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CONDITIONERS

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Introduction

The use of naturally occurring materials as soil-stabilizing conditioners has been part of agriculture and general land management for millennia. Some of the most familiar conditioners in use since ancient times include animal and green manures, peat, crop residues, organic composts, and lime. These early uses of conditioners resulted from knowledge gained from trial and error long before there was scientific understanding of how efficacy was derived. Other conditioners in use for centuries or decades include composted manures, various organic debris, including sawdust or other milling residues, food, textile, and paper-processing wastes and other organic industrial wastes, as well as mineral materials such as rock phosphates, gypsum, coal dust, rock flour, and sand.

Soil conditioner use and technology, since ancient times, has, in great part, been a marriage of convenience between the agricultural necessity for chemical and physical maintenance or enhancement of the land, and for the disposal or management of waste materials from the full spectrum of human activities. However, since about the early nineteenth century, as modern physics and chemistry emerged and were applied systematically to agriculture, soil conditioner identification, development, and use became more creative and deliberate.

With the development of soil science as a specific discipline, the terminology and concept of soil amendments and conditioners was gradually assigned primarily a physical-conditioning connotation. Chemical conditioning, *vis-à-vis* supplying plant nutrients to soil, has been largely ascribed to materials termed fertilizers. Clearly, however, there is substantial overlap. Many fertilizers affect soil physical properties, both directly and indirectly, and many soil conditioners affect soil fertility both directly and indirectly. The overlap of physical and chemical effects occurs because of the intimate association of all soil physicochemical process and their coupling, as well, to soil-supported biotic processes, cycles, and functions. The designation of fertilizer versus conditioner is often based on the dominant effect intended. Categories are often assigned by law, based on the chemical analysis and/or the proof of claims for the materials.

Early Use of Mineral and Organic Materials

This article provides a brief history of early and traditional conditioner technologies and then focuses on recent developments in inexpensive and highly effective synthetic conditioner materials and use strategies. Organic conditioners have generally been applied to increase infiltration and soil water retention, promote aggregation, provide substrate for soil biological activity, improve aeration, reduce soil strength, and resist compaction, crusting, and surface sealing. The effects of organic conditioners often occur bimodally. That is, some effects, such as improved infiltration

and water retention, are evident immediately upon soil incorporation, whereas other effects, such as improved aggregation, depend on chemical and biological processes over time.

Mineral conditioners are often used to affect soil chemical processes as well as soil physical processes. Lime, for example, raises soil pH. Gypsum or lime is often used to increase base saturation, or reduce the exchangeable sodium percentage (ESP) of retained cations. Because the divalent calcium ion has a compact hydrated radius, it also promotes flocculation of clays and increases aggregate stability. These effects help to reduce particle dispersion and detachment – which reduce erosion and surface sealing. Similarly, the calcium ion promotes flocculation and aggregation. These effects can be particularly important in arid soils with low soil organic matter (SOM) contents. The physical properties of such soils are often impaired when the exchange complex is dominated by the sodium ion, which has a much larger hydrated radius, and thus impedes flocculation and aggregation and favors dispersive phenomena. The physical benefits of calcium addition in low SOM saline soils provide for improved leaching of salts and removal of sodium, especially under irrigated conditions.

Mineral conditioners are especially important for the management of arid or tropical soils where high temperatures promote rapid bio-oxidation of incorporated organic material. A variety of other strategies are used with mineral conditioners to exploit soil physicochemical processes, directly or indirectly improving soil physical and/or chemical status. While the uses of lime and gypsum have ancient origins, another interesting approach in recent decades has been the use of various oxides of iron to promote aggregation in low-organic-matter soils. In the 1970s researchers added iron oxides to increase aggregate stability of soils and found peak aggregation at a 2% addition rate, with aggregation favored by acidic conditions. Others in the 1980s found promising results for addition of ferrihydrite compounds to calcareous soils, with the formation of weak quasicrystalline structures. Recent work shows potential for adding ferric hydrides to low-organic-matter soils for structure improvement and wind erosion resistance. Ferric hydrides are common water-treatment and industrial process waste products.

Soil conditioner research to the present has explored the use of many naturally occurring organic and mineral materials, agricultural and industrial waste products, or by-products of other processes. Materials that have been used as conditioners have included crushed rock, ground coal, gypsum (mined or from ground plasterboard), wood chips, bark,

sawdust, food-processing wastes, cheese whey, various manures, composts of manures and/or other organic materials, and, as discussed more fully below, a wide range of synthetic polymer materials, including copolymers of synthetic and naturally occurring substances. All these materials have shown varying capacities to modify soil conditions or soil processes.

Use of Waste Materials as Conditioners

The extent of soil conditioner use has often been limited by economics. The cost of conditioner use has commonly been due more to transportation and application expenses of bulky materials than to the price of the materials *per se*. In many instances conditioner material is available gratis from waste streams of various processes where disposal is an expense. Use of waste materials as soil conditioners eliminates the disposal expense and in some cases creates profitable products. Because of material bulk, transportation, application, and related costs, the widespread use of traditional soil conditioners in mainstream production agriculture has been limited to only a few very highly efficacious materials such as lime, gypsum, and manure. Exceptions have occurred in high-value nursery, cash crops, turf and landscape applications, or in proximity to sources, where transport costs have been minimal.

Advent of Synthetic Conditioners

Since the early 1950s soil scientists have explored using synthetic polymeric conditioners to alter drastically soil physical and, in some cases, chemical properties. During World War II water-soluble polymers were used to stabilize soils in order to hasten the construction of roads and runways. The use of polymeric soil-conditioning chemicals was introduced to agricultural research and the farming community following World War II. In 1949 an industrial process for polymerizing acrylamide molecules was patented. This ultimately enabled a vast new array of water-soluble polymer compounds with thousands of industrial and environmental uses. Sixteen scientific reports of water-soluble polymer soil conditioning appeared by 1952, and 99 reports by 1955.

By enhancing the formation of soil aggregates and prolonging their longevity, water-soluble polymeric conditioners improve soil physical properties, including root penetration, erosion resistance, infiltration, aeration, and drainage. These direct physical improvements usually promote rooting and plant interception of nutrients and water, indirectly improving plant nutrition. The synthetic materials perform

immediate conditioning and structural stabilization that would ordinarily require weeks, months, or years to achieve via a program of organic matter incorporation. Furthermore, synthetic materials can effectively condition soil to the depth of tillage with one to two orders of magnitude less material application than required with traditional conditioners, and can be zone- or spot-applied for even more efficient, targeted application and efficacy. Despite these performance advantages, however, in the early years of synthetic soil conditioner use, cost usually restricted use to high-value crops or specialty applications.

The most common strategy for water-soluble polymeric soil conditioner use from the early 1950s until the early 1990s was the application of sufficient conditioner material to affect significant physical modification of the soil to the depth of tillage. Depending on the nature of the polymer conditioner material, these application amounts often reached hundreds of kilograms per hectare. Generally, this mode of treatment entails multiple application operations, either as bulk solid materials, or as sprayed liquids or slurries. Each application usually requires tillage to incorporate the material to a desired depth. Because the mass of soil in a typical hectare-plow-layer is great (typically 2 000 000 kg per hectare 15-cm slice), many tons per hectare of traditional physical amendments and hundreds of kilograms per hectare of water-soluble polymeric soil amendments are usually necessary to overcome the physical or chemical buffering effect of the large mass of soil being treated.

Some of the most commonly used water-soluble synthetic soil-conditioning polymers since the 1950s have been: hydrolyzed polyacrylonitrile (HPAN), isobutylene maleic acid (IBM), polyacrylamide (PAM), polyvinyl alcohol (PVA), sodium polyacrylate (SPA), and vinylacetate maleic acid (VAMA). Commercial formulations of these compounds sometimes combined polymers and extenders or solubility-enhancing agents. Perhaps the most successful water-soluble soil-conditioning polymer marketed commercially before the 1990s was the Monsanto product Krilium which combined VAMA with a clay extender for improved application uniformity. Krilium and similar products were marketed in the 1950s at costs of \$4–5 kg⁻¹. Then-current application techniques required the application of tens to hundreds of kilograms per hectare, depending on the depth and extent of the soil zone to be treated. This precluded use on all but high-value crops or in specialty situations. After initial enthusiasm for these conditioners, most products have been withdrawn from general marketing to mainstream agriculture because of economic realities.

Hydrogels and Super Water-Absorbent Polymers

There was also interest over the years in super water-absorbent polymers for use in soils. These polymers are not water-soluble, but instead are strongly hydrophilic gel-forming materials that easily absorb hundreds or even 1000–2000 times their weight in water (Figure 1). Hydrolyzed starch-polyacrylonitrile graft polymers (H-SPANs), patented by the US Department of Agriculture in 1975 under the market name Super Slurper, and cross-linked polyacrylamides (gel-forming PAMs) have been the most common polymers for this application. They are used to improve the water retention of soils with low-water-retention properties, or that experience prolonged and untimely drought, especially immediately after planting. Spot placement of gel polymers in proximity to seeds, seedlings, or transplants prolongs the opportunity for emergence and seedling establishment without having to irrigate the entire soil profile. Again, because of cost and application amounts required, it is usually not economically feasible or logistically practical to attempt to modify an entire profile or even tillage zone, even when conditioner cost is as little as \$2 per kilogram.

Polymer chemistry, prior to about the 1980s, generally limited available soil-conditioning polymers to molecules with chain links of a few thousand monomer units. In addition, the purity of the preparations was not always good, sometimes carrying safety or environmental risks from reaction by-products or incompletely reacted base chemicals. Since the 1980s and early 1990s polymer purity and molecular size have increased, greatly improving the efficacy, safety, and affordability of environmental polymers. These changes, coupled with new application strategies that only target critical portions of the soil for treatment,

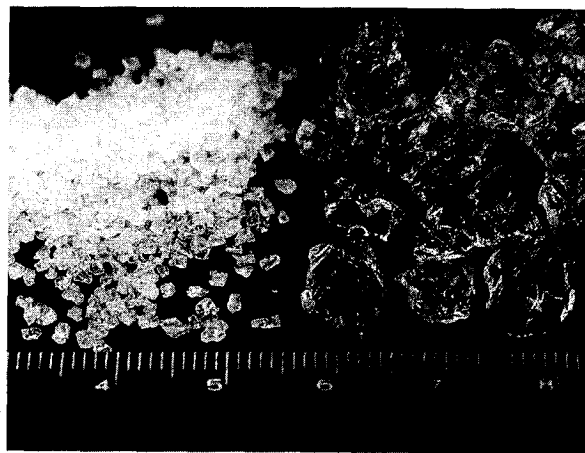


Figure 1 Superabsorbent cross-linked polyacrylamide in the dry state (left) and hydrated state (right); scale is in centimeters.

and that do not depend on expensive field operations for chemical application, have produced a sustained renewal of interest in environmental polymers for a growing number of uses. Perhaps the best example of this advancement has been the use of PAM for erosion control in irrigated agriculture.

Recent Advances Using Polyacrylamide

Isolated reports in the 1970s and 1980s provided a hint that very small amounts of PAM in irrigation water, flowing over soil in irrigation furrows, virtually eliminated detachment and transport of soil particles. These reports, however, were either anecdotal with respect to erosion or did not adequately identify the polymer used. Thus, the potential importance of the PAM-treatment erosion effects went unnoticed for several years. The foundation was laid for the practical use of PAM to halt erosion in furrow irrigation in a series of studies through the 1990s. The success of this new research came from the realization that the best way to treat soil structure to prevent erosion was to use the eroding water to deliver the soil conditioner.

Irrigation is perfectly suited to this mode of application. In this mode of application only 1–2 kg ha⁻¹ of PAM was needed to halt an average of 94% of erosion from irrigation furrows (Figure 2). The treated soil was restricted to about 25% of the field surface area and was only treated to a depth of a few millimeters. Inflows only needed to be dosed as water crossed the field, shutting off applicators when runoff began.

This strategy relies on the use of a highly specific class of food-grade PAM to ensure both efficacy and human and environmental safety. These PAMs are anionic, with a charge density of typically 18%; they are what are today regarded as moderately large molecules, having over 150 000 chained monomer segments per molecule for molecular weights of 12–15 million g mol⁻¹. The molecules are manufactured to a high purity, and are actually identical to PAMs used for food processing and drinking water treatment, with residual unreacted acrylamide monomer (AMD) contents of <0.05%. The low AMD content and anionic nature of the molecule ensures safety for humans handling the PAM and for aquatic species in the event PAM is lost via runoff to surface

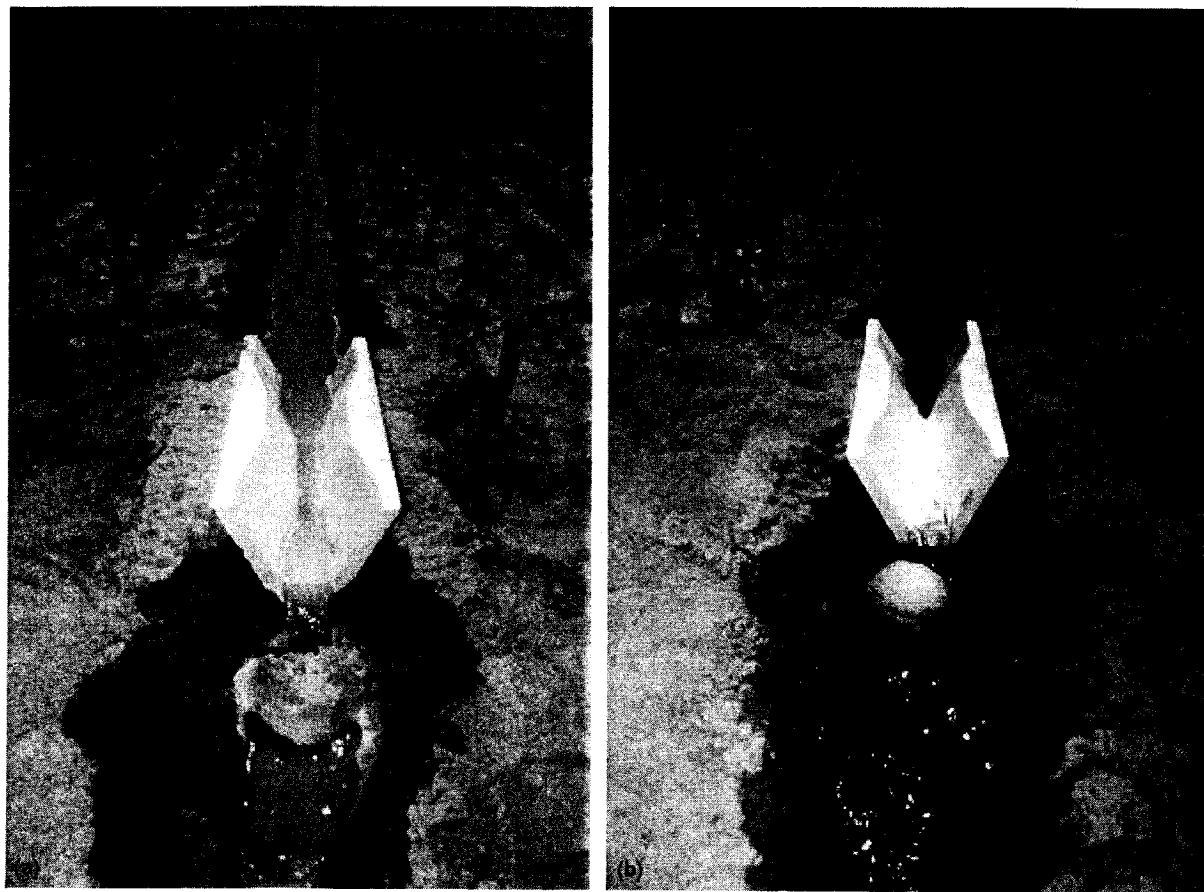


Figure 2 Runoff from irrigation furrows where (a) water is untreated and (b) water is treated with polyacrylamide; note the lack of turbidity, and thus absence of erosion from the polyacrylamide-treated furrow.

waters. However, the anionic charge imparts the need for bridging cations in the solvating water to link the anionic polymer to the anionic surfaces of soil minerals. Waters and soils containing dissolved calcium enable better efficacy than low-electrolyte (pure) water, and efficacy is best when there is little or no sodium present.

PAM is so effective at stabilizing surface structure, even at these small application amounts, that, in most fine- to medium-textured soils, infiltration is increased compared to untreated water, which induces surface sealing. While initial uses of PAM were focused mainly on erosion control, farmers are equally interested in using PAM for infiltration improvement. This is especially true as the technological barriers to use of PAM in sprinkler irrigation are overcome. With proper application strategies, PAM can be used both to increase infiltration amounts or rates as well as to improve infiltration uniformity. Since, with PAM in the water, soil structure is improved and surface sealing is reduced, water droplets enter the ground where they land, rather than causing seals and inducing runoff and ponding.

PAM use with irrigation for erosion control benefits water quality in a number of ways. By preventing erosion it also reduces the desorption opportunity for sorbed nutrients and pesticides, and limits dissolution of soil organic matter in runoff that elevates dissolved organic carbon (DOC) and biological oxygen demand (BOD). PAM-treated irrigation water has also proven highly effective at reducing movement off-site of soil-borne microorganisms and weed seed, greatly reducing the likelihood of downstream inoculation and, ultimately, reducing the need for pesticides.

The prospects for the future development of PAM technology remain good. Because PAM increases the viscosity of water flowing through soil pores, the effects on infiltration are a balance of seal prevention allowing greater infiltration and viscosity slowing the passage of water. Experiments are currently underway to use the viscosity effects with other management strategies for canal sealing, improved infiltration uniformity along long irrigation furrows, and better water retention in soils where infiltration is not a problem.

Natural gas is the cheap abundant raw material from which PAM is currently made. However, current supplies and economics may not reflect the future. Work to develop new copolymers of PAM using chitin and starch as building blocks has proven promising, although results are yet to match those achievable currently with PAMs. Use of these materials as building blocks for effective flocculents and soil stabilizers carries the added benefit of using another agricultural waste stream to produce value-added products. In this case products may eventually be provided that

can add to our inventory of environment-protecting and production-improving agricultural tools.

The field of water-soluble polymers for environmental protection and agricultural management is growing rapidly. These polymers are inexpensive, effective, and safe. They can be easily used in many settings and provide nearly instantaneous results in most instances. They can be used effectively in combination with more traditional land management and water quality protection techniques, such as reduced tillage or riparian buffer strips, either enhancing the effectiveness of these more familiar approaches or providing additional 'insurance' for situations when alone they are less reliable. The work of the last decade has emphasized that agricultural and environmental polymers cannot be regarded as 'silver bullets,' but when used in a well-planned approach to agricultural land and water management or environmental protection, offer a significant new capacity for better resource utilization and environmental protection.

Extensive additional information on the current use of PAM as an environmental polymer for erosion and pollution prevention and for irrigation water management improvement can be found at the website www://kimberly.ars.usda.gov/pampage.shtml.

See also: **Aggregation:** Physical Aspects; **Crusts:** Structural; **Structure**

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Conservation See **Erosion: Water-Induced; Wind-Induced; Sustainable Soil and Land Management; Terraces and Terracing**

CONSERVATION TILLAGE

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Introduction

Conservation tillage (CT) is an umbrella or generic term used to describe tillage systems that have the potential to conserve soil and water by reducing their loss relative to some form of conventional tillage. Precise definitions of conservation tillage are only possible within the context of known crop species, soil types and conditions, and climates. A well-accepted operational definition of CT is a tillage or tillage and planting combination that retains a 30% or greater cover of crop residue on the soil surface. Generally, there are four main types of CT: mulch tillage, ridge tillage, zone tillage, and no-tillage. A main variant of the latter is direct drilling (sometimes termed zero-tillage), while other variants of CT are reduced tillage and minimum tillage. Conservation tillage can provide several benefits for agricultural systems such as soil conservation, economic advantages associated with reductions in crop establishment time and energy use, reduction in soil sheet erosion and nonpoint pollution, and

enhanced storage or retention of soil organic matter and improvement of soil quality at the soil surface.

Evolution of Conservation Tillage Systems

Tillage involves the mechanical manipulation of the soil. In an agricultural, horticultural, or forestry context, it involves manipulation of the soil profile to modify soil conditions and to manipulate plant residues, and to control or remove unwanted plant growth. In agricultural systems, tillage functions as a subsystem that influences crop production mainly through crop establishment, modification of soil structure, incorporation of fertilizer and soil amendments (e.g., lime and manure), and weed control. Tillage is also used to alleviate both climatic and soil constraints.

The evolution of conservation tillage is a complex phenomenon with many varied themes. First, excessive soil tillage is associated with soil degradation processes such as compaction, a decrease in soil stability and structure, and increased soil erosion. Thus, one component of CT is a trend towards reducing or minimizing tillage events to address concerns with tillage-induced soil degradation. Second, most arable farming systems developed in climates where