Structure properties and pore dynamics in aggregate beds due to wetting–drying cycles

Oscar Seguel,[1,2]* and **Rainer Horn**[3]

[1] Instituto Ingeniería Agraria y Suelos, Facultad de Ciencias Agrarias, Universidad Austral de Chile, casilla 567, Valdivia, Chile
[2] Departamento de Ingeniería y Suelos, Facultad de Ciencias Agronómicas, Universidad de Chile, casilla 1004, Santiago, Chile
[3] Institute of Plant Nutrition and Soil Science, Christian-Albrechts-Universität zu Kiel, Olshausenstraße 40, D-24118 Kiel, Germany

Summary

Aggregate hierarchy and porosity changes in aggregate beds as a consequence of wetting–drying cycles were studied in two Andisols and one Mollisol from Chile, collected at two depths. Bulk density and indirect tensile strength were measured in aggregates of different sizes. Aggregate beds were prepared in cylinders with two size classes. Six wetting–drying cycles between 0 and –60 hPa were applied. Bulk density (Db) of soil matrix was controlled after each cycle, and the macroporosity was calculated. A repellency index was measured in one of the Andisols. In addition, also the air permeability was measured after the sixth cycle.

It could be proofed, that the aggregate strength is an appropriate parameter to evaluate the aggregate hierarchy, and this parameter is also more sensitive than aggregate Db to discriminate between the effects of land-use intensity. Aggregate strength is furthermore well correlated with changes in pore water pressure and can be applied to relate strength values with aggregate development level. Only if the predrying exceeds pF > 3.0, aggregate strength correlates with Db. The more pronounced is the land-use, the higher is the increase of Db values for aggregate beds. The decrease of coarse porosity during wetting–drying cycles can be explained by mass differences between saturated and equilibrated water conditions that considers the water around aggregates and within the contact area. Nevertheless, the relation of relative macroporosity change, calculated by P_{exped} where D_{agg} is the Db measured by clod method, and the relative Db change, is useful to explain possible presence of coarse pores inside the aggregates. The newly formed porosity prevents the water repellency, but after six cycles of drying, the repellency index increased in the topsoil while we could detect a decrease in the subsoil samples (under defined conditions in the laboratory) which we assume to be caused by microbial activity. The approaching of aggregates by drying cycles generates in Andisols a reduced area to air fluxes, with low values of air permeability.

Key words: Andisols / tensile strength / porosity / bulk density / water tension.

1 Introduction

A soil aggregate is a structural entity with boundaries defined by the strength decrease in the interaggregate pores of the next largest aggregate in size (*Hallett* et al., 2000). The soil-aggregate hierarchy assumes that soil aggregates are made of smaller aggregates, and these are made of even smaller aggregates (*Dexter*, 1988a). These scaling properties depend on the pore structure and affect the fragmentation by tillage and natural processes (*Munkholm* et al., 2002).

It is well understood, that the first aggregation process is always governed by soil shrinkage and results in vertically oriented cracks which define a prismatic structure. Repeated wetting–drying cycles initially prepare smaller aggregate units but still with rectangular crack propagation followed by shear-induced formation of blocky and subangular-blocky structure (*Horn* et al., 1994). Thus, the wetting–drying processes are the primary factor of soil friability and the mellowing of compacted soils (*Barzegar* et al., 1995). As the result of swelling and shrinkage processes, the individual aggregate becomes denser initially with a higher bulk density (Db) and strength. However, with increasing wetting–drying cycles, the aggregate Db may be reduced while the aggregate strength at the same time furthermore increases (*Horn*, 1993; *Horn* and *Dexter*, 1989). Drying is more intense in smaller aggregates, because the distance from the center to the outer skin (evaporation surface) of the aggregate is smaller. Thus, it is possible, to dry out smaller aggregates more effectively and in a shorter time as compared to the bigger ones, where the distance between the center and the outer skin is much longer (*Hallett* et al., 2000). However, this more intense drying does not simultaneously result in stronger aggregates as the particle arrangement into the most stable system (*i.e.*, parallel arrangement of particles) with the highest amount of contact areas in between them requires time and may be only reached after several wetting–drying cycles and most probably under more moist conditions (under suction) where more pores are still water-filled and coarser to allow the particles to be pulled by the water menisci forces through them (*Horn*, 1994).

The main intention of the seedbed preparation is the breaking of bigger soil units into smaller ones without disturbing the soil microstructure (*Munkholm* et al., 2002). The loose and fragmented structure determines the total volume and size distribution of voids, important to physical characteristics

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* Correspondence: Dr. O. Seguel; e-mail: oseguel@uchile.cl

(*Ghezzehei* and *Or*, 2003). The subsequent wetting–drying cycles decrease the pore volume in nonrigid soils, increasing the soil strength and the hydraulic conductivity (*Peng* et al., 2005). Two mechanisms of age-hardening have been observed: particle rearrangement and particle–particle cementation (*Błażejczak* et al., 1995). Both mechanisms show the stabilizing effect of swelling and shrinkage in developing a more rigid pore system.

The relation between aggregate size and aggregate strength has been widely studied (*Utomo* and *Dexter*, 1981; *Dexter*, 1988a; *Hallet* et al., 2000; *Munkholm* et al., 2002). Nevertheless, the soil-aggregate hierarchy has not been demonstrated in Andisols, dominated by randomly interstratified minerals, and very similar to the Inceptisols with respect to the corresponding horizons and aggregate development (*Arnold*, 1985). Assuming that the smaller is the aggregate, the higher is the density and the strength, we want to examine the physical properties of differently sized soil aggregates in two Andisols, differentiated by their evolution level, and contrasting them with a typical crystalline soil from the Central Valley of Chile. Moreover, considering a seedbed as the arrangement of natural aggregates, we evaluated the porosity changes depending on wetting–drying cycles in aggregate beds.

2 Material and methods

Three soils were sampled from different places of the central valley of Chile. Table 1 summarizes the main characteristics of the soils. Bulk density was measured by cylinders taken at field water content. The Osorno soil is a characteristic volcanic ash soil (Andisol) from south Chile. Pemehue soil is a very young Andisol, very friable at the surface horizon, soft and loose in deeper horizons, with incipient development of structure. Both soils are dominated by allophane. Additionally, the smaller Db in the deeper horizons characterizes the Andisols. Graneros soil, a Mollisol, was selected with 2:1 minerals and a longer management history including a more intense land use.

Undisturbed samples were collected at two depths (0–15 and 40–55 cm, corresponding to Ap and Bw horizons, according to *USDA*, 2003) from the prairie sites, the oldest coming from Graneros soil. Aggregates were separated softly at field water content followed by complete water saturation. The aggregates were equilibrated in a pressure plate extractor at different pore water pressure (pF 1.78, 2.70, and 4.48; pF 4.00 in Osorno soil). The indirect tensile strength (crushing test, *Dexter*, 1988b) was measured for different aggregates sizes (0.5–4 cm; 25 aggregates per suction). The aggregate strength (S) is:

$$S = F / A,$$

where F is the force necessary to crack an aggregate, and A is the area at the center of the aggregate. The Db of the aggregates (clod method as described by *Blake* and *Hartge*, 1986) was measured under air-dry conditions, *i.e.*, at pF 4.5 for 20 aggregates per soil and depth). The aggregate size (1–5 cm) will be defined as the mean diameter, given by the average of the diameter in three axes.

After the crushing test, two groups of aggregate sizes were separated: 0.63–2.0 mm and 2.0–6.3 mm ∅, respectively. These two sizes tend to separate, in continuous ranges of natural aggregates: those that have a higher strength and/or density than the soil matrix and aggregates whose properties resemble those of the soil matrix properties.

The effect of porosity change due to repeated wetting–drying cycles was analyzed with aggregate beds, which were prepared packing the two size classes (0.63–2.0 and 2.0–6.3 mm) in cylinders of 3 cm height and 7 cm ∅. An initial settlement was reached applying a standard soft pressure. The initial bulk densities, in average (± standard deviation) for different aggregate size and/or depth, were 0.87 (±0.06), 0.65 (±0.02), 0.44 (±0.02), and 0.33 (±0.02) Mg m^{-3} for Graneros soil, Osorno soil, 0–10 cm Pemehue soil, and 40–60 cm Pemehue soil, respectively.

To each range of size and depth, one to six cycles of wetting and drying were applied in a pressure plate extractor. The maximum drying was –60 hPa in all soils and –300 hPa in Osorno soil, controlled by a vacuum meter. The equilibrium was reached for each cycle in 4 d. The –60 and –300 hPa (pF 1.78 and 2.48) were selected according to *Semmel* et al (1990) as the more effective drying intensity. After each cycle,

Table 1: Soil-taxonomy classification and some important properties of soils.

Serie	**Soil taxonomy**† **and latitude**	**Depth** (cm)	**Db** (Mg m^{-3})	**C_{org} (%)**‡ (%)	**Clay**‡ (%)	**Silt**‡ (%)
Graneros	Aquic Haploxeroll	0–15	1.32	2.04	18.6	41.0
(Mollisol)	34°50′ S	40–55	1.52	0.66	12.9	32.9
Osorno	Typic Hapludand	0–15	0.99	5.58	23.9	31.6
(Andisol)	40°60′ S	40–55	0.75	2.44	15.9	31.6
Pemehue	Pachic Fulvudand	0–15	0.69	9.30	22.5#	67.3#
(Andisol)	38°80′ S	40–55	0.41	5.58	27.7#	59.9#

† According to *USDA* (2003).
‡ From *CIREN* (1996, 2003).
# From *Mella* and *Khüne* (1985).

the soil cylinders were resaturated. Aggregate beds had six replications for each soil, aggregate size, depth, drying intensity, and number of cycles (192 samples in total).

Bulk density of the aggregate beds was calculated in the cylinder measuring the settlement with a caliper at –60 or –300 hPa after each cycle,. With the Db of each treatment, the interaggregate porosity was calculated by:

$P_{exped} = 1 – (Db / D_{agg})$,

where Db is the bulk density of aggregate beds (cylinders), and D_{agg} is the average Db of individual aggregate (clod method, *Blake* and *Hartge*, 1986) Assuming that the selected intensities of drying drain the interaggregate porosity only and the individual aggregates do not have coarse pores (>10 μm), it is possible to estimate P_{exped} by the difference between the saturated and equilibrated conditions, too.

The aggregate sorptivities in water and ethanol were measured to determine the water-repellency parameter R (*Hallett* and *Young*, 1999) in order to explain the possible effect of soil organic-matter (SOM) content on water movement/retention in the aggregate beds. This measurement was carried out only in Pemehue soil, because of its highest C_{org} content (Tab. 1).

Finally, to evaluate the strength regain of porosity system as a consequence of wetting–drying cycles, a 50 kPa load was applied to the aggregate beds prior to the determination of the air permeability (for more detail of the equipment, *cf.*, *Peth*, 2004).

Soil properties (aggregate strength, Db, porosity change) and aggregate size were fitted by linear and exponential regression equations (depending on best adjusts) by least-significant difference, with $p \leq 0.05$, using Statgraphics Plus v.2.0. Relation between diameter and aggregate strength was normalized by a log/log plot. Because the relative and the percent changes are limited between 0 and 1 and 0 and 100, respectively, the °Bliss-degrees transformation is recommended to obtain continuous values in infinite cartesians axes (*Fisher* and *Yates*, 1938). The transformation is given by [arcsin $\sqrt{(\%100)}$] and it was used on percent values of porosity-reduction comparisons. Analysis of variance was performed (LSD) with $p \leq 0.05$, comparing the effect of wetting–drying cycles on interaggregate-porosity changes.

3 Results

3.1 Individual aggregates

Figure 1 depicts the relationship between Db values as a function of aggregate diameter. Bulk density of individual aggregates is higher than Db of soil matrix (measured by cylinders of two equivalent diameters from nondisturbed samples). In Osorno and Pemehue Andisols, superficial horizons present a better correlation between aggregate diameter and Db than deeper horizons (Tab. 2).

Table 2: Interaction between soil-aggregate properties and aggregate diameter. * denotes significance with $p \leq 0.05$ (Db: bulk density, Mg m^{-3}; d: diameter, log cm; S: aggregate strength, log kPa; A and B: parameters).

Soil	Depth (cm)	Db = –A d + B	R	pF	S = –A d + B	R
Graneros	0–15	–0.042 d + 1.85	0.7886 *	4.48	–0.647d + 3.07	0.7676 *
				2.70	–0.259d + 2.17	0.4206
				1.78	–0.250d + 1.57	0.2672
	40–55	–0.067 d + 1.80	0.8168 *	4.48	–0.534d + 3.21	0.6286 *
				2.70	–0.871d + 1.94	0.7244 *
				1.78	–1.504d + 1.64	0.8585 *
Osorno	0–15	–0.041 d + 1.29	0.8487 *	4.48	–1.488d + 2.36	0.7756 *
				2.70	–1.057d + 1.51	0.5480 *
				1.78	–1.066d + 1.47	0.7386 *
	40–55	–0.041 d + 1.13	0.4321 *	4.48	0.272d + 1.16	0.0943
				2.70	–1.569d + 1.41	0.7491 *
				1.78	Not determined	————
Pemehue	0–15	–0.017 d + 0.79	0.7392 *	4.48	–0.856d + 1.87	0.7108 *
				2.70	–0.691d + 1.48	0.6576 *
				1.78	–0.564d + 1.40	0.4684 *
	40–55	–0.052 d + 0.85	0.4972 *	4.48	–0.093d + 1.68	0.1010
				2.70	–1.974d + 1.82	0.5675 *
				1.78	–1.647d + 1.71	0.5810 *

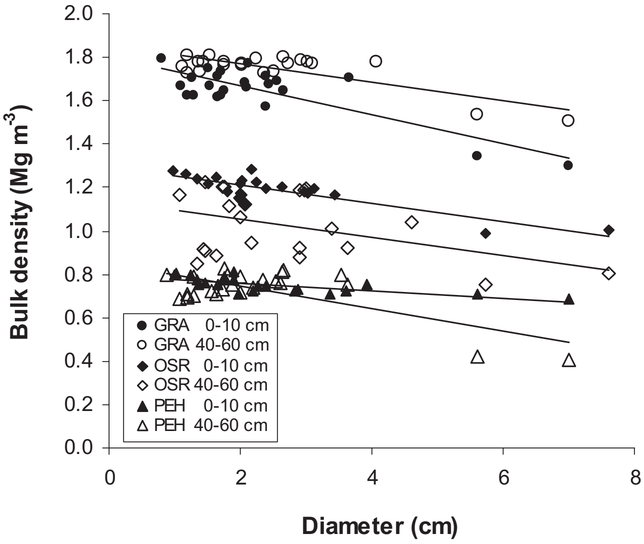

Figure 1: Bulk density as a function of average diameter. Soils are arranged from the oldest to the youngest (GRA, Graneros soil; OSR, Osorno soil; PEH, Pemehue soil). The biggest two diameters are from cylinders (equivalent diameter as the average of three axes). Lines correspond to lineal regressions.

Soil-aggregate strength, at different matric tensions, increased exponentially with decreasing diameter as shown for the 0–15 cm horizon in Fig. 2. Aggregate strengths of Andisols from 40–55 cm depth were, however, not correlated with aggregate diameter if the samples were air-dried (pF 4.48). Samples of Osorno soil, from 40–55 cm, equilibrated at pF 1.78 were not measured because they were very soft and they broke while handling. Table 2 sums up the equations for the two depths. In general, in all soils and horizons, the strength increased with decreasing aggregate diameter.

The relation between aggregate strength and water tension is closely related with soil development (Fig. 3). In general, in all 0–15 cm soil horizons of the investigated three soils, the relation between aggregate strength and water tension shows an exponential curvature with curvature coefficients (1.2; 0.59, and 0.49, respectively) increasing with the evolution. The more developed is the soil, the higher is the coefficient. The oldest Graneros soil is located in a climate zone where drying and wetting are very common and intense down to deeper depth. Figure 3a shows a very intense increase of aggregate strength when soil dries out, and confirms the predessication conditions of that site where most probably suction values > pF 4.2 are reached.

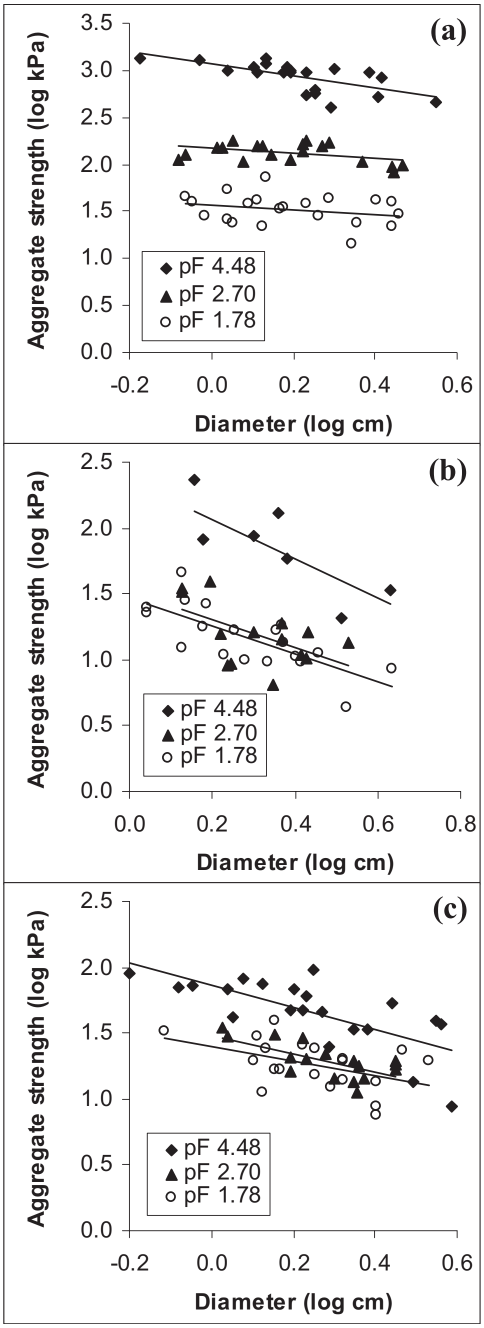

Figure 2: The log/log plot of aggregate strength and aggregate diameter as function of matric tension in (a) Graneros soil, (b) Osorno soil, and (c) Pemehue soil. Samples from 0–15 cm. Lines correspond to lineal regressions.

The 40–55 cm horizon has an exponential behavior only in Graneros soil, as was already derived from the water regime at this site, with higher suctions in deeper horizons during summer. In Osorno, where we can find volcanic-ash soils with greater evolution, the strength increase with the water-tension increase is linear, while in the youngest Andisol (Pemehue soil), the behavior is inverse: the aggregates become softer with the tension increase and show a behavior very similar to sandy soil. In any case, visual observations allow to conclude that some of these aggregates from 40–55 cm of Pemehue soil probably are concretions, and this is the reason why they have higher strength than aggregates from Osorno at the same depth (Fig. 3).

When strength is plotted as a function of Db (Fig. 4), we found a good correlation if the samples are drier than pF 3. The higher C_{org} content in the Andisol "site Pemehue" supports the high mechanical-strength increase at high water content,

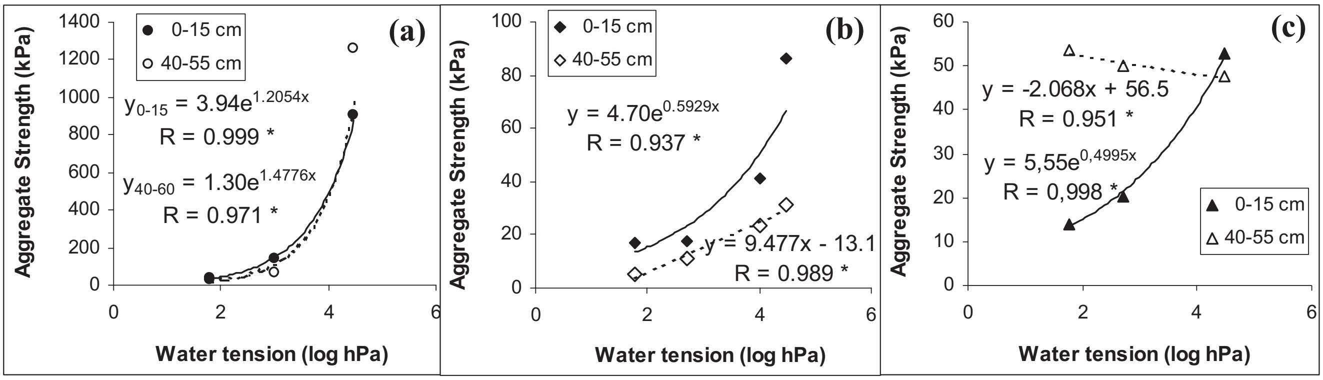

Figure 3: Aggregate strength as function of water tension. Soils are sorted from the oldest to the youngest (a, Graneros soil; b, Osorno soil; c, Pemehue soil). Filled line (0–15 cm) and dotted line (40–55 cm) correspond to regressions with all equations significant with $p \leq 0.05$.

but when this soil dries out, the reduced menisci forces result even in a soil softening and a strength decrease.

3.2 Aggregate beds

Assuming that few cycles of wetting and drying do not affect the Db of natural aggregates, one or six cycles of wetting and drying were applied to the aggregate beds of two size classes, controlling the Db changes. Aggregate sizes are referred in Fig. 5 as “fine” aggregates (0.63–2.0 mm) and “coarse” aggregates (2.0–6.3 mm). When one cycle was applied, Db of Andisols did not change significantly from initial conditions. Nevertheless, one cycle was enough to increase the Db of 40–60 cm aggregate beds from Graneros soil.

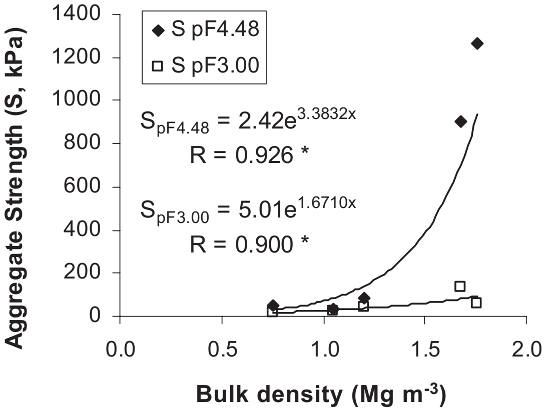

Figure 4: Aggregate strength as function of aggregate bulk density at two water-tension values. Average of all aggregates from each soil and depth. Exponential regressions significant with $p \leq 0.05$.

It is well known that wetting–drying cycles promote the increase of the aggregate Db (*Horn*, 1993) and the age hardening of soils (*Błażejczak* et al., 1995). In aggregate beds, the behavior was similar, as can be derived from the increase in Db with increasing number of wetting–drying cycles. Because the most pronounced changes were detected for the 0 to –60 hPa cycles, as compared to the changes induced by the 0 to –300 hPa range, we primarily continued with the smaller suction range for the other soils.

The most important change in Db was in Graneros soil, where we found 50% increase in the Db of the fine-aggregate beds in the superficial horizon. In this soil, one complete cycle was sufficient to promote differences between depths and between aggregate sizes. The other soils present differences between depths only.

Additionally after six cycles, the behavior was different between the soils. Osorno soil presented an increase in the Db of the aggregate beds from 40–60 cm (at any size of aggregates and intensity of drying), while Pemehue soil had an increase in beds of 0.63–2.0 mm aggregates (at any depth).

Table 3: Interaggregate porosity after (%v/v) one (t0) or six (t6) wetting–drying cycles. Asterisk in bold type: significant changes ($p \leq 0.05$).

	OSORNO (–300 hPa)		**OSORNO** (–60 hPa)		**PEMEHUE** (–60 hPa)		**GRANEROS** (–60 hPa)	
	t0	t6	t0	t6	t0	t6	t0	t6
0–10 cm (fine)	45.7	45.2	44.2	44.2	**42.0**	***33.9**	**52.1**	***28.0**
0–10 cm (coarse)	45.2	46.5	44.9	45.2	40.6	40.5	**49.8**	***36.3**
Total porosity (average 0–10 cm)	74.4	74.6	74.0	74.0	76.7	75.1	**69.1**	***57.3**
40–60 cm (fine)	**40.6**	***34.3**	**39.5**	***28.9**	**56.3**	***50.4**	**48.9**	***43.5**
40–60 cm (coarse)	**40.8**	***37.7**	**38.9**	***31.8**	56.0	55.7	**47.3**	***44.5**
Total porosity (average 40–60 cm)	77.5	75.7	76.9	73.6	86.4	86.3	65.7	63.4

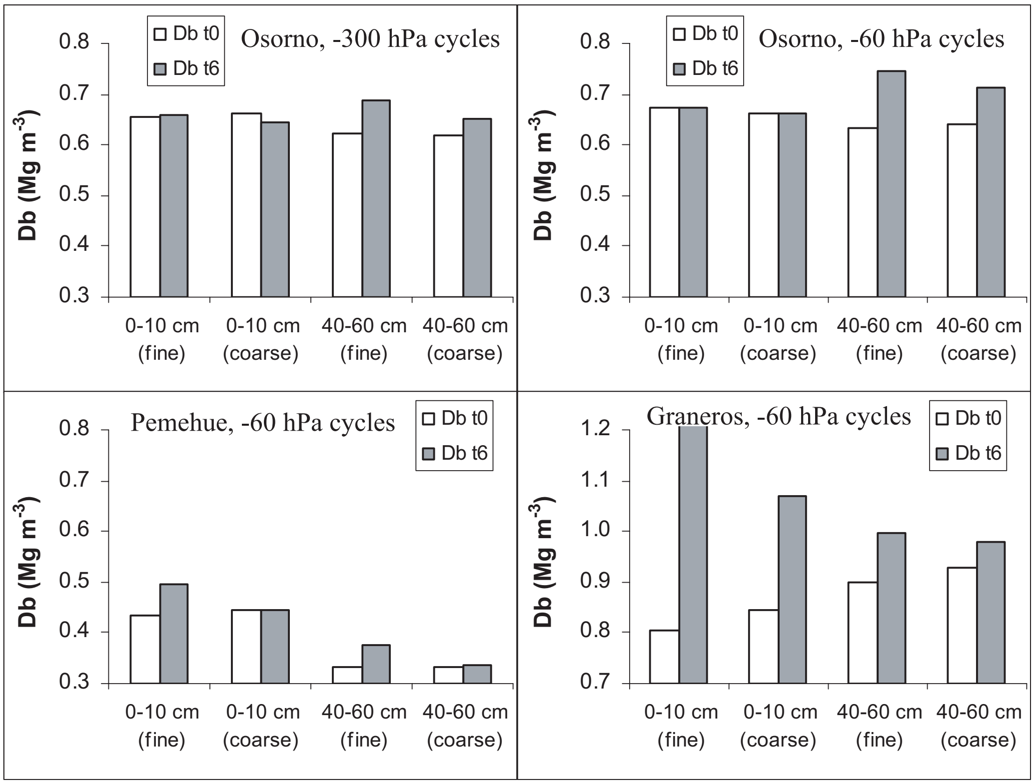

Figure 5: Bulk density (Db) of aggregate beds when one (t0) or six (t6) wetting–drying cycles were applied (fine: 0.63–2.0 mm aggregates; coarse: 2.0–6.3 mm aggregates).

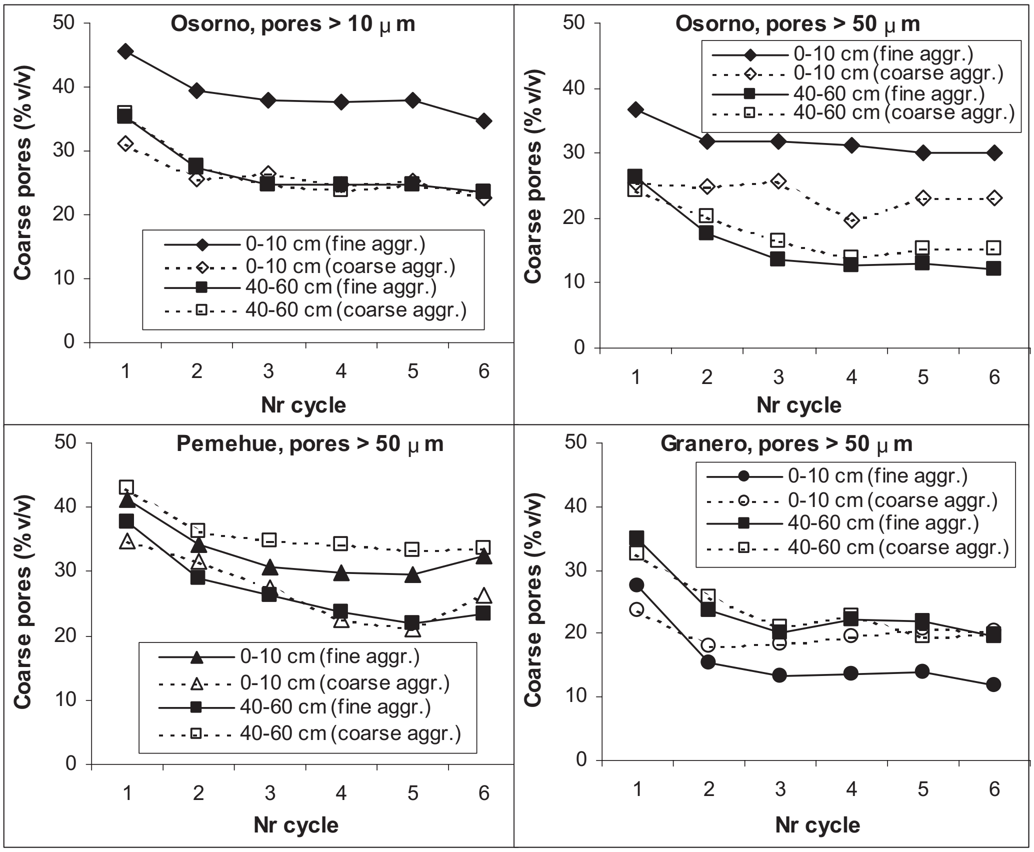

Figure 6: Coarse porosity calculated by the difference between saturated water content and equilibrated at –60 or –300 hPa water content (fine aggr.: 0.63–2.0 mm aggregates; coarse aggr.: 2.0–6.3 mm aggregates).

The greater increase of Db of Graneros soil was in the superficial aggregates beds.

If we assume that the density of natural aggregates does not change significantly with drying cycles, we can calculate the interaggregate porosity ($P_{exped} = 1 - (Db / D_{agg})$), using the Db of the bed (from Fig. 5) and the Db of individual aggregate. Table 3 presents the results for one and six cycles.

Results of Tab. 3 reflect the differences between bars in Fig. 5. The reduction of interaggregate porosity by the drying cycles (t6 *vs.* t0) is very pronounced in the superficial samples of Graneros soil. An additional aspect about the coarse-porosity evolution by drying cycles is presented in Fig. 6, where the differences between the saturated and equilibrated condition at each cycle is shown. We define this mass difference as "coarse porosity" and distinguish it from the "interaggregate porosity" of Tab. 3.

It was expected that data from Tab. 3 and Fig. 6 are identical. Nevertheless, always the interaggregate porosity, calculated by P_{exped}, was greater than the macroporosity, calculated by the difference between the saturated and equilibrated water condition. Figure 6 shows a continuous decrease of coarse porosity from first to third cycle and a corresponding stabilization, with very clear differences between the first and sixth cycle. The coarse pores (10–50 µm ∅) in Osorno soil remained constant during cycles (3%–7% in 0–10 cm aggregate beds and 9%–11% in 40–60 cm aggregate beds, data not shown). So, the main porosity loss is in pores >50 µm. The lower values of macroporosity, derived from Fig. 6, could be explained by changes in Db of aggregates during the measurements, or also the aggregates have coarse interaggregate pores which can contribute to the macroporosity.

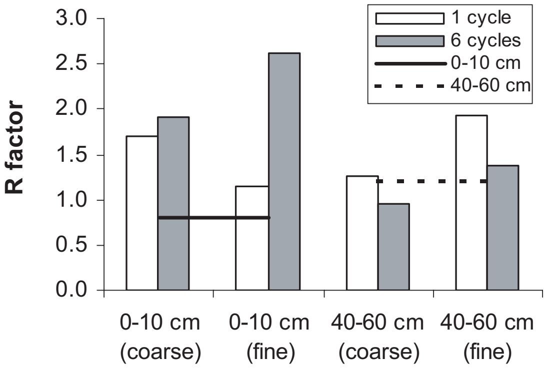

Figure 7: Water-repellency index (R) in aggregate beds of Pemehue soil. R values of nondisturbed soil are presented as full line (0–10 cm) and dotted line (40–60 cm). R > 2.0 denote a repellent soil.

A third explanation could be the water repellency. If some pore surfaces are covered by organic acids, the water saturation of these pores may be prevented and result in an underestimation of the pore system shown in Fig. 6. The R factor of water repellency (*Hallett* and *Young*, 1999) determined from sorptivity in water and ethanol is shown in Fig. 7.

Irrespective of the high C_{org} content, the Pemehue soil is nonrepellent (R values < 2). Only aggregate beds of 0.63–2.0 mm from the superficial horizon became repellent after six cycles of wetting and drying. However, it has to be pointed out that all samples of aggregate beds from 0–10 cm had higher R values than those of the soil matrix (full line in Fig. 7), R values of aggregate beds from 40 to 60 cm are close to the matrix R value.

If the percentage of porosity reduction estimated by P_{exped} is plotted against the percentage of porosity reduction estimated by mass difference, we can obtain a potential adjust ($y = a x^b$). Nevertheless, for percent values is recommended the °Bliss transformation (*Fisher* and *Yates*, 1938). This transformation results in a linear relation (Fig. 8a), with a slope close to 0.5. Thus, the P_{exped} is more sensitive to porosity changes. Nevertheless, when interaggregate porosity of some aggregate beds did not present differences after six cycles of wetting and drying (Tab. 3), the mass-difference method (macroporosity of Fig. 6) presented reductions of about 25% (Fig. 8a).

Figure 8 tries to explain the lower values of coarse porosity by mass difference with respect to the interaggregate porosity. If we assume that there are no coarse pores inside the aggregates, the P_{exped} relation only excludes the volume of individual aggregates as water-filled porosity, not considering the contact point in between aggregates. By mass difference between saturated and equilibrated water condition at –60 hPa, the contact area is considered as water-filled porosity,

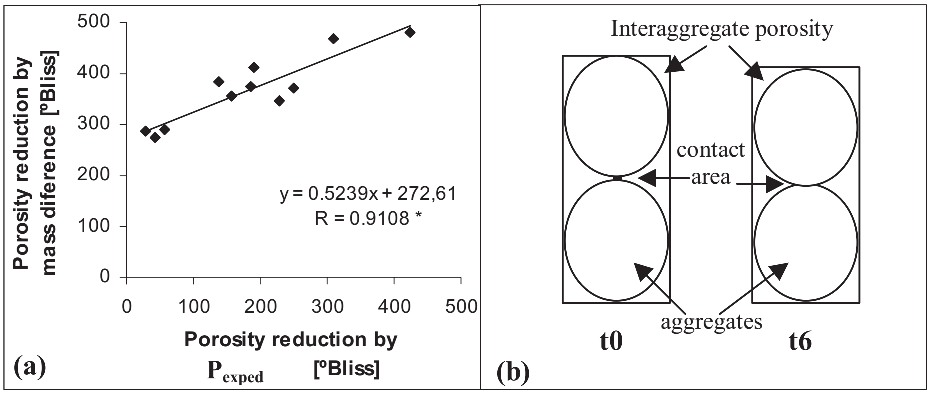

Figure 8: (a) Reduction of interaggregate pores, calculated by P_{exped} against reduction of coarse porosity, calculated by mass difference. Data from significant changes of Tab. 3. Lineal regression significant with $p \leq 0.05$. (b) A simple model to explain the contact-area increases by wetting–drying cycles (t0: initial; t6: after six cycles).

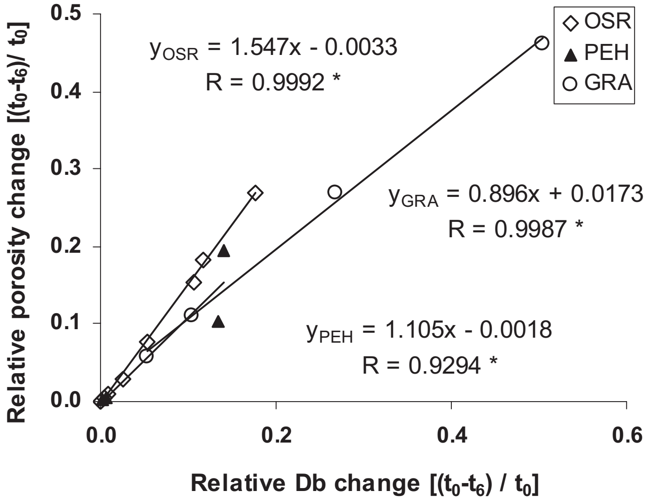

Figure 9: Relatives changes of bulk density (Db) and interaggregate porosity as a consequence of wetting–drying cycles (OSR, Osorno soil; GRA, Graneros soil; PEH, Pemehue soil). Linear regressions are significant with $p \leq 0.05$.

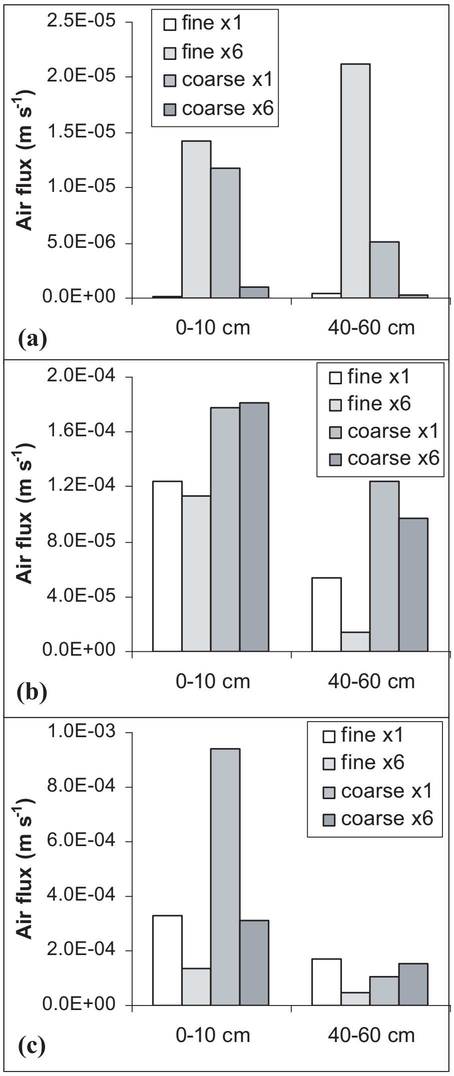

Figure 10: Air conductivity of aggregate beds after 50 kPa load. Fine-aggregate bed (0.63–2.0 mm) and coarse-aggregate bed (2.0–6.3 mm) comparing one (x1) and six (x6) cycles in (a) Graneros, (b) Osorno, and (c) Penehue soils.

showing lower values of coarse porosity compared with the interaggregate method. Increasing wetting–drying cycles result in more pronounced contraction forces which pull aggregates together (*Kemper* and *Rosenau*, 1984; *Nearing*, 1995) and in coarser and more interaggregate pores, even if the average diameter is reduced.

The porosity behavior of different soils when the Db increased is presented in Fig. 9 as a relative change. The relative changes consider the absolute difference between t0 and t6 divided by t0 and correspond, in general, to porosity reductions by Db increases (data for Db from Fig. 5 and for porosity from Tab. 3).

Generally, we should expect slopes near 1.0 between the relative change of interaggregate porosity and the relative change of Db. However, the slope in Osorno soil shows a greater decrease of interaggregate-porosity changes than increase in Db, while on the other hand Graneros soil had a smaller decrease of relative porosity than increase of Db. The more intense aggregate approaching gives to Graneros soil an increase in contact area, without a similar decrease of interaggregate porosity.

Finally, the effect of aggregate-bed packing and rearrangement of the aggregates after stress application of 50 kPa on the air permeability is documented in Fig. 10.

In general, the two Andisols (Osorno and Pemehue) have small air-permeability values after six cycles, due to the narrowing of the single aggregates. The more pronounced decrease was in coarse-aggregate beds of superficial horizon from Pemehue soil, but the final air permeability was higher than of any other aggregate beds from Osorno and Graneros soils. The higher mechanical strength of Andisols compared to 2:1 clay-dominant soils results in better ecological functioning of the Andisols irrespective of the applied external load. In Graneros soil, the high strength of individual aggregates and the increase of Db of the beds by wetting–drying cycles prevent the consolidation of fine-aggregates beds, increasing the air permeability with respect to a single cycle.

4 Discussion

It is well known that wetting and drying always results in a structure formation which in addition is the stronger the drier had been the soil and the more often these cycles have occurred. As the initial normal shrinkage always results in an irreversible decrease in pore space and an increase in Db, repeated wetting–drying cycles can be detected by an elastic structural shrinkage behavior which can be related to the maximum predrying intensity and can be determined as the predrying stress equivalent to the precompression stress (*Baumgartl*, 2002; *Peng* et al., 2005; *Peng* and *Horn*, 2005).

Consequently, our data completely confirm these findings because especially at a depth of 40–60 cm in the Andisols, we could detect a slight proportional shrinkage behavior which can be verified by the increase in the Db and soil strength at pF 4.48.

Furthermore, when superficial samples of Graneros soil are moist ($pF < 2.7$), we could not find a correlation between aggregate strength and aggregate diameter, probably because the long-term plowing destroyed bondings between particles and also prevented aggregate reformation. *Guber* et al. (2004) found that compaction resulted in smaller differences in specific pore volumes between different aggregate-size fractions, while *Horn* (2004) claimed that mechanical properties are time-dependent, while Db is less sensitive to time effects.

The small slope of aggregate strength as function of aggregate diameter of Graneros soil, especially when it is wet, denotes the absence of aggregate hierarchy as a consequence of plowing which is in agreement with the findings of *Hallet* et al. (2000).

A soil without internal macrostructure presents a slope very close to zero, and wetting and drying will induce the macrostructure formation, with an increasing friability of bigger soil units (*Dexter*, 1988b).

Results of Db as a function of aggregate diameter define Graneros soil as the more developed soil, with highest intercept and slope at each depth. The profile of Pemehue soil is soft and loose in deeper horizons, but in the laboratory, at any water tension, it was possible to find structural units, probably concretions or nodules. This is the reason why in 40–60 cm horizon and pF 4.48, there is no correlation between aggregate diameter and aggregate strength. Probably the same situation occurred in Osorno soil. The high amount of Fe and Al in these soils (*Sadzawka* and *Besoaín*, 1985) made the presence of these units or their abundance in the incipient aggregates possible as chemical structural agents. However, we were not able to differentiate between the hydraulic, the mechanical, and the chemical effects but there is more analytical work needed to differentiate between these "groups".

At the same water tension, the intercepts of the equations (Tab. 2) follow a very distinct trend (Graneros > Osorno > Pemehue), according to the more pronounced and longer lasting drying-and-wetting history of Graneros soil showing a more pronounced rigidity of the pore system or structural strength (which is in agreement with the findings of *Peng* and *Horn*, 2005). Both Andisols are developed under an annual precipitation of 1700 mm y^{-1}, while Graneros has 450 mm y^{-1} (*Santibáñez* and *Uribe*, 1993; *Beinroth* et al., 1985). Thus, the soil under xeric climatic conditions includes aggregates which become stronger with the drying intensity (unwatered during the summer and continuously irrigated) at the same aggregate diameter (*Horn* et al., 1995).

The strength increase with drying is normal in soils with fine particles (*Barzegar* et al., 1995). The soil softening of 40–60 cm samples from Pemehue soil is expected because of the high amount of silt, as the effect of menisci forces declines with drying like in sandy soils.

According to *Horn* et al. (1995), the transition from stress-induced increase to decrease of water menisci forces is always affected by the process of mechanical stress–dependent pore-size rearrangement, whereby the properties of the aggregate further define the slope of X factor (from effective-stress theory) on pF curve. According to this, when aggregates of Db ≈ 1.6–1.8 Mg m^{-3} are loaded, coarser pores are diminished in diameter, resulting in higher values of X factor, very close to 1 for a wider range of water tension. In this case, the Db is lower, and probably the aggregates have an important volume of intra-aggregate coarse pores. Unfortunately, because of methodological problems, it was not possible to know a reliable pore-size distribution of individual aggregates, but apparently Osorno soil has pores >10μm in aggregates >2 cm (unpublished data). Thus, there is an intense need to analyze the effective stress of individual aggregates of Andisols.

When aggregate strength is plotted as function of Db, a good correlation is obtained for air-dried soil conditions. Even though the dry condition allows the maximum strength expression, as already explained, the more intense drying gave a proportional shrinkage and affected the strength changes due to this first drying exceeding the previous drying intensity. When soils are wet, there is no correlation because of the high water stability of Andisols and low water stability of Graneros soil (*Ellies* et al., 2002).

Our results furthermore support the idea, that the initial strength increase can be related to the increased density of aggregates. There is either an effect of the initial crack or aggregate formation in order to compensate the same mass at a smaller number of contact points between structure units, and/or it can be explained with the process of particle cementation in aggregates by SOM, Fe, *etc.* In addition, the amount and kind of clay content furthermore affect the particle rearrangement. It is possible to find the higher soil strength in less dense aggregates if at the same time the fine particles are nearly parallel, optimizing the forces per area (*Horn* and *Dexter*, 1989). *Barzegar* et al. (1995) found out that when clay content is about 10%, it is deposited within the pores between sand and silt particles. When clay content increased from 10% to 20%, clay coats sand and silt particles, acting as bridging clay particles. Finally, when clay content is >20%, the clay particles completely coat the units of sand and silt and their bridges dominate soil strength. However, because the analysis of the clay content in Andisols is not easy to measure due to the difficulty of dispersion, further research is needed to differentiate between these two mechanisms of aggregate formation. Identical reactions can be also seen in the presence of SOM, as it increases the water stability, and the contact area between particles will be optimized (*Ellies* et al., 2002).

When cylinders were filled with natural aggregates, the first wetting process promotes the slumping of beds, which is identical to a complete settlement resulting from wetting, but without an aggregate slaking. The wetting itself was slow enough to prevent the hardsetting. This is the reason why in some treatments, there were no differences in bulk densities (Db) between the first and the sixth cycle. However, the first drying process was the most important one with respect to the increase of the Db, which is also in agreement with the results on individual aggregates (*Horn*, 1993; *Zhang* et al., 1997). The 0 to –60 hPa cycle was more effective if we consider the increase of the Db in Osorno soil because the aggregates can be rearranged in wetter conditions more intensely, similar to particles in an individual aggregate, with smaller amount of free energy than in drier conditions (*Horn*, 1993).

One cycle of wetting and drying was enough to obtain a Db value very close to the final value after six cycles. However, in superficial samples of Graneros soil, the subsequent cycles were important in the Db increase. The results show that in Graneros soil, which is oldest but intensely tilled, in 0–10 cm horizon, we have to expect that the initial shrinkage again starts and results in a more pronounced rearrangement of aggregate pieces and/or particles (*Hartge* and *Horn*, 1984).

In general, porosity between 10 and 50 μm of Osorno soil kept constant during the cycles (differences between pores >10 μm and pores >50 μm of Osorno soil), which is identical to a main porosity loss in pores > 50 μm. According to Tab. 3, however, in superficial aggregates of Osorno soil, we could not proof this trend as the Db kept constant after six cycles. Nevertheless, the interaggregate porosity (P_{exped}) was estimated using the Db of air-dry aggregates. If never before the aggregates were dried at pF 4.48, the interaggregate porosity could be overestimated by the more dense aggregates.

Finally we have to draw our attention also to the fact that undisturbed Andisols are water-repellent, which was explained by the high amount of C_{org} (*Orellana* et al., 2004). Nevertheless, in their pedogenetical processes, there are no evidences of C translocation or organic-coating formation. The well-structured aggregates are related to high amounts of C_{org} inside them, higher than in the soil matrix (*Ellies* et al., 2005). The high C amount protects the aggregates against water dispersion and gives them high water stability. In our own experiments, we could not differentiate between the coating and the total amount of C_{org} effect as we prepared just aggregate beds for the experiments, and also the wetting–drying cycles were not sufficient to proof these differences.

The low water repellency of Pemehue soil can be explained by the kind of SOM (*Ellies* et al., 2003) and indicates that the relation between Db and aggregate strength is most probably no wettability problem, according with the SOM accumulation in structural units (*Ellies* et al., 2005).

It is possible to have water repellency inside the aggregate, but with a slow wetting, all pores should be water-filled. Assuming a complete wettability, Fig. 8 explains the differences between Tab. 3 and Fig. 6. The forces acting in the contact area of aggregates are the surface tension of water and the pressure differences between the air and water phases. Perhaps, a large portion of soil water is not only in the capillary wedges of contact area, but is adsorbed in thin films on the aggregate surface (*Kemper* and *Rosenau*, 1984). The mass difference between saturated and equilibrated water content considers these portions of water, giving lower amounts of coarse porosity than the soil matrix and aggregate-Db estimation. The other possibility is the presence of coarse pores inside the aggregates, and the drying cycle increased the aggregate density. So, the increase in Db of the aggregate bed is explained by the settlement of aggregates a little bit dense, and not by the increase in contact area between aggregates.

Because, in addition, the interaggregate water content has an important function in effective stress, as it was demonstrated by *Nearing* (1995), further research is needed on this subject in the future.

Finally, the pore functioning after wetting–drying processes gave very interesting differences. It is well known that the effective stress between aggregates could be altered by mechanical or hydraulic stresses (*Baumgartl* et al., 2000). The drying processes give an internal (hydraulic) stress, while the load applied before measuring the air conductivity gives an external (mechanical) stress. In general, the aggregate beds maintain or decrease the air permeability, except aggregates of 0.63–2.0 mm from Graneros soil. *Horn* (2004) showed that the homogenization of the pore system results in smaller Db values and reduced values of the hydraulic conductivity, but functioning of pores is improved with time with increasing values of hydraulic conductivity even at higher Db values. In the case of air flux, the results were opposite, the increase of Db resulted in an approach of aggregates, with a lower flux area.

According to the greater evolution of superficial horizons in Andisols, at any aggregate size and number of cycles, the topsoil presented the higher values of air flux and underlines the higher mechanical strength of the system. The constant values for the air conductivity in superficial samples of Osorno soil support the idea that aggregates of topsoil horizon from this soil could have continuous pores >10 μm ∅. Thus, finally we can argue that in aggregate beds of Andisols, the phenomenon of settlement of aggregates on their smaller parts, densification of the aggregates themselves, and the shrinkage of the aggregates can occur.

5 Conclusions

It was possible to find a structural hierarchy in the log/log relation of aggregate strength and aggregate diameter of analyzed soils, especially in the two Andisols. The aggregate-strength values allow the differentiation depending on the plowing intensity in the Mollisol, which lost the hierarchy in the superficial horizon. The same is true for Andisols at low water-tension values.

The more intense plowing of the Mollisol explains the higher increase of Db in the aggregate beds. The macroporosity change by wetting–drying cycles was evaluated by two approaches: mass difference and interaggregate porosity (P_{exped}), being more sensitive for the first one. The water in the contact area between aggregates, considered as the mass-difference approach, made it more reliable to analyze the porosity change.

The air conductivity kept constant or decreased with wetting–drying cycles in Andisols, but their final values were higher than those determined for the Mollisol. The low Db of Andisols explains the high amounts of coarse porosity with high values of air conductivity, allowing the aggregate rearrangement during wetting–drying cycles. Nevertheless, the pore dynamic of aggregate beds of Andisols is a complex process that needs further investigation about the effective stress of individual aggregates and age hardening of aggregate beds.

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