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Dust Control on Low Volume Roads

A Review of Techniques And Chemicals Used

Local Technical Assistance Program

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Foreword

This report is intended to serve as a practical dust control guide for low volume roads. It includes a historical review of road building techniques since the Agricultural Revolution and reviews early attempts at binding the surface aggregate with tar or asphalt, techniques which were developed in the mid-1800s and finally lead to the development of hot-mix asphalt pavements in 1901. Problems associated with dust propagation are not new and attempts at controlling dust were first recorded n 500 BC by the military tactician Sun Tzu.

In the United States it has been determined that approximately 39 percent of all officially designated roads are natural earth or gravel surface. In developed countries the proportion of non-paved road varies between 5 and 60 percent of the total network. In developing countries the proportion of earth and gravel surfaced roads may be as high as 97 percent of the available road network.

The study indicates that the ultimate selection of road surface type will depend on traffic volume, economics, and environmental impacts. **A** summary of seven surface maintenance techniques is presented. The report indicates that low-volume does not equate with low-maintenance. **A** table is included that describes the normally accepted maintenance alternatives based on relative severity of the type of distress.

Traditional dust suppressants along with non-standard stabilizers are reviewed. **A** cost benefit analysis compares costs of salts, organics, emulsions, and enzyme treatments. The report includes practical conclusions and recommendations.

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16. Abstract

In the United States nearly 40 percent of officially designated roads are earth or gravel surfaced. This report is intended to serve as a practical dust control guide for such roads. Traditional dust suppressants along with nonstandard stabilizers are reviewed and conclusions drawn as to their benefits.

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Dust Control on Low-Volume **Roads:** A Review of Techniques **and** Chemicals **Used**

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PREFACE

"Low-volume" roads, sometimes referred to as "low cost" roads, represent greater than 50 percent of the world's current total roadway network[1,55] Varying from rudimentary tracks to substantially designed and engineered surfaces, low-volume roads are generally built to serve as "farm-to-market" access ways. In developing countries, these roads may be the sole access for the flow of goods and, even in developed countries, may carry a disproportionate share of that country's gross national product (GNP) as compared to the paved portion of the transportation system.[50,55]

When viewed from the historical perspective of Ancient Rome until the present, one factor invariably comes to mind in connection with gravel or earth surfaced roads – dust. Dust is a by-product of the mechanical breakdown in the surfacing aggregate and is present to some extent in all natural-earth or gravel-surfaced roads. Often referred to in terms of sediment production, excessive amounts of dust can lead to a variety of consequences and environmental damages such as siltation or clogging of water shed areas, particulate matter air pollution, damage to agriculture, and an increase in required maintenance on machinery to name a few.[2,23,39] Low-volume road dust also can become a significant vehicle safety factor due to decreased visibility and lead to serious vehicle maintenance issues as well.

Though it is not economically feasible to pave every road surface, dust can be prevented in many cases by controlling the factors that cause aggregate breakdown. Some examples of this include ensuring proper road cross section and drainage designs; using adequate aggregate material and construction quality control; regulating vehicle weights and tire pressures; and establishing proper road maintenance procedures. Dust effects also can be minimized or controlled through the proper matching of chemical dust abatement additives to the soil types and climatic conditions.

This report represents, in effect, a compilation of current "proven" technology, current research activities, and perhaps some forgotten techniques. Low-volume roads are certainly not a new phenomenon, and dust has been a topic of discussion at least as far back as Biblical times. It is hoped that the recommendations are helpful.

DUST CONTROL ON LOW-VOLUME ROADS: A REVIEW OF TECHNIQUES AND CHEMICALS USED

1. INTRODUCTION

> *"When there is dust rising in a high column, it is the sign of chariots advancing; when the dust is low but spread over a wide area, it betokens the approach of infantry. When it branches out in different directions, it shows that parties have been sent out to collect firewood. A few clouds of dust moving to and fro signify that the army is encamping." Sun Tzu, Chinese Military Strategist 500 BC* [20]

In their earliest form, roads most likely developed in conjunction with the onset of the Agricultural Revolution some 10,000 years ago. As humans developed and refined the techniques of farming and domesticating animals, farmers were able to produce more food than they themselves needed. Permanent villages began to take hold where once there had been only temporary camps. As this revolutionary development progressed, more people were able to spend time on making useful inventions, which were exchanged for surplus food. In many ways the changes and developments in civilization resulting from the Agricultural Revolution were at least as dramatic as those brought on by the Industrial Revolution of the last two centuries.[10,32]

The vast majority of these first roads would likely have been little more than trails or, at best, rudimentary tracks worn into the earth marking the most expedient route from the farms to the village center. Over the centuries that followed, roads and road surfaces would be improved based upon the transportation technology available.[10] In effect, however, the purpose for constructing and maintaining a road system remains very much unchanged even to this day - the movement of surplus food from fields to city centers and a conduit for the rapid deployment of defensive arrangements of the time.

The oldest documented "road" is a 6,000-year-old walkway which was discovered in an English peat bog in 1970.[8] The construction of this road roughly coincides with the arrival of the first farming communities in the United Kingdom around 4000 BC. Although many different versions of roads and road systems have been constructed since this "first," the concept of a bonafide paved road surface is relatively new. Early attempts at binding the surface aggregates with tar or asphalt were developed in the mid 1800s and evolved into the hot-mix asphalt pavements of 1901 and 1903.[11]

Even today in our high technology world, more than half of the described and surveyed roads are native earth or gravel surfaced.[55] In actuality this percentage should be larger yet, since by their nature many low-volume roads are not "official" and are therefore not cataloged, described or surveyed. Low-volume roads, regardless of their status, invariably carry a disproportionate share of their respective area's marketable goods. **As** such these roads represent a significant asset to the communities which they serve.[50]

Often these roads are referred to as "low cost roads" due to their relatively low construction costs. Although native earth and gravel surfaced roads are relatively inexpensive to build, if they are to be kept in a useable state, they must be maintained. It has been said of any road, if the foundation fails, the road will likewise fail. True costs associated with building and properly maintaining low volume roads show that there is no such thing as a "low cost" road.[27]

Low-volume roads are subject to between *6* to 10 basic failure mechanisms depending on the particular criteria used.[7,13,14,45] These basic failure modes are in fact much like those of any paved surface. Avoidance or mitigation of failure is the general emphasis of design and maintenance procedures where the relative strengths of the local surfacing aggregate is matched to the road criteria. The one failure mode that is unique to earth and gravel roads is the physical breakdown or weathering of the surfacing aggregate material which thereby creates dust. This is caused, in part, by the wearing action of the traffic load and can be accentuated by the use of poor quality aggregate, inadequate road surface design or by improper vehicle loading.

As noted in 500 BC by the military tactician **Sun** Tzu,[20] dust propagation is not a new concept and neither are attempts at controlling dust and its effects. In modern times excessive dust has been shown to have significant negative effects particularly in environmentally sensitive areas such as watersheds. It leads to increasing road and vehicle maintenance requirements and reduces visibility on the road which in turn reduces vehicle safety.[17, 50] In some cases, attempts to control dust through chemical palliatives have led to worsened conditions both on the road surface and in the surrounding environment.[2,12,23,39]

Controlling dust must involve **a** "whole road" approach. First, many potential road failures can be prevented by the use of adequate road cross section designs, application of proper drainage principles, use of quality surfacing aggregates, and quality control of the construction. If this approach does not prove to be sufficient, dust generally can be controlled effectively through the proper matching of chemical dust palliative to the local aggregate and climatic conditions. Other potential solutions include load restrictions, tire pressure, and protective overlayments.

2. LOW-VOLUME ROADS: PERSPECTIVES

Since the horse was not developed as a traction animal until medieval times, oxen and mules carried the bulk of ancient land-based cargo. By comparison to the slow moving ox and relatively weak mule, water-born transportation was significantly more efficient.[10] As a direct result, virtually all large ancient cities were located near a suitable bay or large river and ultimately developed quite sophisticated sea or water-based systems for import and export of goods. Overland transportation of materials was performed by pack-mules. Overland movement of large amounts of materials or materials which were not of the proper size, shape or weight to be equally distributed in panniers was simply not practical prior to improvements in wheeled vehicles and traction animal harnessing systems.[10]

The Carthaginians generally are credited with constructing the first "road system" around 600 BC not for the movement of goods, but rather for movement of foot soldiers.[10] The Romans followed suit and eventually constructed nearly 87,000 km of roads within the limits of the Roman Empire - a road system roughly equivalent in length to the current U.S. Interstate system.[10] The Roman road system was intended primarily for military purposes in that it connected camps that were about 30 km apart. Although not used for importing goods, at its peak the Roman road system must have been quite good. In his earliest surviving speech (delivered in 80 BC) Cicero talks of a man making a night-time chariot dash from Rome to Ameria in “ten nocturnal hours.”[10] Given the distance traveled (about 90 kilometers) this would be a significant feat in darkness on most any modern minor road.

The Roman theory of road building was that by making a road solid enough in the construction phase, rebuilding, and even maintenance, would not be required during use. In this way many fully paved Roman roads lasted more than 80 years under normal wearing conditions.[10,32] A “typical” Roman design consisted of four layers with a total depth of as much as 0.9 m. from top to bottom.‘”) In practice, actual road cross-sections varied slightly to suit the local building conditions, materials available, and population factors. As the Roman road network progressed outward from the major population centers, the overall pavement thickness became distinctly thinner. After the fall of the Roman Empire, communities demolished many of the Roman buildings, turning the stone into crude fortifications. In some cases, the Roman roads and bridges were dismantled and either used for building materials or obstructions simply to make it harder for the marauding armies to reach them.[10]

In the early part of the Dark Ages, people lived once again in isolated, self-sufficient farming villages much as they had at the beginning of the Agricultural Revolution. Roads within the limits of a particular village remained in relatively good repair while roads between villages, if they existed at all, quickly deteriorated and became impassible.

With the coming of the Renaissance, cities again began to grow. Streets once adequate for pedestrian and occasional equestrian traffic became mired in cart and wagon gridlock not unlike the traffic problems faced by many a modern city. From the thirteenth century on, kings and councils issued decrees against parking, speeding, and making U-turns. Since medieval streets were not paved, the pedestrian was reported to be "blinded by clouds of dust in dry weather and sank to his ankles in muck during wet spells."[32] Numerous attempts at paving city streets, while not correcting the drainage problems, did keep the wagons from becoming permanent fixtures in the middle of a road.

Road construction continued as erratically as before until the mid 1700s, when Thomas Telford (born in 1757) acting as the "Surveyor of Public Works" for the County of Salop, England, began some of the first documented attempts at maintaining maximum road grades and reintroduced the ideas of a layered pavement section not unlike that of the Romans.[11] The bottom layer was comprised of large stones 100 mm x 75 mm to 175 mm overlaid by two layers of 60 mm stone surfaced with a layer of 40 mm gravel.

This pavement structure was made one step better by John Macadam in the early 1800s.[11] In this case the subgrade was deliberately "sloped" to provide better drainage. Two layers of angular aggregate (maximum size being 75 mm) were placed on the subgrade. This subbase structure was surfaced with an angular aggregate using hand-broken aggregate with a maximum size of about 25 cm. Minor variations on the basic Macadam design have been tried during the past 175 years, and some low-volume roads are built in this labor-intensive manner today.[50]

3. CURRENT WORLD STATISTICS

Highways within the United States are classified by functional type with a subset specifically designated as Federal-aid systems eligible for Federal funding. As of 1997 the published breakdown of road surface types cited that 61 percent of all "official" roads and streets were paved.[1] Taken the other way, as much as 39 percent of all officially designated roads within the United States were natural earth or gravel surfaced. This number may represent a somewhat smaller portion of the total system than is actually the case since some low-volume roads are considered "temporary" and not completely mapped or classified.

Worldwide estimates as to the breakdown between paved/unpaved road systems vary dramatically based on the source of the data. In developed countries the proportion of non-paved roads varies between 5 and 60 percent of the total network. In developing countries the proportion of earth and gravel surfaced roads may be as high as 97 percent of the available road network.[23, 26, 50, 54, 55]

4. LOW-VOLUME ROADS DESIGN AND MAINTENANCE CRITERIA

4.1 "Low-cost" Roads

The difference between the simple earth track and the multi-lane highway represents an enormous range of possible combinations and design requirements. Since low-volume roads are generally constructed with locally available materials and under local climatic conditions, the design and maintenance criteria often tend to be highly localized. Conversely, road failures (particularly when viewed with respect to the mechanism of failure) are much more universal. In terms of low-volume road performance, there are three important design factors: drainage.… drainage.… and drainage.[12]

In terms of process, the road course begins with clearing the land of vegetation in the general direction of travel. These unimproved "roads" are generally not suitable for more than perhaps a few vehicles per day and invariably become impassible in inclement weather. As the demand for travel on the path increases, permanent creek or river crossings are placed, and the road surface is improved to included a crown, slopes and perhaps gravel of some form. If traffic continues to increase, it finally becomes economical to place a "permanent" bituminous or PCC surface and create additional lanes. At some point in this progression, the road transitions from a "track" to "official" road status and is surveyed, described, and mapped. A typical "rule of thumb" is when the traffic volume becomes greater than 250 vehicles per day (vpd) it is more cost-effective to seal the road surface with a bituminous chip seal instead of continuing road grading maintenance and regular applications of dust suppressants.[21, 23]

Roads for light or low-volume traffic are often referred to as "low cost," secondary or farm-to-market roads. Regardless of the description, these roads are the first points of entry for food and raw materials into the market and as such have significant impact on the economy. While low-volume roads are relatively inexpensive to build, they are often expensive to maintain. Invariably, the published "cost" associated with building a road excludes provisions for maintenance. Since all roads require some form of maintenance over their service life, the total cost should represent a combination of construction and maintenance costs. In effect there are three basic types of roads with respect to cost: high volume paved roads which are expensive to build but relatively low to maintain, intermediate paved roads which balance construction and maintenance costs, and the low-volume roads which are least expensive to build but often require extensive maintenance programs.[12, 27, 36, 43] The ultimate selection of road surface type will depend on traffic volume, economics, and more recently, environmental impacts. Table 1 includes a summary of surface maintenance techniques used by the U.S. Forest Service (USFS) and some typical results.

TABLE 1 Typical Surface Treatment Techniques

Surface Treatment	Potential Results [12]
Design aggregate surface for minimal rut depth	Reduced rut depth leads to a reduction in sediment production, runoff, and aggregate deterioration.
Use maintenance blading only when necessary	Maintenance blading should only be performed when ruts have developed to the point that they channel water.
Use larger than normal sized aggregates	Provides an armoring effect for the surface. An experiment using 50-150 mm aggregate resulted in an 80% reduction in sediment yield. Local reductions may vary based on site conditions, surface thickness, and materials.
Use high quality aggregate	Provides a potential for up to an 80% reduction in sediment yield as compared to the sediment yields of marginal and poor aggregates.
Reduce tire pressure on heavy vehicles	Several experiments indicate significant reductions (up to 80%) in sediment yield, road maintenance, and vehicle damages.
Stabilize the surface	Potential reduction in sediment yield and road maintenance required varies with the stabilization technique used. Many techniques are referred to as dust control. However this is perhaps an unnecessary distinction since a stabilized surface also prevents dust.
Asphalt surface	Last resort, but may be the most long term economical solution.

4.2 Quality of Construction Materials

Regardless of road type, soil ultimately forms the foundation of the road and therefore is perhaps the most important constituent of every road design. If the foundation fails, the road fails. Many road failures, described in following sections, can be avoided by little more than applications of standard geotechnical or drainage procedures. The traffic bearing capacity of a road is determined in part by the soil forming the foundation, by modifications to that soil, by stabilization or other techniques, and by the effectiveness of the drainage in the immediate area.

Much of the difficulty in designing low-volume roads arises because high quality road surfacing aggregates may not be available in the immediate vicinity. This dilemma leaves the designer with the choice of (1) hauling in good quality material at a significant increase in project costs or (2) utilizing local marginal quality aggregates. Further confusing the design process is the fact that few types of marginal aggregates have been fully defined in terms of their true properties, potential uses, or performance records.[12,15,47]

4.3 Marginal Aggregates

Marginal aggregates are those aggregates that do not meet specifications or that can potentially change strength or properties during the design life of the road. Marginal aggregates can be used, however allowances for variable performance must be taken into account during the design, and some form of stabilization or special construction technique utilized. Choosing marginal quality aggregates can lead to increased maintenance costs both on the road and the surrounding watershed. During a recent USFS study,[15] certain roads were surfaced using a variety of marginal quality aggregates. These roads produced from 2.9 to 12.8 times as much sediment as a similar road segment surfaced with high quality aggregate. The results of the study clearly indicated the quality of surfacing aggregate as being inversely proportional to higher sediment production. Higher sediment production equals higher particulate air pollution (dust), siltation or in-fill of streams and drainage systems, and increased maintenance and resurfacing requirements.

Basically, marginal aggregates fall into three groups: [12, 26,47]

- Igneous: Extrusive igneous rocks include volcanic cinders, pumice and rhyolite. Intrusive igneous rocks include primarily disintegrating or exfoliating granite. Particular care must be take when using gravel originating from decomposing igneous rock. since large fragments may appear to be sound but, in fact, have decomposed into expansive clay materials.
- Sedimentary: Primarily limerock, coquina, caliche, and decomposed or poorly cemented sandstone (mudstone).
- Soils. Surface deposits of sand-gravel that contain a high amount of clay, shale or baked shale, marine basalt, and topsoil.

Often an aggregate source represents material that “nearly meets’’ or is “just out” of the required specification limits. For example the source may be one or two percentage points away from the required sieve size required to meet the specified gradation. The USFS addresses this issue of marginal aggregates and the construction materials that are “just out” of specification with the following list of potential road design and specifications adjustments: [12]

1: For predominantly wet weather commercial haul roads:

- Use the maximum economical size aggregate, typically 75 mm or larger. This technique can also lead to an increase in tire wear in dry conditions.
- Design the wet portion as a separate road section.
- Use geotextiles at strategic locations within the road cross-section to provide strength to the road structure.

2: For marginal aggregates that tend to degrade:

- Use a larger maximum size, open graded mix adjusting the gradation to account for the amount of material expected to degrade.
- Stabilize the wearing course by adding Portland cement.
- If the fine aggregate tends to degrade more rapidly than the coarse aggregate, scalp the material prior to crushing.
- Use low-pressure tires or Central Tire Inflation (CTI) systems on all heavy vehicles, or adopt load/speed controls.

3: For marginal aggregates that tend to ravel:

- Specify tighter controls on the gradation by narrowing the acceptable gradation band.
- Add natural fine material to produce a maximum density mix. Fines could be silt, sand, manufactured sand, or clay depending on the base material.
- Stabilize by adding cement, fly ash, lime, or other dust abatement product.
- Apply a bituminous surface treatment (BST, DBST) as a last resort.

5. MAINTENANCE PROCEDURES

5.1 General

While maintenance procedures may vary across governing agencies, the fundamental elements of a maintenance program generally follow a typical pattern. First the road network or system must be surveyed and mapped dividing the total network into branches or sections. Each section is cataloged in terms of road structure (type of construction), traffic volume, principle vehicle type, drainage facilities available, and the relative rank within the total network. Once this initial cataloging is complete, the road system is inspected with respect to the type and frequency of road failures occurring. Repair order priorities typically are based on a combination of the severity of the distresses observed and the relative importance of the road section.

Under traffic, loads and varying climatic conditions, road surfaces will ultimately become rutted, corrugated, and potholed. Minor distresses left unattended, will quickly become major failures and road maintenance, reshaping, and blading are a continual process. During maintenance blading, surface material that has migrated to the road edges is pushed from the outside edges in towards the centerline ensuring the proper development or re-establishment of a cambered surface profile and basic drainage pattern. Depending upon the maintenance program, the road is then rolled, compacted and/or treated with a chemical stabilizer. Failure to perform (or deferring) a proper preventative maintenance program ultimately will lead to costly repairs or reconstruction.

5.2 Distress Categories

Although there is always local interpretation, the world road building agencies generally recognize seven distinct types of distress or failures in low-volume roads.[7,13,45] Invariably improper road construction or cross section is one of the primary failures cited in virtually every discussion. Drainage nearly always is cited as the second most common cause of road surface failure. Surface corrugations, excessive dust, potholes, ruts, and loose or raveling aggregate make up the remaining five distress types. But these five are, in a sense, controlled by the original design, quality of construction, and availability of proper drainage systems. The seven failure types and associated principal causes are detailed in Table 2.

TABLE 2 Categories of Distress And Principal Causes

Failure Type	Principal Cause[7, 12, 13, 45, 50]
Cross Section	- Improper design or maintenance procedures - Sand encroachment - Traffic wear or movement of surface materials
Drainage /Scour	- Siltation of ditches and culverts - Improper slope - presence of obstacles - Erosion due to excessive runoff washing out of erodable soils - Non-cohesive or non-stabilized soils - Sudden change of grade
Corrugations	- Inadequate composition of surface material. (Non cohesive materials in dry climates are most susceptible) - Dry climatic conditions
Dust (sedimentation)	- Inadequate particle cohesion - Marginal aggregate surfacing material
Potholes	- Damage by foreign objects - Inadequate surface material composition (excess clays) - Poor initial compaction - Improper road camber drainage system
Rutting	- Settlement of surfacing under traffic stresses - Loss of non-cohesive surface material (dry climates) - Partial liquefaction of clayey surface material (wet climates)
Raveling or Loose Aggregate	- Inadequate surface material adhesion - Improper surface gradation and compaction

Once surveyed, road surface distresses must be rated as to severity. One type of rating scale uses a simplistic approach rating the distress in terms of low, moderate, and high severity. Others attempt to rate the total usable surface and structure with distresses or failures subtracting from a "perfect" score. One common version on this theme is the Unsurfaced Road Condition Index (URCI). The URCI survey is done in two parts. First is a "windshield tour" where the road system is traversed in a vehicle at 43 km/hr. This initial tour is followed by a detailed inspection of those areas where the inspector noted particular problems or failures. At each problem area, the distresses noted are measured and rated and a deductive value calculated. This result is subtracted from the perfect score (100 or excellent condition) and then averaged with the other URCI values for that section. This rating system produces a usable priority matrix which can be used to schedule or plan road repairs and maintenance programs. [13, 50]

5.3 Maintenance Alternatives

Effective road maintenance management must be done on a regular basis if the roadway network is to be kept in operation; low-volume does not equate with low-maintenance. For the seven basic types of road surface failure modes identified in the previous section, Table **3** describes the normally accepted or preferred maintenance alternatives based on the relative severity of the distress type.

TABLE 3 Maintenance Alternatives

Distress	Severity	Maintenance Alternative[13]
Improper Cross Section	Low	Grading
	Medium	Add material, grade and compact; bank curves
	High	Cut to base course; add aggregate; shape, water, and compact
Improper Drainage	Low	Clean ditches and culverts
	Medium	Clean culverts; reshape, construct, or flare out ditch
	High	Install drainage layer, larger culvert, riprap or geotextiles
Corrugations	Low	Grade surface
	Medium	Grade surface; add additional material grade and compact
	High	Cut to base course; add aggregate; shape, water, and compact
Dust Stabilization	Low	Add water
	Medium	Add stabilizer
	High	Cut to base; add aggregate, water, stabilizer; shape, grade, and compact
Potholes	LOW	Grade surface
	Medium	Grade surface; add material, grade, and compact
	High	Cut to base course; add aggregate; water, shape, grade, and comnact
Rutting	Low	Grade surface
	Medium	Grade surface; add material
	High	Cut to base course; add aggregate; water, shape, grade, and comnact
Raveling	Low	Grade surface
	Medium	Grade surface; add material
	High	Cut to base; add aggregate; water, shape, grade, and compact

6. CHEMICAL DUST SUPPRESSANTS AND TECHNIQUES

6.1 General

Severe dust conditions that occur on gravel or native earth roads result primarily from a combination of factors such as accelerated mechanical wearing of loose surface material, low strength or poor quality material, winds, climate and lack of drainage. Short of sealing the road surface with a bituminous coating, there is no known mechanism available to eliminate dust development completely. However dust abatement programs, when applied on a regular basis, can effectively reduce dust emissions to an acceptable level. Before dust abatement techniques can be used effectively, the road surface must have been constructed and maintained properly. **A** well bound, hard crusted wearing surface is considerably less likely to produce dust and will also minimize water penetration into the pavement than a poorly bound surface or one constructed with poor quality materials.

As a general rule, roads carrying between 50 and 250 vpd should be able to utilize an appropriate dust suppressant additive or technique. Roads that carry more than 250 vpd may find greater economy in sealing the road surface rather than spending large amounts of limited maintenance funds for repeated dust suppressant applications.[21, 49,50]

Chemical dust abatement additives or procedures should be considered only after attempts to resolve the problem through proper design, construction and maintenance have proven to be ineffective. The design-remediation process is important because chemical dust suppressants may have detrimental environmental effects for the local area. The optimal type of chemical dust suppressant used is likely to be selected as a result of a combination or compromise between climatic conditions, geologic material composition, economics and environmental acceptability.

Regardless of trade name and marketing strategies, there are effectively only six basic types of chemical dust suppressants available today.[6,12,17,21] These are salts, lignin sulfides, emulsions (generally petroleum-based, however pine pitch is gaining popularity) biological enzymes, pozzolanic, and acrylic polymers. The first three representing the "traditional" chemical dust suppressant solution are detailed in Table 4 and Section 6.2.

The remaining three types are often referred to as “non-standard”, non-traditional, or experimental stabilizers and are detailed in Table *5* and Section 6.3.

Other techniques that have been tried are regulations regarding vehicle speed and load controls, reduced tire pressures, road surface recycling or grinding, and road surface protection (armoring). These are detailed in Table *5* and Section 6.4.

6.2 Traditional Dust Suppressants

The U.S. Forest Service General Specifications identify three types of “standard” or traditional dust suppressant chemicals.[12, 17] Specifically these are salts, lignin sulfides, and emulsions (see Table 4). These chemical additives reduce dust by either retaining moisture in the road surface through a hygroscopic or chemical reaction, producing an increase in the effective cohesion of the surfacing particles, or by sealing the road surface. In all cases the result is temporary and requires annual applications.

TABLE 4 Traditional Dust Suppressants

Type of Treatment or remediation	Action or Stabilization Mechanism	Materials and Techniques used	Typical Concentrations, Depth of Treatments
Salts	Deliquescent or hygroscopic chemical reaction.	Calcium Chloride (6,9,12, 17, 51)	Solution concentration; minimum 36% by weight brine CaCl; applied at a controlled rate varying from 1.31 to 1.36 L/m^2. Flake composition; minimum 77% by weight CaCl; blade mixed at a rate of 0.82 to 1.03 kg/m^2.
		Magnesium Chloride (6, 14, 17)	Solution concentration; minimum 28 % by weight brine MgCl; applied at a controlled rate varying from 1.81 to 2.26 L/m^2.
Organic	Chemical reaction resulting in cohesive effect.	Lignin Sulfonate (6, 12, 17)	Undiluted solution minimum 48% by weight total solid lignin concentration; applied at a rate of 2.26 L/m^2; blade mixed into top 25mm of the wearing course.
Emulsion	Binding effect increases particle cohesion.	Asphalt Emulsion (12,51)	One or more applications of sprayed asphalt followed by a layer of aggregate. Typical total thickness 25 mm or less.

6.2.1 Salts

The use of salts as a dust control and surface stabilizer is documented as far back as 1922.[47] Of the salts specified for dust control, calcium chloride and magnesium chlorides are the most common types currently used. In references from the 1920s to 1940s, sodium chloride also was specified but only as substitute in case that calcium or magnesium chloride was unavailable.[51] Recent research has identified ammonium chloride, an electrolite, as a potential dust suppressant. However, its use is not common and requires a high degree of control during construction.[12, 52]

The main benefits of salts are higher density and moisture retention in the surface or wearing course. Both of these conditions have the simultaneous effects of a higher quality wearing surface, reducing dust, and lengthening the interval between maintenance requirements. While these effects result from a slight chemical reaction in material containing a high percentage of clays or limestone, in most cases these effects are the result of chloride's ability to absorb and hold moisture. Incorporating chloride during road construction will permit compaction of the surface-wearing course to very high densities, increasing stability, and decreasing loss of materials from traffic and erosion.

To be effective, the native-earth or gravel-surfaced road treated with chloride based dust control must have a sufficient amount of fine material to allow for a dense and easily compactable wearing course. The ideal range of fine material is between 10 and 20 percent passing the 75μm sieve.[9] Gradations that have lower than 10 percent passing the 75μm sieve cannot achieve the maximum cohesive effect added by the chloride. Likewise those aggregate mixtures that have more than 20 percent material passing the 75μm sieve tend to retain too much moisture, develop ruts, and become slippery when wet. Additionally, chlorides are not considered effective where the average humidity is less than 35 percent.[12,17,31, 51]

The problems associated with the use of salts for dust control are their tendency to leach out with heavy rains, ineffectiveness in very dry environments, and potential to cause corrosion damage to vehicles. Additionally, they can cause the road surface to become excessively wet and slippery due to their water retention properties.[9,12] Salts are among the easiest to use and generally the most cost effective depending upon local availability. Generally they must be reapplied each year depending on the local climatic conditions; however, they may cause significant environmental effects particularly in the local water system.

When applied during road construction, salts are typically blade mixed into the top 50 mm of surface material. During maintenance operations salts can be blade mixed into the scarified surface material or applied directly. In either the case of maintenance or construction, current USFS specifications indicate that chlorides can be applied in one of two forms: 1) dry flakes (calcium chloride), or 2) as a brine solution (a combination of either calcium or magnesium chloride solids dissolved in water). Dry flakes are placed at a rate of 0.82 to 1.03 kg/m^2 assuming 77 percent pure calcium chloride. Calcium chloride brine solution consists of 36 percent by weight calcium chloride and is applied at a sprayed rate of 1.31 to 1.63 L/m^2. Magnesium chloride brine consists of 28 percent chloride by weight and is applied at a rate of 1.81 to 2.26 L/m^2.[6,12,17] References from the 1940s and earlier indicate specifications for chloride applications, at that time, as high as 3.2 to 6.5 kg/m^2.[9,48,51] One to three applications per year may be required depending on local weather conditions and the amount of precipitation.[12,17,51]

Road surfaces which have been treated with salts can often self-repair their surface after being sheared by heavy vehicles or upon drying out following a heavy rain.[12] This self-repair effect is due to chlorides' ability to absorb and hold moisture. Since there is generally no chemical reaction to use up the chloride, the total amount of chloride remains relatively constant, less the amount leached out during heavy rains. Once re-compacted by traffic, the road is returned to its original constructed condition. This effect is not seen in most other dust palliatives which utilize a chemical reaction to produce the cohesive effect consuming a portion of the suppressant in the process.

6.2.2 Lignin Sulfides

Lignin sulfides have become the nearly universal replacement of the salt dust suppressants in recent years and is currently the cost effective dust palliative of choice for much of the USFS, particularly in the **U.S.** Pacific Northwest.[6,12,17] Lignin sulfide is a waste product from the paper pulp industry. In the pulping process, wood fiber for paper is extracted from wood chips by applying a sulfuric acid solution. The resulting waste solution containing spent sulfuric acid and wood sugars is then refined into a variety of lignin sulfide products. As a dust suppressant, lignin sulfides act as a weak cement stabilizing the fine materials in the roadbed. **A** primary concern regarding lignin sulfide is its tendency to leach out of the roadbed during heavy rains, making frequent re-applications necessary. Being a derivative of sulfuric acid, this leaching effect poses a potential environmental problem in watershed areas affecting the acidity in the nearby water source.[12,17,51]

Lignin sulfides are applicable in a much more variable range of temperatures and humidity than salts, and therefore cover a larger potential number of geographic areas. Since the cementing reaction is chemical in nature, a large portion of the available solution is used in the reaction, and the surface cannot effectively self-repair following shear loads by heavy vehicles. In spite of leaching, re-applications can often be performed at half strength since some residual lignin sulfide will remain in the surface.

The lignin sulfide is sprayed at a rate of 2.26 L/m^2 and allowed to penetrate into the top 25 mm of road surface material. This application may be split into two passes of 1.13 L/m^2 if the surface is loose or does not absorb the full application amount. Two passes of the reduced amount may be necessary when the road is on a grade. The original application also can be field-mixed into the wearing course material. Field mixing can be done by using a motor grader and windrow, mobile roto-tiller, or mobile pug-mill type operation. Regardless of the mechanism, keeping the mix uniform and maintaining quality control during construction is difficult. However this is the key to effective long-term dust control.[6,12,21]

Lignin sulfide is sensitive to the relative amount of fine material (<75 μm) in the aggregate mixture and generally is most cost effective when the total percentage of fine material is more than **8** but less than 20 percent by weight.[6,12] As the overall percentage of fine material in the road wearing course material increases, the water retention properties of lignin sulfides begins to act as a lubricant, and the road surface then tends to become slippery when wet.[12] Lignin sulfides are reported to not bind well on roads that had been treated previously with chloride compounds.

6.2.3 Emulsions

Asphalt, bitumen, and various other petroleum-based surface dust suppressants all function on the basis of adding a cohesive potential to the wearing course material. These generally work best with material gradations containing a minimum of fines (< 75 μm). A typical specification calls for less than 10 percent fine material by mass. Heavy vehicles and hot climates will lead to surface shear type failures and the roads are generally difficult to maintain once sealed. A major concern with all emulsion dust suppressants is their tendency to contaminate the local water source by surface runoff. [12]

In the late 1950s three types of petroleum dust oils were commonly used by the USFS. These were referred to as light, medium, and heavy Arcadia oils and were a combination of petroleum products with either a cutback or heavy lube oil.[6,34] These oils, when matched to the gradation of the surface material worked well and maintained a flexible running surface which could be re-bladed periodically. In the 1970s with the energy crisis, the Arcadia oils were replaced with lower cost asphalt emulsions.

Current petroleum products used by the USFS include a specially formulated family of penetrating asphalt emulsions marketed under a variety of trade names.[6,12] All have been designed for use as dust suppressants and are, in essence, a modified asphalt or petroleum resin emulsion. Performance data available on these types of emulsions is limited and varied, and although they do show promise, they tend to be slightly more expensive.

6.3 Non-Standard Dust Suppressants

Research on the effects of most non-standard dust suppressants is relatively recent. Many of the chemicals used are byproducts of manufacturing or recycled materials. Other non-standard techniques include road surface protection or armoring. These are summarized in Table 5.

TABLE 5 Non-Standard Stabilizers and Techniques Used for Dust Control

Type of Treatment or Remediation	Action or Stabilization Mechanism	Materials and Techniques Used
Salt[12]	Hygroscopic reaction	Ammonium Chloride
Emulsion (pine pitch) [3,6]	Cohesive effect similar to a weak asphalt emulsion.	Pine Tar, "Tall Oil" Pitch
Enzyme[12,52]	Organic molecules produce cohesive or flocculation effect in clay portion of road aggregate.	Biocat, EMC Squared, PermaZyme, PSCS-320
Pozzolan Stabilizers[33]	Produces a cohesive or "cemented" surface course.	Lime Kiln Dust Cement Kiln Dust Fly Ash
Alternate Stabilizers	Acts as a fine silt / clay flocculation agent.	Clay filler[12]
		Bentonite[5,52]
	Act as a binder similar to asphalt cement.	Acrylic Polymer[12,52]
Protection or Surfacing Materials	Protective overlays using natural or man-made materials.	Wood chips or chunk wood protective layer[41]
		Polyester fibers or geotextiles[12,50]
		Large (50-150mm) high quality aggregate[12]
Recycled Materials	Base and surface stabilization using recycled materials.	Shredded tires[18]
		Ground asphalt shingles[37]
		Used Motor Oil[21]

6.3.1 Enzymes

Most of the enzymes on the market are relatively new and therefore do not have a long, proven performance record. Some of the most common enzymes used in the United States are based on a bacterial culture. When exposed to air, the bacteria multiply rapidly producing large organic molecules that are absorbed into the soil or clay particle lattice structure. This reaction first causes a slight swelling, followed by a tightening or compacting effect. The reaction, in effect, mirrors the natural process of forming shale but increases the process from millions of years to a number of days or even hours.[12,52] When compacted, the large clay molecules function essentially as a water repellent for the road surface preventing water absorption.

Generally, enzyme agents work well over a wide range of climates and environments and work particularly well on material containing a high percentage of clay or in iron rich soils. They generally are ineffective on material containing a low percentage of fines or where loose surface gravel is present. In this case, enzyme reactions must be coupled with a biotechnique where the bacteria culture introduced generates organics from carbon dioxide in the air.[52]

Enzyme agents are nontoxic and considered environmentally harmless but must be protected from freezing during transit and initial application. Susceptibility to frost damage once in place was not discussed. [12,52] Additionally enzyme dust suppressants must be "intimately mixed" and compacted at optimum moisture content. Quality control during construction is difficult and is likely a major contributing source of the range of variation in experimental results to date. At this time enzyme solutions are generally considered promising, but are still in the experimental stage of development. [6,21, 52]

6.3.2 Pozzolans

Pozzolan stabilizers are typically added to non-plastic road surface material. These types of additives include fly ash, kiln dust, cement kiln dust, and hydrated lime. These materials are created as byproducts of either the cement manufacturing process or from coal burning power plants. In some cases Portland cement has been used; however, it is more often used for stabilization of the base course prior to bituminous surface treatments or pavements.[12,17,33,51] Pozzolanic stabilizers are field mixed into the road material and compacted. Some amount of water must be added to the mix in order to start the hydration cementation reaction. The resulting surface generally performs well, however, since the cohesion or cementing effect is the result of a chemical hydration reaction, the surface cannot "self-heal" and is difficult to maintain or re-blade once the mix has cured.[2]

6.3.3 Synthetic Polymer Emulsions

Produced under a variety of trade names, synthetic polymer emulsions generally are a by-product of the paint and adhesive industry and have been applied as a tackifier, for erosion control and for surface stabilization. Most information available on these products comes from the manufacturer and not from actual field trials. The results of these tests to date have varied significantly in terms of dust control and surface stabilization.

In general, acrylic and synthetic polymers show promise in terms of performance.[6,12,21,52] However, simply due to the lack of production economies of scale, they are invariably one of the more expensive treatments. Also, the high degree of construction quality control required is an impedance to widespread application and acceptance. At this time, developments in synthetic polymer solutions remain an area of promise, but should be used with caution particularly in environmentally sensitive areas, until the technology can provide more consistent results.[6,12, 21,52]

6.3.4 Protection Techniques

In many cases a road's surface can be protected using a layer of high quality large size aggregate. In wet climates, this technique provides a structural surface for heavy vehicle traffic, and in dry climates can reduce dust by reducing sediment production.[12] Using this technique, some field experiments have reported up to an 80 percent reduction in sediment production compared to similar road segments that were left unprotected. The reduction in sediment is highly dependent upon the site conditions, surfacing layer thickness and the quality of the aggregate used. Since loose surface material can cause significant reductions in a vehicle's tractive efficiency, the use of large unbound aggregate for road surface protection should be limited to relatively level grades, i.e., less than 3 – 5 percent.[22] In addition, increasing the potential shear displacement at the tire-ground interface can lead to washboard or corrugation failures.

Since the quality of the aggregate used is one of the most critical factors, this technique tends to be expensive in terms of construction and also in terms of the potential for increased vehicle maintenance from rock damage. However, in very wet climates, this may be the only solution capable of providing a suitable road surface.

Another surface protection technique uses wood waste from sawmill operations. This technique has been used successfully in Southeastern Alaska where wood waste chips were used both as a fill and also a surfacing protection material.[40] The experiment was conducted by the USFS and concluded that wood waste can be used effectively in that climate area for both road surfaces and embankments. It also concluded that frequent maintenance was required due to the road's tendency for rutting.

6.3.5 Recycled Waste Materials

A variety of waste materials have been tried over recent years with varying degrees of success. (19,24,37,44) In many areas quality aggregates are in short supply which, coupled with the high cost of waste disposal, poses one of the potential benefits of waste products as aggregate, surfacing material or as stabilizers. Ideally the end product is a better, longer lasting road at lower total municipal costs due in part to reduced landfill fees. All recycled materials must be investigated for potential environmental impacts, hazardous materials, and compatibility with the road surface materials.

Of the more recent waste products identified, most were used in experiments as subgrade and embankment fill material or as additives to Portland cement concrete and asphalt cement surfaces. In one experiment, however, recycled asphalt shingles proved to be effective in controlling dust on an Iowa low volume road when ground and mixed with the wearing coarse.[37] Asphalt shingles collected by the county were ground, the nails were removed and the remaining granulated material was mixed with the road surfacing material. In all, 500 tons of shingles were placed on the 0.4 mile section of road and blade mixed with the crushed stone surface. The shingle-treated roadway developed a hard crust surface, which was nearly dust free more than a year after application.

6.4 Vehicle Restrictions, Road Operations, and Maintenance Techniques

Many cases of vehicle restrictions, particularly load restrictions, are seasonal coinciding with the spring thaw in colder climates and severe rainy season in more temperate climates. Both of these examples are related to excess water in the subsurface road structure. Vehicle load restrictions and lower tire pressure technologies have been shown to reduce the amount of sediment produced; however, they have a high cost in terms of transportation efficiency associated with them. In the end, the road must serve the function for which it was built, and in some cases these technologies may not be cost effective. Two of the more common techniques are summarized in Table *6*.

TABLE 6 Vehicle Restrictions and Other Treatment Techniques

Type of Treatment or Remediation	Action or Stabilization Mechanism	Materials and Techniques Used	Typical Concentrations, Depth of Treatments
Reduced Tire Pressure (16,22,42)	Lower surface pressure.	Field airing stations, or Central Tire Inflation System (CTIS).	Typical tire pressures of 620 kPa are reduced **to** as low as 275 kPa on gravel/earth surfaced roads, re-inflated to normal pressures on paved surfaces.
Road Re-surfacing or Recycling Surface Aggregate (4,38)	Produces an improved surface course gradation, allowing higher density surface wearing coarse.	Mobile rock crusher to reshape/grade road.	Breaks larger aggregates and protruding surface rock into a well-graded wearing course; can also be used as the mechanism for field mixing dust suppressant chemicals.

6.4.1 Variable Tire Pressure

By using variable tire pressure (VTP) technologies, the footprint of heavy trucks can be increased, resulting in a significant reduction in the load applied to the running surface from the vehicle.(12,16, 22 29,40) Simply reducing tire pressure from 620 to 480 kPa resulted in a 45 percent reduction in sediment loss during one USFS study.(16)

Demonstrations of VTP technologies by the USFS, and U.S. Army Corps of Engineers (USACE) have indicated a potential reduction in blading maintenance of as much as 80 percent and as much as an 85 percent reduction in local erosion.(16) There are two basic types of VTP; the Central Tire Inflation Systems (CTIS) and the Constant Reduced Pressure (CRP). Installing or retrofitting CTIS on large trucks can cost as much as $15,000 for a standard 18-wheel logging truck. However once installed, the operator does not have to stop the truck at an airing station. Instead the operator can simple adjust the tire pressure to an optimal amount based on load, speed, tire type and operating surface. With CRP systems adjusting pressure can only be done while the vehicle is stopped at an airing station.

USFS studies have estimated that if all heavy vehicles used VTP while operating on Forest Service roads, the annual savings in maintenance could be as high as $1.3 million.(22, 40) Additionally, by using VTP technology, heavy vehicles could be operated year round while producing minimal damage to the road structure.

One of the potential problems with this technology is the inherent load and speed restrictions that generally accompany the lower tire pressure. As a result, examples of VTP systems in use are limited to specific operations in areas that traverse steep grades or curvy roads, where vehicle speeds are somewhat lower by default. The VTP systems can remain a cost-effective option for these operations since they can allow year round operations coupled with lower overall road maintenance costs. VTP systems are not necessarily a viable alternative on areas with long straight road networks due to the high productivity costs of slower operating speeds.

6.4.2 Mobile Rock Crusher/Dresser

Mobile rock crushers or rock dressers use state-of-the-art mechanical crushing equipment which can be mounted on either a front end loader or a pull-behind trailer attachment. This equipment can effectively mill and convert oversized roadside rock and rutted surface material into useable, engineered surfacing material without the additional cost of hauling from a remote quarry. In effect, large aggregates are field broken and mixed into a well-graded material which can be compacted into a dense running surface.

The traditional method to rehabilitate worn road surfaces is to simply replace lost materials with new aggregate from either a new pit-run gravel or blasted and crushed rock. Experiments using mobile rock crushing technology have indicated that roads reconditioned in this way can have a number of cost saving benefits. Some of these include providing an alternative source of “new” material, eliminating or significantly reducing the costs associated with starting a new pit-run or quarry and building its associated haul roads. In addition, the reconstruction techniques proved to be less damaging to the surrounding environment than traditional methods. In the case of roads that are no longer needed, the mobile rock crusher was also used to scarify the road surface producing a roadbed ready to be seeded and fertilized.[4,38]

The mobile **rock** crusher also can be used to effectively field-mix the existing surface material with any of the dust suppressant materials appropriate for that area.[4,38]

6.5 Comparison Of Climate, Geology, and Traffic

The long-term effectiveness of a dust abatement program can be maximized by matching local climatic, geologic, and traffic conditions to the relative strengths of the suppressant chemical or technique. However, there is seldom one "best" answer for every possible condition and the selection is often a compromise of relative strengths. These factors are compared in Table 7.

TABLE 7 Comparison of Climate, Geology, Traffic

Type of Treatment		Materials Used	Climatic Conditions	Geologic/Material Conditions	Traffic Conditions
Chemical Stabilizers	Salts (6, 9, 12, 17, 21, 32, 34,51)	Calcium chloride Magnesium chloride Ammonium chloride	• Salts generally work well in areas with moderate precipitation. • Poor choice for arid or extremely wet regions.	• Moderate amount of surface fines required. • Not compatible with high PI or low CBR. Can become slippery when wet. • Tends to leach into soil/water table. • Surface application technique.	• Generally works well for heavy vehicles. • Can self repair. • May shear or corrugate under fast moving vehicle. • Salts increase the potential damage **to** vehicles.
	Organics (6, 17, 21)	Lignin sulfonate	• Effective in regions with long periods of low humidity. • Water-soluble. • Not effective in extremely wet regions.	• High percentage of surface fines required. • Works best if mixed with surfacing material. • Complex application techniques prone to quality concerns.	• Tends to shear under heavy loads in *dry* conditions. Does not self-repair.
	Emulsions	Asphalt emulsion (6, 12, 21, 34) Pine tar (12) Tall Oil Pitch (3, 6, 21)	• Generally effective in all weather and climate conditions. • Tends to become viscous in hot climates. • Tends to pothole in wet climates.	• Requires a minimum amount of fine material. Lower viscosity emulsions work best with fine-grained soils. Highly viscous emulsions work best with open – graded soils.	• Heavy vehicles will shear surface. • Slippery when wet.
	Enzyme	Biocat (6, 12) EMC Squared (12) PermaZyme (12) PSCS-320	• Most enzyme solutions are effective in any weather or climatic condition.	• Performance is highly dependent on chemical composition **of** soil. • Efficacy is dependent on cation exchange capacity of surfacing material. • Works well in iron rich areas. • PI range **8** – 35.	• Requires a curing or set up time. • Difficult to maintain.

TABLE 7 Continued

Type of Treatment	Materials Used	Climatic Conditions	Geologic/Material Conditions	Traffic Conditions
Pozzolan Stabilizer (19, 24, 25, 27, 34, 44)	Lime Kiln dust Cement kiln dust Fly ash	• Effective in most climatic conditions.	• Used on non-plastic aggregate material. • Needs to be compacted at optimum moisture content.	• Requires a curing or set up time. • Difficult to maintain.
Alternate Stabilizers	"Road Oyl" (12)	• Suitable for moderate climates.	• Performs similar to emulsified asphalt, suitable for most materials with total fines < 20%.	• Wore away within one season.
	Clay filler (6, 12, 21, 34) Bentonite (5)	• More suited for wet environments.	• Acts as an additional cohesive or flocculation. Added as 1.5 to 3 % of dry aggregate weight.	• Suitable for most low volume traffic conditions.
	Acrylic polymer (6, 12, 21)	• Often designed as a weather resistant seal.	• No specific materials noted.	• Difficult quality control.
Protection techniques	Wood chips or chunk wobd protective layer (12, 41)	• Particularly useful in wet and cold climates.	• Wood chunk is used primarily as fill material surfaced with aggregate. • Wood chip surface is used for temporary applications.	• Suitable for all low-volume traffic conditions. Generally of a temporary nature. • Frequent re-applications required.
	Polyester fibers or geotextiles (12, 17, 51)	• Suitable for all climates. Can be subject to deterioration from UV light.	• Minimizes wearing action by binding aggregate layers.	• Can be subject to vehicle shear on curves and grades.
	Large (50–100mm) high-quality aggregate (12)	• Used as an overlay in very wet or very dry climates.	• Only high quality aggregates are suitable. • May be applied to most all geologic conditions.	• Large aggregate (100 mm) should be restricted to heavy trucks due to potential vehicle damage.

TABLE 7 Continued

Type of Treatment	Materials Used	Climatic Conditions	Geologic/Material Conditions	Traffic Conditions
Recycled Surfacing Materials	Shredded tires (18, 19, 24)	• Applied to moderate to dry climates.	• Most examples restricted to subgrade or fill replacement material. Reduced surface moisture by cutting off existing capillary rise condition.	• Surface deflections excessive for repeated heavy vehicle traffic.
	Ground asphalt shingles (24, 37)	• Worked well in a moderate climate.	• NIA	• NIA
	Used Motor Oil (21, 19, 24)	• Should be restricted to dry climates due to potential hazardous chemical leachate.	• Suitable for all geologic materials.	• All traffic conditions.
Reduced Tire Pressure, Load Restrictions	Operator controllable tire pressures (12, 16, 22, 28)	• Applicable to all climatic conditions.	• Reduces aggregate wear and sediment production up to 80%. Particularly effective in marginal aggregate types.	• Commercial vehicles can be retrofitted with CTIS for about $15,000.
	Mobile rock crusher to reshapelgrade road (4, 12, 38)	• Used in all climates.	• Not as effective with rounded aggregates • Not generally effective on large basalt formations.	• Particularly useful when used in parallel with road reconstruction and application (field mixing) of a dust suppressant.

7. ENVIRONMENTAL AND RESOURCE IMPACTS

Every construction project ultimately will have some impact on the ecosystem in which it is located. The total net impact can be positive or negative depending upon the design, development, and selection from alternatives. The final project solution must be consistent with the area's natural resources plan. Two of the most important variables associated with the design of low-volume roads are sediment production runoff and potential watershed contamination from stabilization leachate.[2, 29, 39]

Sediment production has a significant negative impact on water quality and fish habitat. Road designs should include considerations for the quality of aggregate used, mitigation or stabilization techniques, road prism profile, and drainage systems. In general, the road surface is responsible for approximately one third of all sediment production. The remainder is generated in the cut and fill slopes, and the side ditch lines.[12,41,51] Road-generated sediment can be reduced substantially by using high quality aggregate or by applying the appropriate mitigation techniques to match the aggregate to be used. Further controls on tire pressure, load limits, and seasonal restrictions may also be required for a best-fit total solution.

Table **8** represents a summary of potential actions that have been shown to reduce sediment production.

TABLE 8 Environmental Effects Of Dust Control

Stabilization Material or Technique	Runoff	Leaching	Sediment Reduction	Particulate Pollution
Calcium Chloride (12, 29, 39)	High potential for runoff and/or leaching in moderate to heavy rains. Runoff will affect the pH balance of surrounding watershed.		In areas of moderate rainfall, decreases the sedimentation of watershed significantly. Not effective in sediment reduction in dry or very wet climates.	Applied in either liquid or dry form. In dry climates, dust particles will retain portions of the salt creating a more hazardous dust.
Magnesium Chloride (12, 29, 39)				
Ammonium Chloride[52]				
Lignin Sulfide (12, 29, 39)	Runoff water is hazardous to fish stocks (a derivative of sulfuric acid)	Highly water soluble. Tends to leach with heavy rains.	Significantly reduces sedimentation in moderate to dry climates. Tends to form a crust which potholes in wet weather.	Minimal effect on particulate pollution since lignins work well even in arid climates.
Asphalt Emulsion (12, 29, 39)	Runoff water can contaminate local water supply.	When applied properly, does not have a great tendency for leaching.	Next best application to paving. Reduces airborne and surface sediment production up to **97%.**	
Pine Tar (12, 29, 39)	Not noted. Distilled from pulp waste could potentially leach and affect the organic content of local water source.		Works similar to emulsified asphalt.	
Tall Oil Pitch (3, 6, 12)				
Biocat[12,52]	Unknown runoff or leaching effects. Chemical enzymes could cause significant harm to local water sources-if not properly designed.		Promising new technology. Documented test results vary. Very site specific, i.e., material, climate, and design.	
EMC Squared[12]				
PermaZyme[12]				
PSCS-320 (12, 52)				

TABLE 8 Continued

Stabilization Material or Technique	Runoff	Leaching	Sediment Reduction	Particulate Pollution
Lime (12, 25, 29, 33, 39) **Kiln Dust** (12, 19, 29, 33, 39) **Cement Kiln** (12, 19,29, 33, 39) **Fly Ash** (12, 19, 29, 33, 39)	Can affect the pH if subjected to heavy rains prior to proper curing.	Can affect the pH if subjected to heavy rains prior to proper curing.	Reduces sediment production by cementing aggregate material.	Can produce mild, corrosive dust if not wetted and cured properly.
Clay filler (12) **Bentonite** (5, 12)	Not noted	Not noted	Binds aggregates reducing sediment production and airborne particulate.	Binds aggregates reducing sediment production and airborne particulate.
Wood chips or chunk wood protective layer 12, 29, 41)	Potential increases in the amount of organic material contained in runoff.	Potential increases in acidic content (tannic acid) of local water supply.	Protects surface from wear and retaining surface moisture lowering sediment production.	Protects surface from wear and retaining surface moisture lowering sediment production.
Polyester fibers or geotextiles (12, 17, 29, 39)	No adverse effect on runoff.	Not affected by leaching action.	Controls sediment by restricting movement.	No effect on airborne particulate.
Large (50-100mm) high quality aggregate (12)	No adverse effect on runoff or leaching action pollution.	No adverse effect on runoff or leaching action pollution.	Controls sediment production by protecting surface from heavy vehicle loads. Aggregate quality is a critical issue.	Controls sediment production by protecting surface from heavy vehicle loads. Aggregate quality is a critical issue.

TABLE 8 Continued

Stabilization Material or Technique	Runoff	Leaching	Sediment Reduction	Particulate Pollution
Used Motor Oil (19, 24)	Very hazardous to local water supply. Waste oils can contain PCBs among other hazardous substances.	Large potential for leaching hazardous chemicals from waste oil.	Very effective dust suppressant.	Minimal airborne particulate pollution.
Shredded tires (18, 19, 29)	Large potential for runoff contamination.	Potential long term leaching problem.	Produced a very soft surface. Prone to rutting failure.	Potential for fires within the road fill/surface area.
Ground asphalt shingles(37)	No measurable runoff contamination.	Not noted	Significant reduction in sediment production up **to** one year after application.	Shingle material not small enough **to** become airborne particulate problem.
Reduced or Controllable tire pressure (16, 21, 28)	N/A	N/A	Significant reduction (up to 80%) in sediment production caused by loads or point pressure.	
Mobile rock crusher (4, 12, 38)	Reduced sediment in runoff due to more durable surface.		Reduces sediment production by creating a well-graded soil which can be compacted or stabilized more effectively.	

8. COSTS VS. BENEFITS

The true cost of dust suppressants is a combination of the cost of the chemical itself, equipment required for proper application, maintenance required between applications and the amount of material required on subsequent applications. This cost also can be contrasted to the amount of maintenance required over the life of a road network. By stabilizing the road surface, the material subject to wearing action is less likely to break down, thus reducing sediment that could become airborne. Slower rates of aggregate breakdown lengthens the time between requirements for resurfacing the road with new aggregate. This leads to a lower total life cost of the network. In a study performed by the Forest Engineering Research Institute of Canada, three roads were compared for five-year maintenance costs. (3) Two roads were maintained with annual applications of a Tall Oil Pitch dust suppressant (Dustrol E and Dustrol EX), while a control was given no treatment other than the normal grading maintenance. The roads that were maintained with dust suppressants cost $28,569 and $29,499 per kilometer for the five-year test period while the control road cost $36,365 per kilometer over the test period. Total maintenance costs cited included materials and application. Although initial maintenance costs for the dust suppressant applications were significantly higher, the control road required a new aggregate surface at five years due to excessive wearing action. (3)

Typical costs for the commonly used chemical dust suppressants used are included in Table 9. These costs are based on a basis of annual reapplication of the palliative and include preparation, material and application unless noted.

TABLE 9 Effective Costs Of Dust Control

Type of Treatment		Materials Used	Application Rate	Cost$/ km (preparation, material and application)
Chemical Stabilizers	Salts	Calcium Chloride	Sprayed shot @ 1.13L/m²; traffic compacted (USFS 1988)	$1,740
			Sprayed shot @ 0.95 L/m²; reapplied twice per season (Iowa DOT 1993)	$3,200
		Magnesium Chloride	Sprayed shot @ 2.26 L/m², traffic compacted (USFS 1988)	$1,740
			Sprayed shot (2) @ 1.13L/m², traffic compacted (USFS 1992)	$1.490
	Organics	Lignin Sulfonate	2 sprayed shots each @ 2.26 L/m², diluted 1 part lignin to 1 part water, blade mixed (USFS 1988)	$930
	Emulsions	"Choerex" a petroleum resin emulsion	2 sprayed shots @ 1.72L/m², diluted 5.2 parts oil to 1 part water (USFS 1992)	$1,510
		DL-10 emulsified asphalt	1.77L/m², undiluted (USFS 1992)	$1,490
		Tall Oil Pitch	2 sprayed shots @ 1.77L/m², diluted 4.2 parts emulsion to 1 part water (USFS 1992)	$3,920
			2 sprayed shots @ 3 L/m², (FERI Canada . 1992)	$2,800
	Ezyme	Biocat 300	Blade mixed, vibratory compacted, diluted 1 part to 200 with water (USFS 1988)	$2,550
		ECO Polymer PM-10	Sprayed shot @2.54 L/m², and sprayed shot @ L/m², both diluted to 19 parts polymer to 1 part water (USFS 1992)	*$6,000*
		Soil Sement™	4 sprayed shots @ 1.63L/m², diluted 6.8 parts polymer to 1 part water (USFS 1992)	$2,410
Mobile rock crusher to reshape/grade road			Production rates approximately 0.19 km/hr	Project costs between $2,500 and $3,650 per km depending on material

The chemical suppressant type of choice will vary in different parts of the world based on local variations of cost, the availability of the material, and proximity of potential environmental concerns. According to the Australia Road Research Board 1996 report,[21] chloride-based suppressants represent the most cost effective solution. Conversely, the USFS maintains [6, 12, 17] that lignin sulfides generally represent the most cost-effective solution although this may vary from region to region depending on local costs. Both agencies agree that the newer enzyme solutions are currently the least cost effective, although, these may in fact have the most potential for future development.

9. CONCLUSION AND RECOMMENDATIONS

General comments concerning chemical dust suppressants are summarized as follows:

- The chloride family of dust suppressants generally provide the most satisfactory combination of ease of use, durability, and cost while controlling dust in temperate and semi-humid climates. They do not work effectively in arid climates and do not last more than one year before being leached out.
- Lignin sulfides work best in moderate to arid climates but can be effective over a wide range of temperatures and humidity. They are less effective on igneous gravels and those with low percentage of fine material. Road surface failures occur following heavy rains due to high potential for leaching.
- Most types of petroleum emulsions can provide effective dust control in virtually all environments and aggregate types. They work best in surface material which has a low percentage of fines. Waste oil was found to be a particularly effective dust

suppressant. However, it provides a significant negative environmental problem that it is not acceptable in most circumstances. Most all of the petroleum-based applications provide a high level of surface stabilization and dust control

- Enzyme stabilizers, although new on the scene, provided promising results over a wide range of climates and geologic mineral types. They work particularly well on clay and organic material and are least susceptible to leaching. They are among the more expensive and require the most care in application techniques.
- A number of waste products have been tried and have shown promising results. A particularly promising experiment used ground bituminous shingles reducing dust emissions significantly for more than a year following treatment.

Speed, Load and Tire Pressure Controls

The speed and weight of vehicles has a great deal to do with the generation of dust. By slowing the speed and requiring lower weights, the mechanical wearing process is slowed considerably. Variable tire pressure controls resulted in up to 80 percent reduction in sediment production. Vehicle weight and speed controls and variable tire pressure technologies can provide additional protection and dust abatement properties but can come at **a** high price in terms of operational efficiency. As such, these techniques are often limited to seasonal protections.

Road Design, Construction and Maintenance

In all reports reviewed, the first and foremost form of dust control was found to be the proper application of sound engineering principles in road design. Equally important for dust control, was the insistence on construction quality control in the form of proper crown, slope, drainage, material gradation, and the use of high quality aggregates. Second only to design and construction quality, an effective and ongoing maintenance program remains the key to long term dust control.

Only when all of these factors have been satisfied or proven to be ineffective in the local geologic or climatic conditions, should chemical suppressants be considered. The choice of using chemical dust palliatives to diminish the detrimental effects of dust must strike a balance between the usefulness of the road itself, the associated environmental impacts of the chemical agent, and the detrimental environmental effects associated with not providing any stabilization treatment. Ultimately, the type of suppressant to be used must be matched to the climate conditions, traffic type, and the type or gradation of the surfacing materials.

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