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Comparative Physical Properties of a Manufactured Soil Based on Bauxite Residue and a Degraded Natural Soil

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Abstract

A new manufactured soil product (Turba) was produced by acidification of bauxite residue and the addition of 10% green waste compost. The physical properties of this material were compared with that of a natural soil (from under long-term cropping) after 6 months under either fallow or ryegrass. After 6 months under fallow or grass, aggregate sizes separated by sieving were less than the original sieved sizes for Turba and greater for soil. However, wet and dry sieving of 2 - 4 mm dia. aggregates showed Turba aggregates were more stable than those of the soil. Turba aggregates were strongly bound together due to a one-off pozzolanic cementation caused by the presence of Ca aluminates and silicates. The ratio of mean weight diameter for wet sieving to that for dry sieving was less than 0.4 for the soil and greater than 1.0 for Turba. Turba aggregates were extremely stable in water but brittle and could be decreased in size by mechanical action. The ratio was increased by the presence of plants for soil but was unaffected for Turba. Root growth and associated soil microbial activity had no measurable effect on aggregate size or stability in Turba because roots grew between rather than through the solid, compact, cemented Turba aggregates. Turba aggregates had high microporosity and most of the macroporosity occurred between aggregates. The larger the aggregates the larger the interaggregate pores and the greater is the macroporosity. Minimization of disturbance during use (permanent turf, forage or plantation crops and use of minimum tillage) will be important management considerations for the use of Turba.

Keywords

Engineered Soil, Manufactured Soil, Bauxite Residue, Soil Aggregation

1. Introduction

In an alumina refinery, bauxite ore is processed by the Bayer Process whereby Al-containing minerals are dissolved in sodium hydroxide at high temperatures and pressures. For each tonne of alumina produced, one to two tonnes of alkaline, saline, insoluble solids (bauxite processing residues) are also produced. Global use for this residue is estimated to be only 2% - 3% and the bulk of the material is stockpiled in areas close to the refinery [1]. As part of the environmental approval conditions for the newly-built alumina refinery at Al Taweelah in the UAE, Emirates Global Aluminium (EGA) is required to find practical applications for all the residue produced. For this reason, a novel manufactured soil product (Turba) has been developed in association with EGA [2]. Turba is made by mixing acidified, leached bauxite residue with 10% w/w compost and then drying and crushing the product to form aggregates [2] [3]. Laboratory and greenhouse studies have demonstrated that Turba is an excellent plant growth medium and superior to that of dune sand (the main plant growth medium in the UAE) [4] [5]. As a result, a multi-million dollar pilot plant, taking residue directly from the waste stream of the refinery, has recently been be completed to produce Turba for its large-scale field evaluation in the UAE [6].

Preliminary observations have suggested that over time, even under grass, aggregate size of Turba decreases and the decrease is worsened by disturbances such as tillage (R. J. Haynes personal communication). This is in contrast to natural soils where grass root growth through the medium typically increases aggregate size and stability [7]. Initially, aggregation in bauxite residue is the result of the pozzolanic cementing actions of Ca aluminates and silicates [8] and this mechanism is used to produce Turba aggregates when the acidified residue is dried. In natural soils, microaggregates form through linkage of clay particles and humic material and then these are assembled into larger units (macroaggregates) by the enmeshing action of roots, root hairs and mycorrhizal fungal hyphae and temporary polysaccharide binding agents exuded from plant roots and bacteria and fungi in the rhizosphere [9]. Macro-aggregation is a dynamic process and cycles of formation and breakdown occur continuously [10]. It is unknown whether such a plant root-effect occurs in Turba or whether pozzolanic solidification is the main/only aggregation process. Aggregation is a vital aspect of the condition of a manufactured soil because it dictates pore space and pore structure and these properties control how the soil stores and transports water, air and nutrients thereby impacting plant and microbial growth and activity [9]. Macropores (>29 μm dia.) are important since they allow for rapid water drainage and aeration as well as root growth through compacted layers.

A likely initial use for Turba is for culture of grass turf for golf courses, playing fields, landscaped lawns, etc. Golf courses in the UAE usually use Bermuda grass which is over-sown with perennial ryegrass during the cooler winter season (when peak use occurs). In this study, perennial ryegrass was grown for 6 months in Turba and in a regularly cropped, physically degraded natural soil in order to compare plant growth effects on aggregation in the two media. Unplanted (fallow) treatments were included for comparison. Two sizes of aggregates were used, 2 - 4 mm and <2 mm in order to gauge if plant root growth would induce aggregation of small aggregates (<2 mm) into larger aggregate sizes and/or stabilize larger (2 - 4 mm) aggregates. Parameters measured included total porosity, pore size distribution and plant available water in <2 and 2 - 4 mm aggregates, ryegrass shoot and root dry matter yields, aggregate size distribution after ryegrass growth and aggregate stability of 2 - 4 mm aggregates using wet or dry sieving techniques. Microbial properties including soluble C, Microbial biomass C., basal respiration were also measured since these relate to microbial activity in the ryegrass rhizosphere that would potentially promote soil aggregation.

2. Materials and Methods

2.1. Materials Used

The parent bauxite originated from Guinea and was refined at the alumina refinery at Al Taweelah, Abu Dhabi. It had a total elemental content (as oxides) of: Fe_2O 51.0%, Al_2O_3 10.46%, TiO_2 8.08%, SiO_2 6.97%, CaO 4.24% and Na_2O_3 1.74%. Its mineralogical composition was: hematite 23.2%, goethite 32.4%, boehmite 0.4%, sodalite 5.7%, calcite 1.9%, rutile 2.9%, quartz 1.7% and amorphous material 31.9%. Water was added to moist bauxite residue (26% water content) to bring the water content to about 40%. Acid (1M HCl) was added at a rate of 1.1 mmol H^+ kg^{-1} [3] [11]. The mixture was mixed using a rotary mortar mixer and then regularly mixed over a 3 hour period. In order to remove accumulated salts from the suspension (and produce a manageable product) a Marc AS 1210 pressure filter connected to an industrial screw air compressor was used. The final product had a pH_{water} 8.0 and EC_{water} 1.0 $dS \cdot m^{-1}$ Water was added to the moist product to give a water content of 44% and green waste compost (10% w/w on an oven dry weight basis) was added and the mixture was homogenised using a rotary mortar mixer. The resulting Turba material was laid out in drying trays under the sun for 48 h and then crushed and sieved < 4 mm dia. The <4 mm fraction was composed of 42% 2 - 4 mm and 58% < 2 mm dia. aggregates. Green waste compost was sourced from a local garden supply outlet. Its total macroelemental content was Ca 10, Mg 3.2, K 2.1, Na 5.6, P 0.8, S 2.3, Fe 16.2, Al 12.6 $g \cdot kg^{-1}$.

For comparison, a physically degraded natural soil was used to compare plant growth effects on aggregation with those in Turba. A soil sample was excavated (0 - 10 cm) from a sugarcane field near Bundaberg (Queensland) that had been under sugarcane production for more than 25 years. The soil was classified as a Chernic Tenosol by the Australian Soil Classification system [12]. Its mineralogy was dominated by kaolinite with small amounts of goethite and hematite being present as well as minor amounts of illite and smectite. The sample was air-dried and sieved < 4 mm dia.

Bulk samples of Turba or soil (<4 mm) were further sieved using a 2 mm sieve to obtain the 2 - 4 mm (large) and <2 mm (small) aggregates. The <2 mm and 2 -

4 mm fractions represented the small and large aggregate sizes present within the bulk < 4 mm dia. sample. These were used to determine if plant root growth through the medium would result in aggregation of <2 mm aggregates into larger 2 - 4 mm aggregates and if added 2 - 4 mm aggregates would be further stabilized and/or aggregated into larger sized aggregates (>4 mm dia.) (or decrease in diameter to form < 2 mm dia. aggregates).

2.2. Experimental Design

There were four treatments consisting of Turba and soil sieved into two different aggregate size classes (<2 and 2 - 4 mm). Eight replicates of each treatment were prepared and four replicates were sown with perennial ryegrass (*Lolium perenne* L. cv RPR) seeds (seed rate equivalent to 5 kg 100 m^{-2}) and four replicates were left fallow. A volume of 800 mL of each replicate treatment was placed in plastic pots (850 mL, 11.5 cm dia.). The pots were arranged in a randomised split block design and grown at an air temperature of 24˚C to 28˚C for 24 weeks. Planted pots were fertilized with soluble fertilizer every four weeks. The 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·ha^{-1} to a depth of 10 cm at each application. Pots were watered every 2 - 3 days until drainage began. Measurements revealed this allowed about 0.1 pore volume of drainage per watering.

Shoots were harvested after 8 weeks (H1) and 24 weeks (H2) growth. Shoots were oven-dried at 60˚C for 48 h and weighed. Roots were extracted at 24 weeks. At the time of sampling the water content of "field moist" Turba samples was 30 - 33 g 100 g^{-1} and that of the soil was 11 - 13 g 100 g^{-1} (approximately 60% of field capacity). The contents of pots was carefully removed and the "core" was cut vertically down the centre to produce 2 halves. Roots were extracted from one half of each core under running water using a 300 µm mesh sieve. Roots were oven-dried and weighed as above. The other half of each core was used for physical and microbial analyses. Samples were carefully broken apart along natural cleavage planes and sieved through an 8 mm sieve. Roots not adhering/passing through aggregates were removed by hand. The resulting aggregates were then gently sieved through 4 and 2 mm dia. sieves and the percentage mass of sample in the <2, 2 - 4 and 4 - 8 mm size classes was recorded. Because the soil had a poor physical condition, in fallow treatments it had slumped and naturally compacted so did not easily break into small aggregates while in the planted treatments intensive root growth through the soil meant it more easily broke into aggregates. A subsample of wet aggregates (crushed < 2 mm) was stored at 4˚C for subsequent microbial analysis while another subsample was air-dried for physical analysis.

2.3. Chemical Properties

Initial chemical properties of the Turba and soil were measured. The $pH_{1:5}$ and

$EC_{1:5}$ 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) [13]. 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) [13] and P was analysed colorimetrically by the molybdenum blue method. Organic C was measured using a LECO 928 C/N analyser.

2.4. Physical Properties

Bulk density of bulk samples of aggregates (~400 g) was determined on naturally compacted samples [14], particle density by the pycnometer method and total porosity by difference. Soil water content in the samples was determined at −10 and −1500 kPa using a pressure plate apparatus. 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) [15]. 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 [16] was used to measure the stability of air-dried 2 - 4 mm dia. aggregates. A 30g sample of aggregates was transferred to the top of a set of three sieves with 2.0, 1.0 and 0.5 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 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. Microbial Properties

Microbial biomass C was calculated by the difference between organic C extracted with 0.5 M K_2SO_4 from chloroform fumigated and unfumigated soil samples using a K_C factor of 0.45 [17]. Soluble organic C in the K_2SO_4 extracts was analysed using a Shimazu 5000A soluble C analyser. Organic C in K_2SO_4 extracts measured before fumigation was used as a measure of soluble C. Basal respiration was measured by placing 40 g oven-dry equivalent of moist Turba or soil in a 50 mL beaker and incubating the sample for 6 days at 25˚C in a 2 L air-tight jar along with 20 mL 0.1 M NaOH. The evolved CO_2 was determined by titration [18].

2.6. Statistical Analysis

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. For organic matter and microbial status there were no differences in values between <2 and 2 - 4 mm fractions so mean results were analysed.

3. Results

3.1. Chemical Properties

The Turba had a pH of 7.9, an EC of 1.1 dS·m^{-1}, exchangeable Ca, K, Mg and Na of 142, 4.65, 9.06 and 112 mmol$_c$·kg^{-1} respectively and an available P of 103 mg·kg^{-1}. The ECEC was 269 mmol$_c$·kg^{-1} and ESP was 42.6%. The soil had a pH of 5.6, an EC of 0.03 dS·m^{-1}, exchangeable Ca, K, Mg and Na of 38.9, 1.08, 12.9 and 1.06 mmol$_c$·kg^{-1} respectively and an available P of 129 mg·kg^{-1}.

3.2. Physical Properties

Some physical properties of the materials used (before plant growth) are shown in Table 1. Total porosity was greater in Turba than soil. Macroporosity was much greater for soil than Turba. For both Turba and soil, macroporosity was greater for the larger (2 - 4 mm dia.) than small (<2 mm dia.) aggregates. Microporosity and mesoporosity showed opposite trends to macroporosity being greatest for Turba and being greater in the <2 than 2 - 4 mm dia. aggregates. Plant-available water and water held at field capacity were greater for Turba than soil and for both Turba and soil the 2 - 4 mm dia. fraction showed markedly lower values for the < 2 mm aggregates (Table 1).

Table 1. Some physical properties of original Turba and soil aggregates (<2 and 2 - 4 mm dia.) and sand.

Treatments	Total porosity (kg·m^{-3})	Pore size distribution (%)			Plant available water (kg·m^{-3})	Field capacity (kg·m^{-3})
		Microporosity (<0.2 μm)	Mesoporosity (0.2 - 29 μm)	Macroporosity (>29 μm)		
Turba < 2 mm	63.4bc	56.8e	31.6c	6.6a	232d	592e
Turba 2 - 4 mm	72.0c	44.1d	18.1b	37.9b	130bc	447d
Soil < 2 mm	50.2b	20.4c	31.9c	47.7c	160c	262c
Soil 2 - 4 mm	62.1bc	14.2b	17.5b	68.3d	109b	197b

Means followed by the same letter within a column are not significantly different at $P \leq 0.05$.

The size distribution of aggregates (<2, 2 - 4 and >4 mm dia.) recorded after the 6-month experimental period is shown in Table 2. For the Turba the <2 mm treatment (fallow or planted), all aggregates were recovered in the <2 mm size range. For the 2 - 4 mm treatment, 18% - 22% of the aggregates were found in the <2 mm fraction. By contrast, for the soil in both the <2 and 2 - 4 mm treatments 23 and 26% of aggregates were recovered in the >4 mm class for planted treatments and the corresponding values for fallow were 45 and 46% As noted previously, the fallow soil had naturally compacted and when broken through an 8 mm sieve tended to remain as large solid clods while the ramified grass root system resulted in soils breaking into smaller well-defined aggregate structures.

Table 2. Aggregate size distribution (<2, 2 - 4 and >4 mm dia.) after hand sieving in Turba treatments after 6 months fallow or 6 months planted with ryegrass.

Treatments	<2 mm	2 - 4 mm	>4 mm
Turba fallow < 2 mm	100d	-	-
Turba planted < 2 mm	100d	-	-
Turba fallow 2 - 4 mm	18a	82c	-
Turba planted 2 - 4 mm	22a	78c	-
Soil fallow < 2	32b	22a	46b
Soil planted < 2	54c	20a	26a
Soil fallow 2 - 4	26b	29b	45b
Soil planted 2 - 4	51c	26ab	23a

Means followed by the same letter within a column are not significantly different at $P \leq 0.05$.

When aggregate stability of 2 - 4 mm dia. aggregates from the various treatments was measured Turba aggregates were found to be much more stable than soil ones to both wet and dry sieving (**Table 3**). The presence of plants increased the percentage of sample recovered as 2 - 4 mm dia. aggregates and MWD using both wet and dry sieving for soil but there was no effect for Turba. The MWD_{wet}/MWD_{dry} ratio was greater than 1.0 for Turba and <0.4 for soil. The ratio was increased by the presence of plants for soil but was unaffected for Turba.

Table 3. Stability of 2 - 4 mm dia. aggregates for Turba and soil after 6 months fallow or planted with ryegrass as measured by wet or dry sieving. Percentage of sample recovered in the 2 - 4 mm and <0.5 mm fractions shown along with mean weight diameter (MWD).

Treatment	Wet sieving			Dry sieving			MWD_{wet}/MWD_{dry}
	2 - 4 mm	<0.5 mm	MWD	2 - 4 mm	<0.5 mm	MWD	
Turba fallow	8.9c	6.4a	2.8c	80.7c	2.3a	2.5c	1.12
Turba planted	9.4c	5.9a	3.0c	78.8c	2.3a	2.6c	1.15
Soil fallow	1.6a	94.3c	0.32a	24.6a	54.2c	1.0a	0.32
Soil planted	3.4b	92.6b	0.49b	28.7b	48.1 b	1.3b	0.38

Means followed by the same letter within a column are not significantly different, MWD = mean weight diameter.

3.3. Organic Matter and Microbial Properties

Turba had higher values for organic C, total N, soluble C, microbial biomass C and basal respiration than the soil used (Table 4). Values for all five parameters shown in Table 4 did not differ between <2 and 2 - 4 mm dia. aggregate treatments so mean values are shown. Organic C content was similar in planted and fallow treatments for Turba and soil. Values for organic C, soluble C, microbial biomass C and basal respiration in Turba were about double those in soil treatments (Table 4). For Turba soluble C and microbial biomass were greater in planted treatments and for soil soluble C, microbial biomass C and basal respiration were greater in planted treatments.

Table 4. Organic matter status and microbial properties in Turba, soil aggregates and sand with/without grass.

Treatments[b]	Organic C	Total N	Soluble C	Microbial biomass C	Basal respiration
	$g\ C\ kg^{-1}$	$g\ N\ kg^{-1}$	$mg\ C\ kg^{-1}$	$mg\ C\ kg^{-1}$	$\mu g\ CO_2\text{-}C\ g^{-1}\cdot day^{-1}$
Turba fallow	14.7d	1.00abc	121e	449e	26.8e
Turba planted	14.9d	1.06bc	137f	468f	26.9e
Soil fallow	5.71c	0.72b	51.2c	196c	16.0c
Soil planted	6.49c	1.13c	65.1d	229b	17.9d

Means followed by the same letter within a column are not significantly different at $P \le 0.05$.

3.4. Plant Growth

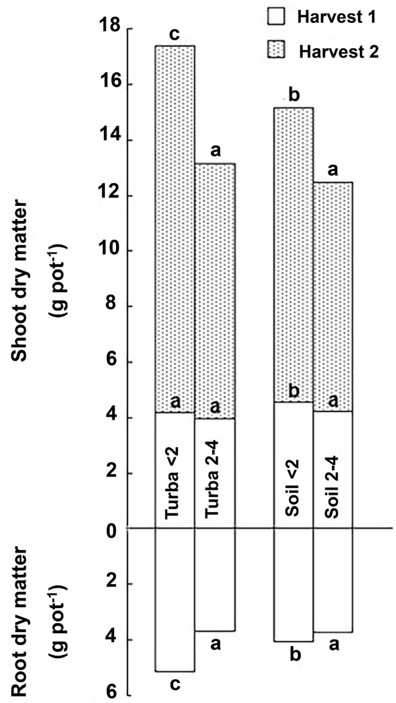

Figure 1. Dry matter yield of shoots (at two harvests; Harvest 1 and Harvest 2) and roots (at Harvest 2) of ryegrass plants grown in Turba and soil aggregates (<2 and 2 - 4 mm dia.) and sand.

At harvest 1, shoot mass was greater in the <2 than 2 - 4 mm fraction for soil but there was no effect for Turba (**Figure 1**). Total cumulative shoot mass was greatest for Turba < 2 and least for the Soil 2 - 4 mm and Turba 2 - 4 mm treatments. For both Turba and soil, cumulative dry matter yields and root yields were greater for the <2 than 2 - 4 mm treatments.

Close up photographs of aggregates from the planted 2 - 4 mm dia. treatments for Turba and soil are shown in **Figure 2**. It is evident that while masses of roots are protruding from aggregates of soil this is not the case for Turba where roots were observed mainly on the outside of aggregates. Observations indicated roots grew mainly between the solidified Turba aggregates rather than through them.

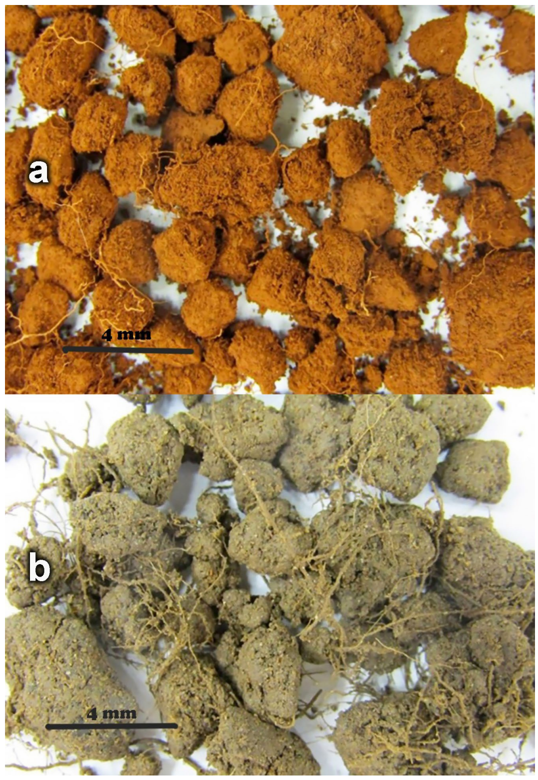

Figure 2. Close-up photographs of (a) Turba and (b) soil aggregates (2 - 4 mm dia) after 6 months growth of ryegrass.

4. Discussion

Chemical properties of Turba in relation to its suitability as a growth medium have been discussed in detail elsewhere [2] [4] [5] [19]. They are considered suitable for growth of ryegrass and results have shown greater dry matter yields than in dune sand [4] [5]. The exchangeable Na concentrations rapidly decline due to leaching and plant uptake and ESP decreases to below 20% within a few months [5]. The soil was low in available K (critical level 2 - 5 $mmol_c \cdot kg^{-1}$) [20] but fertilizer K along with other macro and micronutrients was applied regularly to also both soil and Turba. For the above reasons, it is unlikely that soil chemical properties/nutrient availability were a limiting factor to ryegrass growth in either

Turba or soil.

That after 6 months grass growth, aggregate sizes separated by sieving were less than the original sieved diameters for Turba and greater for soil (**Table 2**) reflects the contrasting mechanisms of aggregation in the two materials. In natural soils, it is a dynamic process whereby macro-aggregation continually occurs under the influence of physical binding (plant roots and associated mycorrhizal hyphae) and temporary cementing agents (e.g. polysaccharides exuded from roots and rhizosphere microorganisms) [9]. Macroaggregates are continually being broken down while new ones are being formed by the above processes. Indeed, observations revealed that plant roots were ramifying through recovered soil aggregates (**Figure 2**) and aggregate stability was greater in planted than fallow treatments (**Table 3**)

By contrast, the major aggregating mechanism for Turba is a permanent, one-off solidification which occurs the first time the material is dried. It shrinks and solidifies through the action of pozzolanic agents (Ca silicate and Ca aluminate gels) which cement the material together [8] to form a solid mass. This is a similar reaction to that which occurs when cement dries [21]. This material is then crushed and sieved to form aggregates. Over time, external forces acting on the material cause cleavage particularly at the edges of aggregates so their size tends to decrease. After 6 months ryegrass growth 100% of aggregates added as <2 mm dia. were still present as <2 mm dia. so no aggregation induced by plant root growth and microbial activity in the rhizosphere was evident.

Even though, over the 6 month experimental period, aggregate size increased for soil and decreased for Turba, both wet and dry sieving demonstrated that 2 - 4 mm dia. Turba aggregates were markedly more stable than the corresponding soil aggregates (**Table 3**). Thus, pozzolanic cementation permanently binds Turba aggregates together more strongly and in a different way to that of temporary soil binding agents such as roots, root hairs, fungal hyphae and short-term organic cementing agents (e.g. polysaccharides) in natural soils.

For natural soils, wet sieving typically yields a lower MWD than dry sieving because hydraulic forces (e.g. slaking, dispersion and breakdown from air pressure during wetting) are more destructive than physical abrasion and mechanical forces occurring during dry sieving [22] [23]. Stable soils can typically have a MWD_{wet}/MWD_{dry} of >0.7 while very unstable soils have a ratio of <0.4 [23] [24]. Thus, the unstable soil used here had a ratio of 0.33 under fallow and 0.44 under grass. By contrast, the Turba aggregates were extremely water stable and were more affected by mechanical action of dry sieving so the ratio was greater than 1.0. The cementing action of Ca aluminates and silicates results in aggregates that are extremely stable in water but when dry they can be brittle and are decreased in size by mechanical action (albeit still more stable to dry sieving than the soil aggregates).

Because of the very low microporosity and solid nature of Turba aggregates they are not easily penetrated by growing roots and few or no roots were observed passing through Turba aggregates (**Figure 2**). In general, a lack of macroporosity is known to restrict root growth [25]. Roots tend to proliferate in the macroporosity between Turba aggregates and grow down water films on the outside of aggregates. Root growth therefore has little effect on aggregation and aggregate stability was therefore unaffected by the presence of grass. Indeed, the larger macroporosity in 2 - 4 than < 2 mm dia. Turba aggregates (**Table 1**) reflects a larger macroporosity occuring between the larger aggregates and that macroporosity occurs mainly between rather than within aggregates. Macroporosity in Turba can be managed by manipulating aggregate size and this inter-aggregate porosity.

In contrast to results presented here, increases in aggregation and aggregate stability with time (along with decreases in ESP) have been recorded on aging/revegetating bauxite residue deposits by a number of workers [26] [27]. This is attributable to Na^+-induced dispersion which predominates in recently deposited residues (the ESP is typically 70% - 90%) (26). Over time, Na is released from Na-containing minerals and leached out while Ca is released from Ca-containing minerals (e.g., calcite) thus resulting in a progressive decrease in ESP and replacement of the monovalent Na^+ with divalent Ca^{2+} as the dominant exchangeable cation [28]. In the present study, the process of OBxR manufacture involves acidification and leaching of excess salts (including Na) so that the ESP of the original Turba was only 42% and exchangeable Ca^{2+} was already present at higher concentrations than exchangeable Na^+.

Since the soil had been under arable cultivation for 25 years it had a low organic matter content (6.14 g C kg^{-1}) while Turba had a higher content of 15.4 g C kg^{-1}. This level is in the range similar to sandy soils under grassland, prairie and shrubs [29]. As a result, Turba had a greater soluble C, microbial biomass C and basal respiration than the soil. As expected, planted treatments of Turba and soil had higher soluble C contents than fallow treatments (**Table 4**). This reflects rhizodeposition of organic material through normal growth and senescence of root segments and root hairs as well as exudation of a wide range of organic substrates by roots and the associated microbial community present in the rhizosphere [30]. In pots, grass root growth is restricted to the volume of the pot and over time the bulk of the soil volume effectively becomes rhizosphere soil and is affected by the dense, ramified grass root system [7]. Changes in total organic C content were not detected in soil and Turba due to the large background level present. For soil, the increased soluble C resulted in greater size (microbial biomass C) and activity (basal respiration) of the microbial community and in Turba there was an increase in microbial biomass. While the size and activity of the microbial community was significantly greater in Turba than soil, there was no indication of aggregation occurring in Turba (the <2 mm fraction remained as <2 mm dia. after 6 months fallow or under ryegrass) suggesting that microbially-induced macro-aggregation is not a significant mechanism for Turba.

The main factor influencing plant yields is likely to have been the available water holding capacity of the growth media [4] [5]. Although the pots were watered to saturation every 2 - 3 days, in the period between irrigation events the plants in the treatments holding less available water are likely to have suffered from incipient water stress thus limiting their growth. Greatest yields were in Turba < 2 and this treatment held by far the greatest plant available water (**Table 3**). In addition, yields were greater in the <2 than 2 - 4 mm treatments in both Turba and soil and in both cases the <2 mm treatment held more available water than the 2 - 4 mm one.

The lack of continual aggregation in Turba means its management will involve conservation of aggregates. External forces acting on Turba aggregates can cause their disruption (particularly at the edges) and a reduction in their diameter over time. In the field, such forces might include tillage, machinery and foot traffic, and raindrop impact. Minimizing disturbance by growing permanent crops (turf grass, forages plantation crops) and using minimum/zero tillage will be important considerations. In the present greenhouse study aggregates used were <4 mm dia. but when research is extended to the field it will be appropriate to use much larger aggregates (e.g. > 25 or >50 mm dia.). The appropriate size will need to be assessed in the field and the fact that aggregates tend to decrease in diameter over time will need to be considered. This will also be important from the viewpoint of maintaining microporosity, and thus aeration, since Turba aggregates have very low macro-porosity and most of the macropores in the Turba medium are between aggregates. Factors that increase the strength of binding within Turba aggregates will also need to be optimized during their manufacture. This will involve maximizing the concentration of pozzolanic materials present prior to drying. Since both Ca aluminates and silicates are highly acid soluble increasing acid additions during Turba manufacture have been found to weaken aggregate binding so there is a balance between lowering pH to promote plant growth while not producing brittle aggregates.

During revegetation of bauxite processing waste areas, the material is left to dry and it solidifies, shrinks causing cracks and macropores to form to depth [31]. Over time the solidified material close to the surface breaks into smaller peds and the surface layer can be ripped and tilled to form a tilth suitable for plant establishment. In the vast majority of cases permanent vegetation is planted (grass, herbs, bushes). It is very likely that plant roots grow predominantly between aggregates (as occurs with Turba) rather than through them as occurs in a natural soil. As has been demonstrated on a number of field sites this is not a problem and revegetation can be highly successful [31] [32]. However, the material is probably not suitable for long-term production of arable crops because tillage will break peds into progressively smaller aggregates until aeration and downward water movement are inhibited.

5. Conclusion

Due to the influence of external forces acting on them, Turba aggregates tend to decrease in size over time. Root growth and microbial activity had no measurable effect on aggregate size or stability in Turba because roots grew between rather than through the solid, compact, cemented Turba aggregates. Important factors in Turba manufacture will include maximizing the concentration of pozzolanic binding agents present and optimizing aggregate size while management practices need to minimize aggregate disruption.

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Conflicts of Interest

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

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