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SOIL TENSILE STRENGTH AS AFFECTED BY TIME, WATER CONTENT AND BULK DENSITY

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Abstract. We investigated the effect of soil water conditions and soil compaction on the age-hardening process of loamy sand and silty loamy sand in relation to the tensile strength. Soil samples from Germany (loamy sand) and Poland (silty loamy sand) were moulded at water contents 10 %, 15 %, 20 % and compacted up to 1.35, 1.45, 1.55g/cm^3. The samples were stored at constant water content. At intervals after moulding, the tensile strengths of the moist samples were measured with the indirect tension (Brazilian) test. The maximum aging time was 10 days. With increasing time the soils became stronger at the same water content. The higher the initial water content the less pronounced was the strength increase with time. Furthermore, increase in bulk density resulted in higher values of tensile strength. Two different mechanisms of age-hardening could be identified.

Keywords: soil tensile strength, Brazilian test, age-hardening.

INTRODUCTION

The mechanical strength of soil is very important in agriculture. Arable soils have to be sufficiently weak and friable to be worked economically during tillage, while at the same time they have to be sufficiently strong to carry loads. Internal parameters like soil structure, texture, water suction or orientation of continuous pores are mostly important in order to withstand any further deformation [2]. The strength properties of soil are influenced in time after straining. When a previously undisturbed soil is disturbed by straining, the soil particles move relative to each other and any bonds between the particles are broken. For this reason, the strength of recently disturbed soil is lower than that of undisturbed soil even at the same density and water content [3]. If, after the disturbance, the soil is kept at constant density and water content, it is usually found that some or all of the orginal strength is regained [1-3,9,14-17]. This effect is known variously as age-hardening, curing, stregth regain, or thixotropy. Therefore Mitchell [14] defined thixotropy as an isothermal, reversible, time dependent process occurring under conditions of constant composition and volume, whereby a material stiffens while at rest, and softens or liquifies when remoulded. The term thixotropic hardening is used if the conditions of the system meet Mitchell's definition. In other cases with other mechanisms involved, the term age-hardening will be used.

THEORY

In investigations of the age-hardening process the thixotropic strength ratio, that is the strength at time *t* divided by the strength at the beginning (at time equals zero), is used in order to permit comparisons between soils of different composition, or between samples of the same soil at different water contents [3,14,17]. In these cases the absolute strength increase may be misleading.

A knowledge of the factors, responsible for thixotropic strength increase, will deepen the understanding of the soil structure and the shear strength behaviour. A number of different processes have been described which can contribute to age-hardening. Two main mechanisms have been obserwed in the age-hardening of soils [3]: particle rearrangement (type A) and particle-particle cementation (type B). An important difference between type A and B is the different relation to compaction pressure. The strength increase ratio was given as S/S_o, where S_o was minimum strength after remoulding and S was the strength of the soil after a certain aging period. Particle rearrangement (Type A) mainly occurs through colloidal particles, especially, the colloidal clay. With this mechanism, new particle-particle bonds are formed by the rearrangement of soil particles. The tixotropic strength ratio, S/S_o, is dependent of the compactive stress (Fig. 1). For particle-particle cementation (Type B) into the reinforcement or strengthening of particle-particle bonds it is necessary for the particles to be in contact initially. With this mechanism, no new bonds are formed, but existing bonds become stronger. The strength increase ratio, S/S_o, is independet of the level of compaction (Fig. 1).

MATERIAL AND METHODS

Indirect tensile Strength (Brazilian test)

Crushing tests are often called 'indirect tests' because a tensile stress is induced in one direction by a compressive stress acting in another direction. Tensile strength is probably the most useful measure of strength of individual soil aggregates. This is true because: it can be determined from simple tests, it can be measured on a wide range of aggregate sizes, and it is very sensitive indicator of the condition of a soil [4]. The crushing of cylindrical samples, loaded along lines at opposite ends of diameter, has subsequently been applied to soils [5-7,9,11,12]. This test is often referred to as the 'Brazilian test'. If a cylindrical soil sample is crushed according to Fig. 2a by a force F, then, at the moment of failure:

$$Y_c = \frac{2F}{\pi DL} \qquad (1)$$

where F is vertical force at breaking, Y_c is tensile strength, D is sample diameter, and L is sample length.

The formula is assuming perfect elasticity up to the moment of failure [13]. The method has the advantage that maximum tensile stress occurs at the centre of the sample away from any surface effects. Also, the tensile stress is fairly uniform through the central region of the cylinder (Fig. 2b), limited amounts of flattening

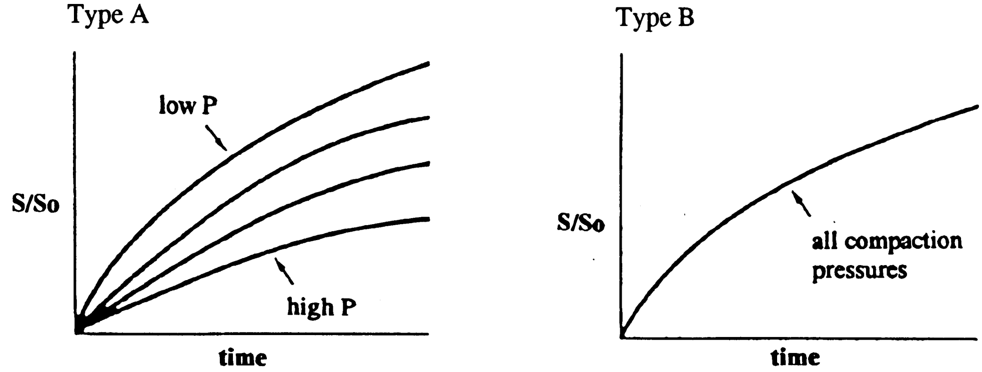

Fig. 1. Age-hardening mechanisms Type A and B. Strength increase ratio, S/S_o, as functions of compaction pressure, P, and time since compaction. It is possible to distinguish between the two possible mechanisms, A and B, by measuring the age-hardening after moulding for soil samples which have been compacted by different levels of stresses, P.

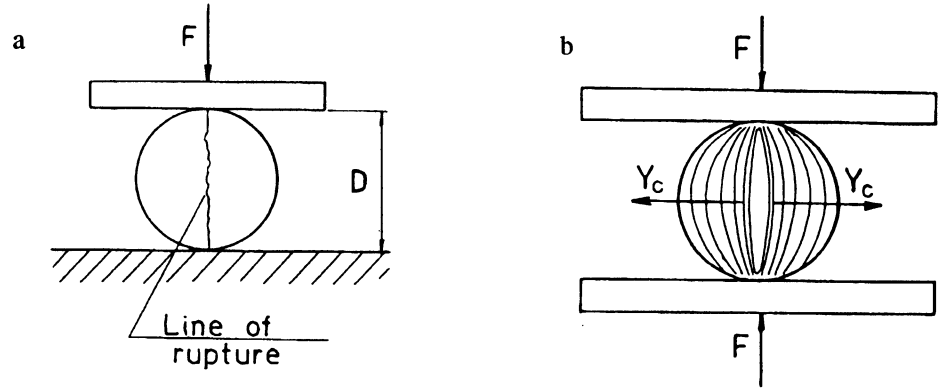

Fig. 2. a) Geometry of tensile strength determination of a soil cylinder material given by Eq. (1). b) Contours of equal tensile stress in a diametrically loaded soil cylinder.

around the lines of loading have only a small effect on the maximum tensile stress [2,5]. The central two contours have values of 0.96 and 0.89 of the maximum tensile stress given by Eq. (1).

When moist aggregates are crushed, some plastic deformation and flattening often occurs at the poles where the load F is applied [5], and according to [4,7]. Frydman [5] examined the effects of this flattening on the Brazilian method for soil tensile strength measurements. By Frydman [5] the tensile strength of the cylindrical samples is given by:

$$Y_c = \frac{2F}{\pi DL}\, g(x) \qquad (2)$$

where $g(x)$ is a reshaping factor. Frydman's theoretical analysis gives:

$$g(x)=-\frac{D}{2a}\left\{2f-\sin 2f-\frac{2y_1}{D}\log\tan\left(\frac{\pi}{4}+\frac{f}{2}\right)\right\} \qquad (3)$$

which predicts $g(x)>0.9$ for $f<0.27$. When no flattenig occurs, $g(x)=1$. When flattening ratio occurs, a flattening ratio f can be defined such that $f = a/y_1$, where a is the half width of the flattened portion and y_1 is the half distance between the portions at failure. Gusli *et al.* [7], reported that in practice $g(x)$ was greater than 0.97 for the large majority of beds tested.

Table 1. Some physical and chemical properties of the two tested soils

Soil type	Horizon	Texture (%)*			Organic carbon (%)	pH	Plastic limit (%)
		sand	silt	clay			
Luvisol glacial till Kiel/Germany	Ap	59	26	15	0.89	6.9	17.6
Chernozem, loess Szczecin/Poland	Ap	47	40	13	1.23	7.2	19.1

*Sand 0.063-2 mm; silt 0.002-0.063 mm; clay < 0.002 mm.

Soil

Two horizons of soil were used in the experiment. The first A_p-horizon of a-luvisol derived from glacial till site Achterwehr, was from around of Kiel in northern Germany. The second soil, horizon Ap-forest-meadow chernozem site Pyrzyce, was from around of Szczecin in northwestern Poland. Some details of these soils are given in Table 1.

Experimental procedure

The air-dried soils were ground to<2 mm and wetted to 3 different water contents (about 10, 15 and 20 % w/w) and stored in sealed plastic bags for 4-6 days to allow redistribution and equilibration of the added water.

The soils were re-mixed before the experimental test samples were prepared. Soil was compacted in steel rings of 56.2 mm radius and 40.2 mm height (100 cm^3), up to 1.35, 1.45, 1.55 g/cm^3, to get artificial cores to a height of 40.2 mm. The stresses applied ranged between 80-240 kPa for the German soil, and between 110-260 kPa for the Polish soil. In order to get most homogenous soil samples without pronounced layering, the required mass of moist soil for each cylinder was compacted in three portions. The addition of water and then mixing caused some re-aggregation of the soils. After compaction, the cores (still in their steel rings) were stored in air-tight plastic cans. The cores were stored in a cool room at a temperature of 13-15 °C and were shaded from the light. For each soil there were 3 water content x 3 bulk densities x 6 ageing times x 8 replicates.

Approximately 0, 8, 24, 72, 144 and 240 h after preparing the samples, the moist soil cores were removed from the rings and their tensile strengths (the Brazilian method) were determined by pressing them with increasing force until the soil core broke. Tensile strength was measured with transportable aggregate crushing apparatus [8]. The apparatus is shown in Fig. 3a. The distance Z was adjusted so that elements T and B were parallel. The force, F, acting on a core at failure was calculated from:

$$F = (W_i + W\,x/y_i)\,g \qquad (4)$$

where g is the acceleration of gravity, and W_i is the starting weight of the apparatus, W is the weigth of water, x is the relevant length of the top element T, y_i is the arm of the acting force F. Indirect tensile strength was calculated through (Eq. (1)) because the reshaping factor $g(x)$ (see Eqs (2 and 3)) in practice was greater than 0.97 and the cylinder material was linearly elastic up to failure. The reshaping factor $g(x)$ and the linear elasticity of the soil cores were determined, on additional samples for the freshly-remoulded (0 h) soil, according to Fig. 3b. The correlation coefficient for vertical (R_y) and horizontal (R_x) directions of strains against the tensile strength were average: R_y=0.98 and R_x=0.93 for Achterwehr soil, R_y=0.98 and R_x=0.90 for Pyrzyce soil.

RESULTS AND DISCUSSION

In figures 4-7 the changes in tensile strength with time at different initial water content and bulk density for the 2 soil samples are shown. In principal it can be seen that the tensile strength increases with increasing time at various bulk density values and water contents. In order to derive relations between the modified parameters the obtained data were fitted to the logarithm equation:

$$Y = a0 + a1\,\ln(x) \qquad (5)$$

where, $a0$ and $a1$ are adjustable parameters, Y is the tensile strength at time x (in hours) after disturbance. The values of the parameter $a0$ were close to the initial state (for the freshly remoulded soil) of tensile strength. The parameter $a1$ can be considered as a gradient of the slope of tensile strength change with time

Table 2. The value of a0 and a1 of Eq. (5), the correlation coefficient (R_{val}) for the curve fit and the tensile strength Y_{co} for the freshly-remoulded (0 h) silty loamy sand (Pyrzyce soil)

Water content (% w/w)	Bulk density (g/cm^3)	$a0$ (kPa)	$a1$ (kPa/h)	R_{val} (-)	Y_{co} (kPa)
10	1.35	1.90	0.49	0.98	2.57
	1.45	6.65	0.15	0.78	6.22
	1.55	10.88	0.38	0.63	9.50
15	1.35	3.58	0.18	0.88	3.44
	1.45	4.29	0.32	0.87	4.53
	1.55	6.83	0.35	0.90	7.29
20	1.35	2.54	0.26	0.93	3.05
	1.45	3.87	0.37	0.92	4.47
	1.55	6.31	0.36	0.93	7.07

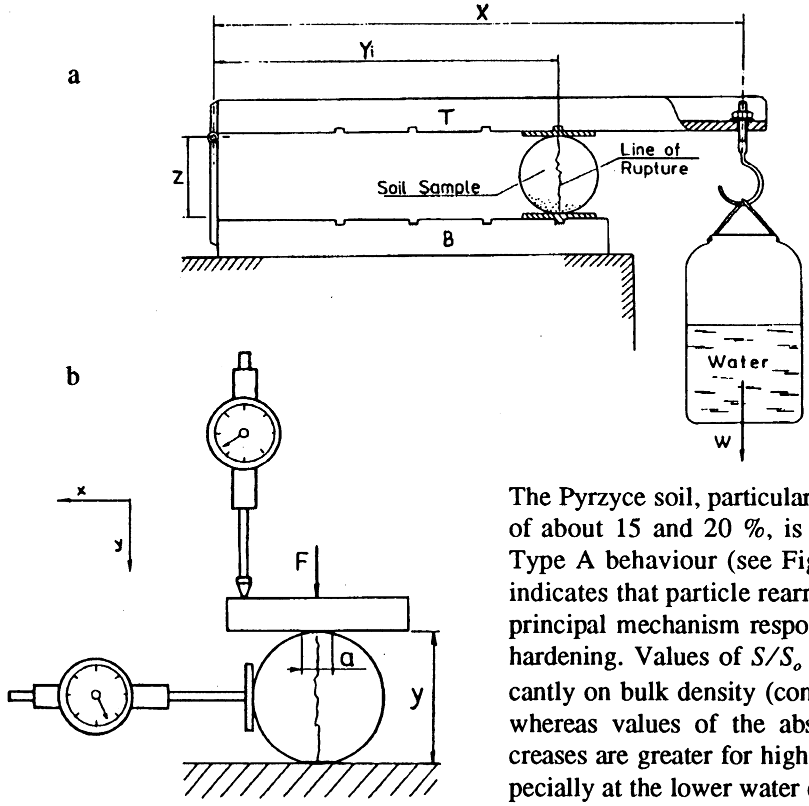

Fig. 3. a) Transportable aggregate crushing apparatus; b) Scheme for the factor *g(x)* and the linear elasticity determination of soil core samples.

(in hours). The values of the adjustable parameters *a*0 and *a*1, together with the correlation coefficient (R_{val}) for the curve fit and the tensile strength, Y_{co}, for the freshly remoulded soils, are given in Tables 2 and 3. For the Achterwehr soil (Figs 6 and 7), the absolute strength increases and the ratios, S/S_o, are not so large as for the Pyrzyce soil (Figs 4 and 5). The Pyrzyce soil, particular at a water content of about 15 and 20 %, is clearly exhibiting Type A behaviour (see Figs 1 and 4) which indicates that particle rearrangements are the principal mechanism responsible for the age-hardening. Values of S/S_o do depend significantly on bulk density (compaction pressure), whereas values of the absolute strength increases are greater for high bulk densities, especially at the lower water content. According to [17] the optimum water content for this mechanism (thixotropic hardening) is around the lower Plastic Limit. For this soil it was 19.1 % w/w.

For the Achterwehr soil (Fig. 6) is also possible to distinguish between the two mechanisms in this case. This is obvious, particulary at a water content of about 15 and 20 %, Type B behaviour with cementation of existing bonds being the principal mechanism of age-hardening. Values of S/S_o (except 10 % w/w) do not depend significatly on bulk density

Table 3. The value of a0 and a1 of Eq. (5), the correlation coefficient (R_{val}) for the curve fit and the tensile strength Y_{co} for the freshly-remoulded (0 h) loamy sand (Achterwehr soil)

Water content (% w/w)	Bulk density (g/cm^3)	a0 (kPa)	a1 (kPa/h)	Rval (-)	Yco (kPa)
10	1.35	1.56	0.07	0.42	1.56
	1.45	3.06	0.09	0.48	3.07
	1.55	5.36	0.26	0.74	4.31
15	1.35	1.84	0.14	0.94	1.95
	1.45	2.87	0.17	0.95	2.82
	1.55	3.90	0.26	0.92	4.19
20	1.35	1.48	0.07	0.76	1.54
	1.45	2.51	0.09	0.55	2.41
	1.55	1.48	0.07	0.76	3.69

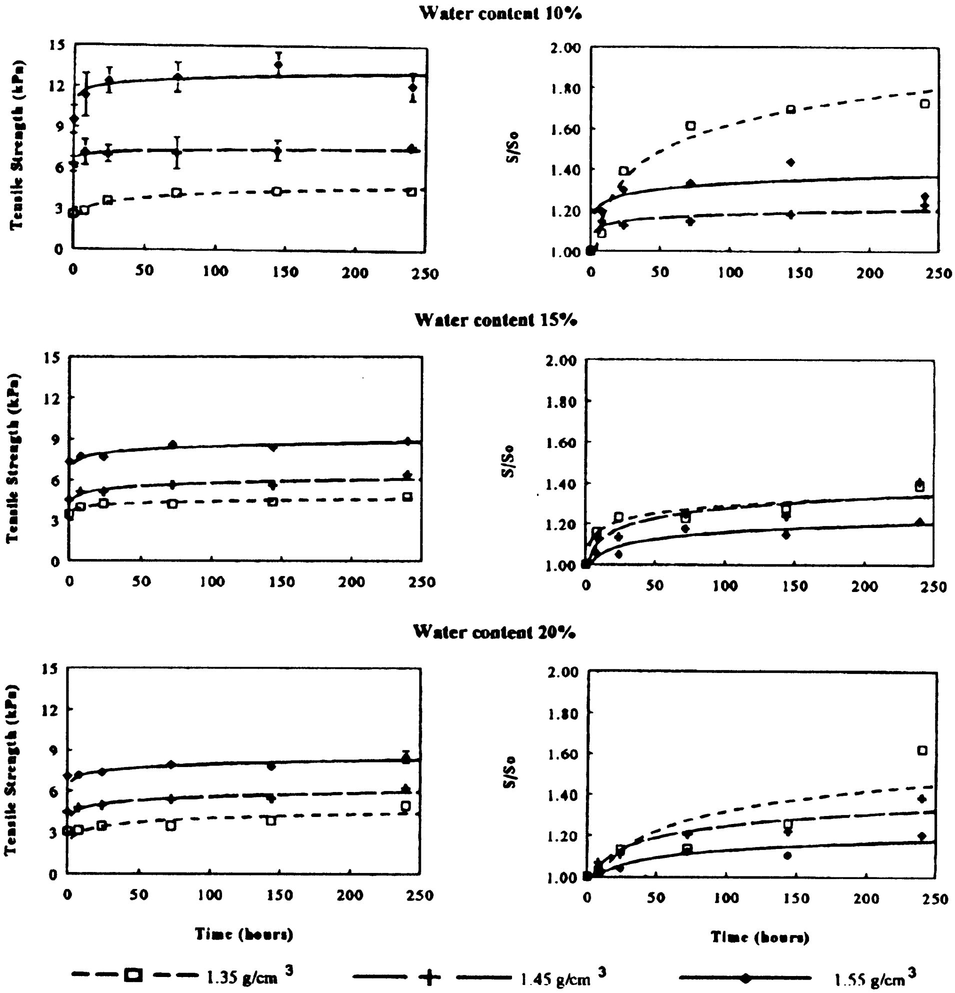

Fig. 4. Tensile strength and strength increases ratios, S/S_o, for silty loamy sand (Pyrzyce soil) for different bulk density (1.35; 1.45; 1.55g/cm^3) as function of time since compaction at 10, 15 and 20 % water content (% w/w)

(compaction pressure), whereas values of the absolute strength increases are greater for high bulk densities, especially at the lower water content.

The results of the absolute strength increases for Pyrzyce and Achterwehr soils (Figs 5 and 7) show the different behaviour of these two soils for different water contents and the same bulk density, especially at the lower water content. A possible explanation of the different behaviour lies in the differential pore size distribution (determined at 0, 60, 300 hPa) and total porosity (determined by submersion in water-maximum water holding capacity) of these two soils (Tables 4 and 5).

The results show considerable strength increases, in 72 h for Pyrzyce soil and 24 h for Achterwehr soil, after moulding and compression. A possible explanation of the different behaviour of these two soils lies in their different organic matter content and their different textures (Table 1). The German soil sample has 0.89 % organic carbon whereas the Pyrzyce has 1.23 % organic carbon. There is some evidence that increasing amounts of organic matter will slow down, or prevent, the

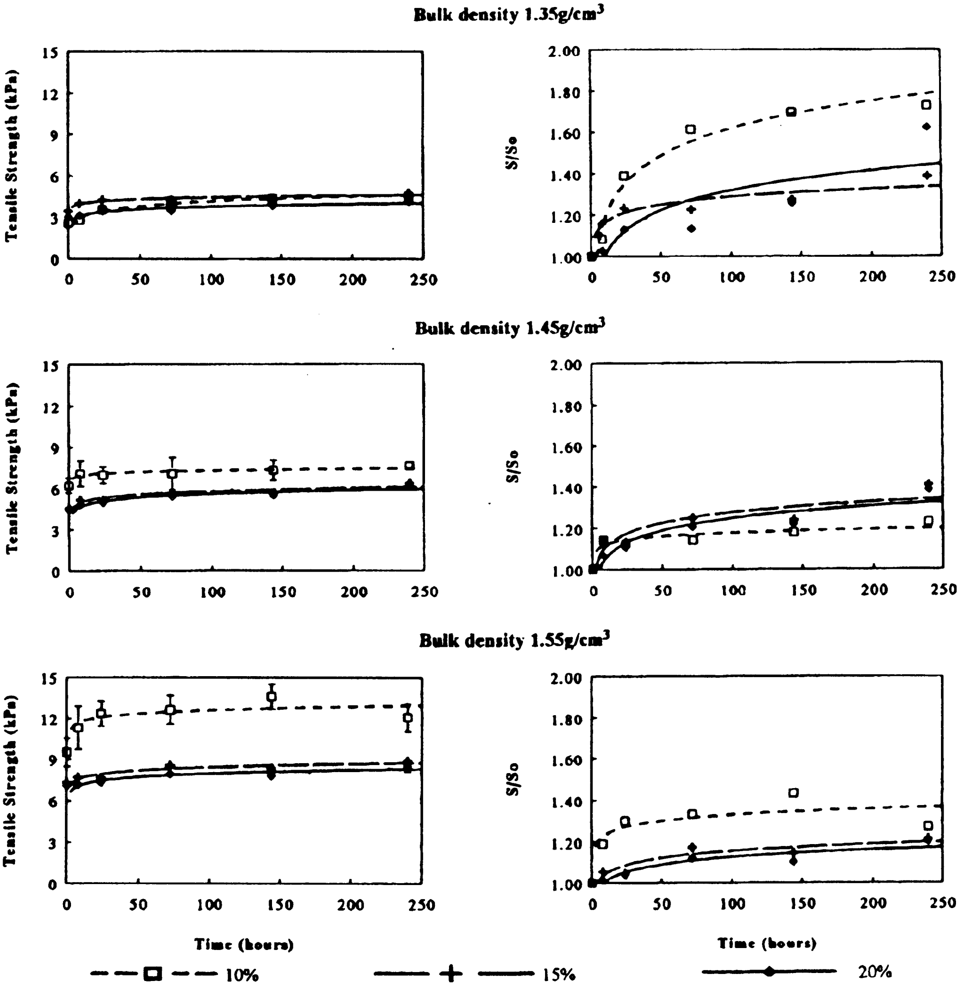

Fig. 5. Tensile strength and strength increases ratios, S/S_o, for silty loamy sand (Pyrzyce soil) for different water content (10; 15; 20 % w/w) as function of time since compaction at 1.35, 1.45 and 1.55 g/cm³ bulk density.

Table 4. The differential porosity and total porosity (T_p) (maximum water holding capacity) for the freshly-remoulded (0 h) silty loamy sand (Pyrzyce soil)

Bulk density	Water content	Pore size distribution (%)			T_p
		>50	10-50	<10	
(g/cm³)	(% w/w)		(μm)		(%)
1.35	10	41	11	48	48
	15	37	9	54	47
	20	29	8	63	42
1.45	10	33	11	55	45
	15	24	10	66	42
	20	26	9	65	43
1.55	10	24	12	64	43
	15	17	11	72	40
	20	16	9	75	40

Table 5. The differential porosity and total porosity (T_p) (maximum water holding capacity) for the freshly-remoulded (0 h) loamy sand (Achterwehr soil)

Bulk density (g/cm^3)	Water content (% w/w)	Pore size distribution (%) >50	10-50 (μm)	<10	T_p (%)
1.35	10	42	9	49	54
	15	36	15	19	47
	20	37	9	54	44
1.45	10	38	8	54	53
	15	32	14	54	48
	20	30	9	61	43
1.55	10	30	12	59	51
	15	24	17	58	46
	20	23	9	68	42

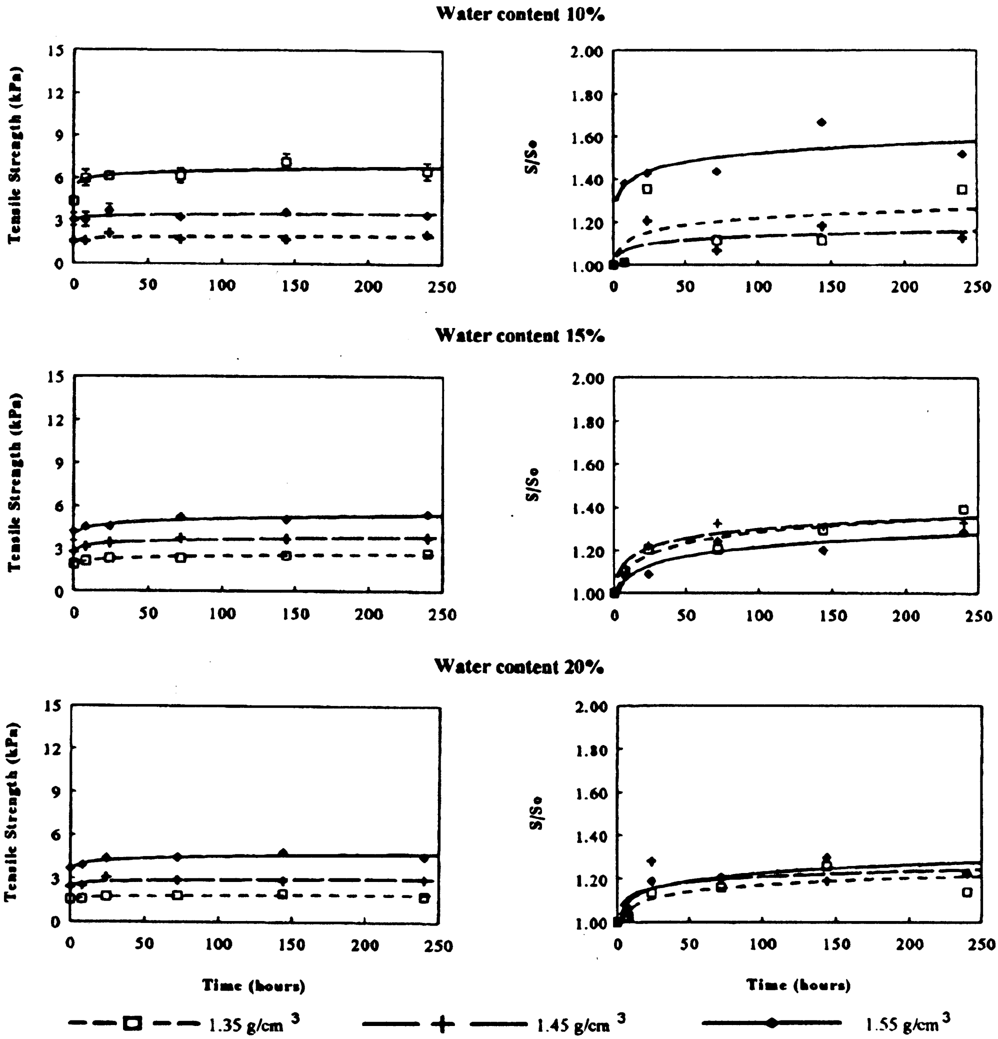

Fig. 6. Tensile strength and strength increases ratios, S/S_o, for loamy sand (Achterwehr soil) for different bulk density (1.35; 1.45; 1.55 g/cm^3) as function of time since compaction at 10, 15 and 20 % water content (% w/w).

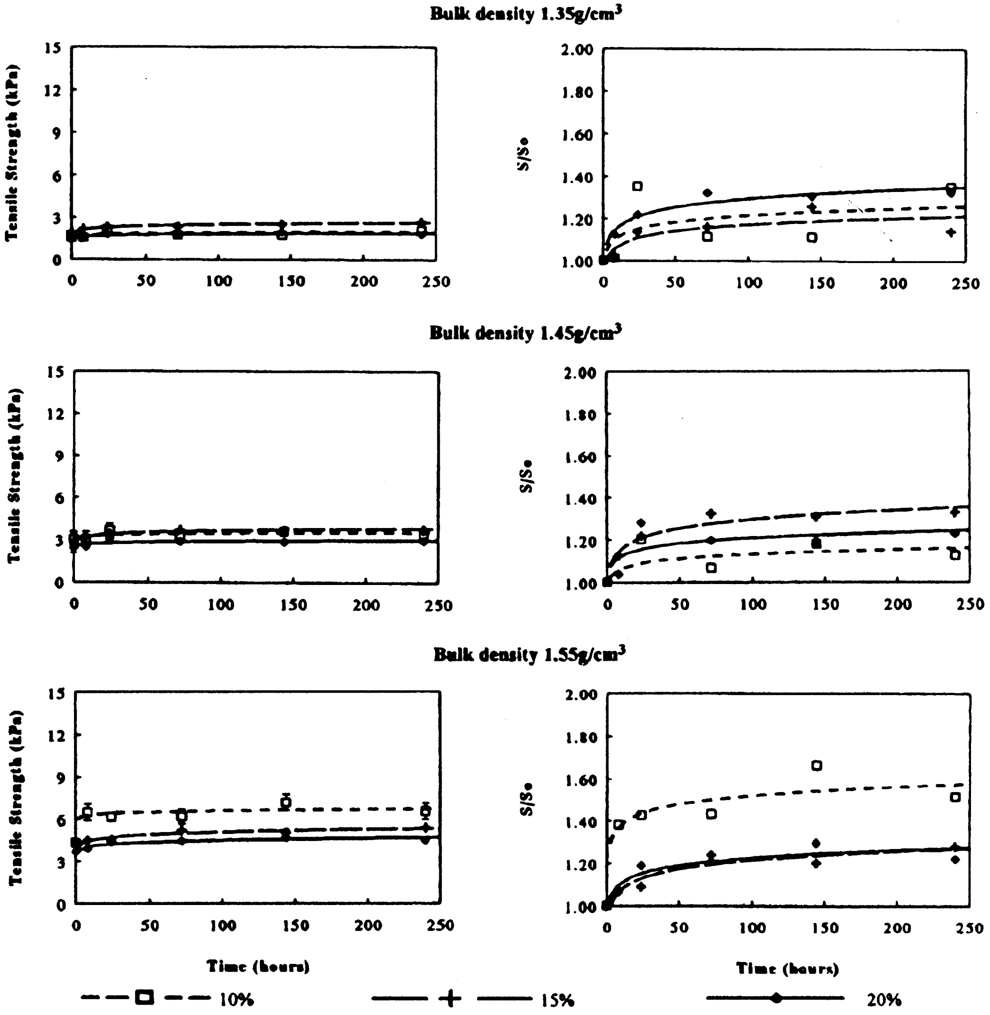

Fig. 7. Tensile strength and strength increases ratios, S/S_o, for loamy sand (Achterwehr soil) for different water content (10;15;20 % w/w) as function of time since compaction at 1.35, 1.45 and 1.55 g/cm^3 bulk density.

mechanism of cementation of particle to particle as long as the creation of new pores at the same water content results in a more negative water pressure at the same water content. If the X-factor of the effective stress equation gets smaller as compared to the suction depended increase in strength, the process of particle movement by menisci forces is also reduced because of a smaller amount of water filled pores with a particle depended pore diameter. This is in agreement with Kemper *et al.* [10], who had found that recovery of cohesion was more rapid if the soil had a 0.4 % than 1.2 % organic matter content.

CONCLUSIONS

It is possible to measure the effect of age-hardening of soils with the tensile strength (the Brazilian method) for freshly-remoulded, moist soils.

Age-hardening increases the tensile strength of soils. The effect of water content and bulk density on age-hardening is remarkable. For silty loamy sand, in this experiment, the effect of age-hardening process decreased at high levels of water content and bulk density. For loamy sand it was not posibble to distinguish the effect of water content and bulk density on age-hardening process.

Furthermore, a high water content had a negative effect on the tensile strength of soil at constant bulk density. A high bulk density, however, had a positive effect on tensile strength at constant water content.

The use of different intensities of compaction (different bulk densities) enabled us to study age-hardening phenomena. The identification of two different mechanisms of age-hardening with the Brazilian method can give information about strength regain, e.g., in the seedbed. Thus, also water erosion processes, or soil crushing, can be eliminated with time at given soil conditions.

The information presented here on the age-hardening may be useful in the development of our understanding of these effects in the field.

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