Suitability of an alluvial overburden material as a plant growth medium at the Berkeley Complex in Butte, Montana

by John Allen Lawson

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Rehabilitation
Montana State University

Abstract:
Absence of a local recoverable native soil for reclamation at Anaconda Minerals Company's Berkeley Complex in Butte, Montana, has prompted a two-phase research project initiated in 1979. Phase I identified the chemical and physical characteristics of an alluvial overburden material proposed for use as a cover-soil. Low fertility and a severe cover-soil crust were identified as the most plant limiting factors. Phase II, completed in 1982, investigated the response of three grass species (Agropyron dasystachym, Festuca ovina and Poa compressa) as influenced by three overburden amendments (incorporated manure, incorporated hay mulch and incorporated fertilizer) . Results indicated that seedling emergence was inversely related to cover-soil crust strength and both were a function of soil moisture. Significant differences in seedling density were noted between the three amendments and the control. Crust strength increased successively and significantly in all treatments throughout the growing season when compared to incorporated manure. A. dasystachyum produced significantly more cover and phytomass than either F, ovina or P. compressa. Preliminary data suggested A. dasystachyum in the manure amendment was the most promising species-amendment combination for rapid establishment and herbage production. Percent volumetric soil water determinations, utilizing the neutron method, found no impedance to water flow at the cover-soil/spoil interface.

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ABSTRACT

Absence of a local recoverable native soil for reclamation at Anaconda Minerals Company's Berkeley Complex in Butte, Montana, has prompted a two-phase research project initiated in 1979. Phase I identified the chemical and physical characteristics of an alluvial overburden material proposed for use as a cover-soil. Low fertility and a severe cover-soil crust were identified as the most plant limiting factors. Phase II, completed in 1982, investigated the response of three grass species (Agropyron dasystachym, Festuca ovina and Poa compressa) as influenced by three overburden amendments (incorporated manure, incorporated hay mulch and incorporated fertilizer). Results indicated that seedling emergence was inversely related to cover-soil crust strength and both were a function of soil moisture. Significant differences in seedling density were noted between the three amendments and the control. Crust strength increased successively and significantly in all treatments throughout the growing season when compared to incorporated manure. A. dasystachyum produced significantly more cover and phytomass than either F. ovina or P. compressa. Preliminary data suggested A. dasystachyum in the manure amendment was the most promising species-amendment combination for rapid establishment and herbage production. Percent volumetric soil water determinations, utilizing the neutron method, found no impedance to water flow at the cover-soil/spoil interface.

INTRODUCTION

A long history of metal mining in the Intermountain West has left permanent environmental records of previous economic enterprises (Larson 1977). One of the most extensive and lucrative mine fields in the American West was first uncovered in 1864 in Silver Bow Creek in Southwestern Montana, near present day Butte (Lewis 1963). Originally, gold and silver were the target minerals, however, by the turn of the century, copper became the most mined metal (Smith 1953).

Over 100 years of combined underground and open pit mining have resulted in nearly 3300 hectares of land disturbances in the Butte area (Parady 1981). The Anaconda Minerals Company administers an open pit truck and shovel operation at the Berkeley Complex in Butte, Montana. The mine extracts lowgrade copper and molybdenum ores. Currently, the mine has suspended activities in lieu of present economic conditions.

Since 1955, the open pit operation has constructed massive stockpiles of spoil material, resulting in an increased surface area requiring rehabilitation. Furthermore, the area has a critical lack of salvageable native soil, which hampers reclamation of the mine waste dumps.

In 1979 a two phase research project was initiated to identify alternate sources to native soil for covering mine waste dumps. Phase I (Parady 1981) identified the chemical and physical characteristics of an overburden material as a potential cover-soil. The selected overburden occurs as a vast deposit of sandy loam alluvial material. Laboratory analyses indicated the alluvium is slightly acidic and lacks nitrogen (N) and phosphorus (P). Parady (1981) reported the alluvium rated "good" in a suitability classification system outlined by Schafer (1979) for topsoil, subsoil and overburden materials used as a cover-soil. Additional analyses performed in phase I reported copper, manganese and zinc concentrations were elevated in the alluvium. However, Parady (1981) recommended amendments of liming and organic matter to decrease the plant availability of these metals. Subsequent field investigations also identified a critical surface crusting problem in fallow alluvium. The mechanism of crust formation was identified in phase I as grain packing, with clays and silts filling voids between sands. Further greenhouse experiments revealed alluvium crust strength was decreased by addition of organic matter. Organic matter added to alluvium reduced crust strength by the formation of stable soil aggregates and reducing clay adhesion in the sand fraction (Parady 1981).

Based on results of laboratory and greenhouse experiments reported in phase I of this study, a second phase was initiated to further research the potential of the alluvial overburden material as a plant growth medium. A field investigation was designed for the purpose of determining the suitability of previously selected alluvium as a plant growth medium. Three surface amendments and three plant species were evaluated. Specific objectives in the second phase of this study were:

1.) To assess three alluvium amendments (incorporated fertilizer, incorporated manure and fertilizer and incorporated hay mulch and fertilizer) for plant growth suitability, including reduction of surface crusting in alluvium.

2.) To assess performance of three grass species [thickspike wheatgrass (Agropyron dasystachyum (Hook) Scribn.), Canada bluegrass (Pos compressa L.) and hard sheep fescue (Festuca ovina L.)] in each amendment as compared to non-treated alluvium.

LITERATURE REVIEW

Overburden As A Cover-soil

The use of overburden or spoil material as a plant growth medium often results from a lack of suitable existant or salvageable native soil (Kelley 1979). Brown and Johnston (1978) observed that many high elevation disturbances are frequently lacking in topsoil. The author pointed out that hardrock mining disturbances on the Beartooth Plateau in southcentral Montana, are extensive enough to dictate the use of select spoil materials for revegetation. In 1979, Schafer acknowledged that select overburden materials may be required to replace unsuitable topsoil or subsoils in the Northern Great Plains. He defines cover-soil as any earthen material used in reclamation to support plant growth. The potential of overburden materials to support vegetation was studied on surface coal mines by Byrnes et al. (1980) in southwestern Indiana. The author concluded that overburden lacked fertility and required surface amendments to establish alfalfa, small grains and tree seedlings. An extensive study was performed to analyze the chemical and physical properties of various overburden and spoil materials important to plant growth at the Jackpile uranium mine in New Mexico (Reynolds et al. 1978). Revegetation of acidic 14 year old sulfur mine spoil with tree and shrub transplants was reported to be successful in the Sierra Nevada mountains of California (Butterfield and Tueller 1980). The use of select coal spoil materials and surface amendments for agricultural corn production was reported by Nielsen and Miller (1980). In Pennsylvania corn production was only 7-22 percent less on mine spoils when compared to native soils.

An extensive study investigating variable depths of cover-soil over select overburden materials (wedge construction) was conducted on 14 field plots at 11 coal mines in the Northern Great Plains (Barth and Martin 1982). The authors compared spoil type groups for plant performance and the chemical and physical status of cover-soil and spoil material over a five year period. Results of the strongly acid (pH 3.6 to 4.3) spoil group indicated that as cover-soil depth increased, plant production increased in a linear manner. Plant cover, however, did not vary as substantially as cover-soil depths increased. Acidification of cover-soil materials was minimal and the chemical and physical nature of the spoil did not significantly affect the cover-soil.

Successful revegetation utilizing mine waste or spoil material exclusively, is dependent upon the chemical and physical characteristics of the proposed material (Schafer 1979). Texture was reported by Sindelar and Plantenberg (1979) to be the major factor controlling plant succession on old coal mine spoils in southeastern Montana. Revegetation of metal mine spoil in the Captains Flat area of New South Wales, Australia, was solely dependent upon liming, fertilizing and the addition of organic matter (Keane and Craze 1978).

Greenhouse and laboratory experiments are often required to fully evaluate the potential of the overburden or spoil material (Butterfield and Tueller 1980, and Berg 1975). In Wyoming, Schuman and Taylor (1978) found, through greenhouse experiments, that vegetative productivity of a native fine loamy topsoil was improved by addition of a heavy clay spoil material. However, in New Mexico, spoil from the Fruitland formation was determined to be saline and sodic and therefore, not suitable for use as a plant growth medium (Gould et al. 1976). Greenhouse studies revealed that Black Mesa coal spoil in Arizona required fertilization and irrigation to reach plant production similar to native soils (Day et al. 1979).

Accurate analysis of all potential overburden materials is critical due to the diversified nature of overburden and the subsequent spoil material after mining. In copper mining as much as 99 percent of all mined material may be waste (Imhoff et al. 1976). Furthermore, once the overburden is spoiled, the resultant dump assimilates the different chemical and physical characteristics of its components. Reynolds et al. (1978) analyzed four uranium spoils of variable age (4-20 years old) for plant growth suitabilities at the Jackpile mine. All four spoils varied in texture and chemical composition and no one spoil was superior as a plant growth medium.

In phase I of this study Parady (1981) characterized 86 alluvial overburden samples and analyzed each for plant growth potentials. A rock fragment percentage of less than 35 was utilized as the criterion for field selection of overburden to be used as a cover-soil at the Berkeley Complex. These recommendations were based on criterion outlined by Schafer (1979) for selection of suitable overburden materials to be used in the plant root zone. Although the author found the alluvium suitable for plant growth, various cultural amendments improved the performance of this material as a plant growth medium.

Establishment of an effective plant growth medium from mine waste or spoil material is dependent upon the chemical and physical status of the soil (Schafer 1979). Although more desirable growth media may exist, in many areas there is no alternative to the use of mine spoil or overburden (Brown and Johnston 1978; Parady 1981; Schafer 1979; Byrnes et al. 1980; and Reynolds et al. 1978).

Numerous studies reported success in establishing vegetation on mine spoil (Butterfield and Tueller 1980, Nielsen and Miller 1980; and Schuman and Taylor 1978), however, cultural treatments are usually required to alter some undesirable aspect of the atypical growth media (Parady 1981; Byrnes et al. 1980; Brown et al. 1978; and Keane and Craze 1978).

Cultural Amendments in Reclamation

Revegetation of mine spoils and waste dumps is often complicated by the adverse physical nature of spoil, droughtiness, inherent low fertility, extremes in pH, salinity, sodicity, heavy metal toxicities, excessive slope gradients and uncompromising weather conditions (Troeh et al. 1980). One method of controlling and/or stabilizing mine spoil is through the establishment of permanent vegetative cover. Development of a vegetation system is dependent upon amelioration of those factors that limit plant growth. Therefore, successful rehabilitation is a process that must be initiated by man (USDA 1979). Reports of techniques to improve the plant growth environment on native soils and mined lands exist extensively in the literature. Reclamation research regarding improvement of the plant growth environment is extensive. Only that portion of research directly pertaining to the objectives of this study is reviewed here.

Organic Mulches

The role of organic mulches in reclamation is many faceted. Generally, mulches function to increase soil fertility, decrease wind and water erosion, increase water infiltration and alter soil microclimates to improve seed germination or improve soil aggregation (USDA 1979).

Straw and hay mulches are the most widely used of all organic mulches. In comparison, cereal grain straw is more available and economic than hay and therefore, more extensively used (Kay 1978). The presence of undesirable plant propagules is a common problem in straw and hay mulches. Annual weeds harvested with a hay crop for mulch in southeastern Montana significantly influenced subsequent vegetative cover on the mulched minesoils (Darling 1983). In addition straw and hay mulches immobilize available soil nitrogen, requiring supplemental fertilization (USDA 1979).

The use of straw or hay mulches to reduce soil erosion is widely documented. In the northern region of Bhana, Bonsu (1980), concluded that straw mulch decreased erosion loss 94 percent over bare fallow soil. An Australian study reported that three tons of hay mulch per acre maintained slope stability on mountain roadcuts during plant establishment (Wild 1979). Meyer et al. (1970) tested six rates of straw mulch in a loam soil in Indiana and concluded that rates as low as 0.56 metric tons per hectare reduced erosion to one half that of unmulched soils. In a greenhouse experiment Singer and Blackhard (1977) found a parabolic relationship (r^2=0.81) between soil loss and straw mulching on a nine percent slope. The mulch reportedly reduced raindrop splash effect and soil crust formation.

Documentation of hay versus straw as a mulch is less common in the literature. However, in 1941, Wenger reported on the use of native hay for the reestablishment of deteriorated Kansas rangelands. Bergman and McKee (1976) found mulching essential for vegetation establishment on Pennsylvania coal spoil and hay was more effective than straw. At the Rosebud coal mine in southeastern Montana, native hay mulches are used exclusively over agronomic mulches. The use of native hay provides similar structural attributes as straw, but contains a valuable source of native seed (Coenenberg 1982). Ries et al. (1980) found that in North Dakota prairie hay improved the microclimate and reduced erosion for seedling establishment in addition to providing a native seed source for revegetating disturbed lands.

The application of animal wastes to improve the chemical and physical status of agricultural soils has been a common practice. Increased crop yields through the addition of manure are reported in international literature. Magdoff and Amadon (1980) reported increased yields of continuously cropped corn in Vermont through incorporation of 44 metric tons (MT) of dairy manure per acre. In Michigan, Guttay et al. (1956) reported stable manure increased the relative yield of small grain and row crops over 100 percent, two years after application. However, small grain production decreased over ten percent six years after application while row crop production declined only slightly.

Phase I of this study utilized a greenhouse experiment to test variable rates of stockyard manure incorporated into the alluvium. Results indicated that increasing levels of manure produced significant differences in aerial biomass of spring wheat plants. However, the greatest differences in plant production were noted with initial addition of low levels of manure, incorporated to a depth of 8 cm (Parady 1981). In addition, crust strength was measured in alluvium mulched with manure at a 1:4 volumetric rate. The 1:4 (manure to alluvium) ratio was based on previous studies of optimum plant performance. It was concluded that alluvium with incorporated manure had significantly less crust strength than either the control or straw mulched plots. These results are similar to a study on soil crusting of native soils in eastern Nebraska. Mazurak et al. (1975) also found that stockyard manure applied at a rate of 360 MT/ha incorporated to a depth of 10 cm, significantly reduced surface soil crusting.

Modest applications of manure have been noted to reduce soil erosion (Kohlman 1978 and Free 1949), increase soil pH and nitrogen concentration (Long et al. 1975), increase soil aggregate stability (Guttay et al. 1956), increase soil cation exchange capacity (Lund and Doss 1980) and soil water holding capacity (Olsen et al. 1970).

In Vermont, Magdoff (1978) reported that manure applied to well drained soil produced more corn than the same amount of manure applied to a heavier clay soil. The benefit of manure additions results from a more rapid release of N in the more coarse textured soil. However, these data indicate subsequent additions of manure will be necessary to sustain production. Magdoff (1980) hypothesized that an increase in cation exchange capacity (CEC) corresponding to addition of manure produces an increase in soil organic matter as well as an increase in soil pH.

In Alabama Long et al. (1975) disclosed that nitrate-nitrogen (NO_3-N) was elevated to a depth of 90 cm in the soil profile when 45 MT/ha of dairy manure was incorporated to a depth of 15 cm in a sandy loam soil. Nearly 35 years ago Free (1949) stated that low rates of farm yard manure applied as a top-dressing was more effective in reducing erosion than heavier rates incorporated into the soil. In addition relative crop yields were 11 percent higher in the top-dressed systems when compared to the incorporated treatments.

The increase in soil pH and CEC reported in many manure studies can be attributed to the elevated number of available cations in the manure. Lund and Doss (1980) reported that an initial surge in pH was due to the release of NH_3 cations when manure was incorporated into the soil. However, the authors felt that soil texture was important in interpreting changes in pH and CEC. The sandy loam soil had larger increases in pH when compared to the loamy sand. The differences were explained by the higher buffering capacity of the heavier soil. Concurrently, CEC increased four fold in the coarser texture loamy sand, due to the lower relative availability of cations in coarse soil when compared to the loamy sand, which had less substantial changes in CEC.

The use of manure to improve the plant growth potential of mine soils is less common than in agricultural environments. However, on the Beartooth Plateau in Montana, Brown and Johnston (1978) reported a substantial increase in plant production on orphaned mine spoil through addition of 4480 kg/ha of dried steer manure. The addition of organic matter in the phase I of this study increased water holding capacity, nutrient availability, aeration, reduced evaporation and modified surface temperature fluctuations (Parady 1981).

In Wyoming, coal spoil was mulched with variable rates of a feedlot manure compost which contained 50 percent sawdust (Mason et al. 1980). It was concluded that the feedlot compost was less effective in producing vegetative cover than the non-treated plots. A wide carbon:nitrogen ratio created by sawdust seemed to contribute to the failure of compost. In addition the cost associated with manure application was substantially higher than the more conventional cereal grain mulches.

Both native hay mulches and animal waste mulches contain undesirable weed species. Weed seed passed through animals and deposited in manure may present difficulties in establishment of desirable plants during initial reclamation phases (Bloomfield and Ruxton 1977). However, manure contains many standard plant nutrients and microorganisms (Magdoff 1978) that may be difficult to maintain in infertile mine spoil. In 1975, Long et al. found the chemical composition of dairy cattle manure provided more N than any other element (807 kg of N/45 MT of manure). Potassium (K), calcium (Ca) and magnesium (Mg) levels were also elevated in manure but in less than half the amount of that reported for N.

The value of animal manure based on relative nutrient amounts was calculated for five farm animals by Walsh and Hensler (1971). Prices per ton of cattle manure in this study varied according to nutrient value and ranged from $2.00 to $2.44/ton depending upon cattle varieties and manure availability.

Organic mulching to reestablish vegetation on mine spoil is commonplace in the western United States. Organic mulches are usually waste or by-products of agricultural systems. Most techniques were originally employed in agricultural systems and many new methods are currently being tested for agriculture in variable climates and edaphic conditions worldwide.

Straw and hay mulches are the most widely used of all organic mulches. Many uses are documented for straw and hay, however, their use in soil loss or erosion control is most widespread. Throughout the world, straw or hay incorporated into soil systems is reported to reduce erosion. Additional benefits include creating favorable microclimates for plant growth by: reducing wind velocity at the soil surface, reducing raindrop impact, reducing the velocity of overland water flow, modifying soil temperatures, increasing water infiltration, creating shade for seedlings and preventing soil crusting (Kay 1978). However, straw and hay mulches may introduce troublesome weed seed into a new environment or even wick water from the soil system (Darling 1983, and USDA 1979).

Animal wastes or manure can function to alter soil chemical and physical status and add essential microorganisms. Many studies report increased crop yields through the addition of manure to agricultural soils (Guttay et al. 1956). Benefits to the plant environment can come through additions of vital plant nutrients (especially N, K, Ca and Mg; Long et al. 1975), higher CEC levels and improved soil water status (Lund and Doss 1980, and Parady 1981). The increase in pH and CEC was documented in soils cropped continuously for corn in Vermont (Magdoff 1978). Increased grain production and decreased erosion was noted in New York (Free 1949). In Alabama Long et al. (1975) found elevated levels of N, K, Ca and Mg when manure was applied to soils. On reclaimed land in the Montana Rockies, total vegetation productivity was increased by additions of manure (Brown and Johnston 1978). However, in Wyoming feedlot compost decreased plant yields (Mason et al. 1980). Parady (1981) reported that manure decreased crust strength of alluvium cover-soil and increased wheat production under greenhouse conditions.

Fertilization

The process of revegetating mine spoil is often hampered by absence of nutrients critical to establishing and maintaining plant growth. Bauer et al. (1978) found that most spoil materials inherently lack sufficient fertility and require supplemental fertilization to support plant growth. Without the aid of cultural amendments, Omodt et al. (1975) calculated that mine spoil in North Dakota would require 350 years to build up organic matter levels comparable to those found on native soils. Furthermore, the author determined that nearly 300 MT of manure /ha would need to be added annually for 40 years, to reach a one percent organic matter level in mine spoil. While these figures seem exceptional, they suggest the need for establishing adequate fertility and an organic matter base in mine spoil. The major nutrients required for revegetation can be supplied through addition of commercial fertilizers (Michaud 1981).

In order to determine fertilizer requirements, various factors must be assessed: plant nutrient requirements, available nutrient status of growth media, fertilizer effect on growth media, refertilization estimates, soil water availability and cost (USDA 1979).

The most common nutrient elements lacking in spoil materials in the West are N and P. Phosphorus is often more deficient than N (Sandoval et al. 1973) in the Northern Great Plains. In the same region DePuit and Coenenberg (1979) found P more limiting than N and K generally nonlimiting in the majority of mine soils. The authors reported increasing amounts of N and P increased plant cover of introduced grasses. However, during the initial phase of seedling establishment, variable rates of N showed no differences in plant density. In a greenhouse study of coal mine spoil Holechek (1982) found two Agropyron species increased in above and belowground biomass through low applications of N and P.

Several studies have shown that plant uptake of P is affected by N fertilization. Various rates of N and P fertilization produced greater overall yields on native range in western Canada when compared to an unfertilized condition (Johnston et al. 1968). When N and P were applied separately and together on mixed grass prairie in North Dakota, Lorenz and Rogler (1973) found increased plant performance from variable rates of N with P, when compared to single applications of each. A laboratory study found thickspike wheatgrass yields nearly doubled in sodic coal spoil, when N was included with P. However, in the same study, nitrogen fixing yellow sweetclover only required P fertilization (Safaya and Wali 1979). In the Upper Teesdale region of England, sheep fescue benefited more from P than from N fertilization on shallow well drained soils. However, angiosperms required both N and P for increased shoot growth (Jeffrey and Pigott 1973). Revegetation of New Hampshire roadcuts with bluegrass and fescue grass species required only low rates of N and P fertilization to promote growth (Palazzo and Graham 1981). Analyses indicated that N and P in the soil were limiting to leaf growth prior to fertilization. In a southeastern Montana study of mine soil fertilizer requirements, Hertzog (1983) found fertilization produced the only significant vegetational responses when compared to N and P. However, the author concluded that indigenous N levels were sufficient in the mine soils to meet the first year growth requirements of the predominately native grass seed mixture.

Fertilization requirements in disturbed areas of higher elevations with coarse textured soils are much different than those of lower elevations that commonly have heavier soils (i.e., Northern Great Plains). Subalpine and alpine ecosystems typically have coarse textured cold soils where N is the limiting nutrient, probably resulting from low rates of microbial activitiy (Nishimura 1974).

Therefore, most high altitude revegetation efforts will begin with additions of N and P, but maintenance N fertilization is often required (Berg and Barrau 1978). These authors found that grasses established on two revegetated sites in the Colorado Rockies were extremely nitrogen deficient within three years after establishment. Due to the decreased organic matter level in high elevation coarse textured spoils and subsoils as well as elevated precipitation levels, 25-35 kg of N/ha is recommended every two or three years to maintain vegetative productivity on disturbed sites (USDA 1979). Working on spoil at the McLaren mine in Montana, Brown et al. (1976) found that fertilization with primarily N and P was imperative to rapid plant establishment. Specifically, the authors reported plant cover values 100 times higher, over a three year period on plots fertilized with 111 kg N/ha than non-fertilized spoils. At the end of the initial year of plant establishment, plant density was three times greater on fertilized spoil and topsoiled plots when compared to non-treated mine spoil or topsoiled plots.

The use of chemical fertilizers to improve plant growth on mine soils is well documented. Although fertilizer requirements are site specific, the basic criteria for establishing macro- and micro-nutrient needs are the same (USDA 1979). A review of the literature demonstrated that overall, mine spoil fertility is essentially quite low. The amount and grade of fertilizer used depends upon revegetation goals which are dictated by the type and location of the disturbance. In the Northern Great Plains P was found to improve plant performance (Depuit and Coenenberg 1979, Hertzog 1983, Sandoval et al. 1973, Holechek 1982 and Safaya and Wali 1979), while in high elevation disturbances, N fertilization initially and often in repeated applications is necessary to achieve revegetation success (USDA 1979, Brown et al. 1976, Nishimura 1974 and Berg and Barrau 1978).

Liming

The creation of a suitable plant growth medium from acidic mine spoil is dependent upon the chemical characteristics of the material. Failure of many plants to survive in a low pH growth medium is rarely the result of the increased hydrogen ion (H^+) concentration (USDA 1979). Rather, decreased plant yields are most frequently due to increased and often toxic concentration of plant available aluminum (Al), manganese (Mn) and iron (Fe) (Tisdale and Nelson 1975). Furthermore, as these metals become more soluble, they form insoluble compounds with phosphates and create a phosphate fixation condition. Other macro-nutrients adversely affected by an acidic soil chemistry (i.e., decrease availability) are N and K, therefore, pH may be the most plant limiting chemical reaction in spoil materials (Vandevender and Sencindiver 1982, and Michaud 1981).

Acidity associated with many western hardrock spoils is generated by the oxidation of pyritic and sulfide minerals. Upon oxidation, these minerals produce acids and ferrous and ferric sulfates (Richardson and Farmer 1981). Sulfuric acid is a product of the oxidation of pyritic materials and is mainly responsible for spoil acidification. The rate of oxidation is dependent upon the size and shape of pyritic minerals (Richardson 1980).

Liming acidic soil and spoil materials to aid in the establishment of vegetation is well documented in reclamation literature. Revegetation of spoil at a western hardrock mine was found by Nielson and Peterson (1972) to be contingent upon liming. In Pennsylvania, researchers reported lime was more effective in establishing crownvetch in coal-breaker refuse than either fertilization or mulching. Lime rates of 2.3 and 4.5 MT/ha had maintained near neutral pH over a seven year period. Other benefits from liming found in this study were increased soil exchangeable Ca and Mg, as well as CEC and percent base saturation (Czopowskyj and Sowa 1976). In Australia, toxic heavy metal mine wastes were limed, buried and covered with a more suitable cover-soil medium. Successful mine dump revegetation required 6.3 MT of lime /ha (Keane and Craze 1978).

Hydrated lime was applied at a rate of 4 MT/ha on coal mine spoil in West Virginia and found to significantly increase spoil pH, the neutralization potential and Ca levels. However, the authors suggested the neutralizing potential of hydrated lime may not be permanent and may require additional applications to prevent reacidification (Vandevender and Sencindiver 1982). In Arkansas, acidic bauxite minesoil was limed with six rates of hydrated lime ranging from 18-63 MT/ha. One month after liming minesoil pH was near neutral for lower rates of lime application, however, at the heavier rates soil pH was high enough to preclude plant growth. Further analyses indicated that minesoil pH decreased in all treatments two years after liming. The author concluded that hydrated lime was initially effective in elevating minesoil pH, but control must be taken to assess the proper lime rate (Harper and Spooner 1982). Reacidification of a copper-cobalt mine spoil at the Blackbird mine in southeastern Idaho occurred two years after initial application of ground limestone ($CaCo_3$) at a rate of 3.2 MT/ha/30.5 cm (1.4 tons/acre/foot). Further analysis suggested a rate of 44.9 MT/ha/30.5 cm (20 tons/acre/foot) would neutralize mine spoil pH for at least 10 years (Richardson 1980). These results further exemplify the need for establishing proper lime requirements to meet revegetation goals.

The use of lime to neutralize mine spoil acidity during plant establishment is an effective tool in many revegetation programs. Adequate amounts of lime added to mine spoil will increase soil pH and reduce Al, Mn and Fe solubility which is often toxic to plants (Michaud 1981). The primary source of mine spoil acidity results from oxidation of pyritic materials in overburden, the rate of oxidation is controlled by size and shape of pyritic materials (Richardson 1980). Numerous studies proved that lime application rates must be based on accurate mine spoil chemical analysis prior to treatment (Vandevender and Sencindiver 1982, Czopowskyj and Sowa 1976, and Richardson 1980).

Soil Crusting

Prior to phase I of this study, research on mine spoil crusting was virtually nonexistent. However, given that many chemical and physical parameters of any growth medium must be similar in order to support plant life, results of agricultural research pertaining to soil crusting are valuable.

The mechanism of soil crust formation is peculiar to chemical and physical characteristics of the soil. Without exception more than one process leading to crust formation and strength was described in each study that identified a mechanism. A sequence of crust formation as outlined by McIntyre (1958a) occurred in three phases: 1) soil breakdown, slaking or dispersion due to raindrop impact, 2) translocation of fine particles to the upper 1-2 mm soil layer, 3) cementation of the translocated particles upon drying. Further research on the affect of soil splash on surface crust formation concluded that washing-in of fine particles and surface compaction from raindrop impact were the main mechanisms of crust formation (McIntyre 1958b). In phase I of this study Parady (1981) identified the mechanism of alluvium crust formation as "a physical problem caused by grain packing and clay adhesion within the sand fraction."

Although crust strength is a function of the formation mechanism, several factors have been identified that contribute to increasing crust strength. Hegarty and Royle (1978) found crust strength a result of rainfall quantity, compaction as influenced by soil moisture during the compaction process and the interaction of compaction and rainfall quantity. Using the modulus of rupture technique of quantifing crust strength, Lemos and Lutz (1957) found crust strength increased by: long hot dry periods, slow drying at low temperatures, compaction, raindrop impact and puddling. The authors also considered soil texture, clay type and bulk density.

In similar studies conducted by Gerard et al. (1972), soil moisture was included as a critical component affecting crust strength. An inverse relationship between crust strength and soil moisture is a well documented phenomenon (Hanks 1960, Arndt 1965, Lemos and Lutz 1957, Holder and Brown 1974). Parady (1981) found a very high positive correlation ($r^2 = 0.97$) between declining percent gravimetric soil moisture and increasing crust strength. Holder and Brown (1974) reported that soil crust strength increased with decreasing soil moisture and was also related to drying time. A north-central Montana soil with a long history of grain production was found to have an inverse relationship between crust strength and soil moisture (Moe et al. 1971). The authors also found that below ten percent soil moisture when crust strength was high, soil water tensions exceeded 15 bars, a level beyond the plant wilting point for this soil. Therefore, soil water (below ten percent) was more limiting than crust strength for overall plant performance.

The purpose of many soil crust research projects identified crusting characteristics that influenced seedling emergence or impedance. Mechanical impedance of emerging seedlings by soil crusts is just one of many problems associated with seedling emergence. In many areas of the world the problem is substantial. Moe et al. (1971) stated that over 60,700 hectares of Montana farmland are affected by soil crusts. Although crusting occurs in a variety of climates, soil crusts formed in semiarid or arid climates undergo rapid drying and can form quickly. Therefore, the rate of seedling emergence becomes quite critical (Taylor 1962). In the arid Negev region of Israel soil crusting is most often the cause of poor wheat yields (Hadas and Stibbe 1977). The effect of crust strength on six important Nevada pasture grasses was reported by Frelich et al. (1973). Their research showed that pubescent wheatgrass, tall fescue and smooth bromegrass were adversely affected by increasing crust strength, while emergence of tall wheatgrass, basin wildrye and Russian wildrye was less affected. Under extreme crusts, tall wheatgrass had the highest emergence percentage. In a similar study on forage seedlings Jensen et al. (1972) reported that alfalfa seedlings exhibited significantly higher emergence force when compared to narrow-leaf birdsfoot trefoil, strawberry clover and alsike clover. Furthermore, they concluded that seed weight of these legume species was positively correlated to greater seedling emergence force. However, Williams (1956) had developed the same conclusions for four legume species sixteen years previous.

Numerous techniques have been reported on chemical and physical amendments applied to crusting soil to increase seedling emergence. Mechanical methods of breaking soil crust have been reported with mixed success. Seedling damage can occur if the process is implemented during seedling emergence periods (Carnes 1934). Chemical agents used to reduce soil crusts include sulfuric acid (Johnson and Law 1967), gypsum (Dollhopf 1971) and numerous synthesized organic soil conditions (Allison and Moore 1956). Although many of these techniques have reportedly reduced soil crusting, chemical amendments are expensive and often labor intensive. Furthermore, Chaudhri et al. (1976) stated that overall, more success was achieved with physical amendments when compared to chemical additives.