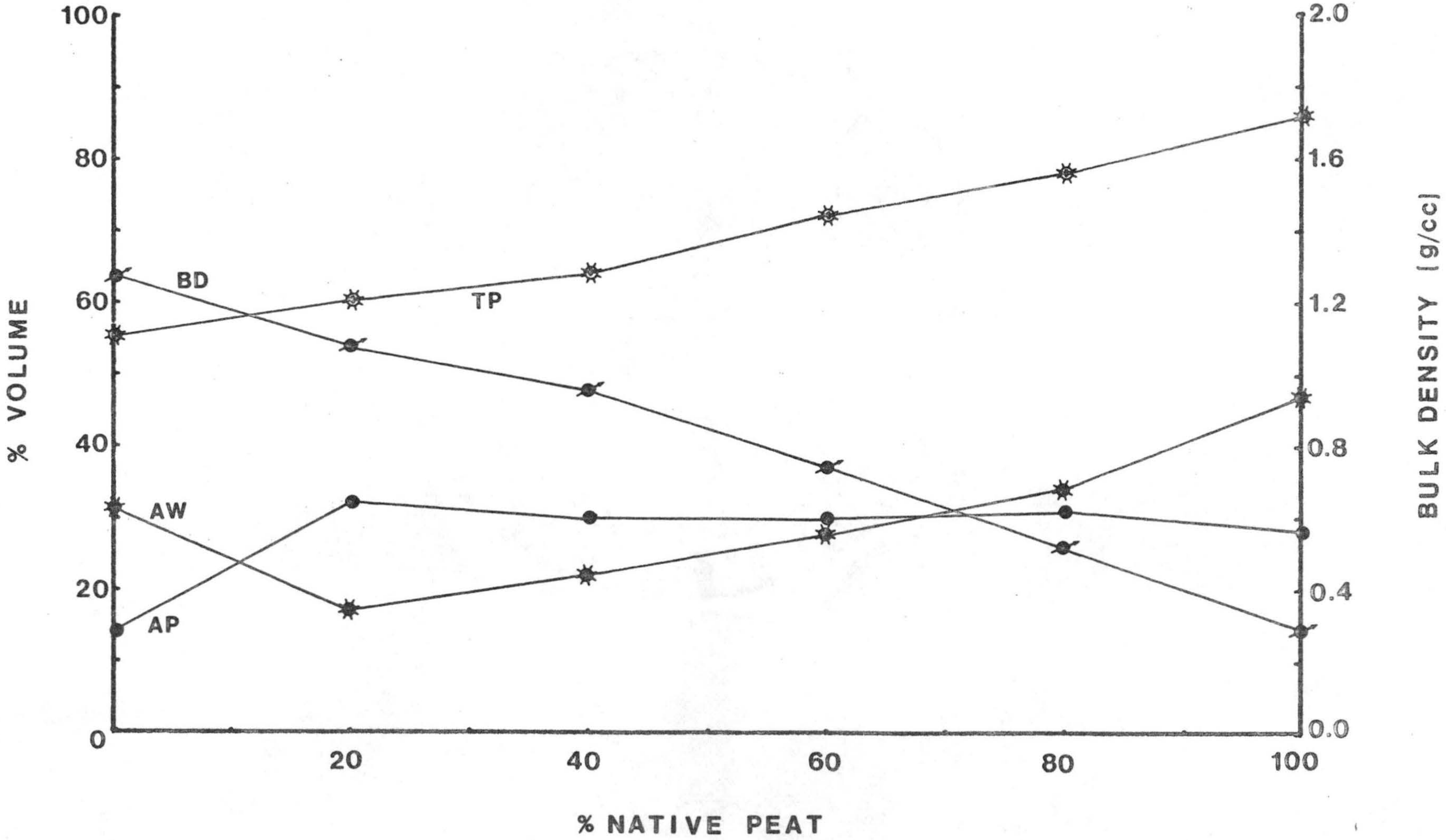
Media containing at least 40% perlite or 60% vermiculite generally had aeration porosities above 30%. Forty percent Canadian peat or above resulted in aeration porosities of at least 30%, except when soil

Figure 4. The effect of increasing amendment proportion on aeration porosity, available water holding capacity, total porosity, and bulk density. Each point is the mean of 5 replicates. The media had been preconditioned in a greenhouse environment for 30 days prior to sampling.

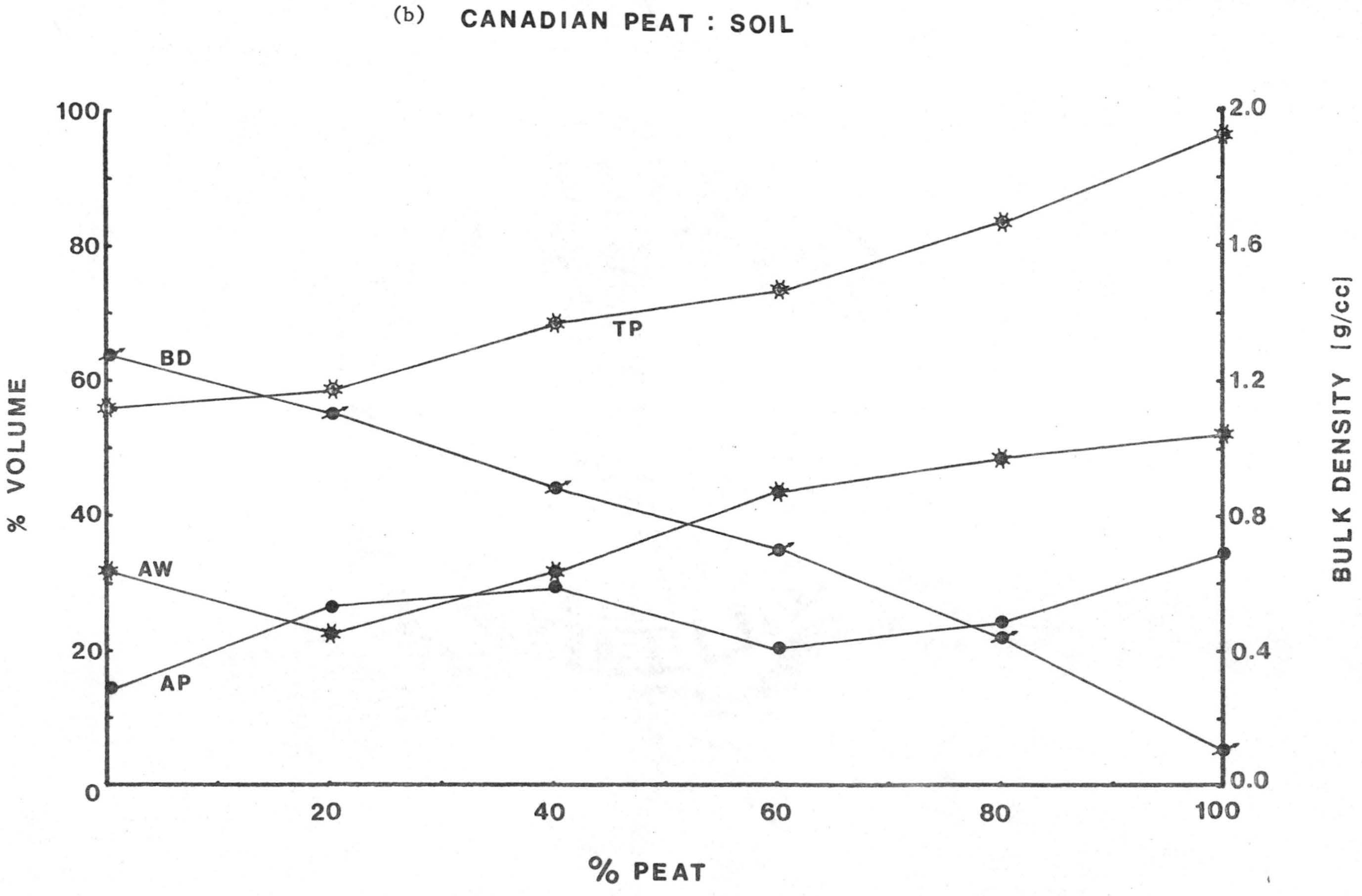
(a) Native Peat:Soil
(b) Canadian Peat:Soil
(c) Sand:Soil
(d) Vermiculite:Native Peat
(e) Vermiculite:Canadian Peat
(f) Perlite:Native Peat
(g) Perlite:Canadian Peat
(h) Vermiculite:Soil
(i) Perlite:Soil
(j) Native Peat:Sand
(k) Canadian Peat:Sand

LEGEND

☼ Total Porosity, % volume (TP)
● Aeration Porosity, % volume (AP)
ø Bulk Density, g/cc (BD)
✸ Available Water, % volume (AW)

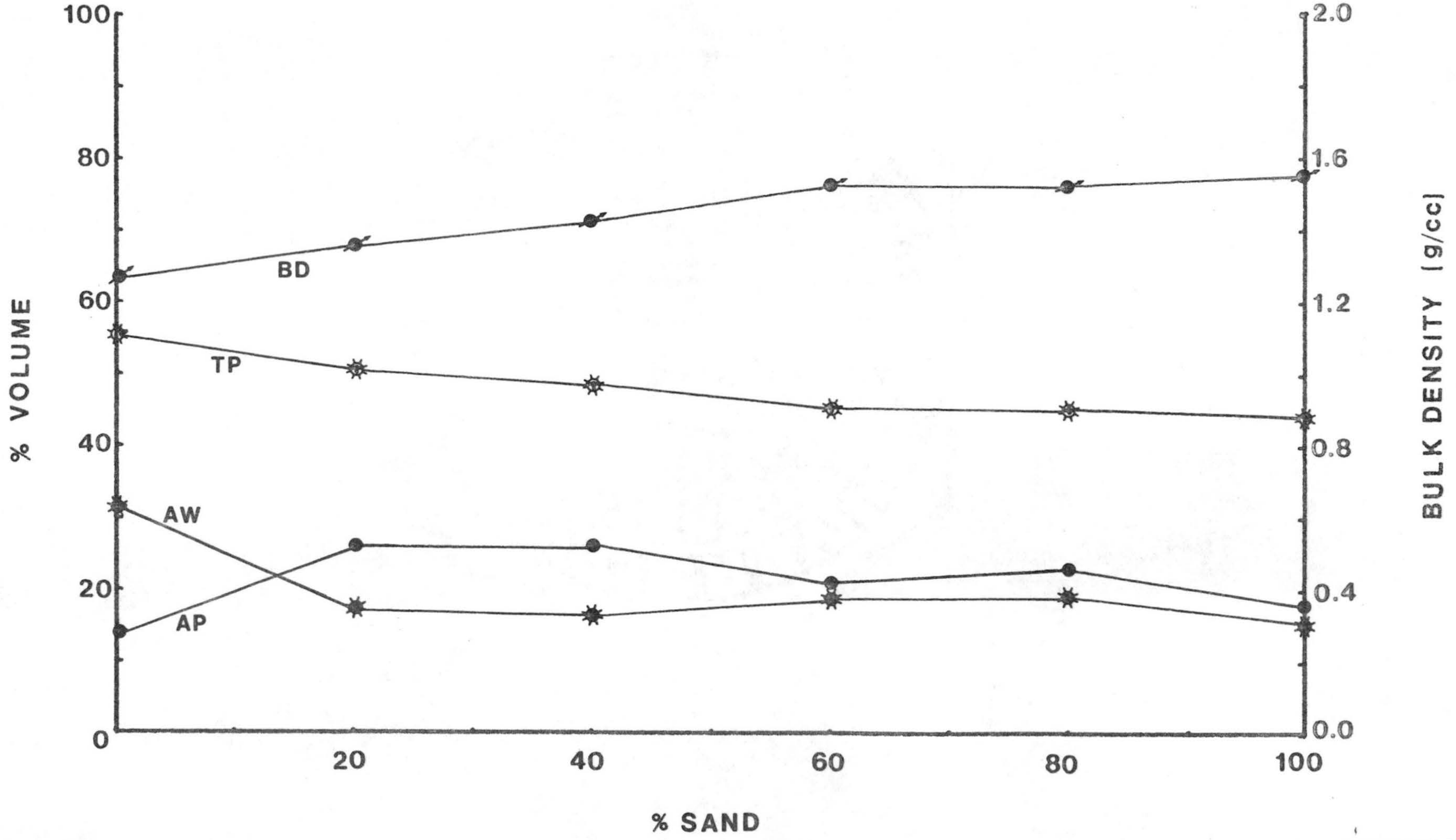


(a) **NATIVE PEAT : SOIL**

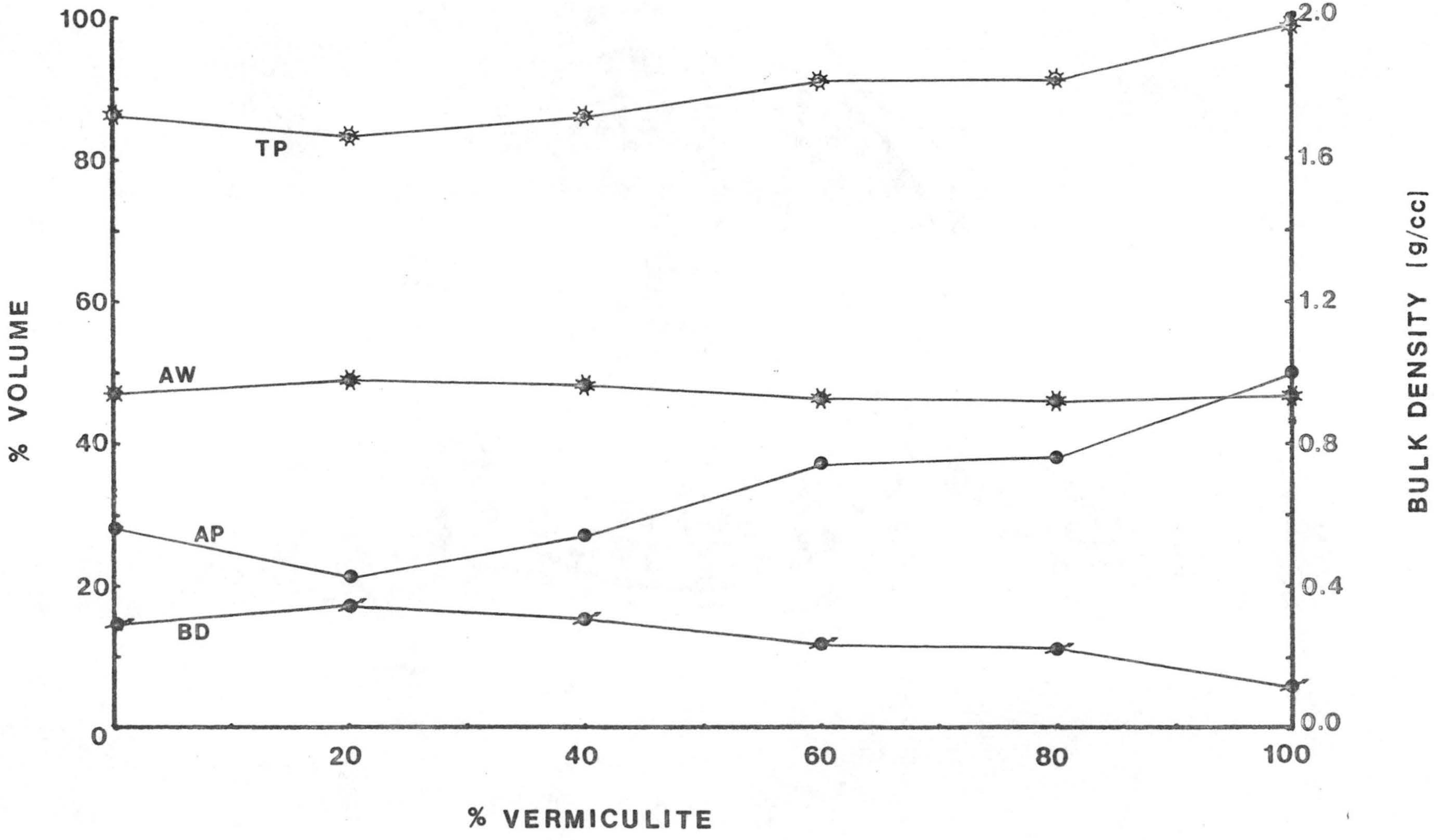


(b) CANADIAN PEAT : SOIL

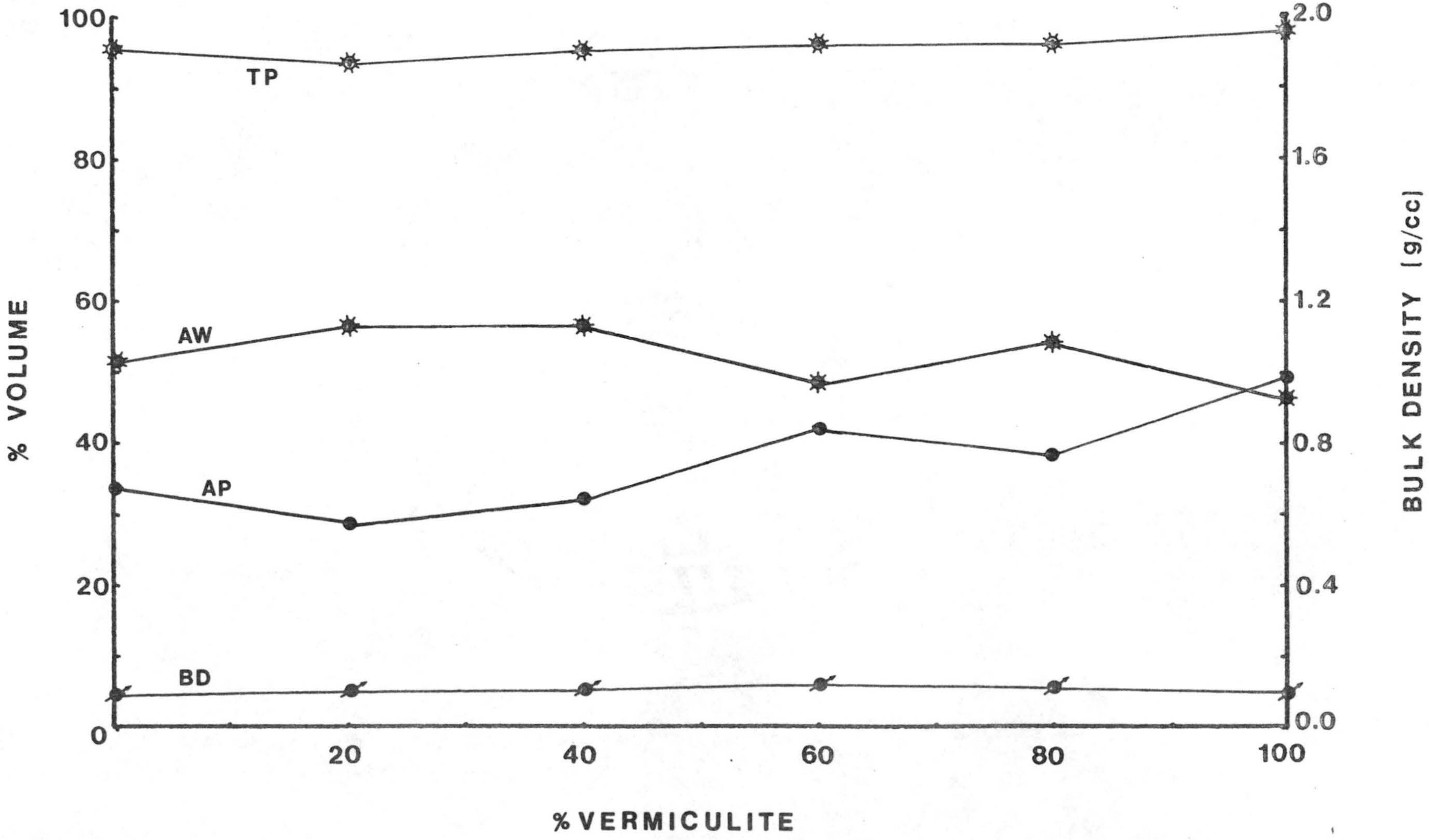
(c) SAND : SOIL


100
80
60
40
20
0
% VOLUME
2.0
1.6
1.2
0.8
0.4
0.0
BULK DENSITY (g/cc)
BD
TP
AW
AP
20
40
60
80
100
% SAND

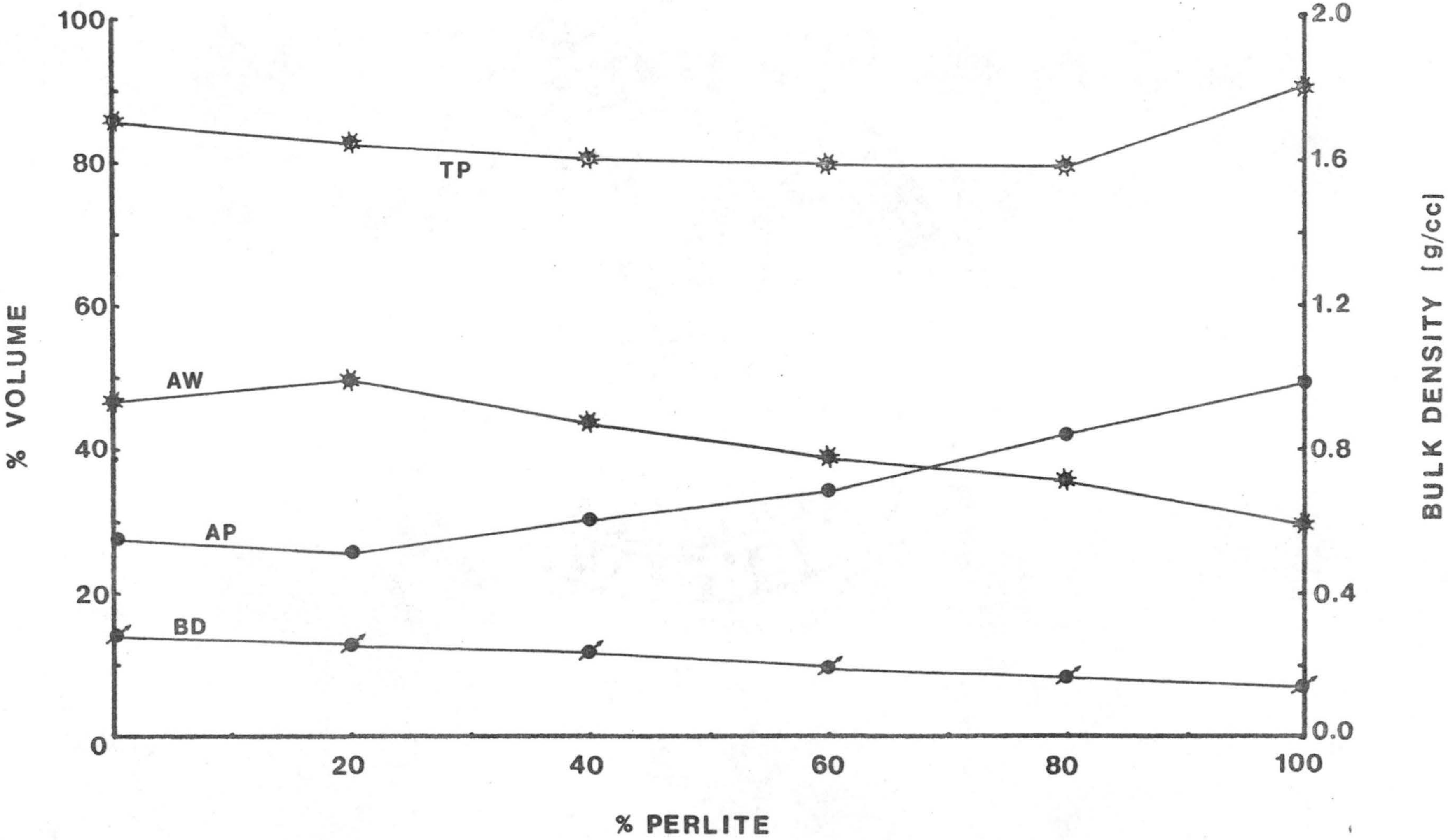
(d) VERMICULITE : NATIVE PEAT



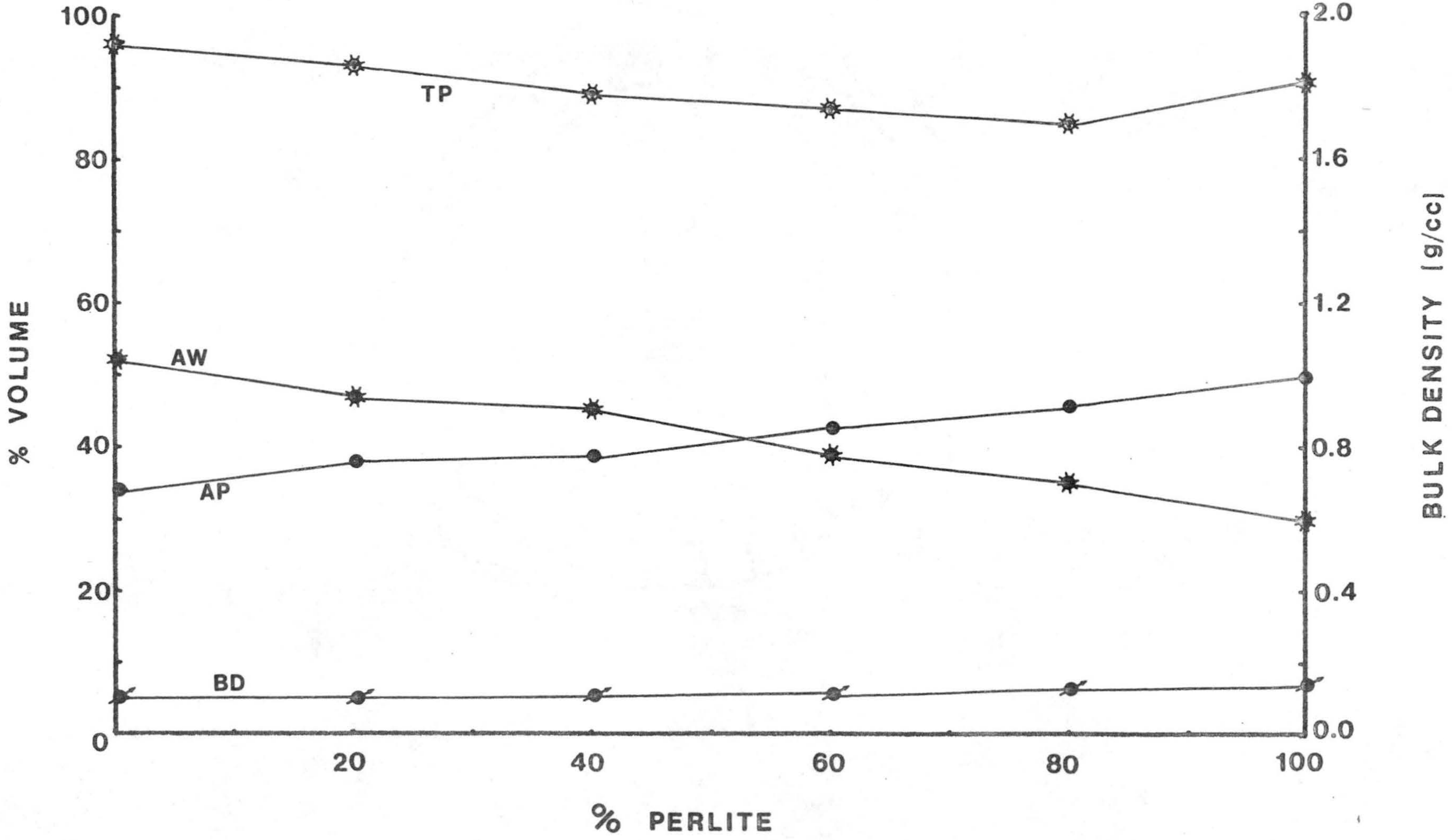
(e) VERMICULITE : CANADIAN PEAT



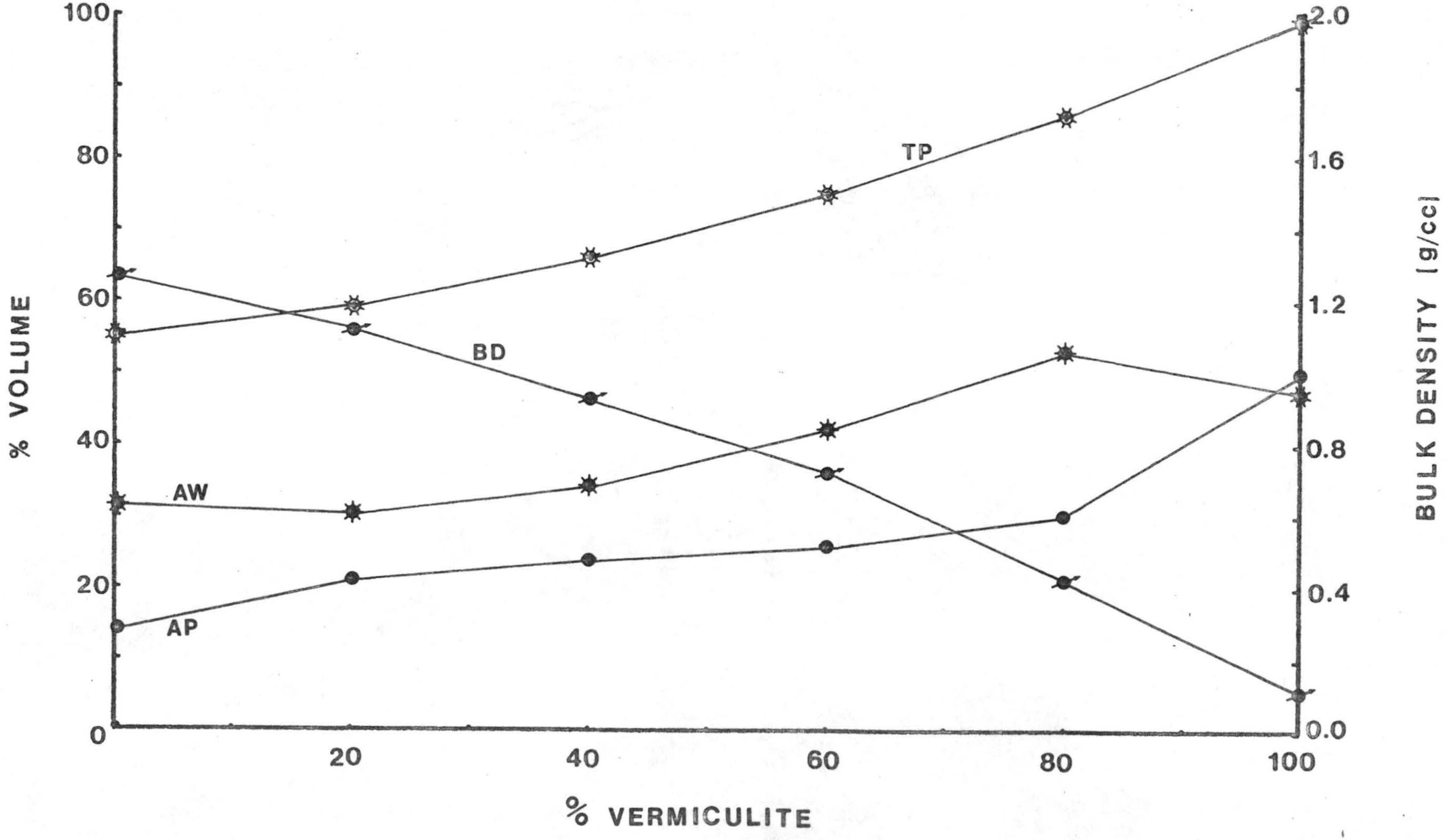
(f) **PERLITE : NATIVE PEAT**

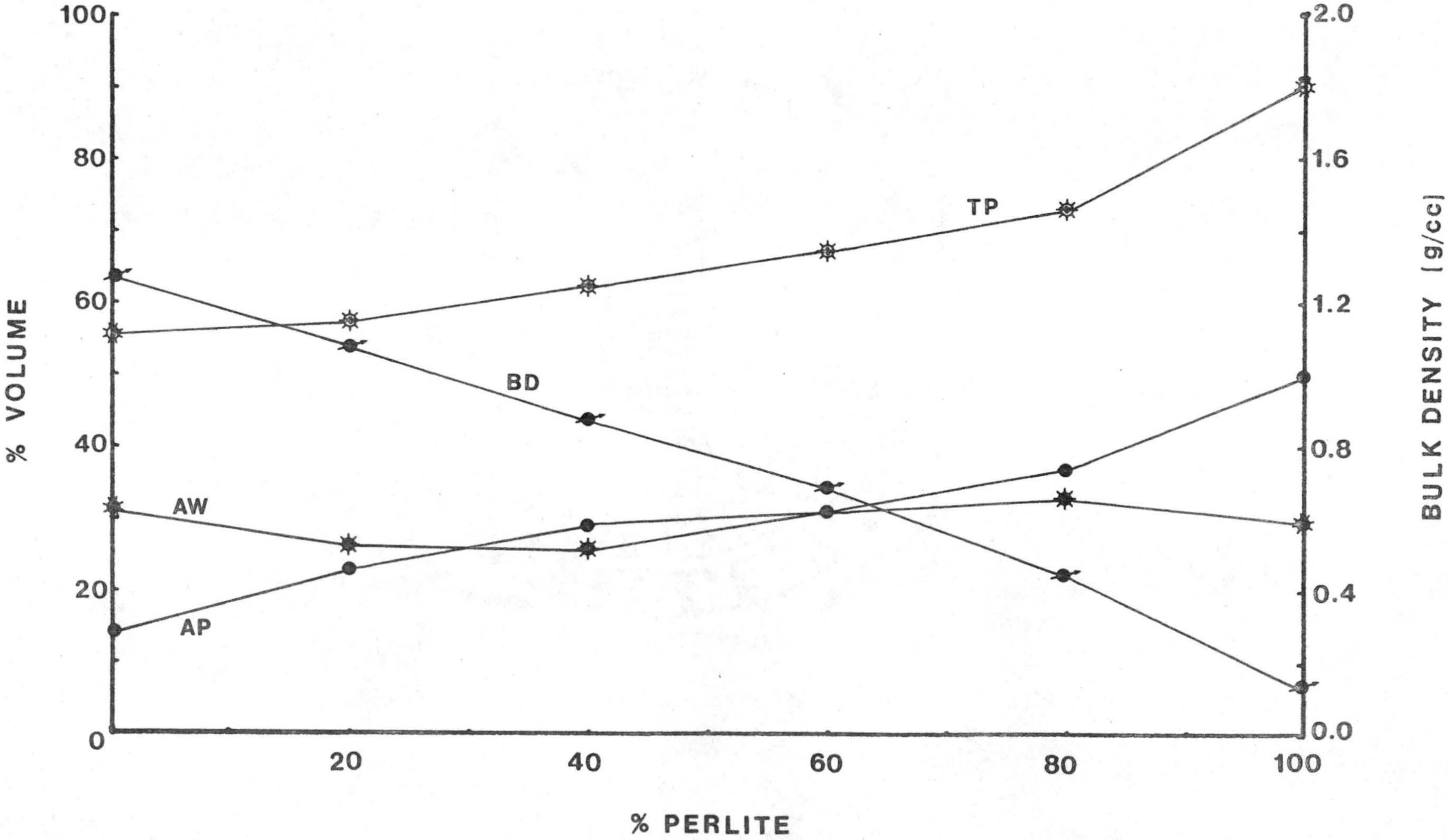


(g) PERLITE : CANADIAN PEAT



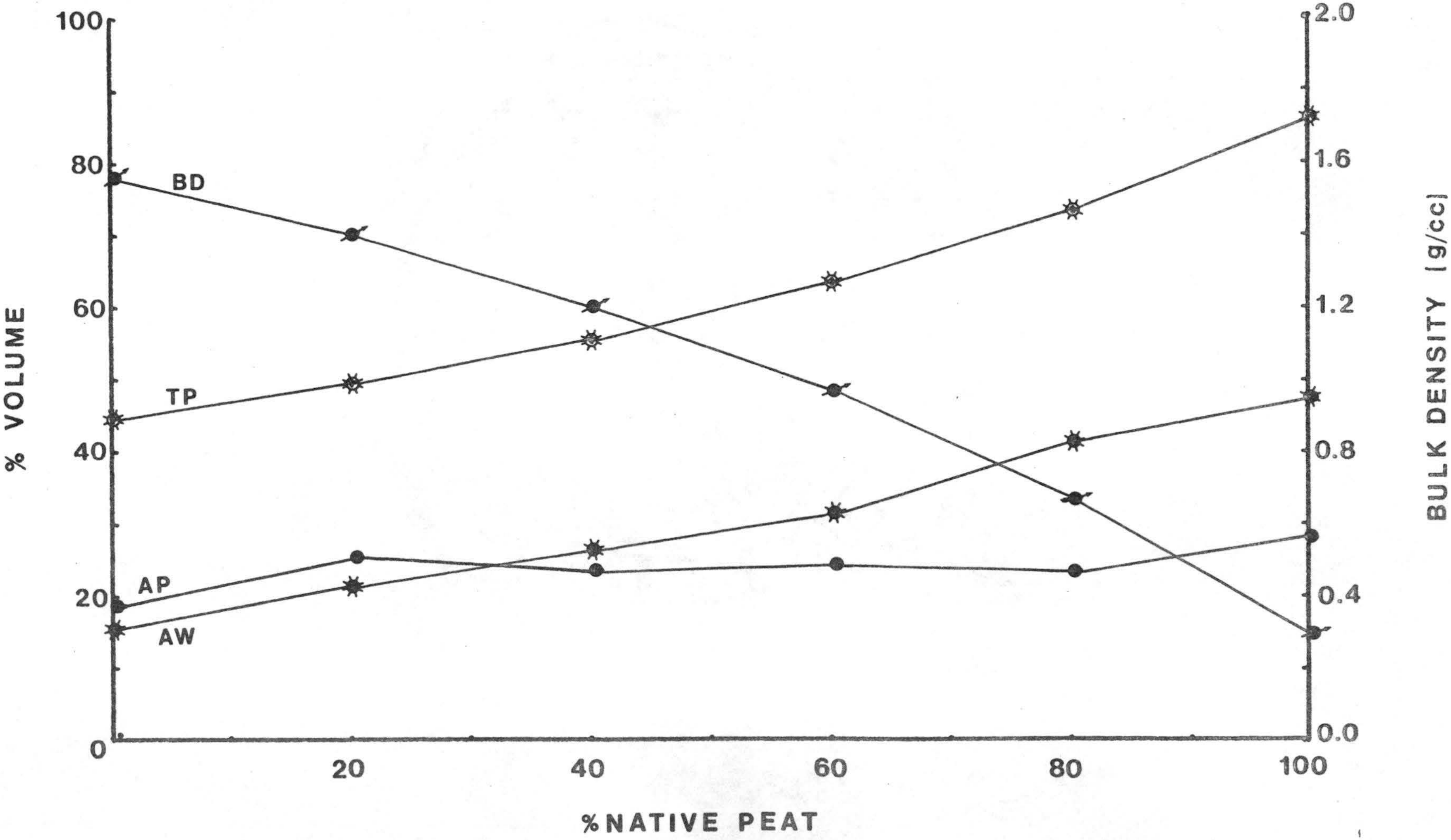
(h) VERMICULITE : SOIL



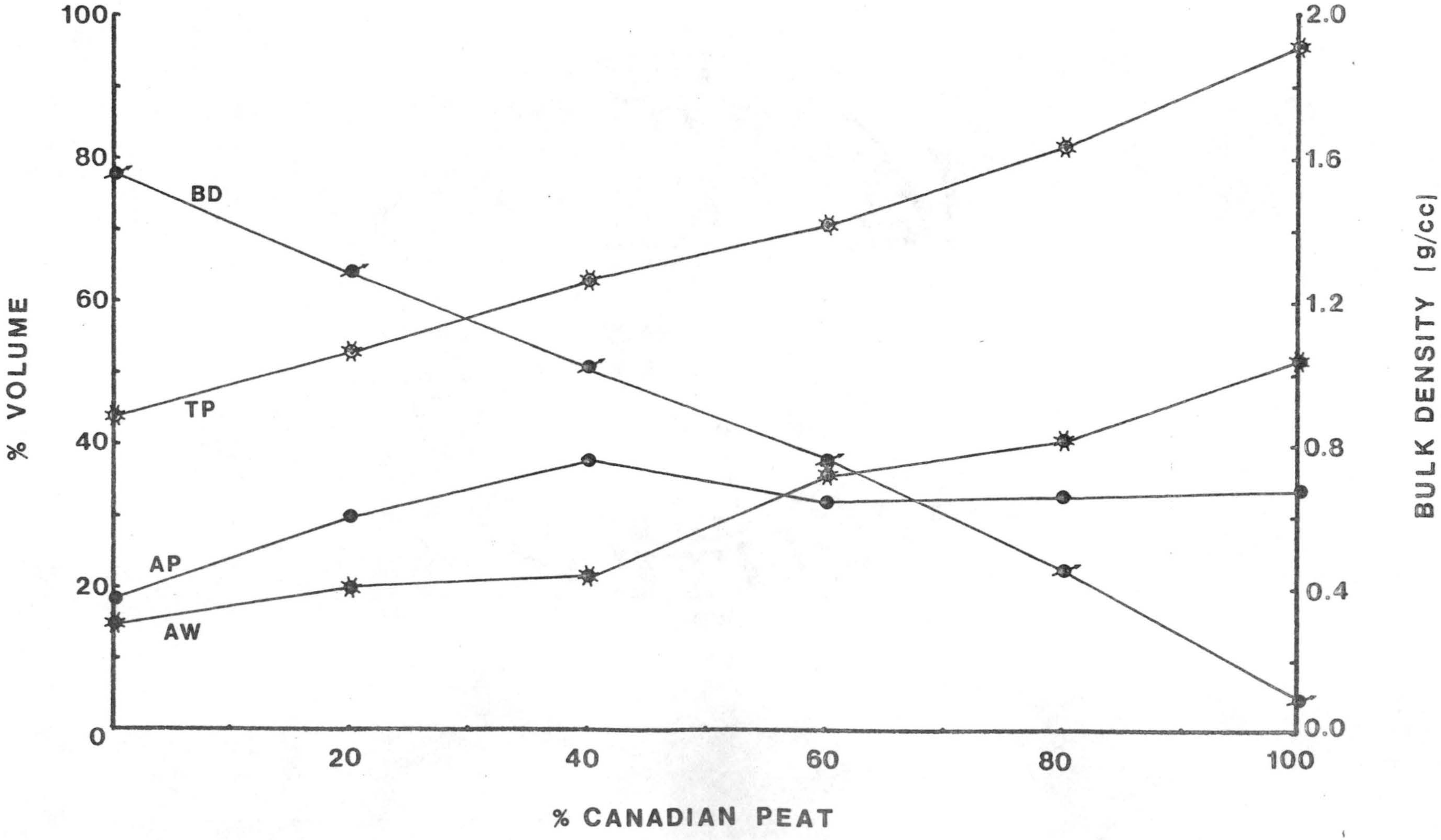


(i) PERLITE : SOIL

(j) NATIVE PEAT : SAND



(k) CANADIAN PEAT : SAND



was the other component. Media high in native peat generally ranged between 20-30%. Soil:sand and native peat:sand combinations resulted in the lowest percentages. The areation porosity of 100% soil was nearly equal that of 100% sand.

Total porosity ranged from 43-97%. All combinations of Canadian peat:vermiculite possessed the highest total porosities, followed by other soilless media. Media containing 20% or less soil or sand consistently had total porosities above 75%. Values were below 75% for media containing more than 20% soil or sand, while combinations of these produced the lowest total porosities.

Available water ranged from 16 to 57%. Media high in Canadian peat, native peat, or vermiculite held the greatest amount of available water, whereas those high in soil or sand held the least. Some soilless media held nearly three times as much water as soil:sand mixtures. One hundred percent soil and 100% perlite retain the same amount of available water, and sand retains almost as much.

Bulk densities ranged from 0.10 to 1.55 g/cc. Soilless media had the lowest densities and media high in soil and/or sand the highest. If densities less than 1.0 g/cc are desired, less than 80% soil or 60% sand should be used.

Infiltration rates ranged from three seconds to greater than 600. Soilless media had much higher rates than those containing large amounts of soil or native peat. Media high in soil or native peat usually had large deviations between replicates for a given medium. This could cause differences in the degree of wetting, rate of drainage, or leachability, which might result in ununiform growth for a given medium.

In general, soilless media possessed the most desirable physical properties, followed by media containing 20 to 40% soil or sand. Media containing only soil and/or sand consistently had the least desirable properties. While the aeration porosity of each medium was within the optimum range described by most investigators, this did not always apply to bulk density, available water holding capacity, or total porosity. Colorado native peat appears satisfactory as a substitute for Canadian peat, based on its physical porperties. Infiltration rates were low when native peat was mixed with soil or sand, but satisfactory when mixed with vermiculite or perlite. Native peat is comparable to Canadian peat for increasing the water holding capacity and decreasing bulk density. Native peat mixtures have satisfactory total and aeration porosities. However, when mixed with sand these two properties are lower than in most other media. In conclusion, native peat is most promising when mixed with perlite or vermiculite, rather than soil or sand, unless a large proportion of native peat is used.

Threshold Proportion

A threshold proportion for total porosity did not exist for most media. A very slight threshold occurred when perlite was added to native or Canadian peat, but it is of no significance since the total porosity was never below 80% for either mixture (Figure 4f,g). Addition of a lightweight amendment to soil or sand always caused a nearly linear increase in total porosity. Addition of vermiculite to Canadian peat or sand to soil affected total porosity very little. The threshold proportion reported by Spomer (116) for total porosity in soil:sand mixtures did not occur in this study.

Significant threshold proportions failed to occur for aeration porosity or available water holding capacity, except for available water in native peat:soil mixtures and aeration porosity in Canadian peat:soil mixtures. Additions of lightweight amendments to soil or sand generally increased or did not affect the aeration porosity or available water. Additions of lightweight amendments to soil or sand linearly decreased the bulk density but additions of sand to soil had little effect on it. Addition of more than 20% sand to soil had little effect on any of the physical properties.

It appears that the threshold proportion concept does not apply to any of the physical properties for most of the media tested in this study. Additions of lightweight amendments might generally be made without concern about the amount added. Since some amendments improve the physical properties and some have no effect, the amount needed will depend mostly on the type of amendment used, its cost, and the degree of improvement desired.

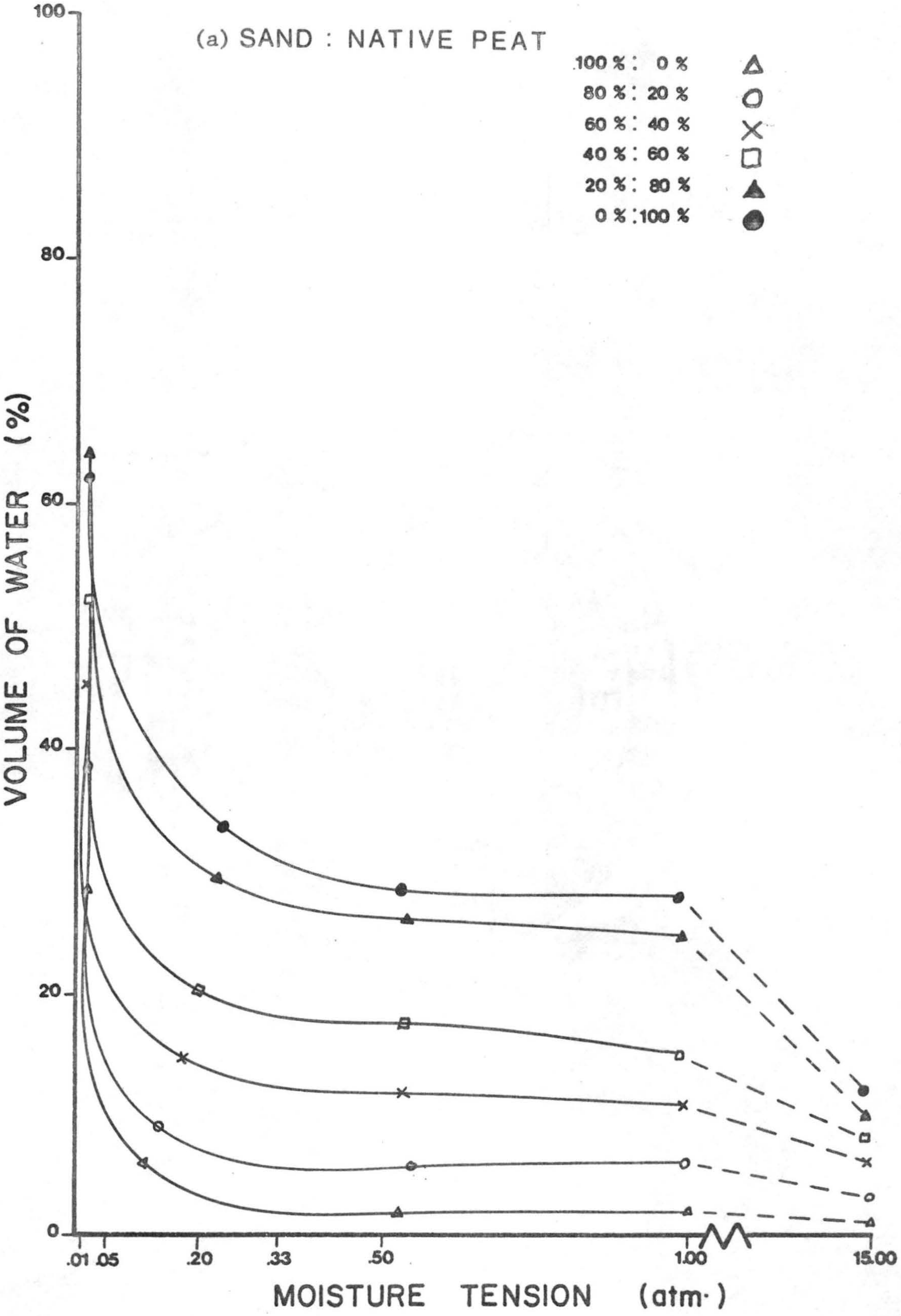
Moisture Tension Relationships

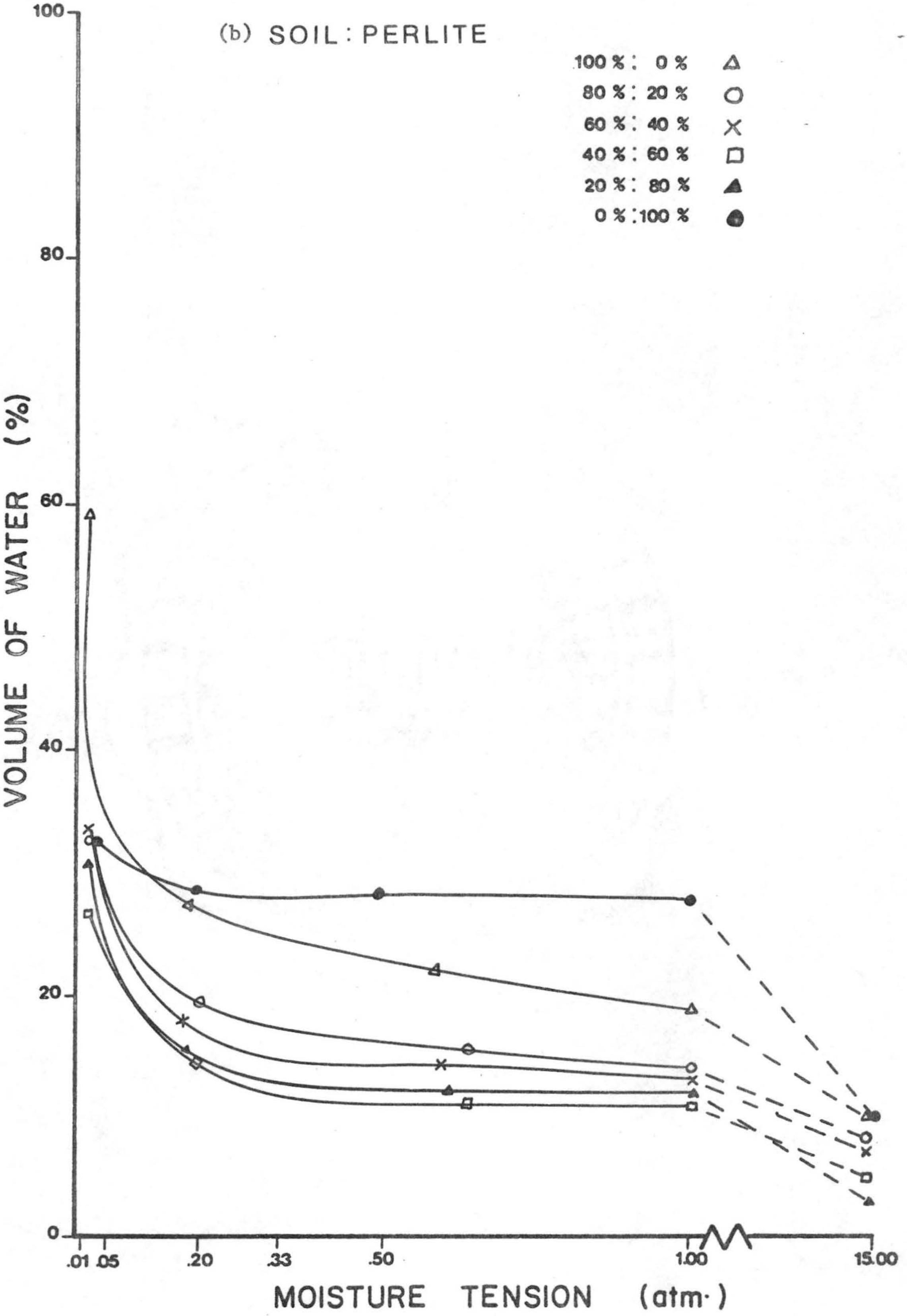
Desorption curves for all media are presented in Figure 5 in which the volume of water in the sample is plotted against its tension. The wilting point percentages determined with the tomato plants were inserted at the 15 atm tension to show the maximum removal of water by plants. It is recognized that the wilting percentage does not necessarily correspond to the 15 atm percentage, but the values were included there as a matter of convenience and information.

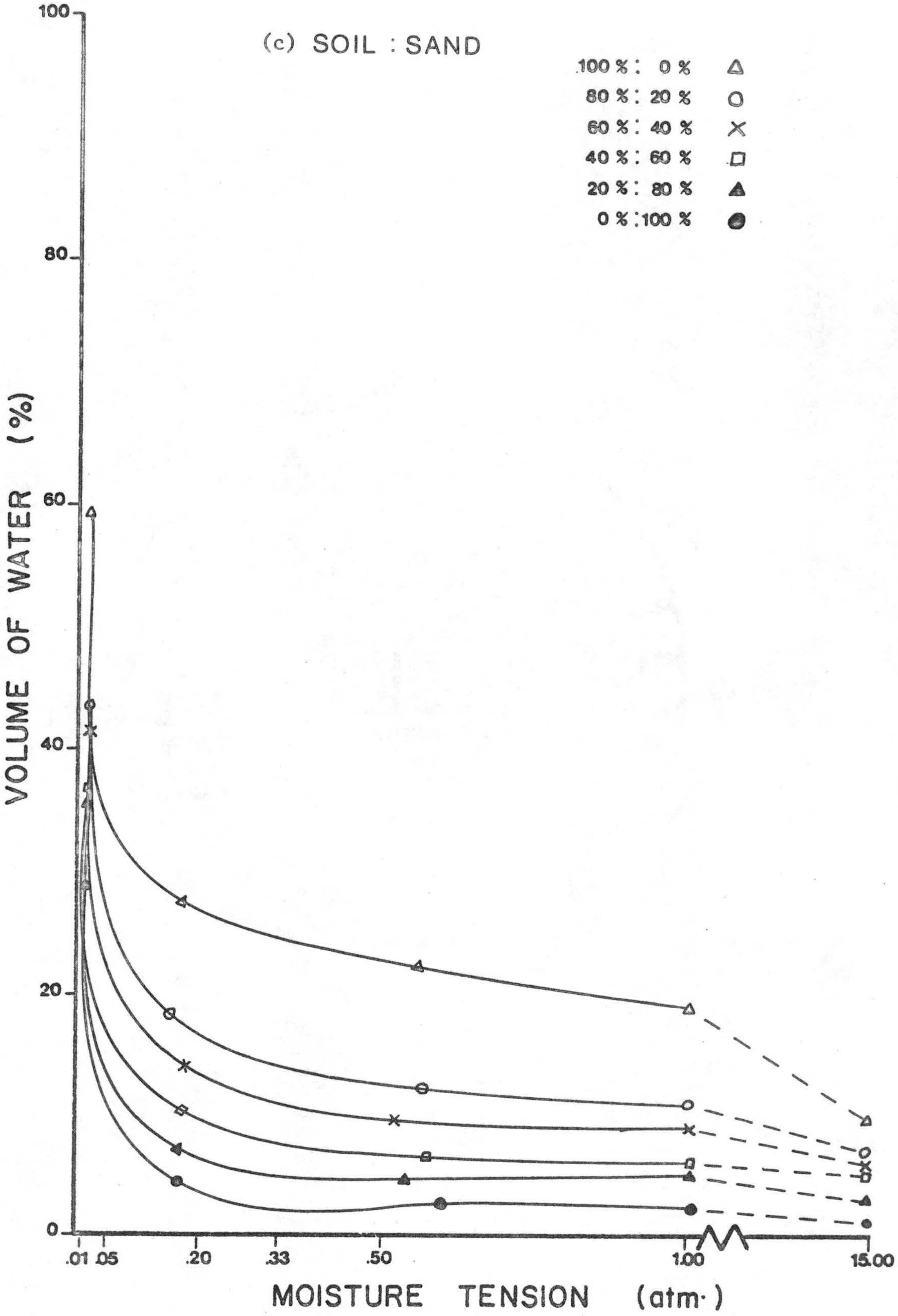
The moisture tension corresponding to container capacity (Table 5) was determined for each medium using the graphs in Figure 5. Values

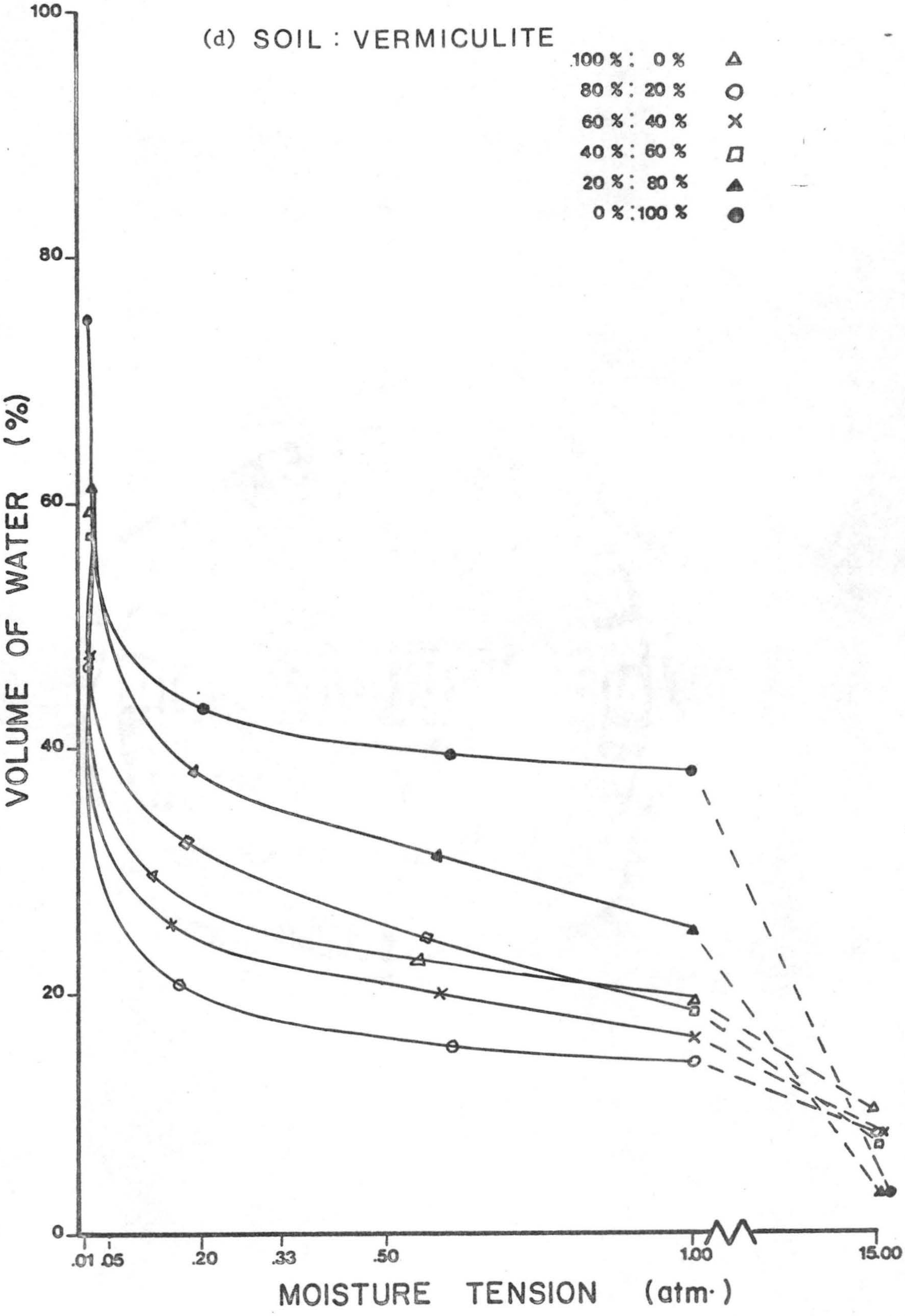
Figure 5. Desorption curves for greenhouse container media, expressed as the percent volume of water retained at pressure plate tensions of 0.01, 0.05, 0.20, 0.33, 0.50 and 1.00 atm. The 15.0 atm values are wilting point percentages determined with tomato plants. Symbols represent media types only, not the actual plotted points.

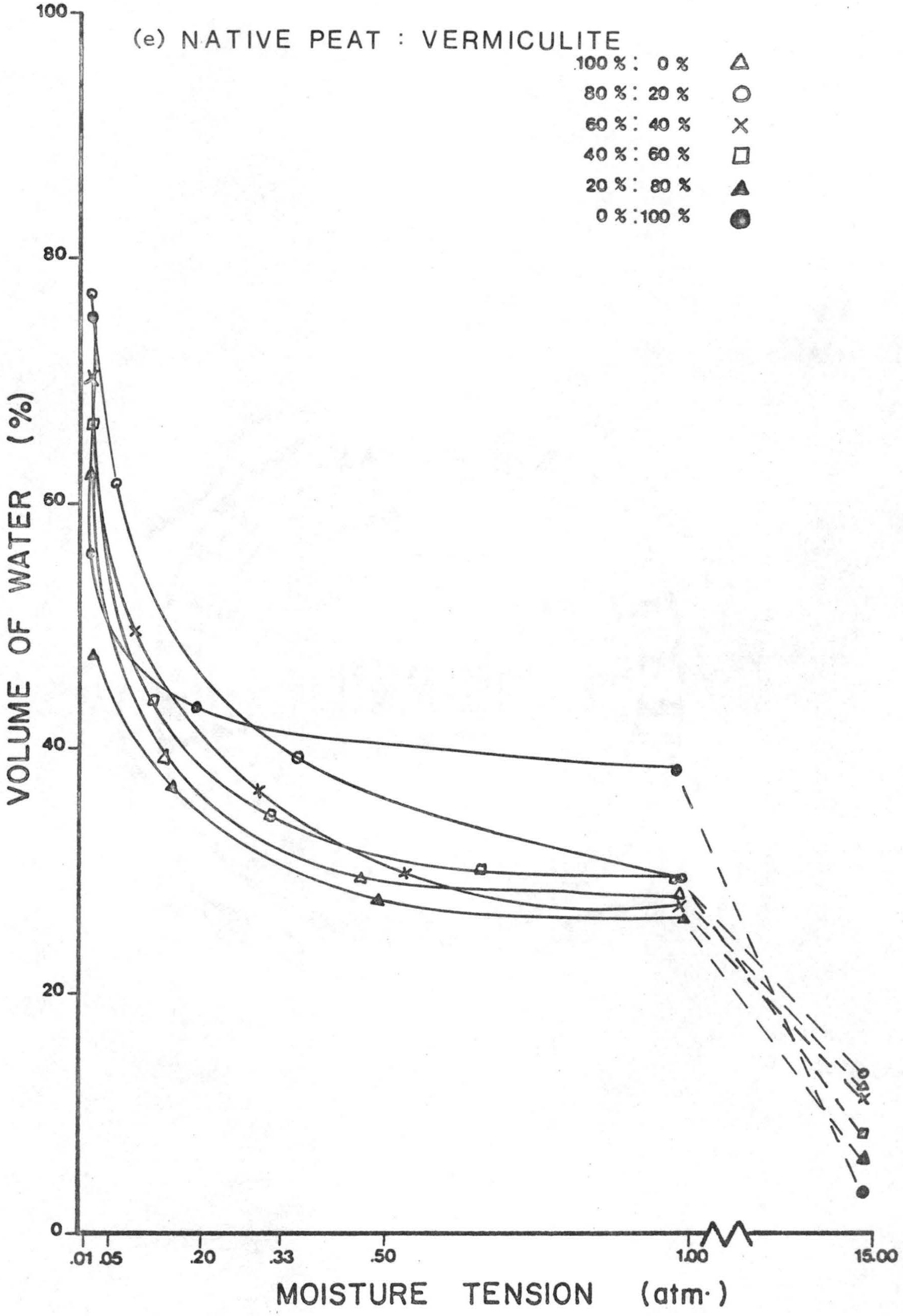
(a) Sand:Native Peat
(b) Soil:Perlite
(c) Soil:Sand
(d) Soil:Vermiculite
(e) Native Peat:Vermiculite
(f) Canadian Peat:Vermiculite
(g) Soil:Native Peat
(h) Soil:Canadian Peat
(i) Sand:Canadian Peat
(j) Canadian Peat:Perlite
(k) Native Peat:Perlite

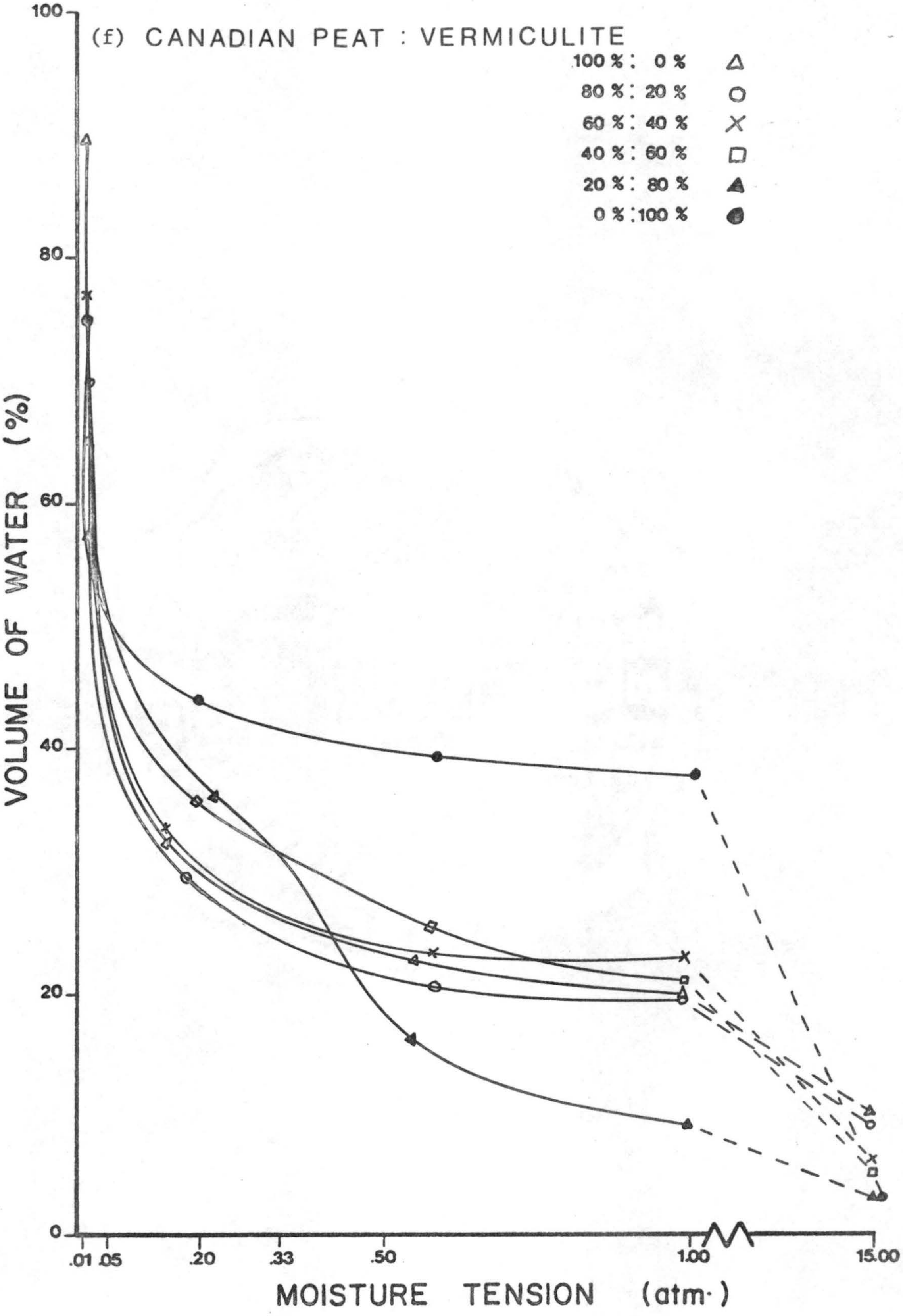

(a) SAND : NATIVE PEAT
100 % : 0 % △
80 % : 20 % ○
60 % : 40 % ×
40 % : 60 % □
20 % : 80 % ▲
0 % : 100 % ●
VOLUME OF WATER (%)
100
80
60
40
20
0
.01
.05
.20
.33
.50
1.00
15.00
MOISTURE TENSION (atm.)

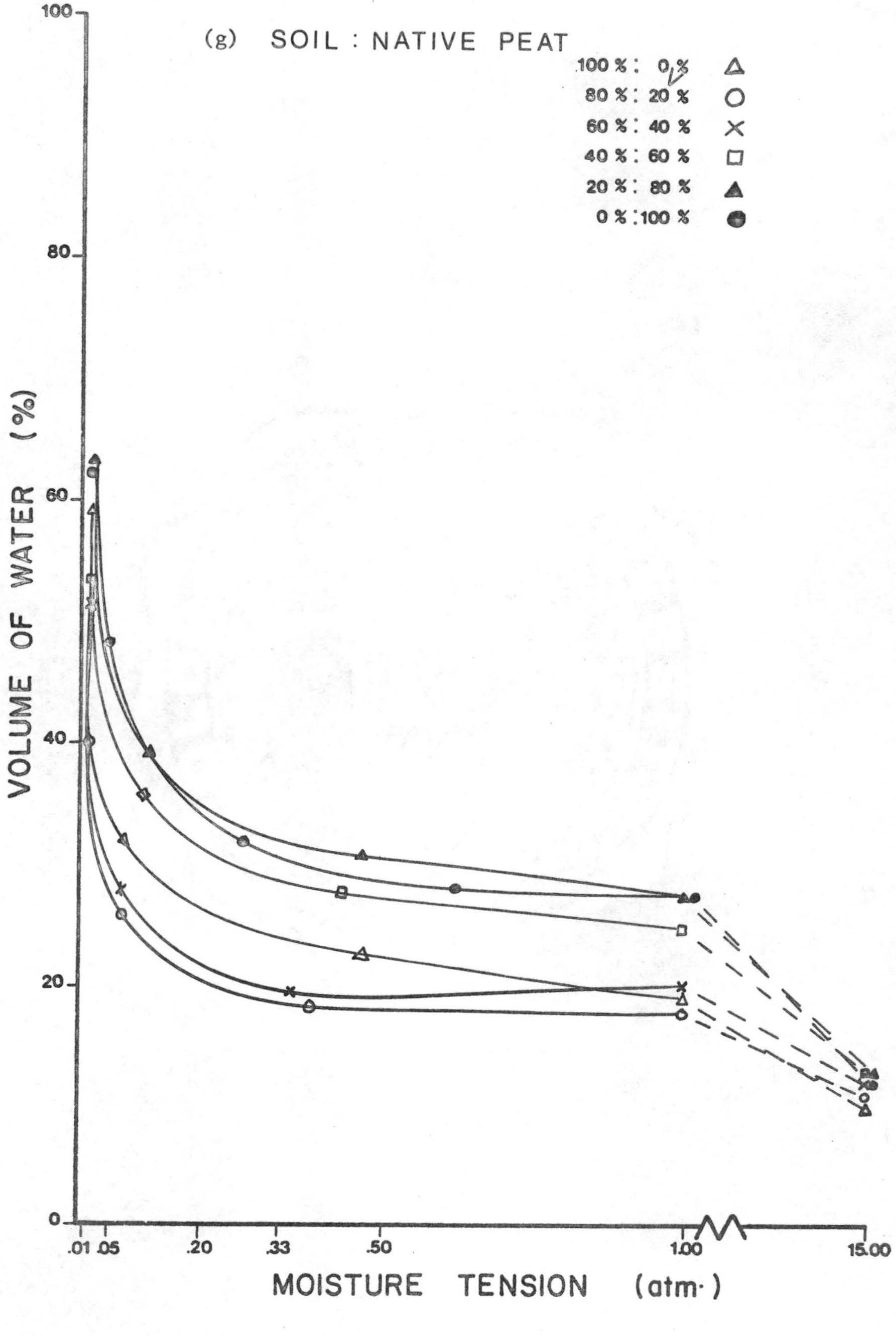

(b) SOIL : PERLITE
100 % : 0 % △
80 % : 20 % ○
60 % : 40 % ×
40 % : 60 % □
20 % : 80 % ▲
0 % : 100 % ●
VOLUME OF WATER (%)
100
80
60
40
20
0
.01
.05
.20
.33
.50
1.00
15.00
MOISTURE TENSION (atm·)

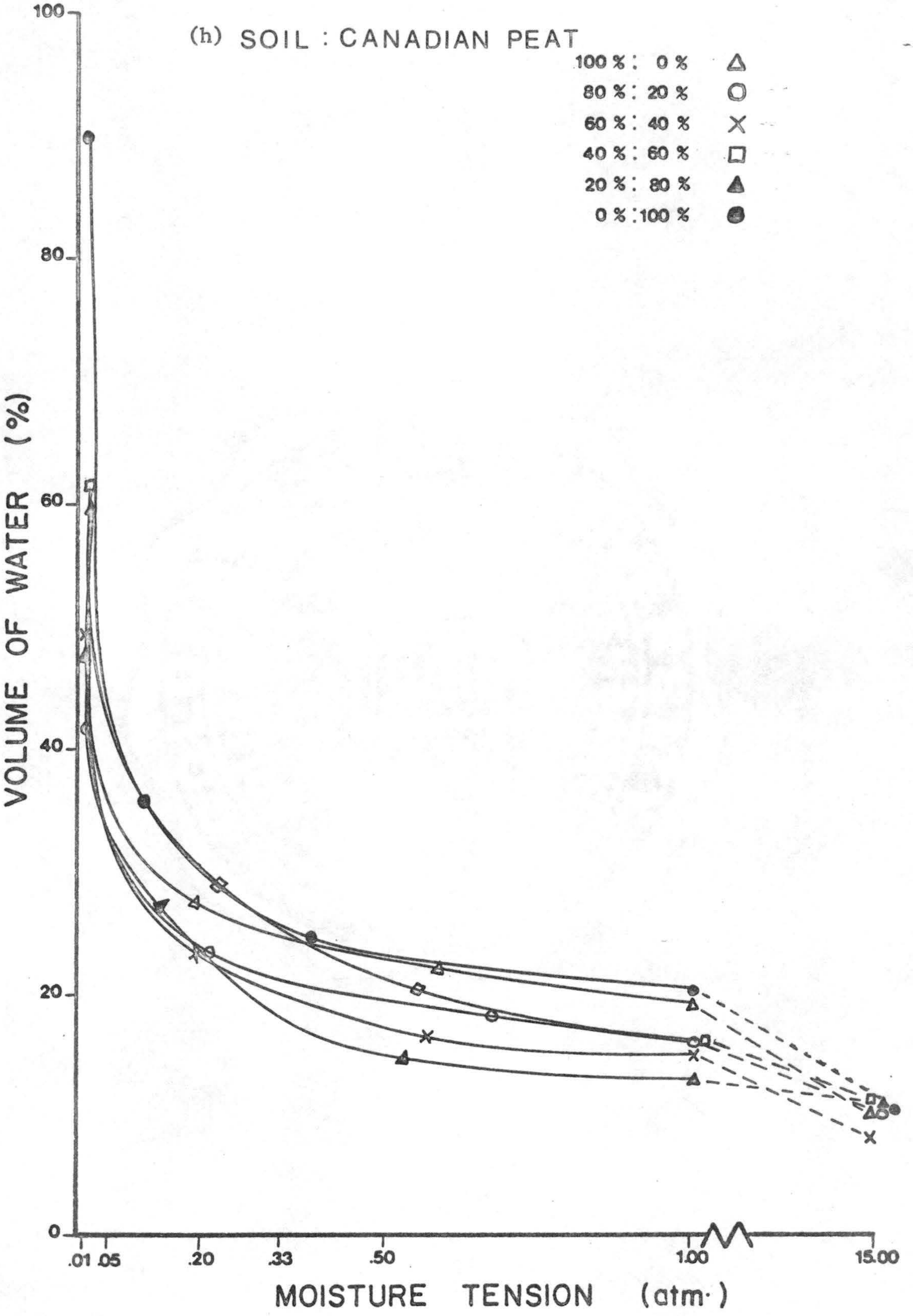

(c) SOIL : SAND
100 % : 0 % △
80 % : 20 % ○
60 % : 40 % ×
40 % : 60 % □
20 % : 80 % ▲
0 % : 100 % ●
VOLUME OF WATER (%)
100
80
60
40
20
0
.01
.05
.20
.33
.50
1.00
15.00
MOISTURE TENSION (atm.)

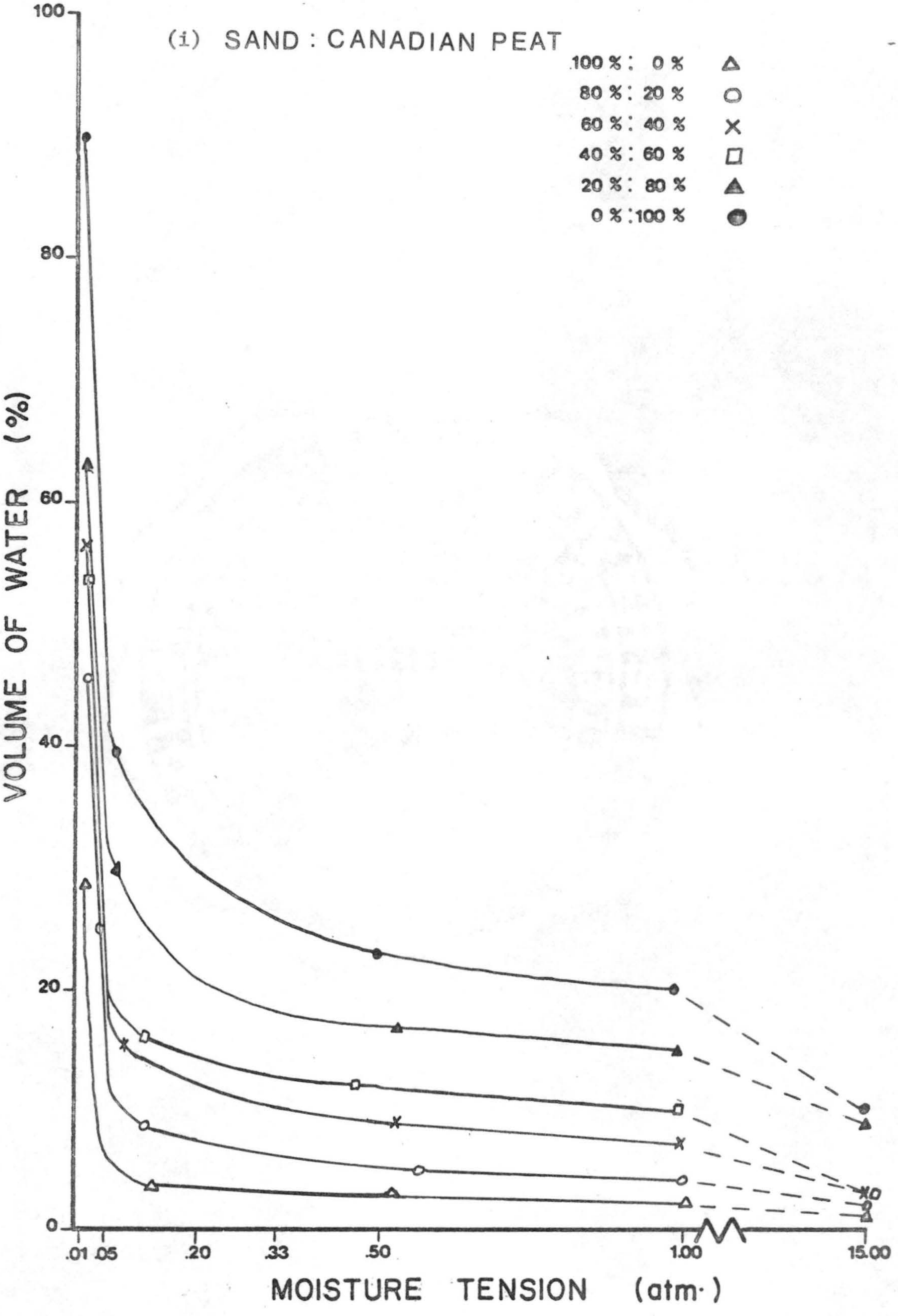

(d) SOIL : VERMICULITE
100 % : 0 % △
80 % : 20 % ○
60 % : 40 % ×
40 % : 60 % □
20 % : 80 % ▲
0 % : 100 % ●
VOLUME OF WATER (%)
100
80
60
40
20
0
.01
.05
.20
.33
.50
1.00
15.00
MOISTURE TENSION (atm.)

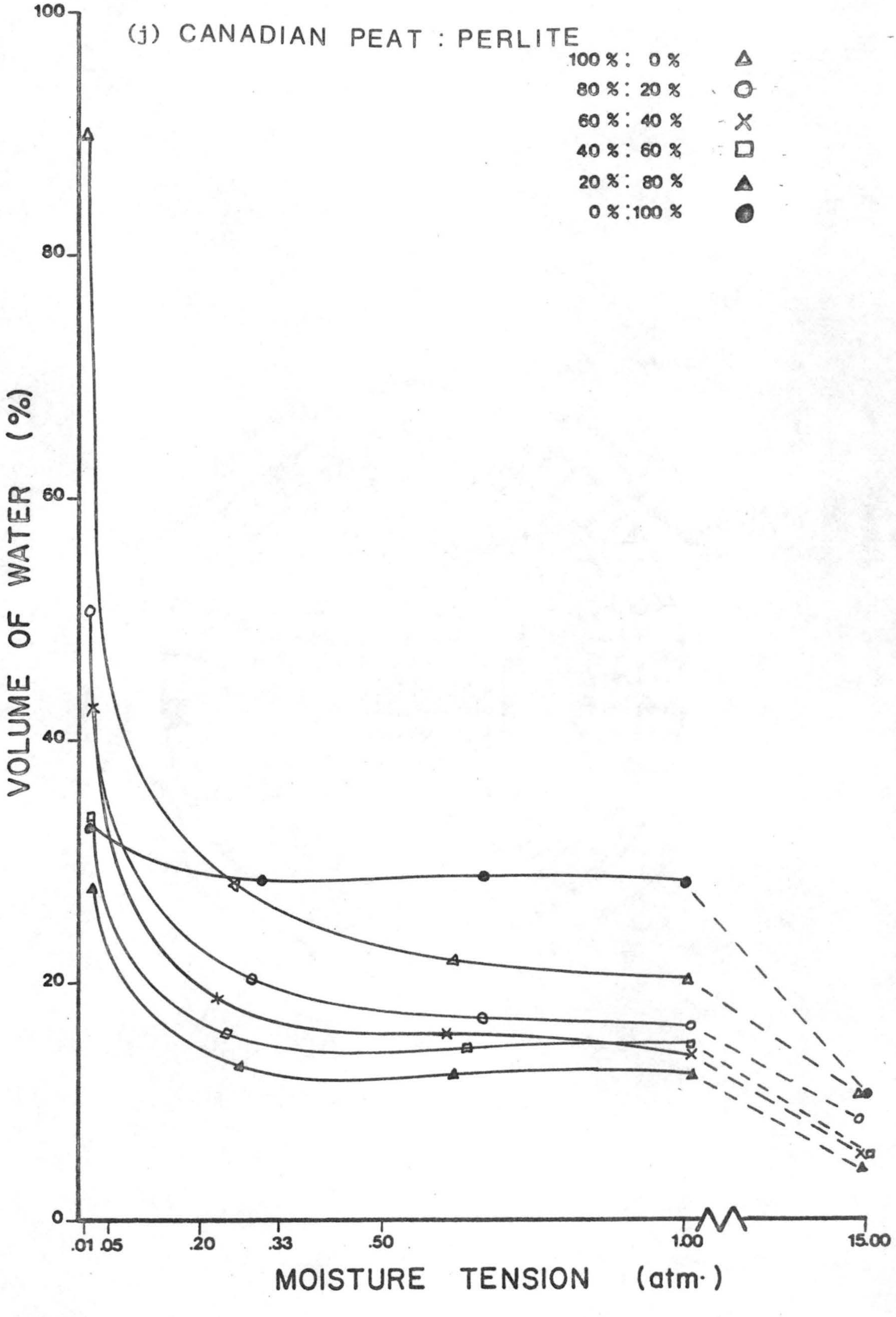

(e) NATIVE PEAT : VERMICULITE
100 % : 0 % △
80 % : 20 % ○
60 % : 40 % ×
40 % : 60 % □
20 % : 80 % ▲
0 % : 100 % ●
VOLUME OF WATER (%)
100
80
60
40
20
0
.01
.05
.20
.33
.50
1.00
15.00
MOISTURE TENSION (atm·)

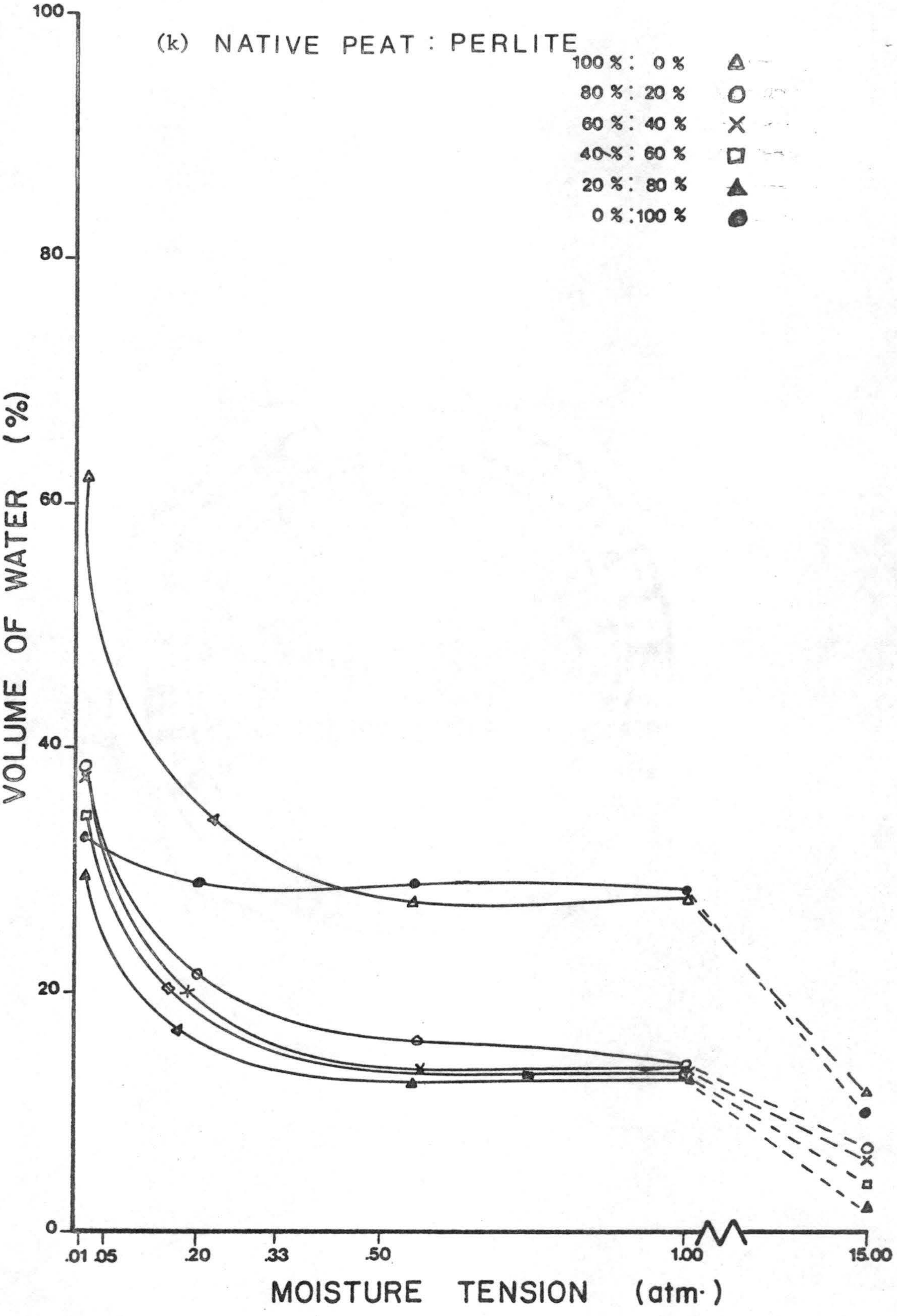

(f) CANADIAN PEAT : VERMICULITE
100 % : 0 % △
80 % : 20 % ○
60 % : 40 % ✕
40 % : 60 % □
20 % : 80 % ▲
0 % : 100 % ●
VOLUME OF WATER (%)
100
80
60
40
20
0
.01
.05
.20
.33
.50
1.00
15.00
MOISTURE TENSION (atm·)


(g) SOIL : NATIVE PEAT
100 % : 0 % △
80 % : 20 % ○
60 % : 40 % ×
40 % : 60 % □
20 % : 80 % ▲
0 % : 100 % ●
VOLUME OF WATER (%)
100
80
60
40
20
0
.01
.05
.20
.33
.50
1.00
15.00
MOISTURE TENSION (atm·)


(h) SOIL : CANADIAN PEAT
100 % : 0 % △
80 % : 20 % ○
60 % : 40 % ×
40 % : 60 % □
20 % : 80 % ▲
0 % : 100 % ●
100
80
60
40
20
0
VOLUME OF WATER (%)
.01
.05
.20
.33
.50
1.00
15.00
MOISTURE TENSION (atm.)


(i) SAND : CANADIAN PEAT
100 % : 0 % △
80 % : 20 % ○
60 % : 40 % ×
40 % : 60 % □
20 % : 80 % ▲
0 % : 100 % ●
VOLUME OF WATER (%)
100
80
60
40
20
0
.01
.05
.20
.33
.50
1.00
15.00
MOISTURE TENSION (atm·)


(j) CANADIAN PEAT : PERLITE
100 % : 0 % △
80 % : 20 % ○
60 % : 40 % ✕
40 % : 60 % □
20 % : 80 % ▲
0 % : 100 % ●
VOLUME OF WATER (%)
100
80
60
40
20
0
.01
.05
.20
.33
.50
1.00
15.00
MOISTURE TENSION (atm·)


(k) NATIVE PEAT : PERLITE
100 % : 0 % △
80 % : 20 % ○
60 % : 40 % ×
40 % : 60 % □
20 % : 80 % ▲
0 % : 100 % ●
VOLUME OF WATER (%)
100
80
60
40
20
0
.01
.05
.20
.33
.50
1.00
15.00
MOISTURE TENSION (atm·)

ranged from less than 0.01 to 0.07 atm, with the majority lying between 0.01 and 0.05 atm. White (132) tested various combinations of Canadian peat, soil and perlite and found container capacity tensions ranging from 0.007 to 0.03 atm, with a mean of 0.013. His conclusion that "the one-third atmosphere value cannot be used to express the upper limit of soil moisture in a container" is substantiated by our findings. It appears, as White concluded, that container capacity is represented by a narrow range of moisture tension values for a wide range of media. The tension at container capacity for perlite and perlite mixed with Canadian or native peat was always below 0.01 atm, regardless of the ratio. White (132) found that media containing 50% or more perlite held more water at 1 atm than at 0.33 atm. This did not occur in this study.

Most media contained less than 10% available water at tensions above 1 atm. However, 100% vermiculite, 100% native peat, 100% perlite and mixtures high in vermiculite and native peat held large amounts of water above 1 atm tension. Perlite contained 27% available water, 4% below 0.01 atm and 23% above 1 atm. This indicates that the water is held at two different tensions, perhaps due to adsorption on the outer surfaces and absorption within the particles. The same relationship exists with native peat and with vermiculite.

The flex points for almost all media occurred at approximately 0.20 to 0.33 atm. Media high in Canadian or native peat, vermiculite, or soil generally released water uniformly over a wide range of tensions. Media high in sand held almost all their available water at tensions below 0.2 atm. Increasing additions of Canadian peat, native peat, or vermiculite to perlite or sand, and additions of soil to sand resulted in higher water retentions at each tension between 0.01 and 1.0 atm. Each addition also resulted in increased water availability, except additions of soil to sand. Additions of vermiculite, native or Canadian peat to each other had little effect on available water holding capacity. A threshold proportion existed for available water when Canadian or native peat was added to soil. Addition of less than 40% peat decreased available water, whereas additions above 60% increased it. Addition of vermiculite to soil increased available water, whereas perlite had no effect. The percentages of unavailable water ranged from 1% to 13%, with a mean of 7.1%. Percentages of unavailable water and container capacity are presented in Table 5.

Correlation of Plant Growth With Media Physical Properties

The physical properties of ten media and the resulting chrysanthemum growth in these media are presented in Table 2. The appearance of all plants within a variety was similar, except for stem thickness and strength. These differences are reflected in the fresh and dry weights. Canadian peat:vermiculite, native peat:vermiculite, soil:perlite:Canadian peat, and soil:sand:Canadian peat resulted in highest fresh and dry weights for both varieties. Pine bark:Canadian peat, native peat:perlite, soil:sand:native peat, and soil:sand resulted in the lowest fresh and dry weights for both varieties. Plants in pine bark:Canadian peat exhibited signs of nutritional hunger, which probably accounted for their low fresh and dry weights. Ground Lodgepole Pine bark was used, which does not have the desirable fibrous texture that some other pine barks possess.

Table 2. Physical properties of ten widely differing media and the fresh and dry weight of two chrysanthemum cultivars grown in each medium.

Medium	Bulk Density (g/cc)	% Aeration Porosity	% Container Capacity	% Total Porosity	Infiltration[a] Rate (sec)	Fresh Wt. (g)		Dry Wt. (g)	
						Paragon	Dramatic	Paragon	Dramatic
60% Can. Peat 40% Verm.	0.12	33	63	95	27	659	685	90	79
50% Pine Bark 50% Can. Peat	0.22	28	55	83	26	448	448	68	67
60% Native Peat 40% Perlite	0.22	31	50	81	15	487	503	65	65
60% Native Peat 40% Verm.	0.30	23	63	86	57	570	664	81	87
33% Soil 33% Perlite 33% Can. Peat	0.47	32	43	75	61	593	655	80	84
60% Sand 40% Can. Peat	1.04	29	32	61	77	577	625	77	82
80% Soil 20% Verm.	1.09	24	36	59	1500	504	513	81	81
50% Soil 25% Sand 25% Can. Peat	1.19	8	45	53	504	571	634	95	88
33% Soil 33% Sand 33% Native Peat	1.22	19	33	52	271	430	467	63	64
60% Soil 40% Sand	1.41	26	22	48	1260	405	456	61	54

[a] Time, in seconds, required for a 1/2-inch falling head to infiltrate a 5 1/2-inch deep saturated column. Infiltration rate values are means of 10 replicates, all other values are means of 5 replicates.

Correlations between plant growth parameters and media physical properties are presented in Table 3. Only two correlations existed: the fresh and dry weight of the cultivar 'Paragon' were positively correlated with percent aeration porosity. It appears that high quality chrysanthemums can be grown in a wide variety of media in six-inch pots. This study was carried out under high light, high transpiration conditions which allowed the media to dry rapidly. Poor aeration conditions probably did not exist very long after an irrigation. Low light conditions or shallower media would probably have produced more differences, due to longer periods of low aeration porosity.

Several relationships between media physical properties were evident. A very strong negative correlation existed between bulk density and total porosity over a wide range of values for these two properties. Bulk density was also negatively correlated with container capacity and infiltration rate. Total porosity generally increased with increasing aeration porosity, container capacity, or infiltration rate. It appears that the total porosity might be useful in predicting media acceptability, since it is correlated with all the important physical properties.

Correlations Between Physical Properties

Values for aeration porosity, available water, bulk density, and total porosity were compared with each other to determine if correlations exist between them. The results are given in Table 4, which gives the correlation coefficients and linear equations for the relationships.

Table 3. Coefficients of correlations among physical properties, and between chrysanthemum weight measurements and physical properties.[a]

Bulk Density (g/cc)	% Aeration Porosity	% Container Capacity	% Total Porosity	Infiltration Rate (sec)	Fresh Wt. (g)		Dry Wt. (g)	
					Paragon	Dramatic	Paragon	Dramatic
Bulk Density:								
--	0.5828	0.8788 (-) (c)	0.9864 (-) (d)	0.8884 (-) (d)	0.5456	0.5222	0.3486	0.5916
Aeration Porosity:								
0.5828	--	0.3560	0.6467 (+) (c)	0.4585	0.6456 (+) (c)	0.5589	0.6627 (+) (c)	0.4238
Container Capacity:								
0.8788 (-) (c)	0.3560	--	0.9033 (+) (d)	0.7099 (+) (d)	0.5525	0.5419	0.4868	0.3169
Total Porosity:								
0.9864 (-) (d)	0.6467 (+) (c)	0.9033 (+) (c)	--	0.8456 (+) (d)	0.5144	0.4701	0.2471	0.2548
Infiltration Rate:								
0.8884 (-) (d)	0.4585	0.7099 (+) (d)	0.8456 (+) (d)	--	0.4756	0.4551	0.1394	0.1902

[a] The r values must be greater than 0.6139 to be significant at the 5% level.

[b] Linear correlation.

[c] Parabolic correlation.

[d] Exponential correlation.

[+] Significant positive correlation.

[-] Significant negative correlation.

Table 4. r Values for correlations between media physical properties at the 95% probability level.

	% Aeration Porosity	% Available Water	Bulk Density (g/cc)	% Total Porosity
% Aeration Porosity	---	0.1154	-0.6749[a]	0.6485[b]
% Available Water	0.1154	---	-0.7620[c]	0.8076[d]
Bulk Density (g/cc)	-0.6749	-0.7620	---	0.9764[e]
% Total Porosity	0.6485	0.8076	-0.9764	---

[a] $Y = 39.06970 - 14.28469\ X$; Y = % aeration porosity.

[b] $Y = 1.07642 + 0.39121\ X$; Y = % aeration porosity.

[c] $Y = 48.87585 - 19.83691\ X$; Y = % available water.

[d] $Y = -8.05211 + 0.59929\ X$; Y = % available water.

[e] $Y = 2.69267 - 0.02783\ X$; Y = bulk density (g/cc).

The results for all 50 media were very similar to the results from the 10 media used in the chrysanthemum experiment (see Tables 2 and 3). Total porosity was strongly correlated with available water and bulk density, and less strongly correlated with aeration porosity. Available water and aeration porosity were negatively correlated with bulk density. No correlation existed between aeration porosity and available water. It appears that bulk density values may be useful in predicting the total porosity of media and vice versa. Total porosity values might be used to approximate available water retention and give a general idea of the aeration porosity.

SUMMARY AND CONCLUSIONS

Media physical properties were very stable over a three month period, with bulk density and total porosity being more stable than available water holding capacity or aeration porosity. When media containing soil were wetted during mixing, the resulting aggregates were very stable and provided excellent physical properties.

The threshold proportion concept was the exception rather than the rule. Additions of perlite, vermiculite, or Canadian peat to soil or sand usually resulted in improved physical properties. Native peat resulted in less optimum, but satisfactory improvements. Native peat may be used as a substitute for Canadian peat for amending soil or sand based on physical properties, but it is best used with perlite or vermiculite. Media containing no soil or sand consistently possessed the most desirable properties. Adding sand to soil produced few, if any, improvements. All media possessed adequate aeration porosities, according to levels set by most researchers. But, for several media the available water holding capacity or infiltration rate was too low, or bulk density too high. If a bulk density less than 1.0 g/cc is desired, less than 80% soil or 60% sand should be used. Soilless media had much higher infiltration rates than those containing large amounts of soil or native peat. With the use of Figure 4, one could prepare a medium which would meet certain physical property requirements.

The moisture tension at container capacity was usually between 0.01 and 0.05 atm. At 0.2 to 0.3 atm most media had released much of their available water. Increasing additions of Canadian peat, native peat, or vermiculite to soil, sand or perlite generally resulted in increased available water.

Media physical properties had little effect on chrysanthemum growth under conditions of high evapotranspiration. It appears that almost any medium will provide satisfactory physical characteristics under these conditions, if it is at least six inches deep.

Total porosity was strongly correlated with available water and bulk density, and less strongly correlated with aeration porosity. Equations are provided which give estimates of available water or bulk density if total porosity is known, or total porosity if bulk density is known.

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APPENDIX

Table 5. Physical properties of container media.[a]

Media Volume Ratios	Infiltration Rate (sec)	Container Capacity (% vol.)	Unavailable Water (% vol.)	Available Water (% vol.)	Moisture[b] Tension (atm)	Aeration Porosity (% vol.)	Total Porosity (% vol.)	Bulk Density (g/cc)
Soil:Perlite								
5:0	600[h]	37	10	27	0.05	19	56	1.18
4:1	600[h]	34	8	26	0.07	24	57	1.06
3:2	117	32	7	25	0.04	29	61	0.87
2:3	68	34	5	29	<0.01	34	68	0.64
1:4	3	35	3	32	<0.01	40	75	0.39
0:5	3	37	10	27	<0.01	54	91	0.12
LSD[c]				4.0		5.9	3.4	0.094
Soil:Sand								
5:0	600[h]	37	10	27	0.05	19	56	1.18
4:1	600[h]	27	7	20	0.06	23	50	1.36
3:2	600[h]	22	6	16	0.06	26	48	1.41
2:3	501[e]	25	5	20	0.01	19	44	1.50
1:4	272	24	3	21	0.01	19	43	1.55
0:5	115	24	1	23	0.01	20	44	1.52
LSD[c]				4.6		6.4	3.1	0.071
Soil:Native Peat								
5:0	600[h]	37	10	27	0.04	19	56	1.18
4:1	600[h]	31	11	20	0.03	28	59	1.07
3:2	559[g]	35	12	23	0.01	27	63	0.95
2:3	546[f]	43	13	30	0.04	26	69	0.76
1:4	561[g]	49	13	36	0.05	27	77	0.54
0:5	447[d]	56	12	44	0.02	30	87	0.27
LSD[c]				4.6		7.5	3.6	0.069

Table 5. Continued.[a]

Media Volume Ratios	Infiltration Rate (sec)	Container Capacity (% vol.)	Unavailable Water (% vol.)	Available Water (% vol.)	Moisture[b] Tension (atm)	Aeration Porosity (% vol.)	Total Porosity (% vol.)	Bulk Density (g/cc)
Soil:Vermiculite								
5:0	600[h]	37	10	27	0.05	19	56	1.18
4:1	600[h]	36	8	28	0.02	24	59	1.09
3:2	600[h]	41	8	33	0.01	27	67	0.88
2:3	600[h]	49	7	42	0.01	26	75	0.69
1:4	198	56	3	53	0.01	28	85	0.42
0:5	6	55	3	52	0.01	42	97	0.12
LSD[c]				4.5		5.6	2.8	0.056
Soil:Canadian Peat								
5:0	600[h]	37	10	27	0.05	19	56	1.18
4:1	600[h]	34	10	24	0.05	26	60	1.06
3:2	306[d]	39	8	31	0.01	30	68	0.86
2:3	565[b]	53	11	42	0.01	21	74	0.70
1:4	77	57	11	46	0.01	23	85	0.40
0:5	25	62	10	52	0.01	34	96	0.10
LSD[c]				5.7		7.7	2.6	0.063
Native Peat:Perlite								
5:0	447[d]	56	12	44	0.01	30	87	0.27
4:1	259	57	7	50	<0.01	27	84	0.23
3:2	48	50	6	44	<0.01	31	81	0.22
2:3	16	43	4	39	<0.01	38	81	0.19
1:4	5	35	2	33	<0.01	45	79	0.17
0:5	3	37	10	27	<0.01	54	91	0.12
LSD[c]				3.9		4.1	2.0	0.028

Table 5. Continued.[a]

Media Volume Ratios	Infiltration Rate (sec)	Container Capacity (% vol.)	Unavailable Water (% vol.)	Available Water (% vol.)	Moisture[b] Tension (atm)	Aeration Porosity (% vol.)	Total Porosity (% vol.)	Bulk Density (g/cc)
Sand:Canadian Peat								
5:0	115	24	1	23	0.01	20	44	1.52
4:1	230	26	2	24	0.04	25	51	1.30
3:2	134	32	3	29	0.04	29	61	1.04
2:3	96	42	3	39	0.04	30	72	0.74
1:4	84	42	9	40	0.04	33	82	0.46
0:5	25	62	10	52	0.04	34	96	0.10
LSD[c]				5.7		7.3	2.9	0.049
Canadian Peat:Vermiculite								
5:0	25	62	10	52	0.01	34	96	0.10
4:1	20	65	9	56	0.01	29	94	0.11
3:2	18	63	6	57	0.01	33	95	0.12
2:3	18	58	5	53	0.01	38	96	0.14
1:4	10	56	3	53	0.01	40	96	0.14
0:5	6	55	3	52	0.01	42	97	0.12
LSD[c]				4.4		5.1	1.9	0.020
Sand:Native Peat								
5:0	115	24	1	23	0.01	20	44	1.52
4:1	307	27	3	24	0.01	21	48	1.40
3:2	435	34	6	28	0.01	21	55	1.19
2:3	448[e]	42	8	34	0.01	21	63	0.96
1:4	576[g]	52	10	42	0.01	21	73	0.66
0:5	447[d]	56	12	44	0.01	30	87	0.27
LSD[c]				4.3		5.0	2.2	0.036

Table 5. Continued.[a]

Media Volume Ratios	Infiltration Rate (sec)	Container Capacity (% vol.)	Unavailable Water (% vol.)	Available Water (% vol.)	Moisture[b] Tension (atm)	Aeration Porosity (% vol.)	Total Porosity (% vol.)	Bulk Density (g/cc)
Native Peat:Vermiculite								
5:0	447[d]	56	12	44	0.01	30	87	0.27
4:1	289[d]	65	13	52	0.05	18	83	0.35
3:2	97	63	11	52	0.01	23	86	0.30
2:3	27	59	8	51	0.01	32	90	0.23
1:4	23	58	6	52	<0.01	34	93	0.20
0:5	6	55	3	52	0.01	42	97	0.12
LSD[c]				4.6		5.5	2.4	0.020
Canadian Peat:Perlite								
5:0	25	62	10	52	0.01	34	96	0.10
4:1	15	53	8	45	<0.01	39	92	0.10
3:2	12	48	5	43	<0.01	41	89	0.11
2:3	7	42	5	37	<0.01	45	86	0.12
1:4	4	36	4	32	<0.01	48	84	0.12
0:5	3	37	10	27	<0.01	54	91	0.12
LSD[c]				3.8		3.7	1.5	0.011

[a] Each value is the mean of 20 samples taken over a 90-day period, except infiltration rates and unavailable water, which are means of 5 samples.

[b] Moisture tension at container capacity, in atm.

[c] LSD values at 95% probability level.

[d] 1 out of 5 replicates were above 600 sec.

[e] 2 out of 5 replicates were above 600 sec.

[f] 3 out of 5 replicates were above 600 sec.

[g] 4 out of 5 replicates were above 600 sec.

[h] all 5 replicates were above 600 sec.

Table 6. Percent aeration porosity, media ranked highest to lowest.[a]

Medium	% Vol.	Medium	% Vol.	Medium	% Vol.
100% P[b]	54	3 NP:2 P	31	3 SO:2 SA	26
1 CP:4 P	48	100% NP	30	4 SA:1 CP	25
2 CP:3 P	45	3 SO:2 CP	30	4 SO:1 P	24
1 NP:4 P	45	2 SA:3 CP	30	4 SO:1 V	24
100% V	42	3 SO:2 P	29	3 NP:2 V	23
3 CP:2 P	41	4 CP:1 V	29	4 SO:1 SA	23
1 SO:4 P	40	3 SO:2 CP	29	2 SO:3 CP	21
1 CP:4 V	40	1 SO:4 CP	28	4 SA:1 NP	21
4 CP:1P	39	4 SO:1 NP	28	3 SO:2 NP	21
2 NP:3 P	38	1 SO:4 V	28	2 SA:3 NP	21
2 CP:3 V	38	3 SO:2 V	27	1 SA:4 NP	21
1 NP:4 V	34	3 SO:2 NP	27	100% SA	20
2 SO:3 P	34	1 SO:4 NP	27	100% SO	19
100% CP	34	4 NP:1 P	27	2 SO:3 SA	19
3 CP:2 V	33	2 SO:3 V	26	1 SO:4 SA	19
1 SA:4 CP	33	2 SO:3 NP	26	4 NP:1 V	18
2 NP:3 V	32	4 SO:1 CP	26		

[a] Each value is the mean of 20 samples, taken over a 90-day period.

[b] P=perlite; V=vermiculite; SO=soil; CP=Canadian peat; SA=sand; NP= native peat.

Table 7. Available water holding capacity, media ranked highest to lowest.[a]

Medium	% Vol.	Medium	% Vol.	Medium	% Vol.
3 CP:2 V[b]	57	2 SO:3 V	42	4 SO:1 V	28
4 CP:1 V	56	2 SO:3 CP	42	3 SO:2 NP	28
2 CP:3 V	53	1 SA:4 NP	42	100% P	27
1 CP:4 V	53	1 SA:4 CP	40	100% SO	27
1 SO:4 V	53	2 NP:3 P	39	4 SO:1 P	26
100% V	52	2 SA:3 CP	39	3 SO:2 P	25
100% CP	52	2 CP:3 P	37	4 SA:1 CP	24
4 NP:1 V	52	1 SO:4 NP	36	4 SO:1 CP	24
3 NP:2 V	52	2 SA:3 NP	34	4 SA:1 NP	24
1 NP:4 V	52	1 NP:4 P	33	100% SA	23
2 NP:3 V	51	3 SO:2 V	33	3 SO:2 NP	23
4 NP:1 P	50	1 CP:4 P	32	1 SO:4 SA	21
1 SO:4 CP	46	1 SO:4 P	32	4 SO:1 NP	20
4 CP:1 P	45	3 SO:2 CP	31	4 SO:1 SA	20
3 NP:2 P	44	2 SO:3 NP	30	2 SO:3 SA	20
100% NP	44	2 SO:3 P	29	3 SO:2 SA	16
3 CP:2 P	43	3 SA:2 CP	29		

[a] Each value is the mean of 20 samples, taken over a 90-day period.

[b] CP=Canadian peat; V=vermiculite; SO-soil; SA=sand; NP=native peat; P=perlite.

Table 8. Total porosity, media ranked highest to lowest.[a]

Medium	% Vol.	Medium	% Vol.	Medium	% Vol.
100% V[b]	97	4 NP:1 P	84	2 SA:3 NP	63
100% CP	96	4 NP:1 V	83	3 SO:2 P	61
1 CP:4 V	96	1 SA:4 NP	82	3 SA:2 CP	61
2 CP:3 V	96	3 NP:2 P	81	4 SO:1 CP	60
3 CP:2 V	95	2 NP:3 P	81	4 SO:1 NP	59
4 CP:1 V	94	1 NP:4 P	79	4 SO:1 V	59
1 NP:4 V	93	1 SO:4 NP	77	4 SO:1 P	57
4 CP:1 P	92	1 SO:4 P	75	100% SO	56
100% P	91	2 SO:3 V	75	3 SA:2 NP	55
2 NP:3 V	90	2 SO:3 CP	74	4 SA:1 CP	51
3 CP:2 P	89	1 SA:4 NP	73	4 SO:1 SA	50
100% NP	87	2 SA:3 CP	72	4 SA: 1 NP	48
2 CP:3 P	86	2 SO:3 NP	69	3 SO:2 SA	48
3 NP:2 V	86	3 SO:2 CP	68	2 SO:3 SA	44
1 SO:4 V	85	2 SO:3 P	68	100% SA	44
1 SO:4 CP	85	3 SO:2 V	67	1 SO:4 SA	43
1 CP:4 P	84	3 SO:2 NP	63		

[a] Each value is the mean of 20 samples, taken over a 90-day period.

[b] V=vermiculite; P=perlite; SO=soil; CP=Canadian peat; SA=sand; NP=native peat.

Table 9. Bulk density, media ranked lowest to highest.[a]

Medium	(g/cc)	Medium	(g/cc)	Medium	(g/cc)
100% CP[b]	0.10	100% NP	0.27	3 SO:2 NP	0.95
4 CP:1 P	0.10	3 NP:2 V	0.30	2 SA:3 NP	0.96
4 CP:1 V	0.11	4 NP:1 V	0.35	3 SA:2 CP	1.04
3 CP:2 P	0.11	1 SO:4 P	0.39	4 SO:1 CP	1.06
3 CP:s V	0.12	1 SO:4 CP	0.40	4 SO:1 P	1.06
2 CP:3 P	0.12	1 SO:4 V	0.42	4 SO:1 NP	1.07
1 CP:4 P	0.12	1 SA:4 CP	0.46	4 SO:1 V	1.09
100% P	0.12	1 SO:4 NP	0.54	100% SO	1.18
100% V	0.12	2 SO:3 P	0.64	3 SA:2 NP	1.19
2 CP:3 V	0.14	1 SA:4 NP	0.66	4 SA:1 CP	1.30
1 CP:4 V	0.14	2 SO:3 V	0.69	4 SO:1 SA	1.36
1 NP:4 P	0.17	2 SO:3 CP	0.70	4 SA:1 NP	1.40
2 NP:3 P	0.19	2 SA:3 CP	0.74	3 SO:2 SA	1.41
1 NP:4 V	0.20	2 SO:3 NP	0.76	2 SO:3 SA	1.50
3 NP:2 P	0.22	3 SO:2 CP	0.86	100% SA	1.52
2 NP:3 V	0.23	3 SO:2 P	0.87	1 SO:4 SA	1.55
4 NP:1 P	0.23	3 SO:2 V	0.88		

[a] Each value is the mean of 20 samples, taken over a 90-day period.

[b] CP=Canadian peat; V=vermiculite; SO=soil; SA=sand; NP=native peat; P=perlite.

Table 10. Infiltration rates, media ranked highest to lowest.[a]

Medium	(sec)	Medium	(sec)	Medium	(sec)
100% P[b]	3	2 SO:3 P	68	2 SA:3 NP	448[d]
1 SO:4 P	3	1 SO:4 CP	77	2 SO:3 SA	501[d]
1 CP:4 P	4	1 SA:4 CP	84	2 SO:3 NP	546[e]
1 NP:4 P	5	2 SA:3 CP	96	2 SO:3 CP	565[d]
100% V	6	3 NP:2 V	97	1 SA:4 NP	576[f]
2 CP:3 P	7	100% SA	115	3 SO:2 NP	559[f]
1 CP:4 V	10	3 SO:2 P	117	1 SO:4 NP	561[f]
3 CP:2 P	12	3 SA:2 CP	134	100% SO	600[g]
4 CP:1 P	15	1 SO:4 V	198	4 SO:1 NP	600[g]
2 NP:3 P	16	4 SA:1 CP	230	4 S :1 P	600[g]
3 CP:2 V	18	4 NP:1 P	259	4 SO:1 CP	600[g]
2 CP:3 V	18	1 SO:4 SA	272	2 SO:3 V	600[g]
4 CP:1 V	20	4 NP:1 V	289[c]	3 SO:2 V	600[g]
1 NP:4 V	23	3 SO:2 CP	306[c]	4 SO:1 V	600[g]
100% CP	25	4 SA:1 NP	307	3 SO:2 SA	600[g]
2 NP:3 V	27	3 SA:2 NP	435	4 SO:1 SA	600[g]
3 NP:2 P	48	100% NP	447[c]		

[a] Each value is the mean of 5 samples.

[b] P=perlite; CP=Canadian peat; V=vermiculite; SO=soil; SA=sand; NP=native peat.

[c] 1 out of 5 replicates were above 600 sec.

[d] 2 out of 5 replicates were above 600 sec.

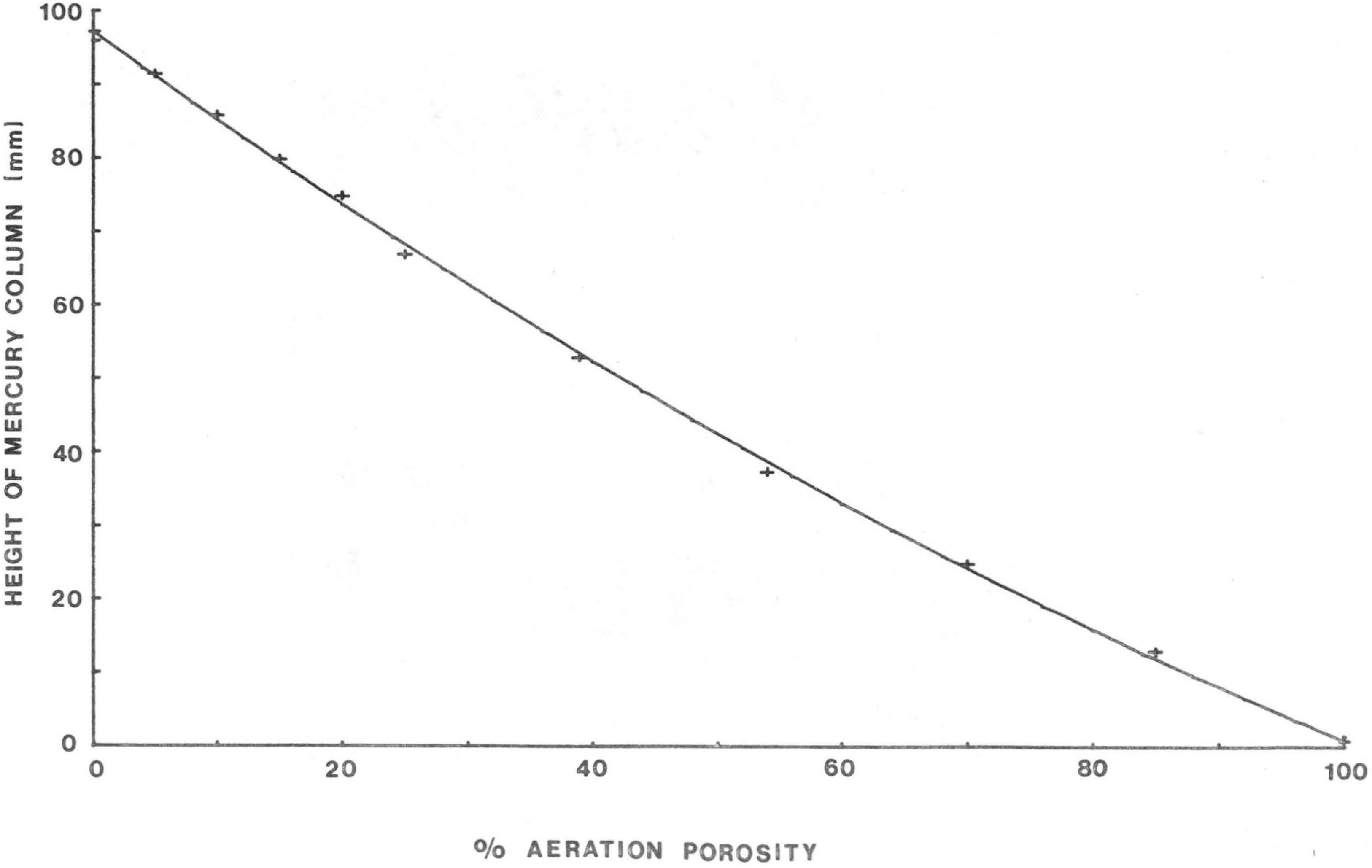
[e] 3 out of 5 replicates were above 600 sec.

[f] 4 out of 5 replicates were above 600 sec.

[g] All 5 replicates were above 600 sec.

Figure 6. Calibration curve for the air picnometer used in this experiment. Height of the mercury column was measured with a cathetometer capable of reading within 0.1 mm. Known volumes of water (thus known volumes of air) were placed in the sampling tube to calibrate the instrument. Each point is the mean of 10 replications.

$Y = 97.14668 - 1.219645\ X + 0.002552\ X^2$ $\qquad r = 0.999153$


HEIGHT OF MERCURY COLUMN (mm)
100
80
60
40
20
0
0
20
40
60
80
100
% AERATION POROSITY