

# Chemical Aspects Of Cold-Mix Asphalt Incorporating Contaminated Soil

*Stephen M. Testa*

*Testa Environmental Corporation, 31831 Camino Capistrano, Suite 100, San  
Juan Capistrano, CA 92675*

**ABSTRACT:** The chemical aspects associated with the incorporation of petroleum hydrocarbons- and metals-affected soil has been studied extensively with respect to pavement properties, leaching behavior, sensitivities to moisture damage, and function group analysis. These studies provide information that can be used to evaluate the stability of these constituents in soils that have been incorporated as an ingredient in asphalt. These studies also indicate that cold-mix asphalt incorporating contaminated soil will be highly stable and perform adequately as an end product. Maximum chemical performance is achieved when the asphalt is comprised of high contents of pyridinic, phenolic, and ketone groups, which can be achieved by selectively choosing the source material. If the situation requires special stability or redundancy, small amounts of shale oil and lime can be used as additives. Situations and conditions that favor the presence of inorganic sulfur, monovalent salts, and high-strength solutions in the asphalt should be avoided because these conditions decrease the chemical stability of the asphalt cement by disrupting the functional group-aggregate bonds and by increasing the overall permeability. However, these conditions are not typically expected in the anticipated uses of asphalt cement to stabilize contaminants in soil using Environmentally Processed Asphalt™ (EPA™)\* or Asphaltic Metals Stabilization™ (AMS™)\*\* remedial technologies.

**KEY WORDS:** cold-mix asphalt, asphalt cement, EPA™, AMS™.

## I. INTRODUCTION

The use of cold-mix asphalt to stabilize contaminants in petroleum hydrocarbons- and metals-affected soil using Environmentally Processed Asphalt™ (EPA™) or Asphaltic Metals Stabilization™ (ASM™) remedial technologies, respectively, has been shown to be a viable and creative method of utilizing affected soil to produce a useful end product instead of a waste requiring disposal (Preston and Testa, 1991; Sciarrotta, 1991; Testa et al., 1992ab; Testa and Patton, 1992, 1994,

\* A process wherein petroleum hydrocarbon-affected soils are incorporated as an ingredient in specified grades of cold-mix asphalt.

\*\* A process wherein metals-affected soils are incorporated as an ingredient in specified grades of cold-mix asphalt.

1994a; Conca and Testa, 1992; Testa and Conca, 1993; Meegoda, 1994). Evaluation of asphalt has traditionally focused on structural performance as pavement and building materials. With the incorporation of affected soil as part of the aggregate, studies conducted over the past 3 decades have shown these materials not to adversely affect the structural behavior of the asphalt as long as general requirements are met (i.e., the mix design must meet its respective end use requirements). However, evaluating the long-term performance of an asphaltic product incorporating affected soil, notably, when the product end use is as a liner, designed fill, or other subsurface use, must focus on the chemical performance and requires more extensive experimental study.

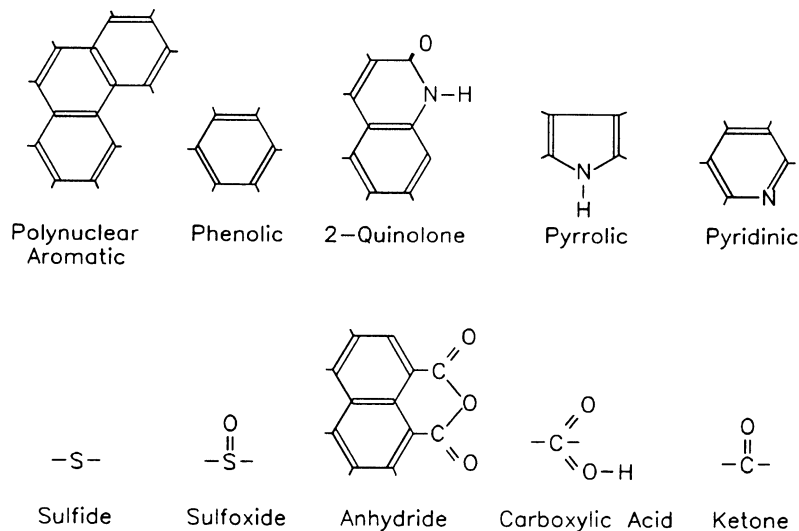
The petroleum products and asphalt components are generally immiscible with respect to the aqueous phases expected under subsurface conditions, with the exception of polar functional groups. These groups or components assist in preventing the release of contaminants from the asphalt and slowing the diffusion of aqueous components out of the asphalt. Therefore, the release of any incorporated contaminant (e.g., petroleum, polynuclear aromatics, metals, etc.) from the asphalt is coupled with the hydraulic conductivity, diffusivity, and structural breakdown of the asphalt itself, which are for all practical purposes very slow processes. For similar crude sources and chemical treatments, the end-product asphalt cement formed from either cold- or hot-mix emulsion has the same general structure, composition, and properties. The greatest effects between the different preparations are on kinetically controlled reactions and sorption processes. Presented in this paper is a discussion of asphalt-aggregate chemistry, including important functional groups and asphalt-aggregate stability. Contaminant mobilities in asphalt and contaminant leachability from asphalt are also discussed.

## II. ASPHALT-AGGREGATE CHEMISTRY

Asphalt is a dark brown to black cementitious material, solid or semisolid in consistency, in which the predominating constituents are bitumens (i.e., high-molecular-weight hydrocarbons) that occur in nature as such or are obtained as residual in the refining process (Yen, 1990).

Asphalt has a complex and poorly understood chemistry and structure. Its chemistry and structure largely depend on the crude petroleum source and any chemical treatment or chemical modifiers added during processing (Wolfe *et al.*, 1986). Asphalt has a large number of heteroatomic groups with a wide range of chemical reactivities (Petersen, 1986). Therefore, it seems likely that a number of asphalt, hydrocarbon, or metal-soil reactions that could affect contaminant mobility might occur in affected soil subjected to EPA<sup>TM</sup> or AMS<sup>TM</sup> methodologies.

Important functional groups found in asphalts include polynuclear aromatics, phenolic, 2-quinoline, pyrrolic, pyridinic, sulfide, sulfoxide, anhydride, carboxylic acid, and ketone, as shown in Figure 1. The number and distribution of these

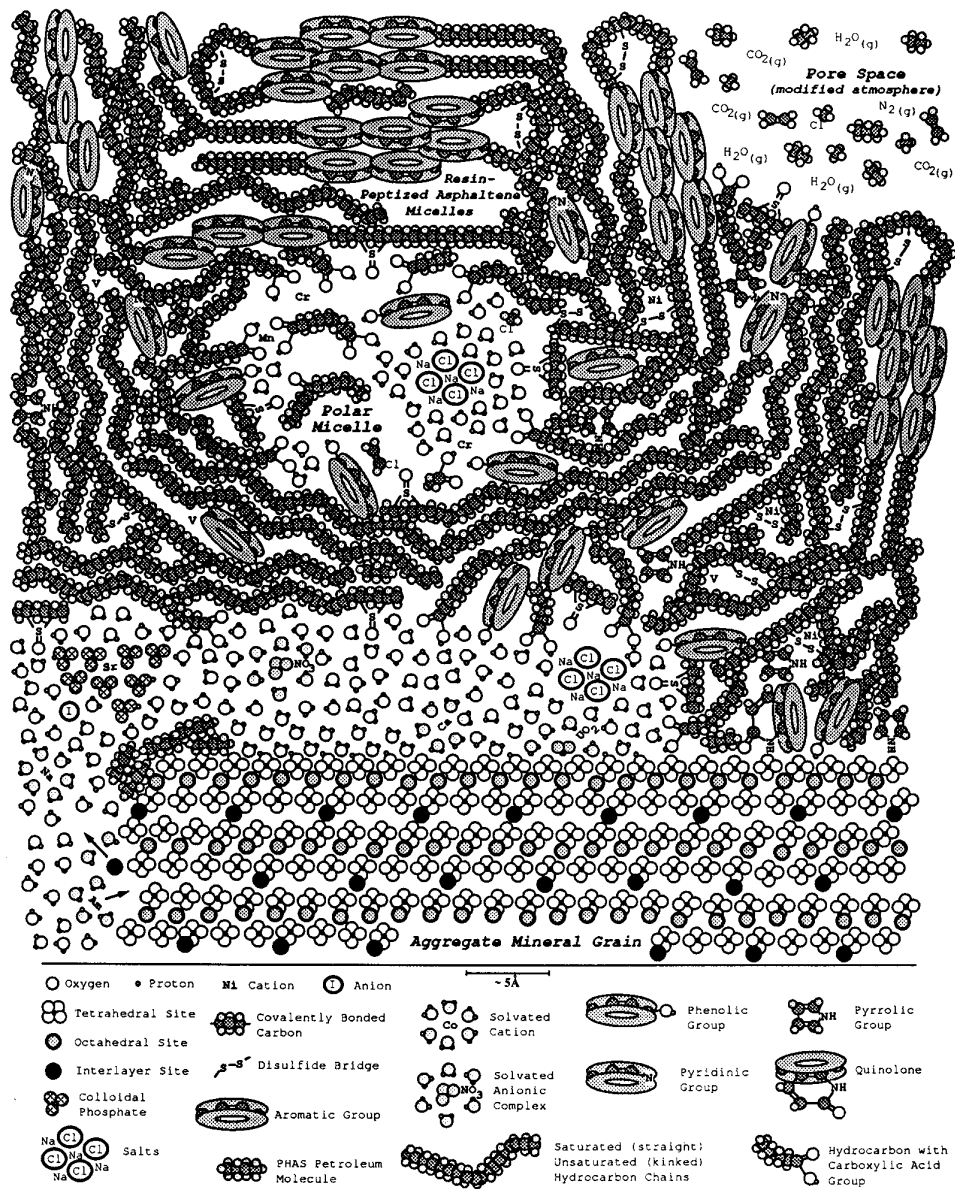


**FIGURE 1.** Important polar and non-polar functional groups present in asphalt (Conca and Testa, 1992; Testa and Conca, 1993).

groups vary widely among different asphalts and determine much of the chemical behavior and performance of these groups. Of these groups, carboxylic acids, ketones, and anhydrides are generally formed by atmospheric oxidation (i.e., ketones and anhydrides) or caustic pretreatment (i.e., carboxylic acids concentrated in treated asphaltic residues), and are rare in fresh asphalts. However, these may be important in waste disposal situations because of possible interactions with oxidizing or alkaline contaminant solutions, or if recycled asphalt is used.

There has been no comprehensive study of asphalt chemistry in relation to the aggregate or to contaminant species; therefore, generalizations about the chemical performance of these systems is difficult. However, extrapolations from asphalt studies of road pavement properties, leaching behavior, sensitivities to moisture damage, and functional group analysis (Wolfe *et al.*, 1986; Benedetto *et al.*, 1970; Haxo, 1976; Petersen *et al.*, 1982; Daiev and Vassilev, 1985; Brule *et al.*, 1986) have provided information that can be used to evaluate the stability of hydrocarbon compounds, metals, and other contaminants in soils that have been incorporated into asphalt.

It is generally assumed that asphalt cements are colloidal systems made up of a suspension of asphaltene micelles in an oily medium. Micelles are units of various molecules, usually organic with minor inorganic components, that have distinct structural and chemical properties. Micelles play an important role in asphalt behavior. The structural and chemical components in affected soil that has



**FIGURE 2.** The asphalt-aggregate interface at the molecular level using space-filling and structural representations to illustrate important functional relationships (Conca and Testa, 1992; Testa and Conca, 1993).

been asphalted are illustrated in Figure 2. The figure is prepared approximately to scale and represents the results and implications of separate studies of asphalt components. Major components include the aggregate mineral grains (i.e., clay

mineral), bulk aqueous phase, sorbed electric double layer on the mineral surface, resin-peptized asphaltene micelles, polar micelles in the asphalt, the asphalt oily medium, asphalt functional groups at the interfaces between these different components, and asphalt pore spaces. Each component is described separately in reference to Figure 2.

The aggregate mineral grain portrayed in Figure 2 is a clay mineral. Clay minerals are important because of their reactive surfaces and their ability to exchange cations from the interlayer sites with contaminant ions in solution. There are two major types of complexing functional groups associated with silicate mineral grains. Complexation (or chelation) is the process by which metal ions and organic or other nonmetallic molecules, referred to as ligands, can combine to form stable metal-ligand complexes. The most important is the siloxane ditrigonal cavity, which occurs in tetrahedral silicate sheets and gives the clay minerals their exchange capacities (Sposito, 1984). However, the most abundant surface functional group is the inorganic hydroxyl group, which is found on almost all mineral and amorphous solid phases. Hydroxyl groups exposed on tetrahedral silica are called silanols; those exposed on octahedral alumina are called aluminols. There can be more than one type of surface hydroxyl on a given mineral surface with different reactivities. For example, the siloxane cavity complexes only positive ions and groups, whereas the surface hydroxyl complexes both anion and cation species, depending on the solution composition and pH. Asphalt functional groups as well as contaminant species will interact with these surface complexes. Several mineral surface interactions are illustrated in Figure 2. A strong complexation with a uranyl anion complex, a weak complexation with a hydrated calcium complex, an exchange of americium with an interlayer cation, sorption of some short-chain hydrocarbons at the mineral surface, and bonding of the asphalt quinoline, pyrrolic, phenolic, and carboxylic acid functional groups are shown.

The bulk aqueous phase has many of the dissolved inorganic constituents of interest to contaminant transport. Because the simple diffusion coefficient of dissolved species in the bulk fluid is approximately  $10^{-5}$  cm<sup>2</sup>/s regardless of species (Conca and Wright, 1991), diffusion of contaminants through the bulk aqueous phase should be the primary route of contaminant release from the asphalt. The release rate, however, depends strongly on the connectivity of the bulk fluid (i.e., the diffusion porosity). In coherent asphalts without moisture damage, this connectivity is small and the effective diffusion coefficient in the asphalt cement as a whole is low, on the order of  $10^{-12}$  cm<sup>2</sup>/s (Hickle, 1976). Release of contaminant species also depends strongly on the retardation properties of the system. Other phases in contact with the bulk aqueous phase can sorb species that are present in the aqueous phase. The strong sorption of strontium and the weak sorption of iodine to a phosphate colloid particle in the bulk aqueous phase is also illustrated in Figure 2.

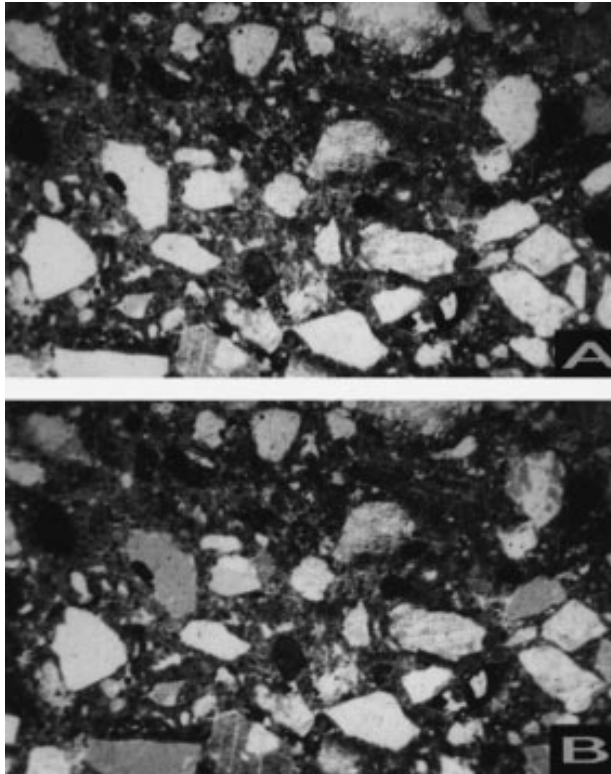
The asphaltene micelles and the oily medium make up the bulk of the asphalt. Asphaltenes are molecules composed of polynuclear aromatic groups and long

hydrocarbon chains and contain much of the inorganic constituents of asphalt. An asphaltene micelle is an aggregate of asphaltene molecules bonded through  $\mu$ -electrons and interactions between the condensed polynuclear aromatic sheets (Brule et al., 1986). Asphaltene micelles can be peptized by hydrocarbon resins into aggregates, as illustrated in Figure 2. The oily medium consists of saturated and unsaturated hydrocarbons, and resins. These resins are a mixture of terpenes, resin alcohols and resin acids and their esters, the complexity of which is not represented in Figure 2. There may be extensive secondary structures to the micelles that could have great structural importance (Brule et al., 1986). Certain metals such as vanadium, nickel, and iron, which are found in asphalts, are thought to be associated with the asphaltenes, although exact molecular sites are not known. They may, however, be associated with sulfides and aromatic groups, and are represented as such in Figure 2.

The possible polar compounds present in polar micelles are also illustrated in Figure 2. Agglomerates or micelles of polar asphalt molecules exist separately in the asphalt and sequester certain polar complexes and acids, such as manganese-acid complexes (Petersen, 1986). Carboxylic acid groups will certainly occur in the polar micelles if they exist in a particular asphalt, and polar functional groups such as the phenols, ketones, and sulfoxides will be concentrated at the interface. This sequestering chemically removes those species from subsequent reactions in the nonpolar phases and aqueous phases of the asphalt. The polar micelles could sequester many metal species of interest. Speculation exists that water molecules and salts can occur in the polar micelles, and this has been incorporated into Figure 2.

The nature of the pore space in asphalt is a highly debated topic. Although pore space is limited with no evident connectivity as shown in petrographic thin section (Figure 3), a great deal of pore space in asphalt can be observed in electron micrographs (Wolfe *et al.*, 1986), but again is not well connected. Depending on the conditions of formation and subsequent history, the pore space may or may not be water filled. The gaseous components in pore spaces will include atmospheric components introduced during formation and processing, and volatile asphalt compounds. Gaseous contaminants of interest may also be incorporated into the pore spaces.

Knowing the structures and components of asphalt incorporating affected soil is crucial to understanding its chemical performance with respect to hydrocarbon and metal contaminants. This is exemplified by several examples. Heavy metal salts of carboxylic acids ( $\text{RCOO}^-\text{M}^+$ ), which are insoluble in water, are soluble in strong acids and in strong polar solvents (Morrison and Boyd, 1974), making polar micelles possible repositories of contaminant metal-carboxylic acid salts in the asphalt incorporating affected soil. Petroleum contaminants in the affected soil will also be strongly hydrogen bonded to the asphalt components as well as possibly bonded through reactions with the functional groups. Furthermore, oxidation-reduction reactions of metals will also be affected by the polar and nonpolar phases



**FIGURE 3.** Photomicrographs of petrographic thin sections of processed cold-mix asphalt under plain (A) and polarized light (B) showing full encapsulation with negligible pore space and connectivity once compacted (3.5 magnification).

in the asphalt incorporating affected soil. Chromium in immiscible cresol/water mixtures has been found to preferentially enter the nonaqueous cresol phase (isomeric phenols), where the oxidation-reduction reaction  $\text{Cr(VI)} \rightarrow \text{Cr(III)}$  occurred much faster than in the aqueous phase (Fish and Elovitz, 1990). This effect has important implications for metals in affected soil, especially chromium interactions with asphaltic phenolic groups. However, these reactions are kinetically controlled and may be unimportant at pH 8 (Fish and Elovitz, 1990).

### III. ASPHALT-AGGREGATE STABILITY

Incorporation of affected soil as an ingredient to produce an asphaltic product is achieved by stabilization, solidification and encapsulation. Stabilization is where chemical fixation techniques render a waste less toxic or harmful to the environment. The hazard potential of what was once considered a waste is subsequently

reduced. Examples of such techniques are ion exchange of heavy metals in an alumina silicate matrix of a cementitious agent, or sorption of heavy metals on fly ash in an aqueous system, among others. Stabilization of asphalt incorporating affected soil can be functionally described in terms of the final product, whereas the constituents of concern are mechanically stabilized and immobilized by fixation and isolation. This differs from solidification, where the waste is transformed into a stable and durable matrix that is more compatible for reuse, storage, or disposal. Solidification creates barriers between the waste components and the environment by reducing the permeability of the waste or matrix, reducing the effective surface area available for diffusion, or both, with or without chemical fixation.

The chemical stability and environmental performance of asphalt incorporating affected soil is, however, dependent on the nature and extent of the asphalt-aggregate bonds. Much of the information concerning these bonds comes from studies of asphalt sensitivity to moisture-induced damage (Petersen *et al.*, 1982). Because of the polar/non-polar and hydrophobic/hydrophilic interactions among the various phases in the system, the functional groups as shown in Figure 1 will be concentrated at the interfaces between phases (i.e., asphalt-aggregate interface, polar micelle-asphalt oil interface, asphalt-water interface, etc.). Stability is thus addressed via the functional groups' relative tendency to be concentrated at the asphalt-aggregate interface, sorption affinity, and ability to be displaced by water.

The behavior of functional groups at the asphalt-aggregate interface determines the chemical stability of the asphalt to a large degree. At the asphalt-aggregate interface, these groups are susceptible to interactions with the aqueous phases and any contaminants present in the affected soil. The relative tendency of the asphalt functional groups to be concentrated at the asphalt-aggregate interface has been determined (Petersen, 1986), in order of decreasing tendency, as:

carboxylic acid > anhydride >> quinoline, phenolic > sulfoxide, ketone > pyrrolic

The sorption affinity of the functional groups with the aggregate surface has also been investigated (Petersen *et al.*, 1982) and is given, in order of decreasing tendency, as:

pyridinic, carboxylic acid >> anhydride >  
quinoline, phenolic > sulfoxide > ketone  
>> pyrrolic, polynuclear aromatic

The third important tendency of the functional groups affecting EPA<sup>TM</sup> and AMS<sup>TM</sup> stability is the ability of the functional group-aggregate bond to be displaced by water. This tendency, listed in order of decreasing tendency, is given as:

anhydride, quinoline, carboxylic acid > sulfoxide > ketone > pyrrolic, phenolic



Combining these tendencies provides some indications of performance and some guidelines for using EPA<sup>TM</sup> and AMS<sup>TM</sup> methodology. For the best chemical performance, the asphalt should have high contents of pyridinic, phenolic, and ketone groups, which can be achieved by selectively choosing the source material or using additives such as shale oil. Also, the presence of inorganic sulfur, monovalent salts, and high-ionic-strength solutions in the asphalt decreases the chemical stability of the asphalt cement by disrupting of the functional group-aggregate bonds, and increases the system's permeability (Petersen *et al.*, 1982). Addition of lime to the aggregate can thus be used, and often is, to counter this effect.

#### IV. CONTAMINANT MOBILITIES IN ASPHALT

Contaminant mobility, especially of metals, in the asphalted cement will be affected by many factors, including diffusivity, permeability, solubility, specification, complexation, redox reactions, sorption, and precipitation. The influence of these factors influence on contaminant mobility in asphalt is summarized below:

- Diffusivity and permeability of the asphalt cement (i.e., as a whole generally less than  $10^{-12}$  cm<sup>2</sup>/s and  $10^{-9}$  cm/s, respectively) (Hickle, 1976; Testa, 1992b)
- Solubility of species in the various aqueous, polar, and nonpolar phases
- Specification of the contaminants (i.e.,  $UO_2$  [nonmobile] vs.  $UO_2 \cdot nCO_3$  [highly mobile])
- Complexation with any chelating organics
- Redox reactions of metals across aqueous-organic phase boundaries
- Sorption on aggregate surfaces, along asphalt-aqueous interface, or on colloids
- Precipitation of solid phases or colloids of metal salts, especially oxyhydroxide and carboxylic acid salts

Many of these properties are not known to the degree that specific contaminant release can be predicted. Leaching tests are the primary method of evaluating contaminant mobility in these systems and have been performed on a variety of asphalts. However, the low diffusivities and permeabilities of asphalt is obviously the greatest factor in the retention of contaminants in asphalt cements. Conditions that adversely affect the diffusivity and permeability will have the greatest adverse effect on contaminant mobility and release. The asphalt acts primarily as a physical containment (i.e., via fixation or stabilization, solidification, and encapsulation) to the contaminants and the aggregate, reflecting on the asphalt cement overall composition and structure.

## V. CONTAMINANT LEACHABILITY FROM ASPHALT

Even though metals such as vanadium and nickel occur in asphalts at the hundreds of parts per million levels (Wolfe *et al.*, 1986), as well as many toxic organic components, asphalt leachates and products have never produced toxic or contaminated solutions that are considered to be hazardous by the Environmental Protection Agency. Asphalt's nonvolatile, viscoelastic properties result in the general observation that asphalt leachates do not contain reported contaminant concentrations above the Environmental Protection Agency's drinking water guidelines (Kriech, 1990). Even in asphalts incorporating metal slags as an aggregate, metals do not become solubilized and do not leach from these asphalts in detectable concentrations when used with strong acidic and alkaline solutions (Kriech, 1990). Some typical test results to assess the potential leachability of certain hydrocarbon compounds- and metals-affected soil incorporated as an ingredient in hot- and cold-mix asphalt are presented in Tables 1 and 2, respectively.

During evaporation phases and compaction, void structure collapses and water leaves the system. Although leachability of contaminants is an issue to be addressed, leachability studies indicate that contaminants are nonleachable during these various phases (Testa *et al.*, 1992; Testa and Patton, 1994a).

Asphalt leachates that have contained detectable concentrations of contaminants have been obtained in studies of asphalted nuclear wastes (Amarantos and Petropoulos, 1981; Daugherty *et al.*, 1988; Fuhrmann *et al.*, 1989; Nikiforov *et al.*, 1987). However, in all of these studies, high concentrations of salts, ranging up to 50% salt/50% asphalt, were used. It is known that high salt concentrations in asphalt mixes disrupt the asphalt structure and is a condition that will not occur in affected soil subjected to EPA™ and AMS™ asphalt methodologies.

On the other hand, in diffusion studies of radioactive wastes with normal salt contents, diffusion coefficients were as low as for normal asphalt conditions:  $10^{-12}$  cm<sup>2</sup>/s (Daiev and Vassilev, 1985) and  $10^{-13}$  to  $10^{-10}$  cm<sup>2</sup>/s (R. J. Serne, personal communication). In all these studies, researchers point out that experimental effects (e.g., slicing of thin asphalt membranes) may introduce errors that are not relevant to the field situation and tend to increase the observed diffusion coefficient.

A number of unplanned leaching experiments have been taking place with asphalt. Asphalt has been used for years to line domestic water reservoirs, especially in California, and to line fish-rearing ponds, with no adverse effects (E. D. Schlect, Asphalt Institute, personal communication). There are over 30 asphalt-lined fish-rearing ponds throughout the states of Oregon and Washington. Trace metal and organic contamination is highly toxic to fry and developing fish, yet, no adverse effects have been observed from the asphalt liners, indicating a high degree of chemical stability with respect to aqueous solutions and an absence of any toxicity effects.

**TABLE 1**  
**Summary of Leach Test Results from Seven Reclaimed Pavement**  
**Hot Mix Asphalts Using Environmental Protection Agency Test**  
**Procedures<sup>a,b,c</sup>**

| Parameter                           | Sample No. |        |        |        |        |        |        |
|-------------------------------------|------------|--------|--------|--------|--------|--------|--------|
|                                     | 1          | 2      | 3      | 4      | 5      | 6      | 7      |
| Barium <sup>d</sup>                 | <0.2       | 0.40   | 0.36   | 0.33   | <0.2   | <0.2   | <2     |
| Cadmium <sup>d</sup>                | <0.2       | <0.2   | <0.2   | <0.2   | <0.2   | <0.2   | <0.02  |
| Chromium (III) <sup>d</sup>         | <0.05      | 0.52   | <0.05  | <0.05  | <0.05  | <0.05  | 0.10   |
| Lead <sup>d</sup>                   | <0.2       | 1.80   | <0.2   | <0.2   | <0.2   | <0.2   | <0.2   |
| Silver <sup>d</sup>                 | <0.04      | <0.04  | <0.04  | <0.04  | <0.04  | <0.04  | <0.04  |
| Arsenic <sup>d</sup>                | <0.005     | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 |
| Selenium <sup>d</sup>               | <0.025     | <0.025 | 0.025  | 0.025  | 0.025  | 0.025  | 0.005  |
| Mercury <sup>d</sup>                | <0.005     | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 |
| 1,4 Dichlorobenzene <sup>e</sup>    | <50        | <50    | <50    | <50    | <50    | <50    | <12    |
| 2,4 Dinitrotoluene <sup>e</sup>     | <50        | <50    | <50    | <50    | <50    | <50    | <12    |
| Hexachlorobenzene <sup>e</sup>      | <50        | <50    | <50    | <50    | <50    | <50    | <12    |
| Hexachlorobutadiene <sup>e</sup>    | <50        | <50    | <50    | <50    | <50    | <50    | <12    |
| Hexachloroethane <sup>e</sup>       | <50        | <50    | <50    | <50    | <50    | <50    | <12    |
| Nitrobenzene <sup>e</sup>           | <250       | <250   | <250   | <250   | <250   | <250   | <12    |
| Pyridine <sup>e</sup>               | <120       | <120   | <120   | <120   | <120   | <120   | <60    |
| Cresylic Acid <sup>e</sup>          | <50        | <50    | <50    | <50    | <50    | <50    | <30    |
| 2-Methyl Phenol <sup>e</sup>        | <50        | <50    | <50    | <50    | <50    | <50    | <30    |
| 3-Methyl Phenol <sup>e</sup>        | <50        | <50    | <50    | <50    | <50    | <50    | <30    |
| 4-Methyl Phenol <sup>e</sup>        | <250       | <250   | <250   | <250   | <250   | <250   | <30    |
| Pentachlorophenol <sup>e</sup>      | <250       | <250   | <250   | <250   | <250   | <250   | <60    |
| 2,4,5-Trichlorophenol <sup>e</sup>  | <50        | <50    | <50    | <50    | <50    | <50    | <30    |
| 2,4,6-Trichlorophenol <sup>e</sup>  | <50        | <50    | <50    | <50    | <50    | <50    | <30    |
| Naphthalene <sup>e</sup>            | 0.49       | <0.13  | <0.13  | 0.30   | <0.13  | <0.1   | 0.25   |
| Acenaphthylene <sup>e</sup>         | <0.20      | <0.20  | <0.20  | <0.20  | <0.20  | <0.20  | <0.15  |
| Acenaphthene <sup>e</sup>           | 0.14       | <0.13  | <0.13  | <0.13  | <0.13  | <0.13  | <0.194 |
| Fluorene <sup>e</sup>               | <0.015     | <0.015 | <0.015 | <0.015 | <0.015 | <0.015 | <0.023 |
| Phenanthrene <sup>e</sup>           | <0.13      | <0.13  | <0.13  | <0.13  | <0.13  | <0.13  | <0.023 |
| Anthracene <sup>e</sup>             | <0.017     | <0.017 | <0.017 | <0.017 | <0.017 | <0.017 | <0.015 |
| Fluoranthene <sup>e</sup>           | <0.017     | <0.017 | <0.017 | <0.017 | <0.017 | <0.017 | <0.037 |
| Pyrene <sup>e</sup>                 | <0.060     | <0.060 | <0.060 | <0.060 | <0.060 | <0.060 | 0.04   |
| Benzo(A)Anthracene <sup>e</sup>     | <0.017     | <0.017 | <0.017 | <0.017 | <0.017 | <0.017 | <0.048 |
| Chrysene <sup>e</sup>               | <0.033     | <0.033 | <0.033 | <0.033 | <0.033 | <0.033 | <0.017 |
| Benzo(B)Fluoranthene <sup>e</sup>   | <0.023     | <0.023 | <0.023 | <0.023 | <0.023 | <0.023 | <0.02  |
| Benzo(K)Fluoranthene <sup>e</sup>   | <0.017     | <0.017 | <0.017 | <0.017 | 0.050  | <0.017 | <0.022 |
| Benzo(A)Pyrene <sup>e</sup>         | <0.024     | <0.024 | <0.024 | <0.024 | <0.024 | <0.024 | <0.023 |
| Dibenzo(A,H)Anthracene <sup>e</sup> | <0.068     | <0.068 | <0.068 | <0.068 | <0.068 | <0.068 | <0.018 |
| Benzo(G,H,I)Perylene <sup>e</sup>   | <0.110     | <0.110 | <0.110 | <0.110 | <0.110 | <0.110 | <0.036 |
| Indeno(1,2,3-CD)Pyrene <sup>e</sup> | <0.022     | <0.022 | <0.022 | <0.022 | <0.022 | <0.022 | <0.021 |

<sup>a</sup> Modified after Kriech (1991) of the Heritage Research Group.

<sup>b</sup> Analytical tests include US EPA Methods SW846-3350, 8080, 1311, 3510, 8310 and 3010.

<sup>c</sup> Symbol < denotes below given analytical detection limit.

<sup>d</sup> ppm = parts per million.

<sup>e</sup> ppb = parts per billion.

## VI. CONCLUSIONS

The incorporation of affected soil as an ingredient to produce a commercially viable asphaltic product is a matter of stabilization, solidification, and encapsula-

**TABLE 2**  
**Summary for Leach Test Results for Bulk Preprocessed Soil Samples and Processed Cold-Mix Asphalt via EPA and AMS<sup>a</sup>**

| Parameter<br>(EPA method)                   | Preprocessed soil sample number |       |       |        | Maximum contaminant level <sup>b</sup>   | Leach test results on Processed asphalt |
|---|---------------------------------|-------|-------|--------|--|---|
|   | EPA-1                           | EPA-2 | EPA-3 | EPA-4  |  |   |
| Total recoverable                           | 375                             | 5120  | 775   |        | No regulatory levels established   | ND <sup>c</sup>                         |
| Petroleum hydrocarbon(418.1)                |                                 |       |       |        |  |   |
| Total petroleum hydrocarbon (8015 M)        | 730                             | 1350  | 79    | 13,000 | No regulatory levels established   | ND                                      |
| Total petroleum hydrocarbon 8015 M leachate | ND                              | ND    | ND    |        | No regulatory levels established   | ND                                      |
| Semi-volatile organic compounds (8270)      |                                 |       |       |        |  |   |
| Detectable Constituents                     | 7                               | 4.9   | ND    |        | No TCLP <sup>d</sup> Regulatory Levels have been established for constituents detected by these laboratory analyses. | ND                                      |
| Acenaphthene                                | 78                              | 17.4  | 11    |        |  | ND                                      |
| Acenaphthylene                              | 56                              | 11.6  | 6     |        |  | ND                                      |
| Benzo <sup>a</sup> Anthracene               | 54                              | 15.7  | 5     |        |  | ND                                      |
| Benzo <sup>b</sup> Fluoranthene             | 79                              | 22.2  | ND    |        |  | ND                                      |
| Benzo <sup>k</sup> Fluoranthene             | 45                              | 11.0  | ND    |        |  | ND                                      |
| Benzo <sup>a</sup> Pyrene                   | 63                              | 20.3  | ND    |        |  | ND                                      |
| Benzo <sup>h,i</sup> Perylene               | 31                              | 15.5  | ND    |        |  | ND                                      |
| Chrysene                                    | 95                              | 19.7  | 11    |        |  | ND                                      |
| Fluoranthene                                | 150                             | 38.5  | 47    |        |  | ND                                      |
| Fluorene                                    | 45                              | 10.8  | 3     |        |  | ND                                      |
| Indeno (1,2,3-cd) pyrene                    | 20                              | 10.4  | ND    |        |  | ND                                      |
| 2-Methylnaphthalene                         | 5                               | 0.8   | ND    |        |  | ND                                      |
| Naphthalene                                 | 105                             | 14.1  | 8     |        |  | ND                                      |
| Phenanthrene                                | 101                             | 23.4  | 20    |        |  | ND                                      |
| Pyrene                                      | 163                             | 39.2  | 57    |        |  | ND                                      |

|                  | CAM Title 22 Metals (TTLC) <sup>a</sup> |                   |      |        | CCR Title 22 regulatory levels |                   |                  |    |
|------------------|---|-------------------|------|--------|--------------------------------|-------------------|------------------|----|
|                  | TTLC <sup>e</sup>                       | STLC <sup>f</sup> | TCLP |        | TTLC <sup>e</sup>              | STLC <sup>f</sup> | TCLP             |    |
| Antimony         | ND                                      | ND                | ND   | 720    | 500                            | 15                | NLE <sup>g</sup> | ND |
| Arsenic          | 7.9                                     | 5.9               | 2.4  | 7,000  | 500                            | 5.0               | 5.0              | ND |
| Barium           | 58.9                                    | 50.3              | 66.2 |        | 10000                          | 100               | 100              | ND |
| Beryllium        | ND                                      | ND                | ND   |        | 75                             | 0.75              | NLE              | ND |
| Cadmium          | 3.9                                     | 4.6               | 1.75 |        | 100                            | 1.0               | 1.0              | ND |
| Chromium (total) | 13.7                                    | 13.3              | 15.2 |        | 2500                           | 5                 | 5.0              | ND |
| Cobalt           | 7.9                                     | 4.75              | 4.40 |        | 8000                           | 80                | NLE              | ND |
| Copper           | 37.2                                    | 26.6              | 12.4 | 27,000 | 2500                           | 25                | NLE              | ND |
| Lead             | 35.4                                    | 80.0              | 5.35 | 450    | 1000                           | 5                 | 5.0              | ND |
| Mercury          | 1.90                                    | 1.0               | 1.80 |        | 20                             | 0.2               | 0.2              | ND |
| Molybdenum       | ND                                      | ND                | ND   |        | 3500                           | 350               | NLE              | ND |
| Nickel           | 79.6                                    | 11.2              | 7.95 |        | 2000                           | 20                | NLE              | ND |
| Selenium         | ND                                      | ND                | ND   |        | 100                            | 1                 | 1.0              | ND |
| Silver           | ND                                      | ND                | ND   |        | 500                            | 5                 | 5.0              | ND |
| Thallium         | ND                                      | ND                | ND   |        | 700                            | 7                 | NLE              | ND |
| Vanadium         | 40.5                                    | 24.0              | 22.0 |        | 2400                           | 24                | NLE              | ND |
| Zinc             | 43.3                                    | 63.4              | 31.6 |        | 5000                           | 250               | NLE              | ND |

TABLE 2 (continued)  
**Summary for Leach Test Results for Bulk Preprocessed Soil Samples and Processed Cold-Mix Asphalt via EPA and AMS<sup>a</sup>**

| Parameter<br>(EPA method)                     | Preprocessed soil sample number |         |         |       | Maximum contaminant level <sup>b</sup>                                       | Leach test<br>results on<br>Processed asphalt |
|---|---------------------------------|---------|---------|-------|--|---|
|   | EPA-1                           | EPA-2   | EPA-3   | EPA-4 |  |   |
| <b>CAM Title 22 metals (STLC)<sup>h</sup></b> |                                 |         |         |       |  |   |
|   |                                 |         |         |       | <b>CCR Title 22 regulatory levels</b>  |   |
|   |                                 |         |         |       | <b>TTLc<sup>e</sup></b>  | <b>TCLP<sup>f</sup></b>                       |
| Lead <sup>d</sup>                             |                                 | 1.86    |         |       | 1000   | 5   |
| Flashpoint; Ignitability (1010)               | >220°F                          | >220°F  | >220°F  |       | >140°F Ref: CCCR Title 22 Sec. 66261.21                                      |   |
| pH; corrosivity (9045)                        | 4.06                            | 3.75    | 3.52    |       | Less than 2 units or greater than 12.5 units Ref: CCR Title 22 Sec. 66261.22 |   |
| Cyanide; reactivity (9010)                    | 32                              | 51      | 26      |       | 250 mg/kg Ref: CalEPA DTSC Mr. Ron Piloran personal communication 11/4/92.   |   |
| Sulfide; reactivity (376.2M)                  | 60                              | 72      | 56      |       | 500 mg/kg Ref: CalEPA DSTC Mr. Ron Piloran personal communication 11/4/92    |   |
| Acute aquatic 96-h                            | 100%                            | 90%     | 90%     |       | Ref: CCR Title 22 Sec 66261.24 <sup>ab</sup>                                 |   |
| LC50 bio assay; toxicity <sup>h</sup>         | Passing                         | Passing | Passing |       |  |   |

<sup>a</sup> EPA trademark.

<sup>b</sup> Concentrations expressed as mg/kg or equivalent to parts per million unless otherwise noted.

<sup>c</sup> ND = Not detected above its respective analytical detection limit.

<sup>d</sup> TCLP = toxicity characteristic leaching procedure (CCR Title 22 Section 66261.24).

<sup>e</sup> TTLc = total threshold limit concentration (CCR Title 22 Section 66261.24).

<sup>f</sup> STLC = soluble threshold limit concentration (CCR Title 22 Section 66261.24).

<sup>g</sup> NLE = no level established. TCLP levels for this element not established by regulatory agency.

<sup>h</sup> CAM Title 22 Metals Laboratory Testing Protocol per CalEPA Waste Classification Unit Guidelines. Any element indicating a TTLc concentration of ten times the STLC Regulatory Level should be analyzed by STLC Methods. The only sample requiring STLC testing was EPA-2, for lead. No other elements were in excess of ten times STLC levels expressed as TTLc concentrations.

<sup>i</sup> CCR Title 22, Sec. 66261.24<sup>ab</sup> requires wastes to pass the 96-h aquatic toxicity testing with greater than a 50% survival rate at 500 mg/l concentration for compliance with non-hazardous criteria. Samples EPA-1, EPA-2, and EPA-3 passed with a mortality not over 10% at waste concentration of 750 mg/l, which is a higher waste concentration by 50% than that required. By CCR Title 22 definition "Acute Aquatic 96-Hour LC50 means the concentration of a substance or mixture of substances in water, in milligrams per liter, which produces death within 96-h in half of a group of at least 10 fish.

tion. Asphalt studies of road pavement properties, leaching behavior, sensitivities to moisture damage, and functional group analysis have provided information that can be used to evaluate the stability of various hydrocarbon compounds- and metals-affected soils that have been utilized as an ingredient to produce an asphaltic end product. These studies indicate that asphalted contaminated soil will be highly stable and perform adequately as a viable commercial asphaltic end product. Asphalt is structurally and chemically complex, poorly understood, and dependent on the crude petroleum source and any chemical treatment or chemical modifiers added during processing. Asphalt is comprised of a minimum of ten important functional groups whose behavior at the asphalt-aggregate interface determine the overall chemical stability of the asphalt. The thermodynamics of the functional groups for asphalt are basically unknown. In addition, no data exist that correlate leachability rates to the presence or absence of specific functional groups. This indicates that the very low permeabilities and diffusivities obviously are the greatest factors in the retention of contaminants in asphalt cements.

For the best chemical performance, the asphalt should have high contents of pyridinic, phenolic, and ketone groups, which can be achieved by selectively choosing the source material. If the situation requires special stability or redundancy, small amounts of shale oil and lime can be used as additives. Situations and conditions that favor the presence of inorganic sulfur, monovalent salts, and high-ionic-strength solutions in the asphalt should be avoided because these conditions potentially decrease the chemical stability of the asphalt cement by disrupting the functional group-aggregate bonds and increasing the overall permeability. However, these conditions are not expected in the anticipated uses of asphalt cement to fixate or stabilize, solidify, and encapsulate a variety of hydrocarbon- and metals-affected soil using EPA<sup>TM</sup> and AMS<sup>TM</sup> asphalt remedial technologies.

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