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SOIL STABILIZATION

Chemical grouting is the practice of injecting liquid solutions of cement or organic materials into soil, rock, or concrete in order to form solid inorganic or organic masses that impart desirable permanent physical characteristics in the soil, rock, or concrete. The solutions that are injected, ie, chemical grouts, undergo either polymerization of monomers or cross-linking of soluble polymers to form insoluble polymer masses. Chemical grouting is often used in construction or repair of buildings, dams, shafts, etc, when it is desired to restrict or reroute the flow of water through a formation, or to strengthen the formation. Repair of sewer systems is an important application of chemical grouting. Chemical grouts, other cement-like materials, as well as the so-called geosynthetics, ie, nonwovens, membranes, grids, and honeycombs, are commonly used individually and in combinations to reinforce soil as foundations for roads, buildings, etc (see Geotextiles). This article focuses on chemical grouts.

Soil conditioners are materials that measurably improve the physical characteristics of the soil as a plant growth medium. Typical uses include erosion control, prevention of surface sealing, and improvement of water infiltration and drainage. Many natural materials such as peat and gypsum are used alone or in combination with synthetics for soil conditioning. This article is concerned with synthetic soil conditioners, many of which are introduced as polymeric systems similar to the gels and foams formed *in situ* by chemical grouts.

1. Chemical Grouting

The early history of chemical grouting has been reviewed (1, 2). The first true chemical grouting technique involved injection of sodium silicate solution and calcium chloride solution through two adjacent bore holes to form a precipitate where the two liquids came into contact. Until the 1950s, all chemical grout materials were variations on the sodium silicate–calcium chloride system and these materials became synonymous with chemical grouting. Portland cement (qv) was used on a large scale in construction of several dams in the United States. Practices, specifications, and theories that became grouting standards were developed empirically, based on procedures used by various government agencies in large construction projects in the first third of the twentieth century.

The ideal chemical grout is a low viscosity solution capable of penetrating finely divided profiles as easily and to the same extent as water. The grout solution viscosity remains low for a predetermined time to allow the desired penetration of the profile. Rapid gelation then occurs to form a water-impermeable barrier filling all the voids in the formation, thereby waterproofing it. The barrier's durability should be adjustable. Long-lived barriers are needed in applications such as repair of sewers or tunnels but short-lived grouts are useful for temporary stabilization of excavations such as in construction. Grouts that are too viscous or that contain particulates are usually not useful in grouting of finely divided formations. Adjustable gel times are important because very short gel times are useful to make seals in the presence of running water and longer gel times may be needed to penetrate profiles to the desired depth. Grout systems must be chemically compatible with the profiles to be grouted and capable of being applied with available equipment. Safe and environmentally sound mixing, use, and disposal of organic grouts are other factors to be considered. Chemical grouts based on several different inorganic and organic polymer systems are commercially available.

1.1. Silicate Grouts

Sodium silicate [1344-09-8] has been most commonly used in the United States. Its properties include specific gravity, 1.40; viscosity, 206 $mPa{\cdot}s(=cP)$ at 20°C; SiO_2:Na_2O = 3.22. Reaction of sodium silicate solutions with acids, polyvalent cations, such organic compounds as formamide, or their mixtures, can lead to gel formation at rates, which depend on the quantity of acid or other reagent(s) used.

In the Joosten or two-shot method (3), successive injections are made of a concentrated solution of sodium silicate and a calcium chloride [10043-52-4] solution into a single pipe. Unconfined compressive tests indicate the stabilized strengths of injected sands to be 2.1–4.1 MPa (300–600 psi). Reaction is almost instantaneous; there is no ground heave and only minimal travel of the grout from the injection point. The relatively high viscosity of undiluted sodium silicate, 50 to 200 $mPa{\cdot}s(=cP)$, and the fast reaction with $CaCl_2$ require closely spaced grout injection points, resulting in high installation costs.

In the Siroc or one-shot method (4), formamide is used to coagulate sodium silicate. The silicate solution used in the Joosten method can be diluted with water to lower its viscosity. Concentrations of sodium silicate between 10–70% are used (viscosities of 2.5–50 $mPa{\cdot}s$). Concentrations of formamide are between 2 and 30%. Other reactants such as $CaCl_2$ and sodium aluminate are used in concentrations between 2.4–12 g/L of silicate solution.

For waterproofing, sodium silicate concentrations below 30% are adequate; concentrations between 35 and 70% are used for strength improvement. Grouts having 35 vol % or higher silicate resist deterioration on freeze–thaw or wet–dry cycles. Water permeability of sands can be reduced from 10^{-2} to 10^{-8} cm/s. Unconfined compressive strengths of stabilized sand can vary from 103 to 4130 kPa (15–600 psi); the normal range is between 690 and 1380 kPa.

Soils containing up to 20% silt or clay can be treated by injection. Low injection rates are used with finer soils to avoid fracturing the profile and forming lenses of chemical grout. The optimum injection rate of a soil depends on such factors as soil texture, density, void ratio, permeability, depth of overburden, as well as the viscosity of the grouting solution. The pH of the grouted material should be between 5 and 11; more acid or basic soils may have to be neutralized before grouting. Sodium aluminate [1302-42-7] reactant is used when acid soil is to be grouted.

Various additives can impart desired handling and performance properties. Sodium bicarbonate used with sodium silicate grouts produces low strength semipermanent grouts to stabilize formations during construction projects. Portland cement is used as a reactant with sodium silicate grouts to obtain short gel times, useful to stop flowing water and seal grouting cavities. Silicate-based grouts containing added Portland cement cannot be injected into medium sands or finer soils. Addition of particulates to grouts generally reduces their ability to penetrate finely divided formations. Several patents describe the use of organic grouting systems in combination with silicate-based grouts.

The Siroc grouting system is considered nonhazardous and nonpolluting. Sodium silicate is essentially nontoxic. Formamide is toxic and corrosive, but does not present a serious hazard if normal safety precautions are followed. Siroc chemical grout materials are two to five times more expensive than Portland cement, depending on the sodium silicate to formamide concentration ratios. Installed costs are generally more similar to those for cement grouts.

Syneresis of sodium silicate gels may occur under some conditions, eg, in pure gels or coarse formations. Cement grouting should then precede chemical grouting. Leaching that results from dissolution under water-saturated conditions may be eliminated by use of proper reagent proportions.

1.2. Organic Polymer Grouts

There are several types of organic grouting systems (5).

1.2.1. Acrylamide

Aqueous acrylamide solution grouts were introduced in the United States in 1955 and rapidly became popular because of lower cost, better flexibility, and superior performance compared to other grouts then commercially available. Acrylamide grouts came closest to matching performance requirements for an ideal grout and set the technical standard for performance of other grouting systems. Specialized equipment was designed for injection of acrylamide grouts. Acrylamide has been the most-often selected grout for use in sewer applications. An acrylamide-based grout was used in construction of the final grout curtain of the Rocky Reach Dam (Wenatchee, Washington); almost 950 m^3 was required. In 1989, about 295,500 kg of acrylamide grout was consumed, approximately 43% of the total grout used.

Polymer gels resulting from acrylamide polymerization are generally regarded as nonhazardous. Acrylamide (qv) monomer, however, has been reported to have potential neurotoxic effects in higher animals (6). This led to a search, promoted by the U.S. Environmental Protection Agency (EPA) (7), for less toxic organic grouting systems. Progress had been relatively slow on account of the difficulties involved in matching the performance of acrylamide grouts with other systems, especially because specialized equipment designed for acrylamide application was not easy to adapt to the requirements of other systems. In the 1990s, systems based on polyurethanes and polyacrylamides offer performance similar to that achievable with acrylamide-based grouts. Citing the reported neurotoxicity of acrylamide [79-06-1] and the availability of other grouting systems, the EPA proposed in 1991 (8) to ban the use of grouts based on acrylamide and *N*-methylolacrylamide [924-42-5] (NMA). Despite opposition from the National Association of Sewer Service Companies (NASSCO) and others, this ban was in the final-rule stage as of September 1996 (9).

Acrylamide grouts generally comprise a 19:1 mixture of acrylamide and methylenebisacrylamide [110-26-9] or some other cross-linking agent. Catalysts include persulfates, peracids, or peroxides; ammonium persulfate is commonly used. Accelerators such as triethanolamine are used; dimethylaminopropionitrile is better from a control viewpoint but is a suspect carcinogen. Sometimes inhibitors, such as potassium ferricyanide, are also added. Acrylamide grouts are available in either solid or liquid form. Liquid forms were developed to facilitate handling and reduce exposure of workers to acrylamide. Packaging (qv) of measured quantities of acrylamide in water-soluble bags has also been described as a method to minimize user contact (10). The monomer and cross-linker are maintained in one solution and catalyst in another. The two solutions are mixed at a Y-junction and injected into the path of leakage that is to be stopped. Chemical reaction then begins.

Advantages of acrylamide grouts include low cost, quick and controllable gel times from a few seconds to several hours, low viscosity of 1–2 mPa·s(=cP), and a long history of reliable performance. Gel times can be accurately controlled by varying the concentration of one or both parts of the catalyst system, or by adding inhibitors such as potassium ferricyanide. Dissolved salts normally present in groundwater have little effect on gel time, especially if groundwater is used to dissolve the reagents. Gel times of a few seconds have been used to shut off flowing water in construction operations; short gel times down to 5–10 s are obtained by omitting potassium ferricyanide and increasing the persulfate and amine components. A low viscosity grout is advantageous for penetration of finely divided formations. Acrylamide grouts are among the lowest viscosity grouts available.

Unconfined compressive strengths of soils stabilized with acrylamide-based grouts are typically in the range of 345–1380 kPa (50–200 psi). Strength increases with increasing density and decreasing grain size of the formation. The stiffness of the grout obtained can be varied by altering the acrylamide:methylenebisacrylamide ratio. A 97:3 ratio, a transparent, sticky, elastic, low strength gel is obtained; at 9:1 ratio, a harder, stiffer, opaque gel is obtained. Gels typically contain approximately 90% water, trapped mechanically in the polymer matrix.

Gels are permanent when located below the water table or in very humid environments. Mechanical deterioration of the gels occurs on exposure to freeze–thaw or wet–dry cycles where dry periods predominate. Long exposure to dry conditions causes gels to shrink. When rehydrated, gels return to their former volume; cracks close but do not necessarily heal. Acrylamide gels have a water permeability of approximately 10^{-10} cm/s. The permeability of unstabilized soils fall in the range of $10^{-1} - 10^{-5}$ cm/s. When polymer fills the soil voids completely, the permeabilities of treated soil and gel are similar.

1.2.2. N-Methylolacrylamide

NMA-based grouts accounted for approximately 3% (27,300 kg) of the total grout market in 1989. The equipment and processes necessary for sewer rehabilitation and manhole sealing, which are the main uses of NMA-based grouts, are the same as those for acrylamide-based grouts, although a different persulfate catalyst is typically used. In the United States, the ban proposed by the EPA on the use of NMA grouts is in the final-rule stage (8, 9).

1.2.3. Acrylates

Acrylate grouts (11–13) such as Geo/Chem AC-400 Chemical Grout (Geochemical Corporation) were developed specifically as acrylamide grout replacements intended for sewer rehabilitation and similar applications. The objective was to provide low viscosity, low toxicity grouting systems that could be used in the same equipment and with the same catalysts as acrylamide grouts to provide controllable gel times and strong, durable, and water-impermeable grouts. Acrylate grouts are formulated using calcium acrylate [6292-01-9] and/or magnesium acrylate [5698-98-6] with lesser amounts of lithium acrylate [13270-28-5], 2-hydroxyethyl acrylate [818-61-1], or polyethylene glycol diacrylate. The catalyst system comprises ammonium persulfate [7727-54-0] and triethanolamine [102-71-6]; the cross-linker is a few percent of methylenebisacrylamide. Use of acrylate grouts in combination with silicic acid [1343-98-2] has been reported (14). The viscosity of a 10% acrylate grout formulation is approximately the same as for acrylamide grouts. The gel is formed by polymerization of the monomers on mixing of two equal volume solutions, one containing monomers and triethanolamine in water, the other a solution of ammonium persulfate in water. Compressive strengths of acrylate gels are somewhat lower than for acrylamide gels. Grouts formed are reported to be roughly comparable to those obtained with acrylamide grouts. Field experience has given mixed results, with some reports of corrosivity, swelling in water, poor durability, etc.

1.2.4. Polyacrylamides

Polyacrylamide gels were designed to obtain the advantages of the performance of acrylamide-based gels while substantially avoiding exposure to acrylamide monomer (15, 16). Low molecular weight polyacrylamides, which form low viscosity solutions in water, are cross-linked on demand to form insoluble gels (see Acrylamide polymers). An early product developed by Dow, but withdrawn in the mid-1980s, comprised a mixture of 20% polyacrylamide and 40% glyoxal (5, 17). Cyanagel 2000 Chemical Grout (Cytec Industries) is an anionic polyacrylamide grout in which gel formation is based on complex formation between anionic (carboxylate) sites on the polymer and ferric ions, generated by oxidation of ferrous ions with a mixture of sodium chlorate and sodium bromate. Gel rates increase with increasing bromate:chlorate ratio. As with acrylamide grouts, ethylene glycol can be added to protect against extremes of temperature and repeated wet–dry cycles. This system forms gels similar to those obtained with acrylamide grout and can thus be operated with equipment designed to handle the latter.

1.2.5. Urethanes

Urethane grouts described in the patent literature (18–25) comprise low molecular weight prepolymers of polyethylene or polypropylene glycol, end-terminated with toluene diisocyanate [1321-38-6] (TDI) or methylenebis(phenyl isocyanate) [101-68-8] (MDI). Gel-strengthening agents, such as aqueous polymeric latex (26), may be added to reduce shrinkage (see Urethane polymers). Fillers such as Celite, silicates, gypsum, or related substances may also be added. Cure rate is controlled through design of the polyol to make it more hydrophilic for faster rates and also through addition of catalysts such as trimethylolpropane, 1-isopropylimidazole, diazabicyclooctane, or organometallic compounds. Biocides, root control preparations, and other similar chemicals may also be incorporated. Polymerized forms of these grouts are considered nonhazardous. Isocyanate monomers are toxic but are converted to nonhazardous ureas on contact with the environment (27) (see Isocyanates, organic).

Foams and gels are both available. For example, Scotch Seal Chemical Grout 5600 (foam) and 5610 (gel) (trademarks of 3M Company) products are available through Avanti International, and are often used in combination for sewer repair. Large cracks are sealed by placing oakum, saturated in a water-activated foam product, into the cracks where it foams and expands to seal the crack as it cures. A urethane gel is then used to seal smaller cracks with an impermeable, flexible mass; to fill any existing voids behind leaking structures; and to permeate soil to create a grouted soil mass outside the leaking joint or crack. The urethane gels are used diluted six to ten times with water, together with any desired catalysts, strengtheners, fillers, etc. Gel grouts can be applied with automated equipment or pumped through and around structures to be grouted using hand-held injection equipment or high pressure multiratio pump systems. Urethane grouts have shooting viscosities 20 or more times higher than acrylamide or acrylate grouts.

Published comparisons (28) indicate that properly used urethane grouts offer cost–performance equivalent or superior to that of acrylamide grouts in many applications. Urethane grouts have good tensile strength, elongation, recovery properties, shrink resistance, and resistance to wet–dry cycles. Relatively low viscosities in diluted formulations are compatible with grouting of finely divided formations. There are some practical difficulties involved, however. For instance, it is difficult to deliver 1:5 or higher diluted mixtures of urethane grout in equipment designed to deliver 1:1 acrylamide grout:water mixtures. A urethane grout designed to be used in 1:1 ratios with water was introduced by 3M in 1991 but is no longer commercially available. Many urethane grouts contain some free organic isocyanates and either contain solvents such as acetone or ethylene glycol, or require them for cleanup.

1.2.6. Epoxies

Grouts based on epoxy resins (qv) are commercially available both as coatings and as gels. Two-part systems are mixed on-site and applied promptly. Application to wet surfaces is possible and sewer repair has been demonstrated. The Part A component can comprise epoxy resin, with inorganic additives such as titanium dioxide, kaolin, silicates, or ceramics. Part B can comprise cycloaliphatic amines and aliphatic polyamines. Injections of epoxy have been used to strengthen large mechanical structures such as the undersides of bridges. Compressive, tensile, and shear strengths greater than concrete make epoxies desirable for such applications.

1.2.7. Other Grouting Materials

Several other organic polymer systems have been used as grouts. These include urea–formaldehyde resins (aminoplasts) (29), phenol–formaldehyde resins (phenoplasts) (2), and lignosulfonates (2) (see Amino resins and plastics; Phenolic resins). When strengthening of soil to support the weight of roads, railroads, or building foundations is desired, combinations may be used of grouts, admixtures with other materials such as fluidized-bed ash (30), concrete (31), and geosynthetics, usually polyolefin- or polyester-based nonwovens, membranes, honeycombs, and grids (32). Such soil reinforcements to support foundations are widely used but long-term durability is a concern and has prompted detailed study of degradation mechanisms and ways to detect resulting degradation (33).

Organic grouts dominate many grouting applications but growth has been slowed by concerns over worker and environmental exposure to toxic monomers and solvents, as well as resulting regulations on use and disposal of the grouts. Improved products are needed which provide the performance of acrylamide grouts in nonhazardous material systems. Combinations of organic grouts and inorganics, including cement and concrete, are promising, especially for containing hazardous materials. For this application organic grouts alone are considered to be neither sufficiently effective nor sufficiently durable.

2. Soil Conditioners

2.1. Agricultural Applications

The emphasis in soil conditioning for agriculture is on formation of soil aggregates that support seed germination, seedling emergence, efficient use of irrigation water, and erosion prevention; and stabilization of these aggregates against the impact of wind, rain, and irrigation water. Chemical treatments can be a useful supplement to other methods used to prepare fields for agriculture. However, chemical treatment alone cannot be used to recover or prepare fields that are too wet or otherwise unsuitable for agriculture (34, 35).

Slaking of weak soil aggregates leads to formation of finely divided material that is deposited on the surface of the soil, forming seals and blocking soil pores. Surface seals impede water infiltration, promote ponding, runoff, and erosion, and reduce water use efficiency, soil aeration, and root respiration. When surface seals dry, they form hard crusts that mechanically impede the emergence of seedlings, reduce stands, lower yields, and require expensive overplanting and thinning or even replanting of crops. Poor water infiltration and internal drainage are common problems on arable soils of the arid southwestern United States (36). Surface crusting and plugging of soil pores caused by fine clay particles (37) and swelling in clay heavy soils (38) result in poor infiltration and drainage. This impairs management of salty or sodic soils, which require adequate leaching and drainage to prevent accumulation of salt and sodium. Inadequate infiltration and leaching result in lower crop yields (39).

Synthetic organic polymers were introduced as agricultural soil conditioners in the early 1950s. A bibliography from 1950 to ca 1995 is available (40). Many different polymer systems have been used, including copolymers of maleic anhydride with either vinyl acetate or isobutene, neutral and anionic polyacrylamides, poly(ethylene glycol), poly(vinyl alcohol), and poly(urea–formaldehyde), as well as polyurethanes and cellulose xanthate. Natural polymers such as polysaccharides and copolymers have also been used (32). Some dramatic improvements in soil properties were possible using polymer systems available in the 1950s, but only at application rates that were not cost-effective. By the mid-1960s, initial enthusiasm had disappeared and there was little activity in polymer soil conditioning. Since that time, improvements in the understanding of soil structure and in organic polymer science have led to better polymers and more efficient ways to apply them for soil conditioning. Cost-effective commercial soil conditioners are emerging; some of the new products produce the same results as the 1950s products did, but at 1% or less of the dose.

2.1.1. Erosion Control

The serious levels of erosion associated with irrigation and especially with furrow irrigation have been recognized (41). For example, in the northwestern United States, approximately 1.5 million hectares are surface-irrigated. Soils are derived from ash and loess, are low in organics and clay, have weak structure, and contain few durable aggregates. From 5 to 50 t/yr of soil per hectare can be lost from irrigated fields (42). Known erosion-control practices coupled with conservation tillage and selected crop sequences can substantially eliminate erosion. Furrow erosion can be reduced using settling ponds (43), minibasins and buried pipe to control runoff (44), straw placed in furrows (45), and sodded furrows (46). Unfortunately, farmers have been reluctant to use methods that may reduce usable acreage and be cumbersome or expensive to employ.

Overland water flow applies shear forces to soil surfaces. When shear forces exceed the stress required to overcome cohesive forces between soil particles, the particles are detached and suspended in the flow. Suspended particles are carried into surface soil with infiltrating water where they block pores and initiate seal formation (47). Thus, erosion results in reduced water infiltration as well as loss of soil from the field and consequent downstream water pollution. If erosion is controlled, good water infiltration is maintained.

Both synthetic organic polymers and polysaccharides have been shown in laboratory tests to maintain structure and permeability of soils under artificial rainfall conditions (48). Several field studies have demonstrated that 1–10-ppm levels of polyacrylamides dissolved in irrigation water, approximately 1 lb/acre, can eliminate most erosion during furrow irrigation (49). Soluble high molecular weight anionic polyacrylamides have been more effective in erosion control applications than lower molecular weight anionic, neutral, or cationic polyacrylamides (50). The preferred polymers have molecular weights in excess of 10 million and contain approximately 20% carboxylate groups. The USDA group in Kimberly, Idaho recommended an application rate of $\leq$10 ppm in irrigation water in the early stages of irrigation. Treatments using this protocol minimize loss of both silt and minerals from the field, while minimizing polyacrylamide in the irrigation effluent. The fate of polyacrylamides in the environment and possible environmental impacts have been reviewed (51, 52). Both dry polyacrylamides and liquid forms have been used to prepare the necessary solutions in irrigation water. Synergies of the polyacrylamides with other chemical agents such as gypsum (53, 54) and certain polysaccharides (55) have been reported. Use of anionic polyacrylamides in erosion control is synergistic with nonchemical erosion control strategies and is a recommended erosion control practice of the Natural Resources Conservation Service (NRCS) in the United States (56).

Different soils, terrains, and irrigation practices may require different application strategies for polyacrylamides, but their effective use to eliminate most silt and mineral, eg, nitrate and phosphate, losses from irrigated fields has been demonstrated at many test sites in the northwestern United States and in Arizona, California (57), and Colorado. Reports from 1996 on the benefits of polyacrylamides are similar to those reported in many studies published since the 1950s (40) except that generally the application rates are much lower. Field productivity is maintained in areas such as the U.S. Northwest where topsoil is thin. Downstream river pollution is reduced. There are other reported benefits, for instance, water infiltration is improved. This effect can be seen clearly in better crop yields on problem fields where high or variable slopes make it difficult to distribute water uniformly by the furrow irrigation method. Better infiltration may also make it possible to use more efficient irrigation strategies. Preventing the formation of soil crusts is another possible benefit. Two commercially available anionic polyacrylamides suitable for erosion control applications are Soiltex G1 soil conditioner (Allied Colloids) and Superfloc A836 Soil Erosion Polymer (Cytec Industries). If polyacrylamide is used on each irrigation throughout the season (not always necessary), the total cost of treatments each season in the mid-1990s would be in the \$49–\$74/ha range.

2.1.2. Prevention of Soil Crusting

Acid-based fertilizers such as Unocal's N/Furic (a mixture of urea with sulfuric acid), acidic polymers such as FMC's Spersal (a poly(maleic acid) derivative originally developed to treat boiler scale) (58), the anionic polyacrylamides described previously, as well as lower molecular weight analogues such as Cytec's Aerotil L Soil Conditioner, have all been used successfully in at least some circumstances to prevent the formation of soil crusts. It is difficult to prove benefits in the laboratory, and field tests may give variable results depending on local weather conditions. The results of 86 trials of crust prevention agents in Europe and Africa under conditions where rainfall supplied water for agriculture have been summarized (34). In this circumstance, crusts do not form or impede seedling emergence unless it rains between the time of planning and seedling emergence. Individual results were therefore variable but on average the crop yields were increased 16%.

2.1.3. Improvement of Water Retention

Sodium acrylate–acrylamide copolymers cross-linked with methylenebisacrylamide, the so-called superabsorbent polymers, have been used to improve soil properties, specifically water distribution, availability, and drainage characteristics in situations where soil texture is coarse (sandy) or rainfall is marginal for agriculture. The cross-linked gels absorb large volumes of water, swelling and preventing gravity-induced downward flow in the soil. The absorbed water can later be lost to evaporation or extracted by plant roots. When intimately mixed with soils at application rates of 49–74 kg/ha (more may be needed in sandier soils), the gels may make it easier to cultivate crops under marginal conditions of soil and rainfall. Proper placement of the polymers by spraying (59) or other means (60) can disrupt undesirable soil capillary action while providing a water reservoir (61) in the right location to promote desirable root system growth.

Typical products are supplied as white powders having particle diameters ranging in size from a few micrometers to a few millimeters, depending on the grade. Gel powders can be mixed dry with the soil or partially hydrated and then sprayed onto the soil. Some manufacturers also sell liquid forms. The gels resist aerobic biodegradation and persist in soil for several years even under wet conditions. Decomposition occurs in several months under exposure to sunlight. The particles hydrate when in contact with water, absorbing from 40 (seawater) to 500 (distilled water) times their weight of water and swelling proportionately. Full absorption requires a few hours. The pH of absorbed water is neutral. Hydration and swelling are reversible. Plant root systems create a sufficient pressure gradient to extract more than 90% of the water held by the polymer. The polymers, which may be used in combinations with mulches (62) or other treatments designed to slow evaporation, improve water retention and location in porous soils and help to protect plants where rainfall is marginal. The gels are considered nonhazardous and are compatible with many fertilizers, although polymer dose rates may have to be increased.

Commercial products that are available include Alcosorb 400 Water-Retaining Polymer (Allied Colloids), Aquasorb PR 3005 Superabsorbent Polymer (S. N. Floerger), and Aquastore Absorbant Polymer (Cytec Industries). These products are also sold by distributors, often combined with synergists, under various trade names. A saponified starch-graft polyacrylonitrile copolymer originally developed by the USDA is also available as a biodegradable super slurper (63). Application rates and hence application costs for these products are too high to allow cost-effective use in most large-scale agriculture. Urban uses such as golf courses in arid climates are common. Additional uses include hydroseeding, hydroponics, transplanting of annual plants, and mulching for trees and shrubs.

2.2. Other Applications

Construction of highways creates many steep slopes which must be stabilized against erosion by water or wind. Excavations as part of construction projects and natural disasters such as the Oakland, California fire storm of 1991 also create severe erosion problems. Many types of inert structures are available for slope stabilization and erosion control, including retaining structures of various types, revetment systems, and ground covers such as artificial mulches (cellulose fibers, fiber glass); chemical systems such as tackifiers and emulsions; blankets, mats, and nettings to cover slopes (64); and cellular confinement systems. Many of these systems offer very high strength in surprisingly light structures, such as polyethylene-based honeycombs formed into blocks. Although designed for long life, these inert systems, whether based on steel, concrete, or synthetic polymers (65), slowly degrade (66) with time. Hence, reestablishment of vegetation is highly desirable and is possible with porous retaining structures, revetments, or ground covers (67).

Hydroseeding is widely used in slope stabilization. A mixture comprising grass seeds, fertilizer, synthetic polymer, and water is sprayed onto banks. Polymers that include poly(vinyl alcohol), poly(vinyl acetate), polyacrylamide, methacrylates, acrylate–acetate copolymers are used by different manufacturers in formulations for hydroseeding. Many products include a cohesive binding agent (tackifier), such as a latex copolymer emulsion (68), mixed at 2–4% levels in water and sprayed onto the soil, where it forms a thin water-resistant crust that reduces dust formation and controls erosion and then gradually decomposes as vegetation becomes reestablished. Applications of polymer mixed with seed may range from 0.5 to over 5.0 m^3/ha, depending on circumstances (69).

Other chemical systems used in stabilization of highways and embankments have been described (70). Commercial products include $CaCl_2$ and $MgCl_2$ for dust control, soil agglomerating systems that may include active ingredients such as ammonium laureth sulfate, and lignosulfonates used for dust control and road stabilization which act by agglomerating clay particles in soil. Cementitious products, such as the lime-based product produced by Chemical Lime Corporation, are used at a rate of about 5 t/ha, applied with about 4000 liters of water per ton of dry product and sprayed on the soil. The product is applied after the hydromix to hold soil in place, gradually breaking down as vegetation is reestablished. U.S. Gypsum produces a soil stabilizer containing calcium sulfate hydrate which forms a crust after it sets. This material requires 4–6 h to set; it gradually dissolves, supplying calcium and sulfur to the soil.

Control of surface-irrigation-induced erosion using dissolved anionic polyacrylamides at ppm levels is generally regarded as effective, safe, and affordable in large-scale agriculture. Possible ancillary benefits such as improved crop yields, prevention of soil crusting, and improved water infiltration into soil are under active study. Chemical soil and water conditioning used in combination with other established methods for soil preparation and erosion control is likely to play a key role in the development of truly sustainable irrigated agriculture. Many of the polymer systems used in soil conditioning in the 1990s were originally developed for other purposes. Development of next-generation systems specifically designed for soil conditioning is expected. Use of geosynthetics to support, direct, and control soil profiles is also on the rise.

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