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Physical and Chemical Properties and Plant Growth in an Engineered Soil Manufactured from Bauxite Residue, Green Waste Compost and Increasing Amounts of Sand

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Abstract

A new manufactured soil product (Turba) was produced using acidified bauxite residue into which 10% green waste compost had been incorporated. A laboratory/greenhouse experiment was carried out to determine if sand could be used as an ingredient or an amendment for Turba. Sand was added at rates of 0%, 5%, 10%, 25, 50% and 75% (w/w) in two different ways 1) by incorporating it into the Turba during its manufacture (IN) or 2) by mixing it with Turba aggregates after their manufacture (OUT). Incorporation of sand into Turba aggregates (IN) decreased the percentage of sample present as large aggregates (2 - 4 mm dia.) after crushing and sieving (<4 mm) and also reduced the stability of 2 - 4 mm dia. formed aggregates (to dry/wet sieving) and are therefore not recommended. In a 16-week greenhouse study, ryegrass shoot yields were greater in Turba than in sand [and decreased with increasing sand additions (OUT)] while root dry matter showed the opposite trend. The greater grass growth in Turba than sand was attributed to incipit water stress in plants grown in sand and this may have promoted greater allocation of assimilates to roots resulting in a greater root-to-top mass ratio. The much lower macroporosity in Turba coupled with the solid cemented nature of Turba aggregates resulted in production of thinner roots and therefore greater root length than in sand. Turba (manufactured from bauxite residue and compost added at 10% w/w) is a suitable medium for plant growth and there is no advantage in incorporating sand into, or with, the Turba aggregates.

Keywords

Engineered Soil, Manufactured Soil, Bauxite Residue, Optimized Bauxite Residue, Sand, Ryegrass Growth

1. Introduction

For every tonne of alumina generated in an alumina refinery, 1 - 2 tonnes of bauxite residue waste is also produced. This material is highly saline, alkaline and sodic and considered as a hazardous waste. Because of the alkali, saline/sodic nature of the material, less than 5% is used [1] and the vast bulk of it is stockpiled in storage areas close to the refinery which eventually needs to be rehabilitated and revegetated. Emirates Global Aluminium (EGA) has developed a method for treatment of residue immediately after it exits the refinery involving acidification and subsequent removal of salts to produce Optimized Bauxite Residue (OBxR) which is a non-hazardous product. The wet OBxR can be mixed with 10% green waste compost and then dried to form an engineered soil product called Turba (the Arabic word for soil) [2]. During its drying, the product irreversibly solidifies and it can then be crushed and sieved to form Turba aggregates. Turba has been shown to have soil-like properties and be a suitable growth medium for plants [2] [3].

A characteristic of Turba aggregates is that they have a high microporosity and low macroporosity and this can restrict root growth through them [3]. In-corporation of a material with high macroporosity and low microporosity, such as sand, might improve their physical properties. Indeed, sand is a possible additional material that could be incorporated into Turba since throughout the world it is commonly used as a component of engineered soils [4]. Sand can be sourced as river sand or sand-sized particles produced from rock crushing or crushing of demolition waste or in the UAE dune sand is a ubiquitous resource. Sand could be incorporated into the wet material, along with compost, before drying so that it became incorporated inside aggregates. Alternatively, it could be added with the dried Turba aggregates after their manufacture as an additional component of the final product.

In this study, sand was added to Turba at rates of 0%, 5%, 10%, 25%, 50% and 75% (w/w) in two different ways either by (1) incorporating and homogenizing it with the OBxR/compost mixture (IN) and then drying, crushing and sieving the mixture or (2) producing Turba aggregates from an OBxR/compost mixture and after drying, crushing and sieving, adding the sand (OUT). Chemical and physical properties of the materials were measured, and a greenhouse study was conducted to compare above- and below-ground dry matter production of ryegrass in Turba, Turba/sand mixtures 25%, 50% and 75% added sand (OUT) and sand.

2. Materials and Methods

2.1. Materials and Experimental Design

Optimized Bauxite Residue (OBxR) was produced by a method developed by Emirates Global Aluminium. The parent bauxite originated from Guinea and was refined at the alumina refinery at Al Taweelah, Abu Dhabi. Bauxite processing residue was taken from the residue stream at that plant and OBxR was produced by acidification of the residue [5] and removal of excess salts to create a final product with a pH_{water} of 8.0 and EC_{water} of 1.0 $dS \cdot m^{-1}$.

The sand used was fine silica sand which was a surrogate for dune sand. The sample was made by blending silica sand <400 µm with <600 µm dia. sourced from an industrial sand supplier. Sand particle size within the mechanically sieved silica sand size classes was consistent. The combination gave the same particle size analysis as dune sand sampled in the UAE (*i.e.*, 16% 250 - 500 µm, 66% 125 - 250 µm, 17% 63 - 125 µm). Water release curves constructed for the two materials were shown to be interchangeable. Composted municipal green waste was sourced from a landscape garden supplier and was sieved <2 mm prior to use.

To produce Turba, water was added to wet OBxR to give a final water content of 44%. Green waste compost (10% w/w on an oven dry weight basis) was added to wet OBxR and mixtures were homogenised using a rotary mortar mixer. Sand was added to Turba in two ways. There were four replicates for each treatment. The first method was by incorporating and homogenizing it with the OBxR/compost mixture (IN) and the second was by producing Turba aggregates from an OBxR/compost mixture and after drying and sieving adding the sand (OUT). To prepare "In" treatments, 0%, 5%, 10%, 25%, 50%, 75% (w/w) sand was mixed with a wet OBxR/compost mixture. Turba products were then laid out in drying trays to a depth of about 1.5 cm and allowed to dry in the sun for 72 h. The dried, solidified material was then crushed using metal rollers which broke the material into small pieces. The material was then placed onto a 4 mm sieve (50 cm dia.) and force was applied from above using a ceramic pestle to push the material through the sieve. This was done to try to replicate a commercial operation where a trommel would be used to screen/sieve the material. Preliminary experiments with replicate runs showed this method gave a consistent particle size distribution in the final sieved product. To prepare "OUT" treatments, Turba was produced as above using an OBxR/compost mixture. Sand was then added to the <4 mm sieved Turba aggregates at 0%, 10%, 25%, 50% and 75% (w/w).

2.2. Chemical Properties

The pH_{water} and EC_{water} of samples were determined in a 1:5 w/v water extract using a pH/conductivity meter. Exchangeable bases (Ca, K, Na and Mg) were extracted with 1 M ammonium acetate (pH 7) (1:5 w/v for 1 h) and analysed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) [6]. Effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable bases. Exchangeable sodium percentage (ESP) was calculated as the percentage of exchangeable bases present as Na. Available P was extracted with 0.5 M $NaHCO_3$ (pH 8.5) (1:100 w/v for 16 h) [7] and P was analysed colorimetrically by the molybdenum blue method.

2.3. Thin Section Analysis

For thin section analysis, samples of dried Turba solid were impregnated with epoxy resin, ground using a diamond disc, affixed to a glass slide and ground and polished to a thickness of 30 microns using the methods of Thin Section Australia Pty [8]. A scanning electron microscope (Hitachi SU3900) with a Bruker energy dispersive detector fitted with advanced mineralogical identification and characterization software was used to produce photos of the mineralogical phases present in samples.

2.4. Physical Properties

Bulk density of bulk samples of aggregates was determined on naturally compacted samples [9], particle density by the pycnometer method [10] and total porosity by difference. Soil water content in samples was determined at −10 and −1500 kPa using a pressure plate apparatus [11]. Pore size distribution was calculated as macropores (>29 μm diameter; air-filled pores at -10 kPa), mesopores (0.20 - 29 μm diameter; drained between −10 and −1500 kPa) and micropores (<0.20 μm diameter; water-filled pores at −1500 kPa) [12]. Field capacity was determined as the volumetric water content at −10 kPa and available water as that held between −10 and −1500 kPa.

The wet sieving technique was used to measure the stability of dried 2 - 4 mm dia. aggregates. A sample of 30 g of aggregates was transferred to the top of a set of four sieves with 2.0, 1.0, 0.5 and 0.25 mm dia. apertures. The water level was maintained to ensure the upper sieve was just submerged at the highest point of oscillation. The oscillation rate was 40 cycles per minute; the amplitude (distance between highest and lowest point) of sieving was 20 mm, and the period of wet sieving was 15 min. The residue remaining in each sieve was collected and weighed after oven drying. Mean weight diameter (MWD) of each sample was calculated as the sum of the fraction of soil remaining on each sieve multiplied by the mean diameter of the adjacent sieve apertures. The upper and lower limits of MWD were 3.0 and 0.25 mm respectively.

For dry sieving, an Endicotts Octagon 200 sieve shaker was used. The shaker was set to maximum amplitude and a set of sieves with 2.0, 1.0, 0.5 and 0.25 mm dia. apertures was used. A sample of 30 g of 2 - 4 mm dia. aggregates was transferred to the 2 mm sieve and the sample was shaken for 30 minutes. Particles remaining on each sieve were collected and weighed and the MWD was calculated as above.

2.5. Greenhouse Experiment

Since the results of physical properties of mixtures showed it was not practicable to incorporate sand into Turba (*i.e.* IN) only (OUT) treatments were included in the greenhouse study. There were five treatments consisting of Turba, and Turba with additions of 25%, 50% and 75% sand (OUT) and sand only. A volume of 800mL of each replicate treatment was placed in plastic pots. Four replicates of each treatment were prepared and sown with perennial ryegrass (*Lolium perenne* L. cv RPR) seeds. Ryegrass was used because in the UAE bermudagrass fairways on golf courses are often oversown with ryegrass each autumn to give a playing surface that can tolerate heavy traffic.

The treatments were replicated four times and pots were arranged in a randomised block design in a greenhouse with an air temperature controlled between 24 to 28˚C. fertilizer used was "Miracle-GroMaxFeed all-purpose Soluble Plant Food (24:6:12)". Its composition was 24.2% N, 5.6% P, 11.7% K, 3.6% S, 0.8% Mg, 0.17% Fe, 0.02% B, 0.07% Cu, 0.05% Mn, 0.06% Zn and 0.0005% Mo. It was applied in solution at a rate to give an equivalent N application of 100 $kg\cdot ha^{-1}$ to a depth of 10 cm at each application. Pots were watered until drainage began every 2 - 3 days. This regime was used as a balance between very frequent irrigation appropriate for sand (low available water) and infrequent irrigation appropriate for Turba (fine particles trend to waterlog if irrigated frequently). Measurements revealed this allowed about 0.1 pore volume of drainage per watering.

Plant tops were harvested three times after 8 (H1), 12 (H2), and 16 weeks (H3) growth. At the last harvest, roots were extracted from the growth medium and washed under running water using a 300 μm mesh sieve. Total root length was calculated by spreading a weighed subsample of roots (~0.1 g) on a grid paper (grid size 1 × 1 cm) and counting the total number of intersections between roots and horizontal and vertical lines [13]. Shoots and roots were oven-dried at 60˚C for 48 h and weighed.

2.6. Greenhouse Experiment

The statistical significance of experimental treatments was determined by subjecting the data to Analysis of Variance using Minitab Software Package. Differences were calculated at the 5% level using Tukey's test.

3. Results

3.1. Chemical Properties

Chemical properties of the Turba-sand mixtures are shown in **Table 1**. The pH of sand was 7.3 and that of Turba 8.1 and Turba-sand mixtures had a pH of 8.0 - 8.1. As expected, sand was low in all nutrients and its addition to Turba lowered EC, exchangeable Ca, K, Mg and Na and available P. There were no differences in chemical properties between IN treatments and OUT treatments.

3.2. Physical Properties

The size distribution of aggregates formed after crushing and sieving of treatments (IN) or crushing and sieving plus the addition of sand (OUT) is shown in **Table 2**. For both IN and OUT treatments, progressive addition of sand greatly reduced the proportion of the final sample in the 2 - 4 and 1 - 2 mm range and increased that in the <1 mm size class (*i.e.*, sand-sized particles). The proportion of sample in the 2 - 4 mm fraction was less in the IN than OUT treatments and the reverse tended to be the case for the 1 - 2 and <1 mm fractions.

Table 1. Some chemical properties of Turba, Turba amended with sand at rates of 5%, 10%, 25%, 50% and 75% either incorporated in the Turba (IN) or added to Turba after its manufacture (OUT) and sand.

Treatments	pH	EC ($ds \cdot m^{-1}$)	Exchangeable cation ($mmolc \cdot kg^{-1}$)					ESP (%)	Available P ($mg \cdot kg^{-1}$)
			Ca	K	Mg	Na	ECEC		
Turba	8.10b	1.01f	144f	3.55f	8.72f	108f	264f	40.9b	118f
IN5	8.10b	0.96f	135f	3.33f	8.27f	99.8f	246f	40.6b	111f
IN10	8.08b	0.89e	126e	3.09e	7.84e	92.7e	229e	40.4b	104e
IN25	8.07b	0.72d	100d	2.54d	6.46d	74.5d	184d	40.6b	85.3d
IN50	8.02b	0.48c	61.7c	1.66c	4.14c	45.8c	113c	40.4b	57.7c
IN75	8.00b	0.22b	27.9b	0.79b	2.02b	20.5b	51.2b	40.0b	27.3b
OUT5	8.09b	0.97f	134f	3.32f	8.26f	99.1f	245f	40.4b	110f
OUT10	8.08b	0.90e	127e	3.07e	7.80e	92.9e	230e	41.4b	103e
OUT25	8.08b	0.69d	99.1d	2.49d	6.39d	73.4d	181d	40.5b	84.5d
OUT50	8.06b	0.49c	60.5c	1.61c	4.09c	44.9c	111c	41.4b	56.9c
OUT75	8.01b	0.23b	26.8b	0.75b	1.97b	19.7b	49.2b	40.0b	26.8b
Sand	7.25a	0.01a	1.01a	0.09a	0.16a	0.05a	1.31a	3.82a	9.35a

a. Within a column, means followed by the same letter are not significantly different at $P \leq 0.05$.

Table 2. Size distribution of aggregates after crushing and sieving (<2 mm dia.) for Turba, Turba amended with sand at rates of 5%, 10%, 25%, 50% and 75% either incorporated in the Turba (IN) or added to Turba after its manufacture (OUT) and sand.

Treatments	2 - 4 mm (%)	1 - 2 mm (%)	2 - 4 mm (%)
Turba	32.5g	15.8e	51.7a
IN5	28.0fg	15.7e	56.3b
IN10	26.3f	14.9e	58.8c
IN25	22.2e	13.7de	64.1d
IN50	12.5d	9.42c	78.1ef
IN75	7.52b	4.01b	88.5f
OUT5	32 .2g	15.8e	52.0a
OUT10	31.0g	12.2d	56.8bc
OUT25	27.4f	8.70c	63.9d
OUT50	19.3e	5.81bc	74.9e
OUT75	11.3c	3.60b	85.1f
Sand	0a	0a	100g

a. Within a column, means followed by the same letter are not significantly different at $P \leq 0.05$.

Table 3. Percentages of aggregates collected in the 2 mm sieve, those passing the 0.5 mm sieve and calculated mean weight diameter (MWD) after wet or dry sieving 2 - 4 mm dia. aggregates of Turba and Turba with sand at rates of 5%, 10%, 25%, 50% and 75% incorporated (IN).

Treatments	Wet sieving			Dry sieving		
	2 - 4 mm	<0.5 mm	MWD (mm)	2 - 4 mm	<0.5 mm	MWD mm
Turba	88.7d	4.1a	2.77d	81.6e	9.7a	2.59d
IN5	88.0d	6.2b	2.72d	78.8d	11.0b	2.51d
IN10	85.9cd	7.1bc	2.68d	77.5d	13.0c	2.47d
IN25	81.7c	10.7c	2.57c	68.3c	17.9d	2.26c
IN50	69.6b	17.3d	2.29b	49.0b	28.9e	1.82b
IN75	46.7a	28.2e	1.80a	26.0a	54.0f	1.22a

a. Within a column, means followed by the same letter are not significantly different at $P \leq 0.05$.

Table 4. Some physical properties of Turba, Turba amended with sand at rates of 5%, 10%, 25%, 50% and 75% either incorporated into the Turba (IN) or added to Turba after its manufacture (OUT) and sand.

Treatments	Bulk density ($kg \cdot m^{-3}$)	Total porosity (%)	Pore size distribution (%)			Plant available water ($kg \cdot m^{-3}$)	Field capacity ($kg \cdot m^{-3}$)
			Microporosity (<0.2 μm)	Mesoporosity (0.2 - 29 μm)	Macroporosity (>29 μm)		
Turba	1.00a	65.5d	52.5g	33.3f	14.2a	218h	562i
IN5	1.00a	65.0cd	51.3g	32.5f	16.2b	211h	545hi
IN10	1.01a	64.6cd	47.9f	28.1ef	24.0c	182gh	491h
IN25	1.03a	63.7d	43.3e	22.6d	34.1d	144fg	420g
IN50	1.12ab	59.7c	35.7d	15.0c	49.3e	89.6e	303e
IN75	1.27b	53.1b	25.9b	11.8b	62.3f	62.7c	200c
OUT5	1.03a	64.1cd	52.2g	31.6f	16.2b	203h	537
OUT10	1.05a	63.0c	50.8g	26.2e	23.0c	165g	485h
OUT25	1.15ab	59.2c	47.6f	20.6d	31.8d	122f	404f
OUT50	1.28b	53.6b	39.6e	13.3bc	47.1e	71.0d	284d
OUT75	1.40c	48.1b	29.5c	9.73b	60.8f	46.8b	189b
Sand	1.57d	41.1a	4.23a	3.74a	92.0g	15.4a	33.0a

a. Within a column, means followed by the same letter are not significantly different at $P \leq 0.05$.

Wet sieving 2 - 4 mm aggregates showed that the stability of Turba was the highest with 88.7% of the sample being recovered in the 2 - 4 mm size class (Table 3). With progressive increases in sand addition (IN) there were progressive decreases in aggregate stability as measured by the proportion of sample recovered as 2 - 4 mm aggregates or as MWD and there were concomitant increases in the amounts of sample recovered < 0.5 mm dia. With the 75% addition of sand, the amount recovered in the 2 - 4 mm fraction (47%) was about half that recovered for Turba alone. Turba aggregates were less stable to dry than wet sieving with 81.6% of the sample being recovered on the 2 mm sieve and the decrease with increasing sand addition was more pronounced with dry than wet sieving (Table 3). For example, the amount recovered on the 2 mm sieve for the IN75 treatment was 46.7% for wet sieving and only 26.0% for dry sieving.

Pore size distribution of treatments is shown in Table 4. Sand had the greatest bulk density and macroporosity and lowest total porosity, microporosity, mesoporosity, plant available water and water held at field capacity. Sand additions to Turba increased bulk density and decreased total porosity. This trend was more pronounced in the OUT than IN treatments. Increasing additions of sand also caused decreases in microporosity, mesoporosity, plant available water and water held at field capacity and increases in macroporosity in both IN and OUT treatments. At the same sand addition, OUT treatments generally had less total porosity, mesoporosity, plant available water and water held at field capacity and greater microporosity than IN treatments.

3.3. Plant Growth

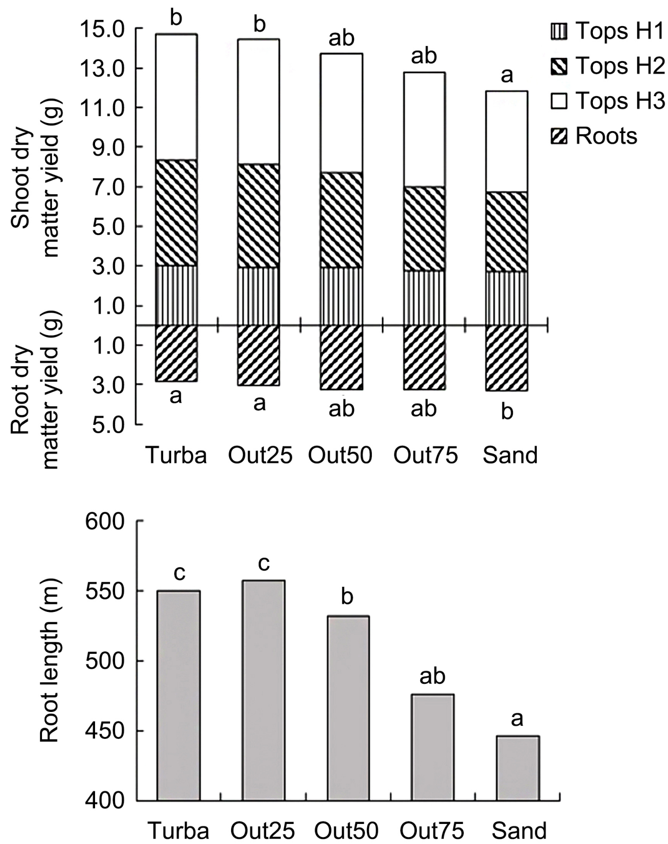

Figure 1. Shoot dry matter yield at three harvests (H1, H2 and H3), root dry matter yield at the third harvest (g pot-1) and root length at the third harvest for Turba, Turba amended with sand at rates of 25%, 50% and 75% (OUT) and sand. Columns denoted by the same letter are not significantly different at P ≤ 0.05.

Shoot dry matter yields at all three harvests plus root mass and root length at the third harvest are shown in **Figure 1**. There were no marked differences in shoot mass between treatments at H1. Nonetheless, cumulative shoot dry matter yields were greatest for Turba and Turba plus 25% sand and least for sand. Root dry matter yields were greatest for sand and least for Turba. As a result, the root to shoot ratios at H3 were 0.45. 0.48, 0.54, 0.56 and 0.65 for Turba, OUT25, OUT50, OUT75 and sand respectively. Root length was greatest for Turba and OUT25 and least for sand (**Figure 1**).

3.4. Thin Section Analysis

A scanning electron microscope image of a thin section of solidified Turba containing 10% w/w compost and 25% w/w dune sand is shown in **Figure 2**. A large number of small sand particles (quartz; shaded pink) can be seen incorporated throughout the residue matrix while there are a much lesser number of larger black compost particles present.

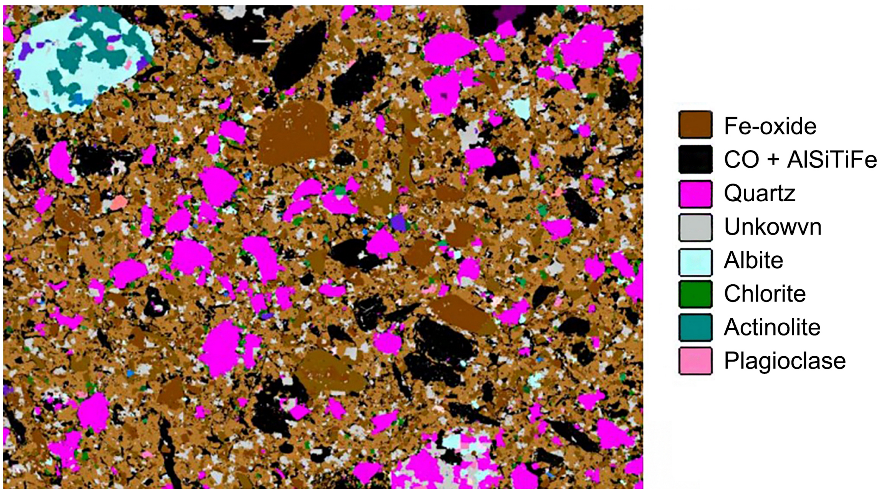

Figure 2. Scanning electron microscope photograph of elemental micro-area distribution analysis of a thin section through solidified Turba containing 10% compost and 25% sand.

4. Discussion

As expected, additions of sand to Turba, either IN or OUT, increased bulk density, decreased total porosity, increased macroporosity at the expense of meso and microporosity and lowered plant available water (**Table 4**). This reflects the fact that sand particles are more dense and have greater macroporosity than Turba. There were, however, clear differences between IN and OUT treatments with the bulk density being greater and total porosity less in OUT treatments. This is indicative of the added sand filling the voids between larger Turba aggregates and therefore increasing density of the mixture. This effect also resulted in a significant increase in microporosity compared with IN treatments and decreases in meso and macroporosity and available water. Addition of 25% sand to Turba (OUT) resulted in a 44% decrease in plant-available water so irrigation scheduling would become a much more important agronomic consideration the more sand that was added.

A characteristic of Turba aggregates is that they are highly water stable. This is demonstrated by over 80% of 2 - 4 mm dia. Turba aggregates being retained in the 2 mm sieve after wet sieving (**Table 3**). The reason for this high stability is that upon drying bauxite residue for the first time an irreversible pozzolanic solidification reaction occurs [14]. This involves soluble silicate and aluminate reacting with Ca2+ in alkali solution to form hydrated gels of calcium silicate and aluminate [15] [16]. When dried these materials have an irreversible cementing effect. Indeed, because of its ability to solidify upon drying, bauxite residue has been used to make non-fired bricks, cementitious fillers and impermeable barriers often with the addition of supplemental Ca as an activator to promote Ca silicate and aluminate formation [16]. Turba aggregates are obtained by crushing and sieving the solidified Turba matrix (*i.e.* <4 mm in this experiment) and are therefore highly water stable. Increasing proportions of sand incorporated into Turba prior to drying resulted in the 2 - 4 mm aggregates produced being substantially less water stable (**Table 3**) and even incorporation of 10% sand caused a measureable decrease in the proportion of aggregates remaining on the 2 mm sieve and in MWD.

The decrease in stability with increasing incorporation of sand was more pronounced for dry than wet sieving (the percentage decrease in the quantity retained in the 2 mm sieve between Turba and the IN75 treatment was 47% for wet sieving and 68% for dry sieving) (**Table 3**). This is because of the greater mechanical energy the aggregates are subjected to during dry sieving. Cementation of Turba aggregates together results in them being inherently water stable but they will break apart if subjected to enough mechanical energy and incorporation of sand promotes such breakdown. That is, while aggregates are relatively stable in the face of irrigation, raindrop impact and wetting and drying they are brittle with regard to input of mechanical energy such as that which occurs during tillage.

Of even more significance is that incorporation of sand into Turba resulted in less large (2 - 4 mm) aggregates being produced (**Table 2**) as well as the ones being produced being less stable. For example, with 10% incorporated sand the percentage of 2 - 4 mm aggregates produced was reduced from 33% down to 26% and with 25% sand incorporation down to 22% (**Table 2**). It is evident that the pozzolanic binding and solidification of the particles within the Turba material is interrupted by the presence of significant quantities of small inert sand particles incorporated within the residue matrix. The sand particles form potential fracture planes within the aggregates. Indeed, as shown in a scanning electron microscope image (**Figure 2**) of a thin section of solidified Turba containing 10% w/w compost and 25% w/w dune sand, there are a large number of small sand particles (quartz) incorporated throughout the Turba matrix. A much lesser number of larger black compost particles were also present.

Turba aggregates have been observed to decrease in diameter over time due to various mechanical forces (e.g., handling aggregates, tillage, compaction, etc.) with the increased production of fine material [3]. Observations suggest that a substantial amount of fine material in Turba can result in a waterlogged growth medium immediately after irrigation. Minimizing production of fine material during manufacture is, therefore, an important goal. Since incorporation of sand into Turba increases the amount of fine material (<1 mm) formed during crushing and sieving and decreases the strength of larger aggregates that are formed (thus increasing the formation of fine material over time) this practice is not recommended.

Using Turba as an amendment to sand by, for example, mixing 25% Turba into the surface layer (*i.e.*, Out75) had a substantial effect on physical properties. Compared to sand, there was an increase in total porosity, meso and microporosity (at the expense of macroporosity) and a 3-fold increase in plant-available water and a 6-fold increase in water held at field capacity. The increase in plant-available water is important in an arid environment (particularly where sand is the main growth medium) since water is a scarce commodity and plant survival and growth relies on a regular supply of water by irrigation. The poor water retention capacity of dune sand makes it a difficult medium to manage in an arid environment and necessitates frequent irrigation. If plants are grown in Turba (with no sand added) the available water retention capacity of the growing medium is increased 14-fold compared with dune sand. This means irrigation management is less critical and water can be applied less frequently.

Turba has a relatively high ECEC that would be considered in the high range for soils (200 - 400 $mmol_c \cdot kg^{-1}$) [17] and therefore it has a strong ability to hold exchangeable cations (Ca, Mg, K and Na). As expected, increasing additions of sand diluted concentrations of extractable Ca, Mg, K, Na and P. In Turba, K and Mg were adequate (critical exchangeable levels often quoted as 1.4 - 2.7 and 2 - 4. $mmol_c \cdot kg^{-1}$ respectively for Mg and K [18] [19]; and available P was high [20]. This reflects the high P content of the parent bauxite rock used [21] and occurs despite of the variable charge surfaces on Fe oxides having the ability to strongly adsorb P. Exchangeable Na in Turba originates principally from the NaOH used to digest the crushed bauxite while the Ca originates from the Ca content of the parent bauxite rock plus lime added during Bayer digestion and both were present in substantial quantities. The relatively high ESP in Turba (40%) is much less than that of the original bauxite residue (83%) but still high enough to have an inhibitory effect on growth of some plants. For example, moderately tolerant plants are adversely affected at ESP values between 20% - 40% and tolerant plants between 40% - 60% [22]. Subsequent experiments have shown that most plants grow vigorously in the material and that over a 6-month period EC and ESP decline with ESP decreasing to about 20% as more extractable Na comes into solution and is leached out.

In comparison with sand, above-ground dry matter yields of ryegrass in Turba were greater while root dry matter tended to be less so the root/shoot mass ratios were least in Turba (0.45) and greatest in sand (0.65) and increased with increasing sand additions. The main limiting factor for grass growth in sand is likely to have been incipient water stress in the 2 - 3 days period between irrigation events. Plants did not wilt over this period but observations have shown wilting over longer periods in sand while plants in Turba show no such signs. That is, the plant available water held by sand was very low and Turba held 17 times the volume of water at field capacity (**Table 4**). An increase in root to shoot ratio on a dry matter basis has been widely reported as a response to water stress [23]. Such a response allows for re-allocation of assimilates from shoot to root growth thus allowing for greater root growth through the soil and therefore more efficient water acquisition. Thus, root to shoot ratio was greatest in sand and an addition of 25% Turba resulted in both a massive increase in plant available water (**Table 4**) and a substantial reduction in root to shoot ratio (*i.e.*, from 0.65 to 0.56).

As shown in **Figure 1**, root length was least in sand and greatest in Turba and adding Turba to sand increased root length. This confirms visual observations that roots were much thicker for plants grown in sand compared with those in Turba. It is well known that as well as providing for transmission of water and oxygen through the soil, macropores provide channels where plant roots can penetrate and proliferate [24]. The very large macroporosity in sand (**Table 4**) allowed for root growth through the sand medium while in Turba the much lower macroporosity may have restricted root growth resulting in plants having a lower root mass and thinner roots (greater root length and root length per unit root mass). Because individual Turba aggregates are strongly cemented together, dense (bulk density about 1.4 $kg \cdot m^{-3}$) and have a low macroporosity plant roots tend to grow around and between aggregates rather than through them [3]. Indeed, bulk densities above 1.4 $kg \cdot m^{-3}$ tend to impede root growth [25]. This attribute of Turba aggregates coupled with the lower macroporosity most likely contributed to a restriction in root mass and root diameter.

5. Conclusion

As expected, incorporation of sand into Turba aggregates increased their macroporosity. However, the practice is not recommended since it weakens the solidified dried material resulting the production of more fine material and less large aggregates when it is crushed to form aggregates and the aggregates that are formed are less stable. While addition of sand to Turba after its manufacture also increased macroporosity, and subsequent root growth and shoot dry matter tend to be reduced. This was attributed to incipient water stress in plants grown in sand because of its low available water holding capacity. Turba (manufactured from bauxite residue and compost added at 10% w/w) is a suitable medium for plant growth and also a suitable amendment for sand which increases CEC, nutrient retention and available water holding capacity in the rooting medium. There is no advantage of incorporating sand into Turba aggregates.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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