LAYERS IN GOLF GREEN CONSTRUCTION

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For

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EXECUTIVE SUMMARY

Project Title: **Layers in Golf Green Construction**

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SUMMARY

The USGA recommendations for putting green construction allow for either a two-layered profile (i.e. a rootzone layer over a drainage layer) or a three-layered profile, which includes an intermediate layer between the rootzone and drainage layers. The main purpose of the intermediate layer is to prevent finer particles from the rootzone migrating downwards and blocking the pore space within the drainage layer when relatively coarse gravels are used. The objectives of the current study were, firstly, to examine how variation in particle size and shape within the intermediate and drainage layers affected moisture retention in the rootzone. Secondly, to assess rates of particle migration from the rootzone into the drainage layer in relation to particle size differences between the two layers.

For two layered profiles, constructed in 300 mm diameter columns under laboratory conditions, increases in the size of the underlying gravel caused a slight increase in water retention in the rootzone after gravitational drainage. For example, water retained in the upper 150 mm of the rootzone after 48 hours drainage averaged 25.1 mm for the finest gravel (D_{15} = 2.2 mm) compared with 27.4 mm for the coarsest gravel (D_{15} = 5.6 mm).

In a second study, the effects of different intermediate layers were examined, using a 1-4 mm grit with increasing amounts (0-50%) of either coarse sand (0.5-1.0 mm) or medium-coarse sand (0.25-1.0 mm). Although increases in the amount of fine material within the intermediate layer caused greater water retention in the intermediate layer, this had no significant effect on the moisture content of the rootzone.

In the two layered profiles, particle migration from the rootzone into the drainage layer was examined after the application of 3000 mm of water over a period of thirty weeks. Plaster of Paris and epoxy resin containing a fluorescent dye were used to stabilise the profiles so that they could be sectioned and photographed under ultra-violet light. Particle migration was minimal except when a very dry rootzone based on a medium sand (89 % < 0.5 mm) was placed over coarse gravel ($D_{15} \geq 4.4$ mm). Even for these profiles, no more than 34% of the pore space within the gravel immediately below the rootzone/gravel interface was blocked by rootzone material. At depths of more than 25 mm below the interface, no more than 10% blockage of the pore space was recorded.

On the basis of the results, it is proposed that in two layered profiles criteria for the bridging factor between the rootzone layer and the drainage layer should be relaxed. Furthermore, the amount of material between 0.25 mm and 1.0 mm within the intermediate layer can be increased when three layered profiles are used.

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INTRODUCTION

Before 1993, the USGA green construction method always included an intermediate layer between the rootzone mixture and the gravel drainage layer. The purpose of this layer is to: [i] prevent the downwards migration of particles from the rootzone into the gravel; [ii] to form a textural break to disrupt capillary flow, thus helping retain moisture in the rootzone layer. The intermediate layer must be carefully installed to ensure a uniform thickness and freedom from contamination. This increases construction time and costs. Accordingly, in the 1993 revision of the USGA green construction recommendations (USGA Green Section Staff, 1993), an alternative method was also allowed in which the rootzone is laid directly on a fine gravel base. Strict bridging criteria are used to prevent particle migration.

The bridging factor used in the 1993 revision of the green construction method is fairly stringent, particularly as soil or organic amendments in the rootzone mix tend to hold material together. This contrasts with the more pronounced movement that can occur in dry sands. Consequently, it may be possible to relax the filter criteria. This possibility is supported by observations by Brown & Duble (1975) and Brown *et al.* (1980) on laboratory columns containing profiles of golf green rootzones and by Baker *et al.* (1991) using resin impregnation on slit drains of sand overlying gravel. There is therefore a need to find out exactly how much variation can be tolerated in the discrepancy in particle size between the rootzone mix and the gravel drainage layer.

When an intermediate layer is used there is also a need to ascertain exactly what range of particle sizes can be permitted in this layer. USGA Green Section Staff (1993) give a fairly restricted range with 90% of the material between 1 mm and 4 mm, whereas in the United Kingdom a higher content of material <1 mm is permitted, as long as it is above 0.25 mm and the majority is between 1-4 mm (Baker 1990).

The presence of coarse textured layers under a finer textured material has a major influence on soil water movement. During periods of excess rainfall, water can move from the rootzone into a gravel drainage layer within which it can move laterally to any pipe drains. However, in dry conditions, when water needs to be retained in the rootzone, the low unsaturated hydraulic conductivity of the gravel and the difference in capillary potential between the rootzone and the underlying layer means that vertical drainage is minimised (Miller 1973, Clothier *et al.* 1977a. b.)

Moisture retention in the rootzone layer is a function of the desorption characteristics of the rootzone, its depth and the coarseness of the underlying layer. Taylor *et al.* (1993, 1994) found that water retention in 300 mm deep rootzone layers was greatest when the rootzone was placed directly over a gravel layer. Water retention declined when the rootzone was placed over sand and gravel or directly over sand and was least when the rootzone had a subsoil base. Brown & Thomas (1980) calculated moisture retention using the desorption characteristics of the rootzone and unsaturated hydraulic conductivity data for the gravel layer. They found that total available water in a 300 mm profile was lower when an intermediate layer was included but that the difference compared to the situation with the rootzone directly overlying gravel was small.

Hunt & Baker (1996), examining moisture distribution in laboratory columns after 48 hours drainage, found that the use of coarse (5-10 mm) or fine (4-6 mm) gravel in the drainage layer had little effect on moisture relationships in the rootzone but there were significant effects attributable to the selection of the intermediate layer. Moisture contents in the rootzones were greatest where there was no intermediate layer, lower with a coarse (1-5 mm) intermediate layer and lowest with a fine (0.25-2.0 mm) intermediate layer.

The current project therefore had two objectives. Firstly to examine how particle migration from the rootzone layer was influenced by particle size of the drainage layer where no intermediate layer was present. Secondly to examine moisture distribution in the rootzone after gravitational drainage in relation to the particle size characteristics of the intermediate and drainage layers.

MATERIALS AND METHODS

PART 1. PARTICLE MIGRATION AND WATER RETENTION IN SITUATIONS WHERE THE ROOTZONE DIRECTLY OVERLIES THE GRAVEL LAYER

Experimental design

The experiment used plastic cylinders of 300 mm diameter each containing a golf green profile (Fig. 1). An inner cylinder was fixed in the base of the main cylinder and set 25 mm below the rootzone/gravel interface. This avoided problems of edge effects which can occur when the packing system of the gravel at the interface is affected by the wall of the cylinder. The 180 mm diameter inner cylinder was used in the resin impregnation process discussed below.

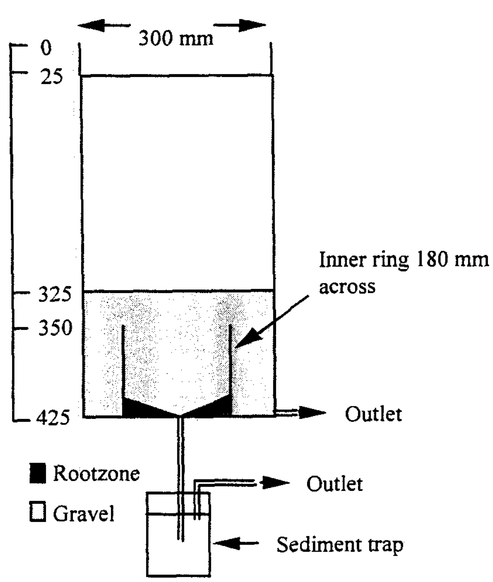

FIGURE 1. Cylinder arrangement to examine the effect of different gravels under the rootzone layer (depths in mm).

Four factors were included in the experimental design:

- Five gravel sizes.
- Two gravel shapes - well rounded and angular .
- Two rootzone mixes - one mix with a medium-grade sand and relatively low organic matter content, the other with a coarser sand but a higher organic matter content. *Sphagnum* peat was used as the organic matter source.
- Two moisture contents of the rootzone mix during construction. One mix was prepared with air-dry sand, the other mix prepared using moist sand. The average gravimetric moisture contents of the mixes with moist sand were 8.2% for the 70:30 blend of medium-coarse sand and peat, and 6.0% of the 85:15 mix with medium sand. Corresponding figures for mixes made with dry sand were 3.4% and 1.4% respectively.

The trial was set out in a factorial design with a two-fold replication.

Selection of materials

The rootzone materials were based on two sand materials (Table 1) with the medium sand being mixed with 15% *Sphagnum* peat and the medium-coarse sand being mixed with 30% *Sphagnum* peat.

TABLE 1

Particle size analysis (%) and organic matter content (%) of the two rootzone mixes.

Category	Diameter (mm)	85:15 mix of medium sand:peat	70:30 mix of medium-coarse sand:peat
Coarse gravel	8.0-3.4	0	0
Fine gravel	3.4-2.0	0	T
Very coarse sand	2.0-1.0	T	T
Coarse sand	1.0-0.5	11	31
Medium sand	0.50-0.25	67	67
Fine sand	0.250-0.15	20	T
Very fine sand	0.15-0.053	1	1
Silt + clay	<0.053	1	1
Organic matter	—	0.8	2.7

T = TRACE

The gravel materials encompassed a range of sizes with five angular gravels and five rounded gravels. These were prepared by sieving and blending material from several different gravel sources. Gravel size for the study was chosen on the basis of the bridging factor given by USGA Green Section Staff (1993), i.e.

$$D_{15\,(\text{gravel})} \leq 5 \times D_{85\,(\text{rootzone})} \qquad \text{Eq. 1}$$

The D_{85} values for the medium and medium-coarse rootzones are approximately 0.45 mm and 0.60 mm respectively. Under these circumstances, the maximum permissible D_{15}

value for the gravel using Eq. 1 should be 2.25 mm and 3.0 mm respectively. At the other extreme, preliminary laboratory tests using dry rootzone material suggested that both sands were likely to migrate once the D_{15} of the underlying gravel exceeded 5 mm. Thus, five angular gravels and five rounded gravels were prepared having D_{15} values based on equal steps in a logarithmic progression as follows: 2.2, 2.8, 3.5, 4.4 and 5.6 mm. The resulting bridging factors are given in Table 2. Figures 2 and 3 show the particle size distribution of the ten gravels.

TABLE 2

Bridging factors for the combination of two rootzones and five gravel sizes. (Note: the 1993 revision of the USGA *Recommendations for a Method of Putting Green Construction* requires a value of ≤5).

	Bridging factor	
D_{15} of gravel (mm)	Medium rootzone D_{85} = 0.45 mm	Medium-coarse rootzone D_{85} = 0.60 mm
2.2	4.9	3.7
2.8	6.2	4.7
3.5	7.8	5.8
4.4	9.8	7.3
5.6	12.4	9.3

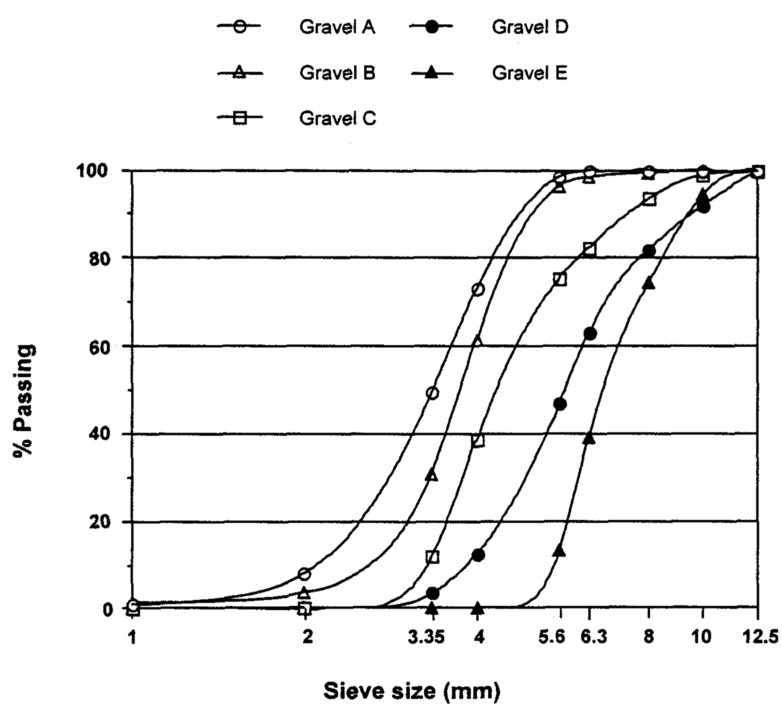

FIGURE 2. Particle size distribution of the rounded gravels A to E.

ii) Bulk density and volumetric water content

After the final application of water, the profile was left for 48 hours to allow gravitational drainage. The profile was then carefully excavated in 50 mm increments to a depth of 250 mm to allow bulk density and volumetric water content to be measured following oven drying of the rootzone material at 105°C.

iii) *Resin impregnation to examine particle migration*

Once bulk density and water content measurements had been completed, any remaining rootzone was carefully removed leaving a 10 mm layer above the gravel. Then the gravel outside the inner sampling area (see Fig. 1) was removed using a vacuum cleaner. Two holes approximately 20-25 mm in diameter were carefully excavated in the remaining rootzone to expose the gravel. A liquid slurry of plaster of Paris was poured into one of the holes with the other hole allowing air to escape. The purpose of the plaster of Paris was to stabilise the gravel and rootzone material before resin impregnation. The level of plaster of Paris was continually raised until it had completely filled the pore spaces within the gravel and covered the thin layer of remaining rootzone material. The plaster of Paris was then allowed to set for three to four days at room temperature, then left to dry out for one to two weeks at a temperature of c. 25-30°C. Once the structure had been stabilised, the surrounding plastic container was cut away and one side of the plaster of Paris and gravel (approximately one quarter of the section by volume) was chipped away to ensure that the central section of the block was successfully impregnated when resin was used. The block of plaster of Paris was then placed in a tight-fitting plastic bag and impregnated from beneath using a mixture of three parts epoxy resin (Araldite MY753) and one part hardener (Araldite XD716). 0.1g of UV fluorescent dye (Tinopal SWN conc.) was added to each 100 ml of total solution. To reduce the viscosity of the impregnating solution, it was further diluted with a 20% (v/v) addition of acetone. The impregnating medium was added in increments of about 20 mm over a period of two days. The blocks were then dried at a temperature of approximately 20-25°C for two to three weeks before being sectioned using a continuous rim diamond saw at right angles to the two holes excavated for adding the plaster of Paris. Photographs were taken of the sections under ultra-violet light using a black and white (100 ASA) film.

iv) Assessment of particle migration

At the end of the irrigation period, particle movement into the sediment trap was determined using pipette sampling to determine the silt and clay content, while sieving was used to analyse the amount and distribution of sand size particles collected with the sediment trap.

As very little rootzone migration occurred for most gravels, accumulation of material from the rootzone layer was determined by visual analysis of the sections. These were assessed for three different layers – upper layer (top 20 mm), middle layer (c.20-80 mm depth), lower layer (bottom 20 mm, immediately above the original plastic base). Particle accumulation was assessed on a 1-10 scale (10 = most contamination) using the mean of two observers acting independently.

To give a quantitative figure of the amount of contamination, the sections with greatest contamination (i.e. the dry, medium sand rootzone over the four coarsest gravels, two rounded, two angular) were assessed in terms of the number of pores containing evidence of rootzone material. A sampling grid at 5 mm intervals was produced on transparent film and superimposed over the sections. Transects were made across the profile at depths of 5, 15, 25, 35, 55 and 75 mm (32 points per transect). At each sampling point, the profile was classified as being gravel, pore space with no visible contamination or pore space with contamination from rootzone. This contamination frequently took the form of blockage of the "neck" between particles below the pore rather than complete filling of the pore. The percentage of pores with any degree of contamination was determined from the number of contaminated pores divided by the total number of pores.

PART 2. WATER RETENTION IN THE ROOTZONE LAYER OVER INTERMEDIATE LAYERS OF VARYING SIZE COMPOSITION

Experimental design

Profiles were constructed with a 300 mm rootzone layer and a 50 mm intermediate layer over gravel (Figure 4). Both the gravel and rootzone material conformed to USGA specifications. For the gravel 84% of the particles fell between 6.3 mm and 9.5 mm and 85% of the rootzone contained particles between 0.25-1.0 mm (Tables 3 and 4). The rootzone was a blend of sand, sandy loam topsoil and *Sphagnum* peat. Table 5 lists the physical properties of the rootzone material.

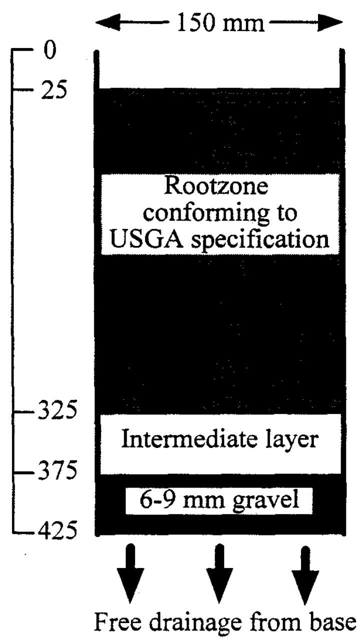

FIGURE 4. Cross-section of cylinder arrangement to examine moisture retention in the profile with intermediate layers of varying composition.

(depths shown are in mm)

TABLE 3
Particle size analysis of gravel forming the drainage layer

Particle Size (mm)	Sieve Analysis (%)
> 12.5	0
12.5 - 9.5	6
9.5 - 6.3	84
6.3 - 4.0	10
4.0 - 3.35	0
3.35 - 2.0	0
2.0 - 1.0	0
< 1.0	Trace

TABLE 4
Particle size analysis of rootzone material

Category	Particle Size (mm)	Sieve Analysis (%)
Stones & Coarse Gravel	> 3.4	1
Fine Gravel	3.4 - 2.0	1
Very Coarse Sand	2.0 - 1.0	3
Coarse Sand	1.0 - 0.5	26
Medium Sand	0.5 - 0.25	59
Fine Sand	0.25 - 0.15	5
Very Fine Sand	0.15 - 0.05	1
Silt	0.05 - 0.002	2
Clay	< 0.002	2
Organic Matter Content (%)	-	1.0

TABLE 5
Physical properties of the rootzone material after compaction

Hydraulic conductivity (mm h^{-1})	283
Bulk density (g cm^{-3})	1.65
Total porosity (%)	37.3
Air-filled porosity at -4 kPa (%)	20.8
Capillary porosity at -4 kPa (%)	16.5

The intermediate layer contained a clean 1-4 mm grit with 43% falling between 2.0-3.35 mm, 55% between 1.0-2.0 mm and 2% less than 1.0 mm. Increasing contents of medium and coarse sand were added as follows :

- 1-4 mm grit + 0, 10, 20, 30, 40, 50% coarse sand (0.5-1.0 mm diameter).
- 1-4 mm grit + 0, 10, 20, 30, 40, 50% medium-coarse sand (the sand component consisted of 30% 0.25-0.5 mm diameter and 70% 0.5-1.0 mm diameter).

The sands included in the intermediate layer were artificially manufactured using sieved components from several different sands. This gives a variation in shape and avoids any concentration of particles of any specific size. The sand combinations also satisfied the bridging factor for placing a rootzone layer directly over a gravel. The particle size distributions of the resulting mixtures with coarse and medium-coarse sands are plotted in Figure 5.

The experiment was replicated in a three-fold factorial design.

Profile construction
Profiles were built inside rigid PVC tubes of 425 mm length and 150 mm diameter (Fig. 4). A strong filter membrane of porous fabric was attached to the base of the tube allowing free drainage of water from the profile.

The profiles were constructed by first adding 50 mm of gravel to the bottom of the cylinder, this was tapped down and levelled with a static weight of 8.48 kg. Then, 50 mm of intermediate material was added, tapped down and levelled with the static weight. Finally, the rootzone material was added in 100 mm layers and the static weight was again used to consolidate each layer. Once complete, a packing energy of 10 kJ m^{-2} (10 blows of a 5.75 kg hammer dropped from a height of 0.31 m) was applied to the whole profile to simulate compaction after construction.

Measurement of rootzone drainage
To initiate surface ponding, water was sprinkled onto the surface of each rootzone through a fine mesh to minimise disturbance. A constant head of water was maintained over the profile for a period of 20 minutes before measurements started. Infiltration rates were measured over a further 20 minutes based on the volume of water required to maintain a constant head. Infiltration values were standardised to a common temperature using the ratio of water viscosity at 10°C to that at the measurement temperature.

To examine the rate of water loss from each profile, changes of weight over time were recorded. Timing started when the ponded water disappeared from the rootzone surface and no further water applications were made. Each profile was then allowed to drain under gravity for four weeks and weighed 1, 2, 4, 8, 24, 48, 120 hours, 1, 2 and 4 weeks after the start of timing. Whilst drainage took place, lids were placed loosely over the cylinders to minimise evaporation and an extra cylinder with a sealed base was used to estimate evaporation losses.

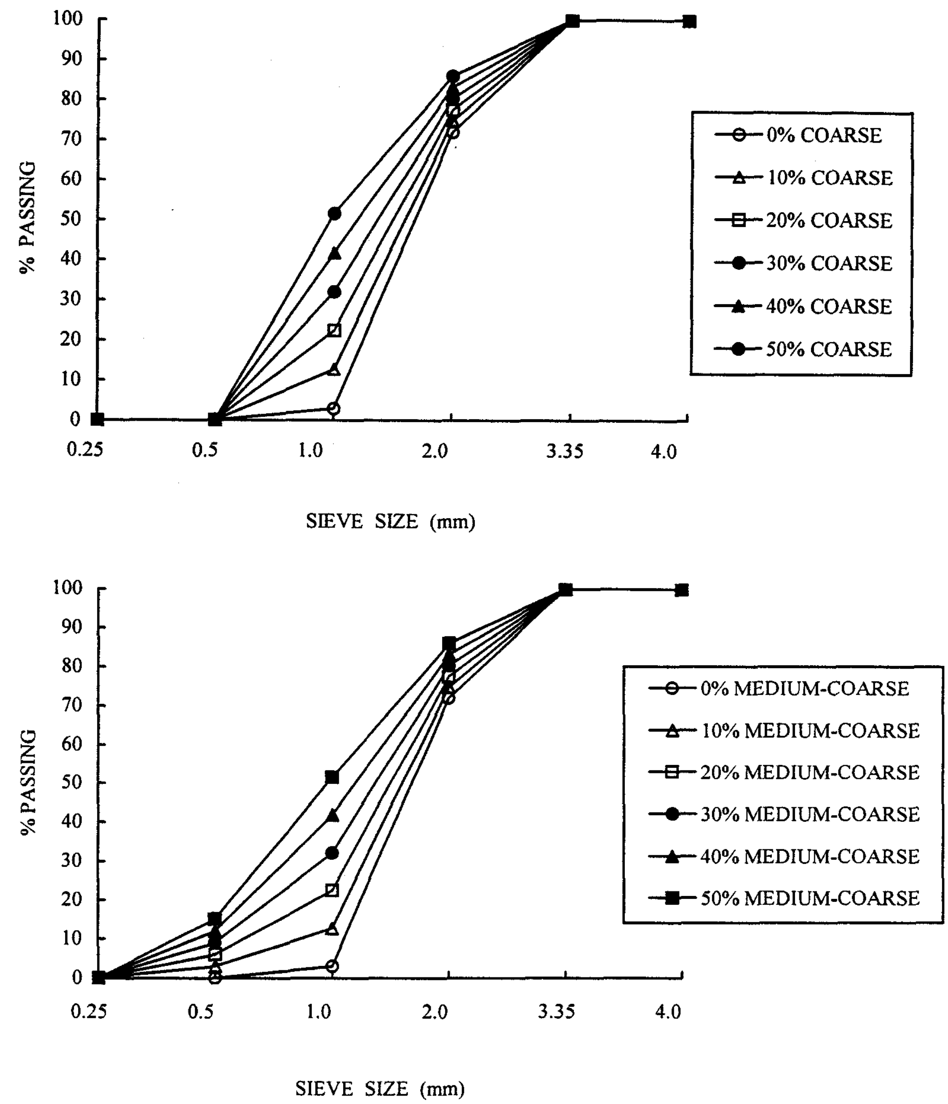

FIGURE 5. Particle size distribution of the ten sands used in the intermediate layer

Moisture profiles
After four weeks, each profile was re-saturated with the addition of 5.3 litres of water, this being the equivalent volume of rootzone per cylinder. After gravitational drainage for 48 hours, the material from each 50 mm layer was carefully excavated and weighed. The gravimetric moisture content of each layer was then measured by taking a sub-sample of approximately 200 g and oven-drying it at 105°C. The bulk density of each 50 mm layer was also determined by calculating the dry weight of rootzone material and its volume for each section. For the 250-300 mm depth, it was difficult to measure bulk density accurately because of the presence of the rootzone / intermediate layer interface. Consequently, bulk density was assumed to correspond to that of the 200-250 mm layer when subsequently used in calculations of volumetric moisture content.

Data analysis
The main data examination for both Part I and Part II of the study was by analysis of variance with a factorial model, using a significance level of $P<0.05$. Least significant difference (LSD) values were calculated at the $P=0.05$ level to indicate differences between treatment means. Regression analysis was also carried out using a significance level of $P<0.05$.

RESULTS

Moisture distribution after 48 hours gravitational drainage for rootzones placed directly over the gravel drainage layer
Volumetric moisture content increased with depth and was consistently higher for the 70:30 mix with medium-coarse sand than the 85:15 mix with medium sand (Fig. 6). The moisture content at which the rootzone was installed and subsequently compacted also influenced the moisture content approximately seven months later. A significant effect ($P<0.05$) was recorded at all depths, for example for the 0-50 mm depth, moisture content after 48 hours drainage was 16.0% for material compacted under dry conditions and 18.3% for rootzone material compacted under moist conditions. Comparable figures for the 200-250 mm depth were 24.2% and 26.9% respectively.

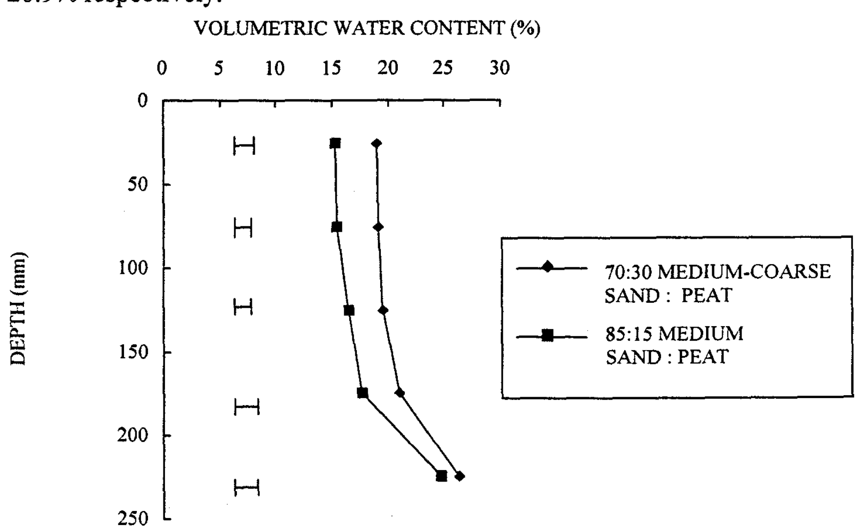

FIGURE 6. Changes of moisture content with depth for the two rootzone mixtures (values averaged over all gravel types and both rootzone moisture contents). Horizontal bars shows LSD (5%).

For the individual rootzone depths, significant ($P<0.05$) effects of gravel size on volumetric moisture content were only recorded at the 100-150 mm depth. The rootzones overlying the finest gravel (D_{15} = 2.2 mm) had an average moisture content of 17.4%, while rootzones over the coarsest gravel (D_{15} = 5.6 mm) averaged 19.3%. For all other depths, the highest moisture content was always recorded over the coarsest gravel and the lowest moisture content over the finest gravel, although differences were not significant at $P<0.05$. For gravimetric moisture content, values were higher on the rounded gravel than on the angular gravel for two of the five sampling depths. The difference was however comparatively small, averaging 0.7 percentage points.

When the moisture content values were combined to give the total water retention in the upper 250 mm of the profile, there was a significant relationship between water retention and the D_{15} size index of the gravel (Fig. 7). Based on an average of the two rootzones, increasing the D_{15} value of the gravel from 2.2 mm to 5.6 mm increased water retention in the upper 250 mm after 48 hours drainage from 46.8 mm to 51.3 mm. In many situations, root penetration would not be sufficient to exploit most of the moisture retained below 150 mm. When water retention values were calculated for the upper 150 mm of the rootzone, the finest gravel (D_{15} = 2.2 mm) gave 25.1 mm water retention compared with 27.4 mm for the coarsest gravel (D_{15} = 5.6 mm).

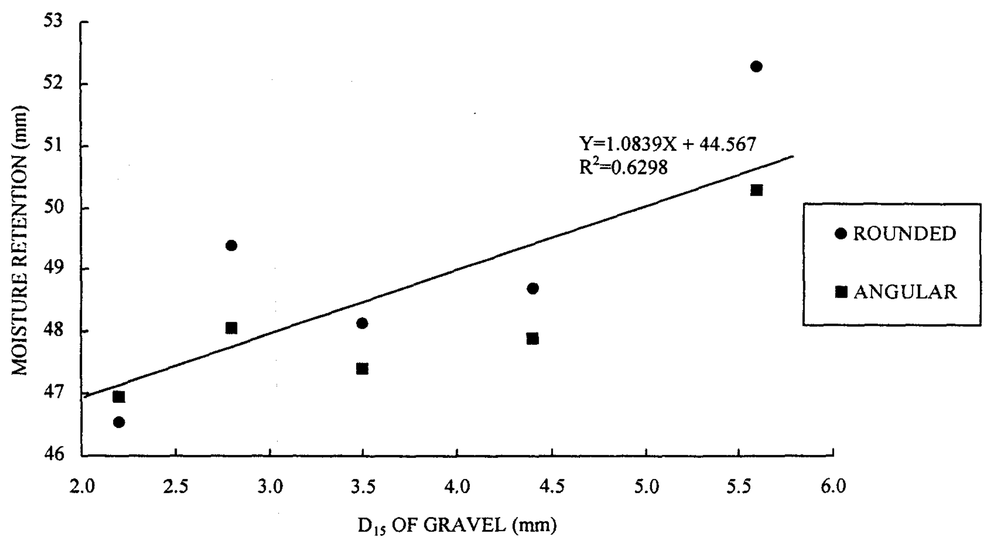

FIGURE 7. Effect of gravel size and shape on water retention in the upper 250 mm of the profile (results averaged between the two rootzone materials)

Moisture distribution after 48 hours gravitational drainage for rootzone material placed over intermediate layers of varying size composition.

The majority of gravitational drainage took place in the first hour after the cessation of ponding. Averaged over all profiles and assuming that the change of cylinder weight over time was solely attributable to drainage from the rootzone, 55% of all drainage over a four-week period took place in this first hour and 74% in the first 24 hours. Evaporation losses over a four-week period were estimated to be less than 1.2 mm, based on cylinder measurements with a sealed base.

After re-saturation and gravitational drainage for 48 hours, increasing amounts of coarse and medium-coarse sand had significant effects on the moisture content of the intermediate layer (Fig. 8). For example volumetric moisture content increased from 7.5% when the 1-4 mm grit included no sand to 18.4% when 50% coarse sand was added to the grit. However, no strong significant relationships were found between the composition of the intermediate layer and moisture retention in the rootzone. As would be expected, moisture content of the rootzone increased with depth (Fig. 9). The greatest amounts of moisture were found at a depth of 250-300 mm. Mean pore saturation was calculated as 36% in the top 200 mm of rootzone as opposed to 78% in the bottom 200-300 mm layer.

Infiltration rates averaged 392 mm h^{-1}. The differences in intermediate layers had no significant effect on water infiltration rates.

Particle migration

A set of photographs of the sections showing the rootzone layer over the gravel drainage layer is given in Appendix I.

The amount of particle migration that took place was very limited and restricted mainly to the top 20 mm of the gravel (Table 6). Only four of the eighty sections were given scores greater than 3 when observed for particle contamination and figures for the amount of contamination of pore space with the gravel for the sections are shown in Table 7. All four sections were taken from columns containing the 85:15 sand : peat mix with medium sand which was added when dry. The gravels in these profiles were from the two coarsest size categories ($D_{15} \geq 4.4$ mm) with two sections having angular gravel and two sections rounded gravel. Within the top 10 mm of the gravel, occasional pores were completely filled by rootzone material. More usually, and particularly at depths below 10 mm, when pores contained rootzone material, it was in the form of a small amount of accumulated material at the base of pores within the "neck" formed by adjacent gravel particles. For the four sections shown in Table 7, between 25.0-34.0% of the pore space located 5 mm below the rootzone/gravel interface showed signs of contamination. Pore blockage decreased substantially below 25 mm and at 55 mm or below at most 1.6% of the pore space within the gravel contained rootzone material.

The amount of material recorded in the sediment trap was never more than 3.7 g, (mean = 1.2g) less than approximately 0.1% by weight of the material held in the soil columns.

There was some slight settlement of the rootzones during the period when the 3 000 mm of water was applied, averaging 8.7 mm across all samples. There was a significant ($P<0.05$) effect of the moisture content when the rootzone was added (7.6 mm for the dry rootzone, 9.8 mm for the moist rootzone), however no effect of gravel type was recorded.

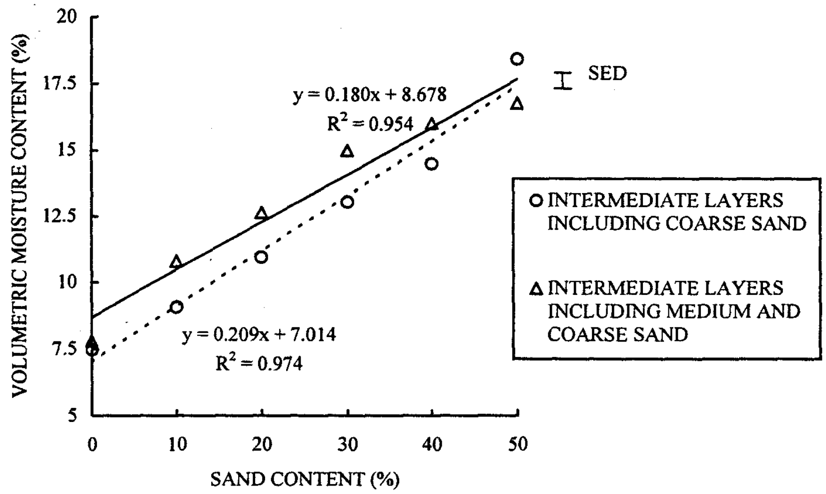

FIGURE 8. Comparison of volumetric moisture contents measured in the intermediate layer in relation to increasing proportions of coarse and medium-coarse sand

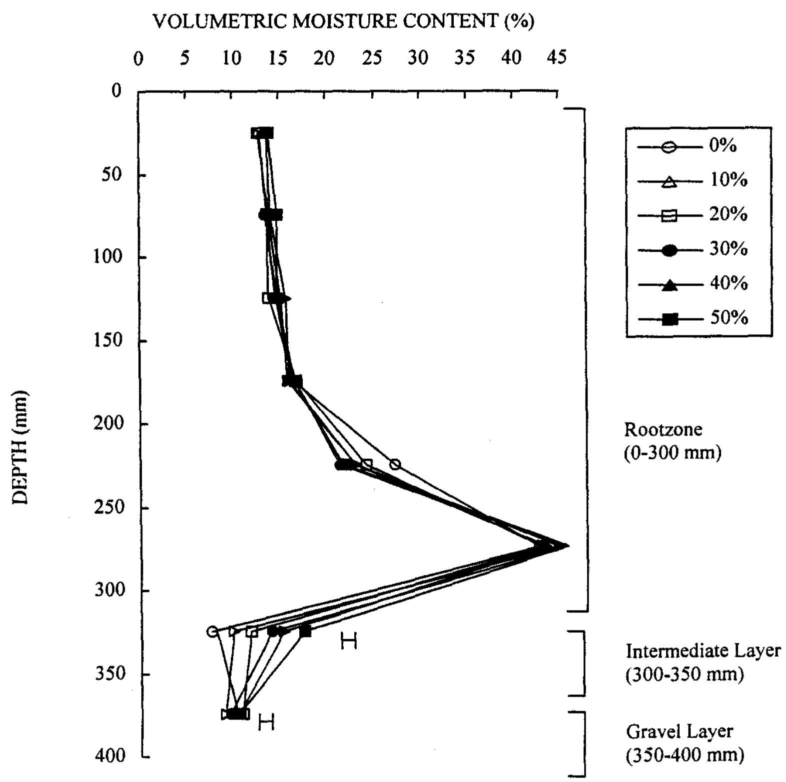

FIGURE 9. Moisture profiles comparing differences in volumetric moisture content with increasing proportions of sand in the intermediate layer. (LSD 5% values are shown by the error bar for any depth where a significant difference in treatment means was recorded. For all other depths no significant differences were found).

TABLE 6

Main treatment effects on visual scores for particle migration (1-10 scale, 10 = worst)

	Sampling depth (mm)		
	Upper 20 mm	**20-80 mm**	**Lower 20 mm**
Mixing ratio (sand : peat)			
70:30 Medium-coarse sand	1.8	1.2	1.0
85:15 Medium sand	2.3	1.4	1.0
LSD (5%)	0.22	NS	NS
Moisture content during packing			
Dry	2.3	1.3	1.1
Moist	1.9	1.2	1.0
LSD (5%)	0.22	NS	NS
Gravel shape			
Rounded	2.2	1.3	1.0
Angular	2.0	1.2	1.0
	NS	NS	NS
D_{15} gravel size			
2.2	2.1	1.3	1.1
2.8	1.8	1.2	1.0
3.5	2.1	1.1	1.0
4.4	2.1	1.3	1.0
5.6	2.3	1.4	1.1
	NS	NS	NS

TABLE 7

Contamination of pore space within the gravel by rootzone material for the four coarsest gravels with the medium sand rootzone installed under dry conditions

	Pore space contaminated by rootzone material (%)			
	D_{15} gravel = 4.4 mm		**D_{15} gravel = 5.6 mm**	
Depth (mm)	**Rounded**	**Angular**	**Rounded**	**Angular**
5	28.3	28.1	34.0	25.0
15	22.2	23.8	28.3	17.4
25	4.3	19.2	4.2	5.3
35	8.0	9.1	5.9	0
55	1.6	0	0	0
75	0	0	0	0

DISCUSSION

For the two layer profile, the amount of particle migration from the rootzone into the gravel was very limited and occurred mainly when the finer of the two sands was used and installed under very dry conditions (gravimetric moisture content of the rootzone < 1.4 %). It would appear therefore that it is possible to make the requirements for the bridging factor less stringent and a change in the constant from five to eight is suggested, giving a revised bridging factor of:

$$D_{15\,(gravel)} \leq 8 \times D_{85\,(rootzone)}$$

Increasing the size differential between the rootzone and the underlying gravel can cause slightly greater water retention in the rootzone. When the D_{15} of the gravel increased from 2.2 mm to 5.6 mm in the current study, water retention in the top 150 mm of the rootzone rose from 25.1 mm to 27.4 mm. For most rootzone materials, this slight increase in moisture retention would be a marginal advantage. The only situation where slightly greater moisture retention would be a disadvantage would be for mixes where capillary porosity was already excessive and there would be a corresponding slight decrease in air-filled porosity.

Where an intermediate layer was used, increasing the amount of material in the range 0.25-1.00 mm from zero to 50% appeared to have no effect on either water infiltration rates into the rootzone or on water retention after gravitational drainage. Consequently, although 1-4 mm is the preferred range for the intermediate layer, an increase in the amount of particles in the range 0.25-1.00 mm can be justified.

RECOMMENDATIONS

The two principal recommendations are as follows:

a) For situations where an intermediate layer is not used, the criteria for the bridging factor for the gravel should be relaxed. The following conditions are suggested:

Bridging factor $D_{15\,(gravel)} \leq 8 \times D_{85\,(rootzone)}$

b) For situations where an intermediate layer is used, the requirements for the intermediate layer should be made less stringent and to allow up to 30% of material < 1 mm diameter, as long as no more than 10% of the material is < 0.5 mm diameter and no more than 2% of material < 0.25 mm diameter.

An amended form for Tables 1 and 2 in the 1993 revision of the *USGA Recommendations for a Method of Putting Green Construction* is given in Table 8. However, for situations where an intermediate layer is used, it is considered that it would be more effective to produce guidelines in terms of grading curves for both the drainage layer and intermediate layer. These alternative proposals are given in Appendix II and also allow for a coarser gravel to be used.

TABLE 8
Suggested amendments to the recommendations for drainage layer and intermediate layer materials based on the current format of 1993 USGA Recommendations for a Method of Putting Green Construction

PARTICLE SIZE DESCRIPTION OF GRAVEL AND INTERMEDIATE LAYER MATERIALS

Material	Description
Gravel: Intermediate layer is used	Not more than 10% of the particles greater than ½" (12 mm) At least 65% of the particles between ¼" (6 mm) and ⅜" (9 mm) Not more than 10% of the particles less than 2 mm At least 70% of the particles between 1 mm and 4 mm
Intermediate Layer Material:	• Not more than 10% greater than 4 mm • Not more than 30% less than 1 mm • Not more than 10% less than 0.5 mm • Not more than 2% less than 0.25 mm • D_{90}/D_{15} no more than 4.0

SIZE RECOMMENDATIONS FOR GRAVEL WHEN INTERMEDIATE LAYER IS NOT USED

Performance Factors	Recommendations
Bridging Factor	• $D_{15\,(gravel)} \leq 8 \times D_{85\,(rootzone)}$
Permeability Factor	• $D_{15\,(gravel)} \geq 5 \times D_{15\,(rootzone)}$
Uniformity Factors	• $D_{90\,(gravel)} / D_{15\,(gravel)} \leq 2.5$ • No particles greater than 12 mm • Not more than 10% less than 2 mm • Not more than 5% less than 1 mm