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SOIL CONDITIONING FOR BETTER SOIL MANAGEMENT

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Soil conditioning for better soil management

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Polymeric substances in the organic matter of soils aggregate soil particles into a 'crumb structure' which greatly influences such properties as water movement, aeration and heat transfer. Poorly-structured soils may be improved by the incorporation of synthetic polymers where the main objects are: promoting germination or establishing crops, improving drainage, combating wind and water erosion, and reducing evaporation from the surface of soil under arid conditions.

The first soil conditioner, Krilium*, was marketed by Monsanto Chemical Company in 1951. After a period of high expectations with many new products interest waned; the chemicals were too expensive and their interaction with the soil was poorly understood.

Two decades later new interest developed; synthetic polymers had become much cheaper and their mode of action better understood. Now soil conditioning is again considered to be promising, and it may be of interest to discuss some of its more practical applications.

Soil conditioning may be defined as upgrading a poorly-structured soil to one with suitably sized aggregates through proper tillage at the right moisture content and subsequently stabilizing the ensuing tilth by the application of small amounts (commonly around 0·1%) of synthetic polymers, either dissolved or emulsified in water. Depending on the nature of such products the conditioned soil will become either more hydrophobic or more hydrophilic and it may also change colour, with consequent changes in heat absorption. The most important aspect of soil conditioning, however, is its aggregating and stabilizing action, the function of the soil conditioner being analogous to that of the humus and sesquioxides naturally present in stable and well-structured soils (Figures 1, 2).

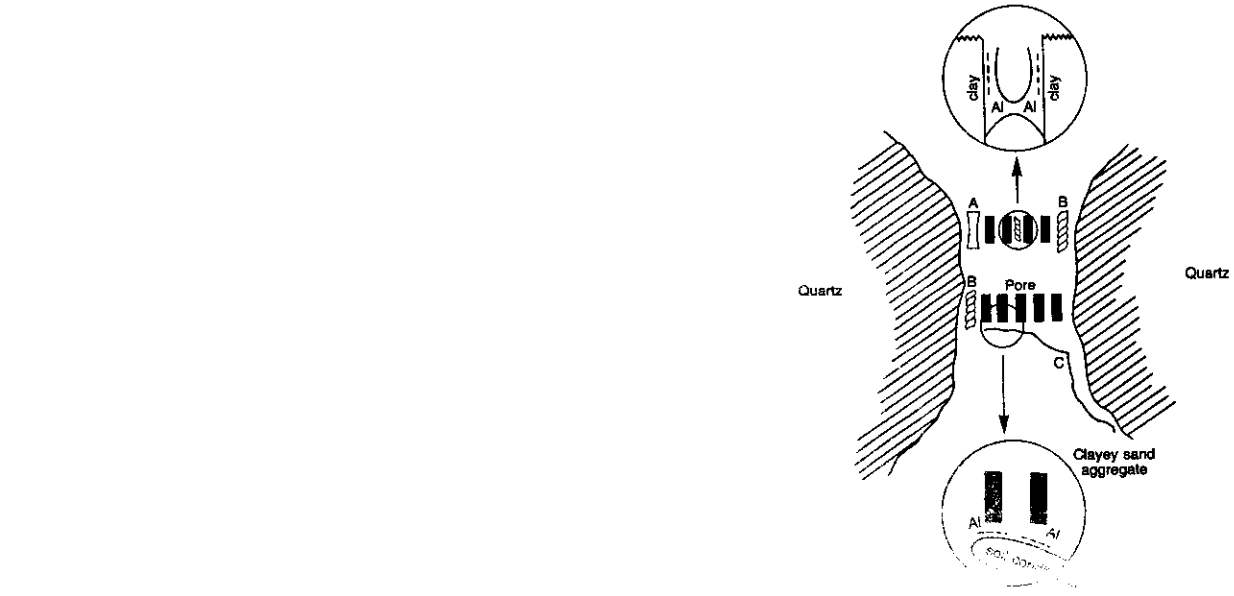
The mechanisms of the linkages involved on a molecular level between the soil particles and the long chains of the polymers have been studied extensively; comprehensive accounts are given by Greenland (1965, 1972).

Briefly, soil conditioners which are cationic or anionic have the property of making either a direct electrostatic linkage with the negatively charged clay surfaces or an electrostatic linkage with the adsorbed divalent or trivalent cations on the clay particles.

Non-ionic conditioners can make linkages with the soil particles either through hydrogen bonds or Van der Waals forces. Examples are the hydrogen bridges either of the OH groups on the edges of the clays with the NH_2 groups of the conditioners or the OH groups of the conditioners with the oxygen on the soil particles.

In recent years, however, soil conditioning has meant more than just stabilizing a given soil structure. De Boodt (1971, 1972) pointed out that a cheap hydrophobic material such as asphalt, when combined with

*Trademark adopted by Monsanto for substances such as CRD-189, the sodium salt of a hydrolyzed polyacrylonitrile, and CRD-186, a carboxylated polymer used as a partial calcium salt.



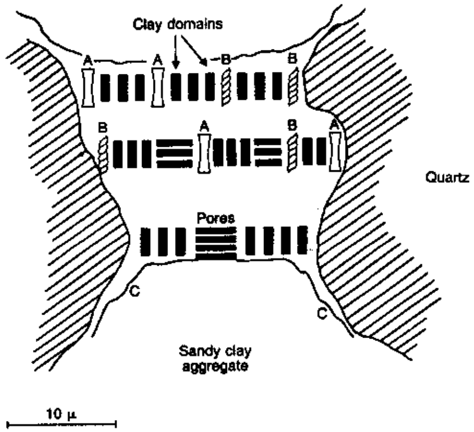


Figure 1 Model of a soil aggregate stabilized by organic matter or by soil conditioners showing clay domains, organic matter, polymers and quartz. The size of clay domains is strongly exaggerated: A = weak linkage due to water meniscus; B = linkage due to humus or sesquioxides; C = linkage due to micelles or polymers (soil conditioners). Dotted lines indicate H-bonding. Notice also the role of aluminium ions. Magnified inserts: organic matter-clay interaction or polymer-clay interaction (after Emerson 1977).

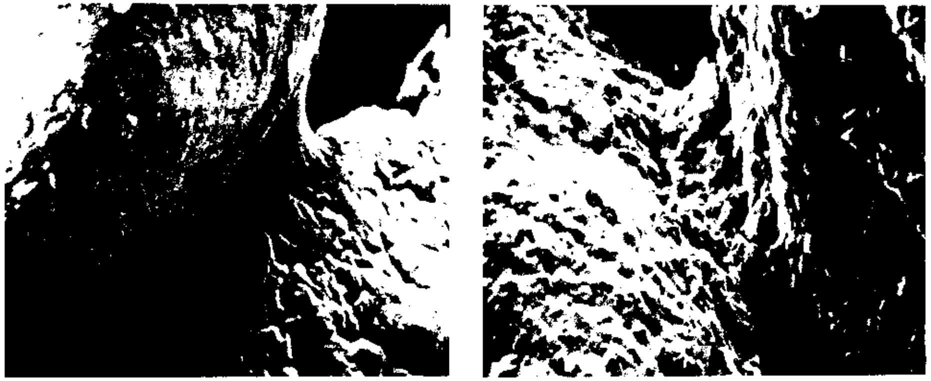


Figure 2 (left) Sand particles joined by micelles which have accumulated at the contact points (magnification × 300).
(right) Aggregate formation between sandy particles with poor stability due to poor dispersion of the bitumen micelles and surface tension of the emulsion applied (magnification × 300).

non-phytotoxic emulsifiers, was an effective soil conditioner for the treatment of soils suffering from excess of water. Carr and Greenland (1975) studied the potential application of another hydrophobic conditioner, polyvinylacetate.

Examples of the more important soil conditioners now on the market are shown in Figure 3. The list is far from complete; over one hundred patents, mostly dating from the 1950s, have been filed. Conditioners which make the soil more hydrophilic are listed in group A, which constitutes polymers or adhesives soluble in water. Those with the capacity for making soils more water repellent (hydrophobic) are listed in group B and are polymers or adhesives emulsified in water.

The structural formulae of the conditioners as such are no indication of how much a soil may change its behaviour towards water after treatment. The formulae do not show the exact steric configuration of groups like CH_2 which repel water and those such as C=O, COO, NH_3, OH which attract it. Consequently the hydrophilic/hydrophobic ratio of a particular soil conditioner has to be assessed by measurement of the contact angle at the soil/water interface. As this has often been measured inaccurately a better approach was developed by De Bisschop (1979); by determining the height of a water-drop in contact with the dried soil conditioner under simple standard laboratory conditions the contact angle can be calculated.

Also important is the degree of coverage of the soil particles by the applied products. Rigole and De Bisschop (1972) used the formula:

$$\cos \theta^x = \varepsilon \cos \theta_1 + (1 - \varepsilon) \cos \theta_2$$

in which: θ^x = overall contact angle between the emulsion and the solid,
θ_1 = contact angle between the water and the emulsified substance,
θ_2 = contact angle between the water and the fraction (ε) of the solid not covered by the flocculated micelles.

So, from the overall contact angle and knowing θ_1 and θ_2 the % coverage can be assessed. To be effective the degree of coverage should be about 15–20%. This is not only a matter of the quantity applied but also of the dilution, the dispersion, the moisture content of the soil and finally the method of incorporation. How the micelles of the colloidal solution migrate to the points of contact between the particles has been studied by De Boodt (1972), Rigole and De Bisschop (1972) and De Bisschop (1979). Factors involved are surface tension, the contact angle of the dissolved or emulsified conditioners with the soil particles and the percentage of soil pores filled with the diluted synthetic product at the moment of treatment. Thus, clearly, soil conditioning is more complex than is the application of soil fertilizers. It is probably true to say that, not least in temperate regions, adverse conditions for soil management are more frequently met with than are ideal situations; how and when to apply soil conditioners may be deduced from an analysis of the main field applications and the mechanisms involved.

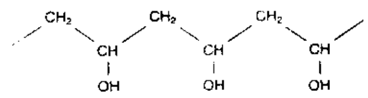
Improving seed germination and emergence

Arable land often suffers from unstable soil tilth due to lack of organic matter and the effects of using heavy machinery. When the soil moisture content is satisfactory, a seed bed may be prepared that will satisfy plant needs for the time being, but rain, which is often abundant at seeding time, may destroy the fine tilth and surface crusting may appear. Mechanical impedance is by no means the only cause of subsequent poor seedling emergence. There is, in addition, poor aeration under the crust at seed level, which leads to fungal and bacterial attack and inhibition of uptake of both water and nutrient elements. This phenomenon has been well studied in recent years (see Lynch *et al.* 1977), while the influence of oxygen in the soil on plant development and final yield has been discussed by Goss *et al.* (1977) and Lee (1978).

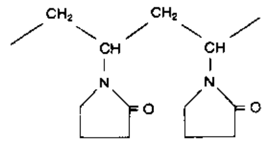
On the other hand, after a certain time the soil may get too dry, and this, too, can give rise to poor germination and emergence; both oxygen and moisture should be freely available.

Soil temperature at seeding time is also important for good germination; cold spring weather often retards germination and growth of plants for many days or even

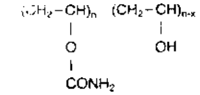
A. Polymers soluble in water: hydrophilic soil conditioners



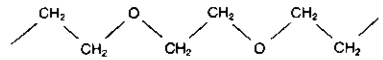
Polyvinyl alcohol (PVA)



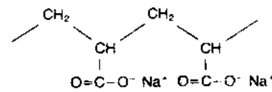
Polyvinylpyrrolidone (PVP)



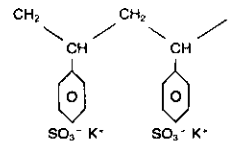
Polyvinyl alcohol, urethanised (PVAu)



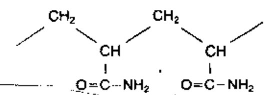
Polyethyleneglycol (PEG)



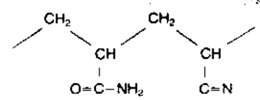
Sodium polyacrylate (SPA)



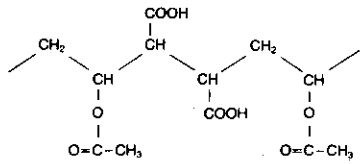
Potassium polystyrenesulphonate (PS)



Polyacrylamide (PAM)

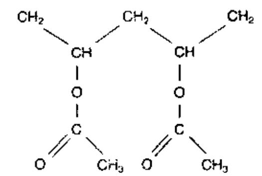


Partially hydrolysed polyacrylonitrile (HPAN)



Vinylacetate maleic acid (VAMA) copolymer

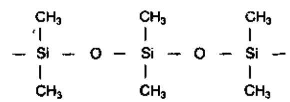
B. Polymers emulsifiable in water: hydrophobic soil conditioners



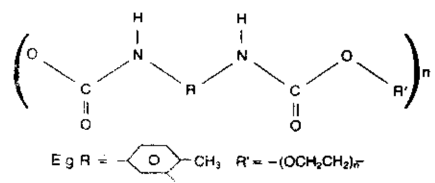
Polyvinylacetate (PVAc)

$(CH_2 — CH = CH — CH_2)_n$

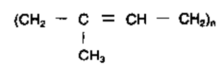
Polybutadiene (BUT)



Polysiloxane



Polyurethane



Natural rubber latex

Asphalt (bitumen)

Figure 3 Some examples of soil conditioners.

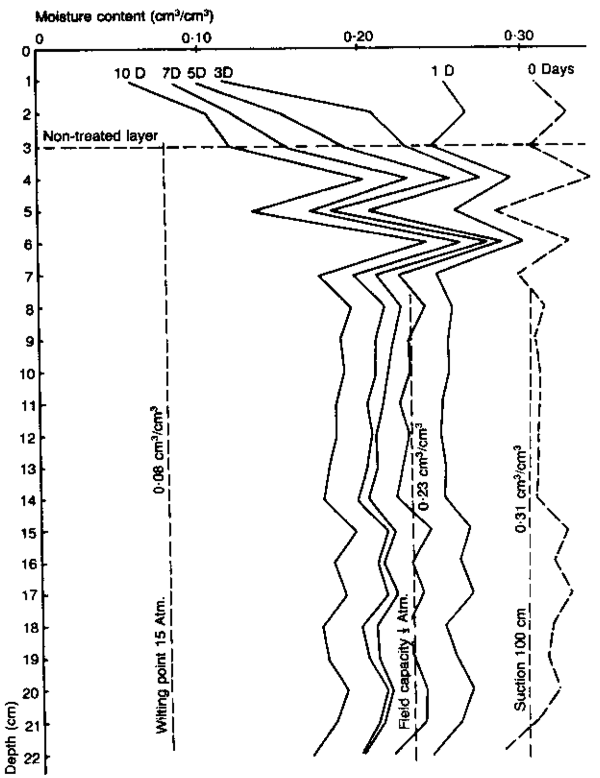


Figure 4 Evolution of the moisture distribution in a heavy silt loam soil profile of which the initial moisture content was 30%. The soil surface was subjected to a daily evaporative demand E_0 of 11 mm/day. After ten days the average moisture content in the profile was 17%.

weeks, when nutrient elements are poorly taken up and growth is retarded appreciably (Monteith 1979). For example, Cantliffe (1972) has shown that for each 1°C increase in soil temperature the nitrate uptake of spinach is enhanced by 240–1540 mg/kg dry matter produced.

Such adverse conditions at seeding time respond to the application of soil conditioners. In the case of 'capping', or surface crusting of soil, treatment with a hydrophobic emulsion is recommended. A single spray some 10 cm wide, applied as a mulch on the seeding lines at a dose of 20 g a.i. per 10 m will give good results or, for closely sown crops an overall treatment of 20 g/m² may be more appropriate.

A single application of a suitable dark-coloured soil conditioner can improve both soil water economy and temperature regime of the seedbed; in temperate regions such treatment may result in an increase in the surface temperature of a clayey soil of some 2–3°C over a period of a week (De Boodt, unpublished data).

Combating semi-arid conditions

Shortage of water may present two distinct conditions. In dealing with water-repellent soils a treatment with a hydrophilic chemical such as polyacrylamide is recommended at a dose of 20 g/m². The diluted product, after being sprayed on the surface, should be incorporated in the soil to a depth of 3–5 cm using a harrow.

Water-repellent soils are commonly characterized by an angle of contact with the liquid of $\theta^x = 80$–$90°$ and the above treatment will reduce this to $\theta^x = 20$–$25°$.

However, when the soil has to be treated to conserve water in the profile, which is often the case in the Mediterranean region (characterized by winter rains followed by a hot summer) then a hydrophobic soil conditioner such as polyvinylacetate should be used at a dose of 20–50 g/m² harrowed into the upper 3–5 cm. The high angle of contact ($\theta^x = \pm 60°$) produced at the surface will then act to prevent water loss from the subsoil by capillarity. Figures 4 and 5 show how the amount of available water at low suction may be enhanced in a treated soil by a factor of 10 over that in untreated soil.

As mentioned, soil temperatures may be increased in spring by making the soil darker. Conversely, when temperatures need to be diminished a white soil conditioner is recommended; using a reflecting white coverage on the soil surface in a warm region can reduce the surface temperature of a loess soil by as much as 10°C for 2 weeks (Stanhill, cited by Monteith 1979.)

Enhanced infiltration and percolation of rainfall

It is not uncommon to find that field drainage is ineffective due to silting-up of the pipes or slaking of the backfill which thus becomes impervious. Silting-up may be delayed by putting a filter, a few centimetres thick (made of peat, flax straw or coconut fibre) around the pipes, but this is not a permanent solution, expecially in unstable sandy soils where filters are particularly liable to clog up, sometimes very rapidly. Poor drainage may also be due to impermeability of the soil above the drain as evidenced in very heavy clay soils such as occur in the UK or with salt-affected soils in the Mediterranean area. The traditional solution for this problem, and one which is still practised, is the use of washed gravel as backfill but prices and labour for handling such material have increased to the point where, in the UK as well as in other parts of the world, its use represents at least 60% of the entire cost of drainage. So other solutions have had to be found.

To cope with the silting-up Dierickx and Gabriels (1976) showed that refilling the drain trench with a soil layer of maximum 30 cm which was treated with either 1% bitumen emulsion or 0·1% polyacrylamide (PAM) is satisfactory, whilst, as an economic replacement for washed gravel De Boodt (1978) discussed the possibility of treating the backfill with soil conditioners which would stabilize the soil aggregates and ensure a continuous high permeability. However, when using emulsified polymers the soil to be treated must be dry before it is put in the trench in order to fix the micelles in the contact points of the soil particles. Such treatment allows unimpeded water movement from the top soil to the drains and can be used with great success in countries where washed gravel is expensive.

Water soluble polymers are even more promising as they can stabilize the backfill almost instantaneously. The product is sprayed from a digger-mounted spray boom onto the soil at the moment it falls back into the trench. It has been calculated that carrying out field drainage in such a way will reduce labour costs by almost 30%, and will allow work to proceed under adverse conditions.

Table I is derived from laboratory experiments and shows that treatment of a loam soil improves the saturation permeability several hundred-fold. The difference in behaviour of emulsions compared to water-soluble products is striking in respect of the drying time after treatment necessary for good performance.

Polyacrylamide at a rate of 0·2% ai is currently under test in a

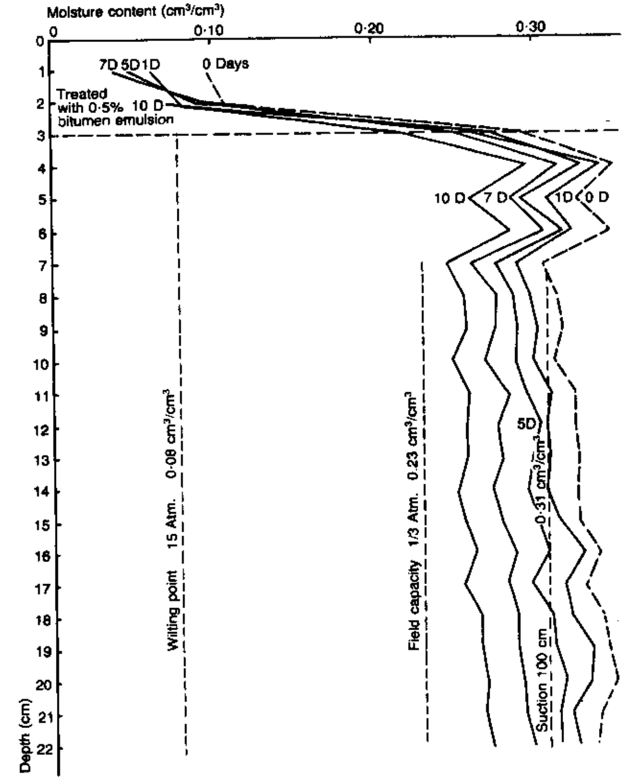


Figure 5 The same soil and conditions as in Figure 4, but in this case the top 3 cm was treated with 0·5% bituminous emulsion. After ten days the average moisture content in the profile was 27%.

Table I
Permeability values (K_t, after a waterflow period of 19 days) of treated and untreated loam soil as a function of the concentration of the soil conditioners and the drying time after treatment

Product	Form	Product concentration (%)	K_t (cm.sec⁻¹.10⁻³) 2 hours $\theta = \pm 17{\cdot}5\%$	24 hours $\theta = \pm 11\%$	air dried (5 days) $\theta = \pm 3\%$
Untreated			2·4	2·7	2·9
Bitumen	emulsion	1·0	aggregate	27·8	96·1
		0·5	breakdown	11·9	50·0
Butadiene	emulsion	1·0	4·9	7·3	48·1
		0·5	6·3	2·2	20·0
Polyvinylacetate	emulsion	1·5	6·8	33·0	151·5
		0·75	10·0	8·1	44·0
Polyacrylamide	solution	0·2	733·6	1330·2	536·7
		0·1	633·4		
Polyurethane	solution	0·6	809·6	934·7	812·1
		0·3	230·5		
Mixed polyvinyl alcohol + lignosulfonates	solution	0·5	284·0	1199·3	1090·5
		0·25	256·6		
		0·10	82·2		
		0·05	25·7		

θ: moisture content Derived from: Goossens *et al.* 1979 replicated field trial on heavy silt loam near Ypres, in Belgium. Early observations show that on December 27, 1978 following 2 weeks heavy rain (50·1 mm) the moisture content of the soil above the untreated backfill was 35·6 ± 1% and above the treated one 31·9 ± 0·5%, statistically significant at the 0·01 level (De Boodt, Dierickx & Goossens, unpublished data).

Combating erosion

Erosion starts when an aggregate slakes under the beating action of raindrops; the fine soil particles are then carried along the slope of the field. So, stable aggregates diminish erosion indirectly by increasing the infiltration rate of the surface soil, thus preventing run-off, and directly by binding together the fine soil particles (see Figure 6).

But, before erosion is recognized as such, another important and detrimental change may occur in fields and their surroundings. De Boodt *et al.* (1979) found that even under West European conditions, before the soil erodes, rainwater carries appreciable amounts of fertilizers down-slope during the winter period, with the result that surface waters often become polluted. This phenomenon has been extensively studied in the last decade (Taylor 1967, Burwell *et al.* 1975, Larson 1978).

Using polymers in solution and spraying them over the soil will help to fix fertilizers on the soil surface. Where liquid fertilizers are used, as little as 20 kg/ha polymers in the solution can result in more than 70% reduction of fertilizer loss even where there is no obvious erosion problem. Where erosion is paramount and leaching of fertile elements is a recognized problem as in the humid tropics, soil conditioners, especially those such as asphalt and latex emulsions, have an even more important role to play.

Where trees are to be planted, the following procedure is proposed: a planting hole is dug and the excavated soil is mixed with fertilizers; a diluted soil conditioner at a dose of 1% a.i. is then also mixed in. The young tree roots are put in the hole and covered with the treated soil. In this way the aggregated soil ensures good infiltration of water into the planting hole, while the polymer prevents fertile elements from being leached. Table II shows the effectiveness of such a treatment in an experiment on rubber in Java (Lenvain *et al.* 1972, Keersebilck and Bols 1977).

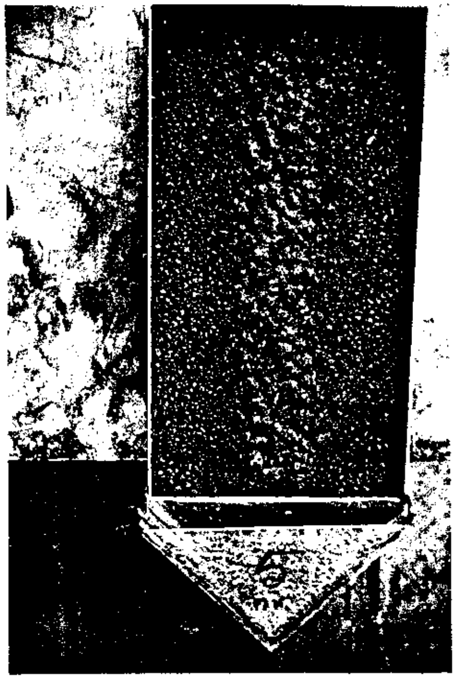


Figure 6 Laboratory trial on loamy soil. The central part is not treated and hence is slaked after an application of 60 mm of rainfall. Side parts, treated with PAM (20 gr/m²), stay well crumbled.

Equally striking differences have been described by Lenvain *et al* (1972) for soil-conditioning treatment of the fast-growing tropical tree *Albizzia falcata*. After 22 months the average girth of treated trees was significantly greater, and the amount of wood produced per hectare, taking into account enhanced tree survival, was ten times greater than with fertilizers alone.

Similar trials with cashew *(Anacardium occidentale)* in the neighbourhood of Jogjakarta, Java (Keersebilck & Bols 1977) showed that, after a growing period of three years, nuts could be picked from the trees where soil conditioners and fertilizers were applied; but there were practically none on untreated trees. The yield differences between fertilizers alone and fertilizers with soil conditioners were statistically significant at the 0·01 level.

Such results are of interest both from the standpoint of economic crop yield and that of control of soil erosion by water.

Wind erosion can also be completely or partially prevented by the use of soil conditioners. In *Soil Conditioners,* the SSSA Special Publication No. 7 (Stewart 1973) a number of striking examples from the 'dust bowl' in the USA and others from the Near East are discussed. Good results have been achieved in Libya, Iraq and Iran using hydrophobic emulsions which, when incorporated in the upper 5 cm, have been shown to be capable of aggregating sand particles and preventing loss of moisture from the subsoil even under high evaporative (wind and insolation) demands, thus allowing grasses and bushes to grow and stabilize the sand dunes (Anter *et al.* 1976, Hartmann *et al.* 1976).

Table II

Effect of soil conditioners and fertilizers on rubber (Hevea brasiliensis Clone WR101) in Java. 18 trees per plot ×4 replicates. Tree girth at planting 10·6 cm ±4%

Treatment	Observations Aug 1974* 20 months after planting		Observations April 1977† 52 months after planting	
	Tree survival %	Average girth(cm)	% trees ready to tap (girth 45 cm)	Average girth (cm)
Control	90	11·50	6	35·3
Fertilizers only	85	12·28	23	40·1
Bitumen emulsion (50%) 3 l. per plant hole	92	12·18	5	35·7
Bitumen emulsion, as above, + fertilizers	94	13·23‡	39	42·2‡
Polyacrylamide (2%) 2 l. per plant hole	89	11·85	10	34·7
PAM (2%) 3 l. per plant hole, + fertilizers	93	13·23‡	40	42·7‡

*after Lenvain *et al.* 1972.
†after Keersebilck & Bols 1977.
‡sig. different from fertilizers only treatment ($p = 0·25$), and from untreated control ($p = 0·01$)

The effect of soil conditioning on field crops

Soil conditioners and their use have formed the subject of four major symposia in recent years: Ghent 1972, Las Vegas 1973, Ghent 1975 and Adelaide 1976. The proceedings, to which reference has been made, altogether cover more than eighty papers.

Still more recently a great number of practical results have been obtained in countries such as Japan, France and Belgium where the greatest developments have taken place in vegetable cropping, and in England, where it is mainly sugar beet fields that are treated.

Some 85 trials have been carried out in Belgium during the past two years on the effect of soil conditioners on the rate of germination of various crops. Soils in which the trials were carried out ranged from sandy-clayey to loams and silty loams. The crops tested, mostly rootcrops which apparently respond best, were: chicory (53 trials), carrots (9), sugar beet (6), mangold (6), salsify (5), endive (3) and spinach (3). Treatments examined were, in 1977 and 1978 respectively, emulsified polymers (some of which were black) (18, 25), polymers in solution (12, 10) and polymers in solution made black by the addition of carbon black (10, 10).

In 80% of these trials germination on the treated plots was greater than that on the untreated. In general, emulsified soil conditioners gave somewhat better results and if these happened to be black (e.g. asphalt), or were made black, germination was improved in virtually all cases, mostly by 43% or more. Yields were taken in only 19 trials but these showed crop increases in 17 cases; in 14 of these trials increases of 10% or more were realised.

Table III

The effect of a soil conditioner, black polyacrylamide, on the germination and yield of carrots, Ardennes 1978. Means of 4 replicates and (in brackets) relative values.

Germination (number/ha)		Final yield (kg/ha)	
Untreated	black PAM	Untreated	black PAM
440,000 (100)	715,000 (162·5)	19,152 (100)	21,572 (112·6)

In all four trials taken to yield where black soil conditioners were used increases were greater than 10%.

Table III shows the effect on germination and final yield of carrots, of seed-bed treatment with black polyacrylamide (PAM). The crop was sown on a clayey soil in the Ardennes, in late June 1978 when the summer was cold and wet. Each plot was 25 m² and fertilizers were applied at the rate of 30 kg/ha N, 60 kg/ha P_2O_5, and 150 kg/ha K_2O.

The increase in germination of 62·5% and in yield of 12·6% was statistically significant at the 0·05 level. It will be noted that, according to the number of germinated seeds, the yield is relatively low, possibly due to insufficient fertilizer, especially nitrogen. In the same trial, in a split plot design, black polyacrylamide supplemented with an extra 120 kg N gave an average yield of 32,208 kg/ha, a relative yield increase of 50% compared with black PAM alone and 68% greater than untreated, both statistically significant at the 0·05 level.

It is clearly important that adequate fertilizer for full development should be available to the plants if the full benefit of soil conditioning is to be realised.

The economics of soil conditioning

Soil conditioning is still at an early stage of development though a number of uses already appear to be economic, particularly in vegetable crops under adverse conditions where a return of some three to five times the cost of treatment may be expected. In the trials discussed the cost of the products varied between £80 and £100 per hectare.

In the UK where use is mainly on sugar beet grown on 'capping' soils a cost of £33 per hectare seems to be an acceptable level for treatment. In such cases less product has to be used and consequently stabilization and other effects are less pronounced. Nevertheless, germination of sugar beet is generally improved and yields increased.

Soil conditioning can thus be regarded as an acceptable insurance against poor germination of vegetables and sugar beet in particular. Other applications such as combating water and wind erosion or stabilizing the backfill in field drainage may well become, in the near future, standard practice to replace present-day methods which are becoming too expensive.

References

Antar F, De Boodt M (1976) *Proc. 3rd int. Symp. Soil Cond.* Ghent 1975, De Boodt M & Gabriels D (Eds). Fac. Agric. Sci., Ghent p. 287.

Burwell R E, Timmons D R, Holt R (1975) *Proc. Soil Sci. Soc. Am.* **39**, 523

Carr C E, Greenland D J (1975) p 47 in *Soil Conditioners* SSSA Spec. Publ. No. 7

Cantliffe D J (1972) *J. Am. Soc. hort. Sci.* **97**, 674

De Bisschop F (1979) Thesis *Aggregaat Hoger Onderwijs* Fac. Sci. Ghent

De Boodt M (1971) *Pochvozn Agrokhim* **6** (5) 3

De Boodt M (1972) p 43 in *Optimizing the soil physical environment towards greater crop yield* Hillel D (Ed) Academic Press, N.Y.

De Boodt M (1978) *J. Sci. Fd Agric.* **29**, 1

De Boodt M, Vandenberghe C, Gabriels D (1979) In *Role of soil physical properties in maintaining productivity of tropical soils* Greenland D J, Lal R (Eds) J. Wiley & Sons, Chichester (in press)

Dierickx W, Gabriels D (1976) *Proc. 3rd int. Symp. Soil Cond.* Ghent 1975. De Boodt M & Gabriels D (Eds). Fac. Agric. Sci. Ghent. p 293

Emerson W W (1977) p 29 in *Soil factors in crop production in a semi-arid environment* Russell & Greacen (Eds). Univ. of Queensland Press

Emerson W W, Bond R D, Dexter A R (Eds) (1978) *Modification of soil structure. Proc. 4th int. Symp. int. Soil Sci. Soc.* Adelaide, 1976. J Wiley & Sons Ltd, Chichester. 438 pp.

FAO (1960) *Soil erosion by wind and measures for its control on agricultural lands* Agric. Dev. Paper No 71, FAO, Rome

FAO (1965) *Soil erosion by water: some measures for its control on cultivated lands* Agric. Dev. Paper No. 81, FAO, Rome

Goossens F, Dierickx W, Gabriels D, De Boodt M (1979) *J. Sci. Fd Agric.* (in press)

Goss M J, Douglas J T, Howse K R, Williams J M, Ward MA (1978) *ARC Letcombe Lab. Ann. Rep. 1977.* p 37

Greenland D J (1972) *Proc. Symp. Fundamentals of Soil Cond.* M De Boodt (Ed). Meded. Ghent. Fac. Agric. Sci. p 897

Hartmann R, Verplancke H, De Boodt M (1976) *Proc. 3rd int. Symp. Soil Cond.* Ghent 1975. De Boodt M & Gabriels D (Eds). Fac. Agric. Sci., Ghent p. 219

Keersebilck N, Bols P (1977) *Bogor (Java) Soil Sci. Inst. Ann. Rep. 1977* p 95

Larson W E, Holt R F, Carlson C W (1978) ASA Spec. Publ. No. 31. p 1

Lee R B (1978) *ARC Letcombe Lab. Ann. Rep. 1977.* p 64

Lenvain J, De Boodt M, Suwardjo (1976) *Proc. 3rd int. Symp. Soil Cond.* Ghent 1975. De Boodt M & Gabriels D (Eds). Fac. Agric. Sci., Ghent p 141

Lynch J M, Harper S H T, Pryn S J (1977) *ARC Letcombe Lab. Ann. Rep. 1976*

Monteith J L (1979) In *Role of soil physical properties in maintaining productivity of tropical soils* Greenland D J, Lal R (Eds) J Wiley & Sons, Chichester (in press)

Okigbo B N (1977) p 151 in *Soil conservation and management in the humid tropics* Greenland D J & Lal R (Eds) J Wiley & Sons, Chichester

Rigole W, De Bisschop F (1972) *Proc. Symp. Fundamentals of Soil Cond.* De Boodt M (Ed) Fac. Agric. Sci. Ghent p 938

Taylor A W (1967) *J. Soil Wat. Conserv.* **22**, 118

Stewart B A (Ed-in-chief) (1973) *Soil Conditioners* Proc. ISSS Symp. Exp. methods and uses of soil conditioners. Las Vegas. SSSA Spec. Publ. No. 7.