CURRENT AND PLANNED REMEDIATION DEMONSTRATION PROJECTS OF THE OKLAHOMA PLAN FOR TAR CREEK[1]

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Abstract: The Tar Creek Superfund Site is a portion of the abandoned lead and zinc mining area known as the Tri-State Mining District (OK, KS and MO) and includes approximately 104 km^2 of disturbed land surface and contaminated water resources in northeastern Oklahoma. Underground mining from the 1890s through the 1960s degraded over 1000 surface ha, and left nearly 500 km of tunnels, 165 million tons of processed mine waste materials (chat), 300 ha of tailings impoundments and over 2600 shafts and boreholes. The site was listed on the National Priorities List (NPL) in 1983 and received a Hazard Ranking System score of 58.15. Initial remediation efforts in the 1980s focused on addressing surface and ground water quality. In 1993, an Indian Health Service study demonstrated that 35% of children had blood lead levels above thresholds dangerous to human health. Since 1995, the focus has been excavation and replacement of contaminated residential soils. In 2004, the University of Oklahoma (OU) and Oklahoma Department of Environmental Quality (ODEQ) began a series of related projects to demonstrate applicable technologies and establish a longer-term remediation and restoration process. The site was divided into five "perimeter" areas where initial projects would be focused and a single core area, based loosely on watershed and community boundaries. OU is leading projects on i) construction and evaluation of a passive treatment system to address contaminated mine drainage, ii) establishment and assessment of a test road section incorporating chat into asphalt pavement and iii) remediation and restoration monitoring in support of all projects, including collection of water quality, hydrology, air quality, soil ,chat, fine tailings and meteorological data. ODEQ projects include i) mine hazard attenuation (i.e., closing open shafts and boreholes), ii) chat utilization as fill and in pavement, iii) land reclamation to productive use and iv) stream restoration. Initial projects are anticipated to be completed in 3-5 years.

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Introduction

Although often associated with mining operations in the Rocky Mountain west, significant hard rock abandoned mining problems exist in other portions of the United States. Noteworthy are the myriad difficulties associated with remediation and restoration of the Tri-State Mining District of Kansas, Missouri and Oklahoma. Ore deposits consisted of lead and zinc sulfides (galena and sphalerite) associated with cherty carbonate host rock (e.g., McKnight and Fischer 1970). Lead and zinc were extracted from the district from the mid-19th to mid-20th centuries in three major fields: Galena (Kansas), Joplin (Missouri) and Picher (Oklahoma). Peak production occurred in the mid-1920s when the mines accounted for over 55% of total U.S. zinc production. In 1925-26 alone, over $74M in lead and zinc concentrates were produced (Weidman 1932). Stewart (1986) estimated that nearly 500 million tons of material were mined in the Tri-State District from 1850 to 1970, producing almost 3 million tons of lead and nearly 12 million tons of zinc, with mean ore grades of approximately 0.6% lead and 2.4% zinc. By the late 1950s, depressed global markets resulted in the suspension of most mining operations. By the early 1970s, mining ceased. Significant post-mining problems have been identified by several authors (e.g., Playton et al. 1980, Luza 1983; McFarland and Brown 1983; McCauley et al. 1983; Dressel et al. 1986, Nairn et al. 2001) and include polluted surface and ground water, open shafts and boreholes, stability hazards and contaminated waste piles and soils.

Soon after passage of the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA or Superfund) in 1980, portions of the Tri-State District were proposed for listing on the National Priorities List (NPL). In Oklahoma, the Tar Creek Superfund Site received final listing in September 1983. The site Hazard Ranking System (HRS) score is 58.15 (EPA 1999). Sites scoring higher than 28.5 are eligible for listing on the NPL. The site encompasses approximately 104 square kilometers (Fig. 1), including the towns of North Miami, Picher, Cardin, Quapaw and Commerce and other areas of northern Ottawa County (EPA, 2004).

In Oklahoma, approximately 1,000 hectares are underlain by underground mines in all or part of 47 sections (Luza, 1983). During mining, large capacity dewatering operations pumped approximately 50,000 cubic meters of water per day from the mines (Reed et al., 1955). Upon decline and ultimately the cessation of mining, groundwater began to accumulate in the mine voids. Approximately 94 million cubic meters of contaminated water exist in underground voids. In late 1979, metal-rich waters began to discharge into Tar Creek from natural springs, bore holes and abandoned mine shafts. DeHay et al. (2003), Coffey and Nairn (2003), Iverson and Nairn (2003) and Nairn and Iverson (2004) documented substantially lesser contaminant concentrations in mine shafts, mine drainage discharges and stream waters than those occurring soon after the discharges began (Table 1). However, iron, zinc, lead and cadmium concentrations were still above National Recommended Water Quality Criteria for maintenance of aquatic communities (EPA 2002). Substantial decreases in native macroinvertebrate and fish populations in Tar Creek have been documented (Aggus et al., 1983; Iverson, 2003).

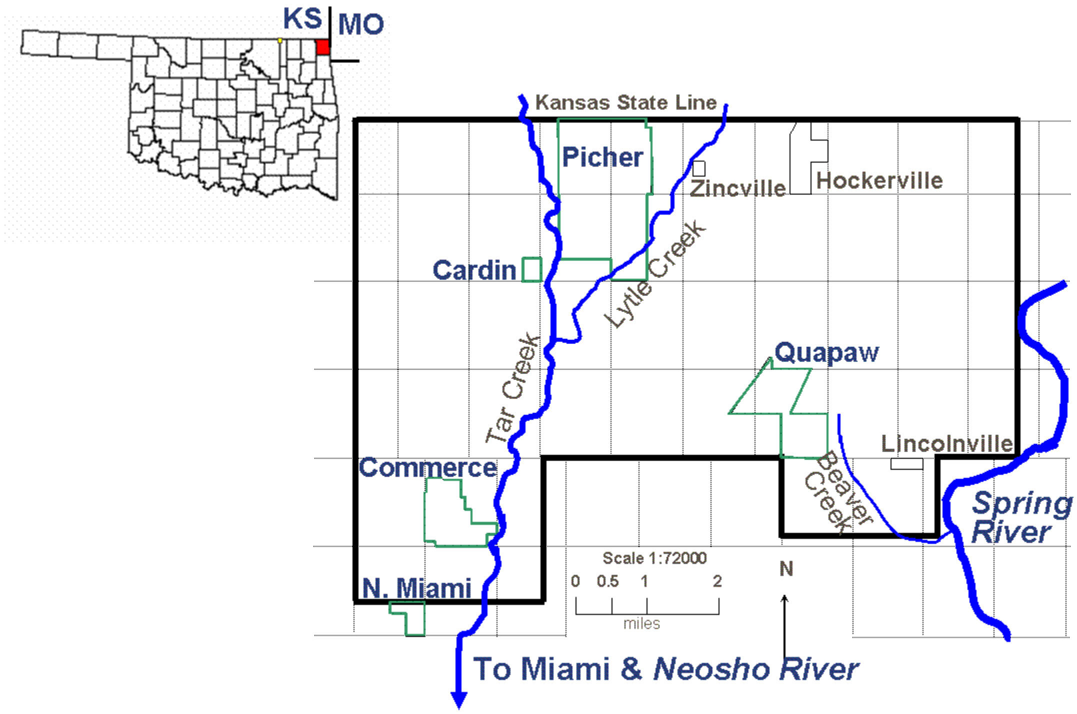


Figure 1. Schematic of the Tar Creek Superfund Site, Oklahoma; inset state map of Oklahoma shows location of Ottawa County.

Table 1. Historical comparison of water quality data collected at a single mine drainage discharge (Commerce Springs or Site 14) at the Tar Creek Superfund Site approximately five (USGS 1985) and 20 years (OU 2000) after discharge began. Values are mean ± standard deviation.

	1985	2000
pH	5.9±0.2	5.9±0.3
Alkalinity (mg/L as $CaCO_3$ eq.)	553±6	456±41
Ca (mg/L)	680±113	744±27
Mg (mg/L)	147±6	145±2
Fe (mg/L)	403±12	156±11
Zn (mg/L)	47±10	11±0.5
Cd (mg/L)	0.01±0.01	0.02±0.01
Pb (mg/L)	0.02±0.03	0.03±0.04

In addition, approximately 75 million tons of mine waste materials (known locally as chat) litter the land surface in large piles and approximately 325 hectares of flotation tailings ponds exist on site. Chat piles are characterized by a greater percentage of larger particles, while flotation tailings ponds contain a greater percentage of smaller size fractions or fines. Both the chat and tailings contain elevated concentrations of lead, zinc and cadmium (EPA, 2004 and Table 2). Datin and Cates (2003) documented that the smaller size fractions of chat (especially those particles <#40 sieve or 0.425 mm) contained greater concentrations of lead. In their study, although particles <0.425 mm represented only 20% of chat volume, they contained 50-80% of the lead mass. Recent data support this finding (Table 3). Chat pile sand flotation tailings, as well as contaminated soil, pose an exposure hazard to the local population, especially children. In 1993, an Indian Health Service (IHS) study indicated that approximately 35% of children tested in the Superfund area had blood lead levels (BLLs) greater than 10μg/dL, the amount identified by the Centers for Disease Control as being dangerous to children's health. Remediation efforts were initiated in 1995 to clean up lead-contaminated residential areas through soil removal and disposal operations (EPA, 2004). In addition, substantial public health education efforts were begun. The Agency for Toxic

Table 2. Total metals concentrations and summary statistics for bulk pile-run chat samples, demonstrating heterogeneity across 20 sampling locations at the working face of the Kenoyer North chat pile, Cardin, OK.

	Pb (mg/kg)	Zn (mg/kg)	Cd (mg/kg)
KN1	1090	12400	31.8
KN2	577	5250	9.9
KN3	472	6970	21.7
KN4	303	4300	11.5
KN5	644	8490	18.9
KN6	479	8500	24.6
KN7	343	9130	22.2
KN8	400	9500	31.9
KN9	212	4830	15.0
KN10	415	10800	28.0
KN11	488	63813	28.2
KN12	351	10800	43.3
KN13	574	14900	59.3
KN14	604	28900	169.0
KN15	404	8310	23.4
KN16	753	18400	74.0
KN17	473	7670	27.0
KN18	303	8010	25.7
KN19	368	6280	11.5
KN20	432	8237	29.0
Mean	484	12775	35.3
Median	452	8495	26.4
SD	193	13232	35.1
SE	43	2959	7.8

Table 3. Mean metal concentrations for two samples of size-fractionated chat collected from the Kenoyer North chat pile, Cardin, OK.

Sieve Size (μm)	Pb (mg/kg)	Zn (mg/kg)	Cd (mg/kg)
4750	102	975	5.5
2000	259	3260	20.6
425	408	5765	29.4
180	800	14800	63.8
75	2070	24800	55.0
<75	2995	44250	61.8

Substances and Disease Registry (ATSDR) reported in 2004 that less than 3% of children had elevated BLLs.

The Tar Creek Superfund Site represents one of the most challenging hard rock abandoned mine sites in the United States and on the NPL. Significant remediation efforts have been ongoing for over 20 years and are summarized elsewhere (e.g., Nairn et al. 2001; EPA 2004) and comprehensive strategies have been proposed (e.g., Governor's Task Force 2000).

Remediation Demonstration Projects of the Oklahoma Plan for Tar Creek

In 2004, the initial stages of the Oklahoma Plan for Tar Creek (OPTC) were implemented by a technical team led by the University of Oklahoma (OU) and Oklahoma Department of Environmental Quality (ODEQ) and in conjunction with several federal, state, local and tribal collaborators (EPW 2003). Remediation demonstration projects of the OPTC focus on perimeter watersheds outside of the Upper Tar Creek Basin (Elm Creek, Quapaw Creek, Ontario Creek, Beaver Creek and Lower Tar Creek, including the communities of Commerce, North Miami, Miami, Quapaw, Hockerville and Zincville). Beyond these projects, the plan also includes additional work to protect human health in the Upper Tar Creek Basin (including Picher and Cardin). The remediation demonstration projects focus on four objectives: a) improvement of surface water quality, b), reduction of exposure to lead dust, c) attenuation of mining hazards and d) reclamation of disturbed land. Seven initial remediation demonstration projects were identified: 1) construction and evaluation of a passive treatment system to address contaminated mine drainage; 2) establishment and assessment of a test road section incorporating maximum amounts of chat into asphalt pavement; 3) remediation and restoration monitoring in support of all projects, including collection of water quality, hydrology, air quality, soil ,chat, fine tailings and meteorological data; 4) mine hazard attenuation including closing of open shafts and boreholes; 5) chat utilization as subsidence and shaft fill material and in large-scale paving operations, 6) land reclamation to productive and practical use; and 7) stream channel restoration. OU has responsibility for projects 1-3, while ODEQ leads efforts to complete projects 4-7.

Passive treatment. Mine drainage discharges at the Tar Creek Superfund Site are characterized by elevated concentrations of metals (especially iron, zinc, lead and cadmium), mineral acidity and sulfate. However, due to the carbonate nature of the mined strata, discharges are net alkaline. Passive treatment technologies rely on natural biogeochemical and microbiological processes to ameliorate mine drainage problems, and may provide a viable and effective treatment alternative. Passive systems require less operational and maintenance labor and have lower initial costs but require larger land areas than traditional active chemical treatment systems.

The goal of this project is remediation of polluted mine drainage discharges to acceptable quality for the maintenance of the receiving water body aquatic community through design, construction and evaluation of an ecologically-engineered passive treatment system. Objectives include demonstration of improvements in mine drainage water quality prior to discharge to the receiving waters, ecosystem development in the passive treatment system itself, and documented biogeochemical and ecological recovery of the receiving waters. Mine drainage discharges in southeast Commerce, which degrade a first order unnamed tributary to Lower Tar Creek, have been identified for the initial demonstration project with work slated to begin in mid-2005. Additional discharges in the Beaver Creek watershed will be addressed in subsequent years.

Based on existing water quality and quantity data, conceptual passive treatment system designs include a sequential series of aerobic surface flow unit processes and vertical flow cells or Reducing and Alkalinity Producing Systems (RAPS). This design is necessary to i) effectively remove iron via aerobic means, concurrently removing some trace metals via sorption or co-precipitation, ii) sequester zinc, lead and cadmium via reductive mechanisms in the substrate, iii) re-aerate the water to strip hydrogen sulfide and add oxygen and iv) polish the waters (removal of remaining dissolved and suspended solids) before final discharge (Table 4 and Fig. 2).

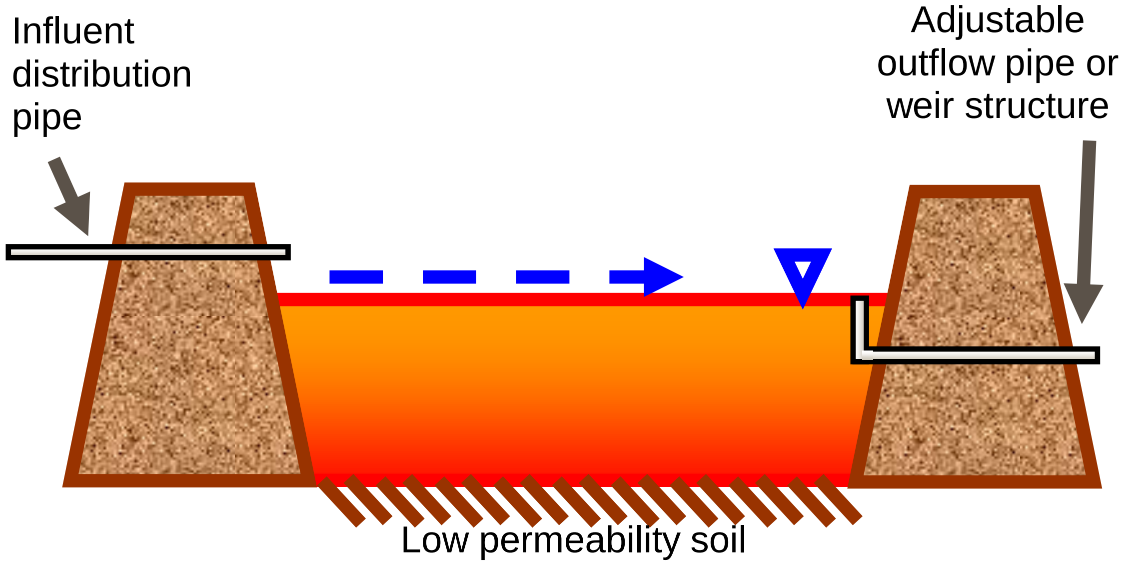
Pavement test road. Chat in its bulk form contains elevated levels of metals. Completed laboratory testing shows that encapsulation of chat in hot mix asphalt (HMA) presents an environmentally responsible and cost effective means to use this material and decrease environmental risk However, chat is traditionally size-separated and washed prior to use in asphalt, with only the larger size fractions used as aggregate. A relatively small percentage of chat is currently used in most standard asphalt applications. Recent data show that use of up to 80% and 40% pile-run chat as aggregate in Superpave HMA surface-mix and base-mix designs, respectively, meets mechanical specifications (Figure 3).

Based on the results of laboratory mix design studies completed at OU (Zaman et al. 2004), a pavement test section of road was constructed in the Elm Creek watershed in fall 2004 using raw or pile-run (not size-separated) chat. The test section incorporates 40% pile-run chat in the base course and 80% pile-run chat in the surface course. Initial mechanical tests are positive and environmental evaluation is ongoing.

Table 4. General design considerations for passive treatment of net alkaline, ferruginous, lead-zinc mine drainage at the Tar Creek Superfund Site.

Unit process	General design and function	Targeted water quality parameter
Initial oxidation ponds	Aerobic surface flow pond with passive windmill-driven aeration; iron oxidation, hydrolysis and precipitation	Fe, Oxygen
Primary vertical-flow systems	RAPS - organic material overlying limestone drainage layer with appropriate flush pipes; bacterial sulfate reduction and geochemical dissolution	Pb, Cd, Zn, Sulfate
Primary aerobic cells	Aerobic surface flow ponds; re-aeration and further oxidative metals retention	Fe, Oxygen
Secondary vertical-flow system	RAPS - organic material overlying limestone drainage layer with appropriate flush pipes; bacterial sulfate reduction and geochemical dissolution	Pb, Cd, Zn, Sulfate
Secondary aerobic cells	Aerobic surface flow ponds; re-aeration	Oxygen
Limestone cells	Sub-surface flow high quality limestone-filled cell; $ZnCO_3$ precipitation	Zn
Polishing cells	Polishing swale; final re-aeration and solids retention	Solids

a)



b)

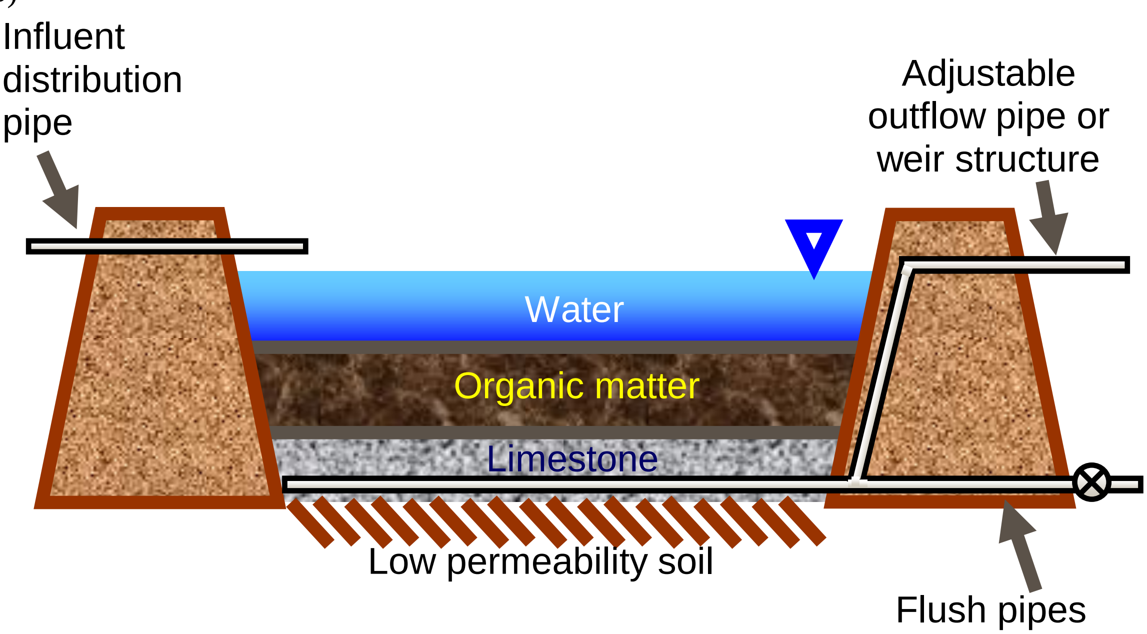


Figure 2. Generalized schematic cross-sections of a) surface-flow and b) vertical-flow cells of proposed passive treatment system. Figures are not to scale.

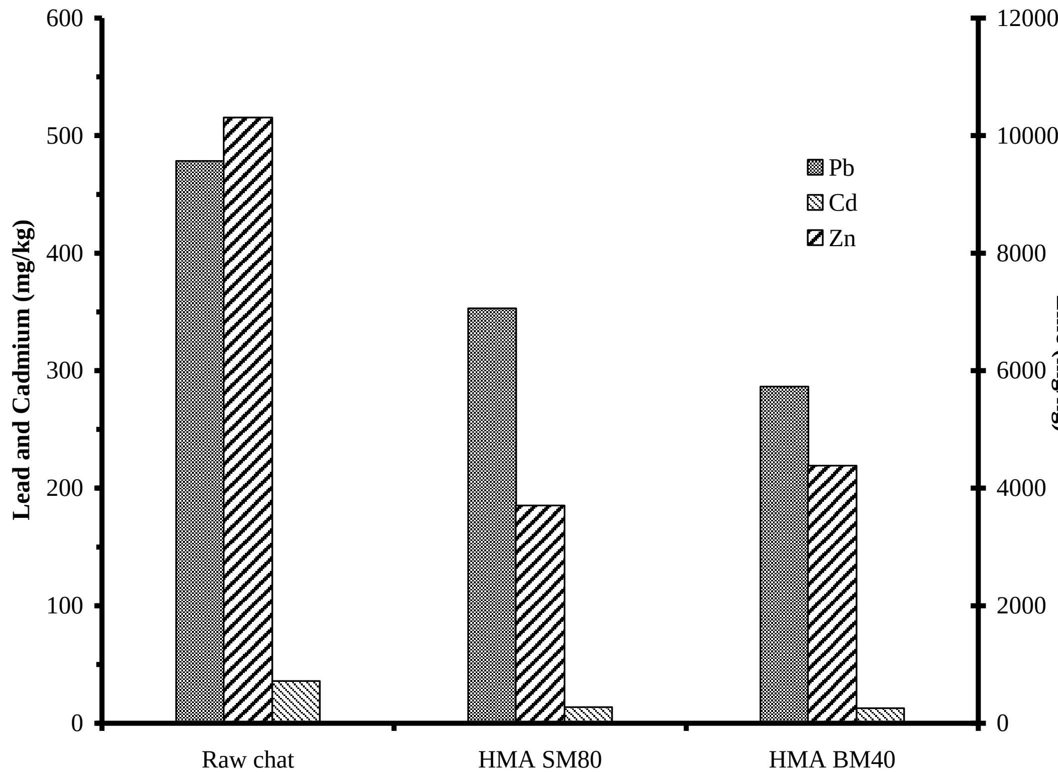


Figure 3. Mean total Pb, Cd and Zn concentrations for composite raw (pile-run) chat samples and two HMA designs.

Remediation and restoration monitoring. The Tar Creek Superfund Site is characterized by contaminated surface and ground waters, soils, mining wastes (both chat and flotation tailings) and air. Any efforts implemented to alleviate human health and ecological exposure hazards from these media require collection and analysis of adequate types and amounts of both pre- and post-implementation environmental data. Environmental monitoring is essential to ensure proper and comprehensive evaluation of remediation demonstration projects.

Baseline data collection for this project began in late summer 2004. A surface water monitoring network (both mine drainage discharges and stream sites) was established. Initial air quality and meteorological data collection began in support of the pavement test road. Three USGS stream gaging stations and one mine pool station were either re-activated or established. Collection and analysis of soils in support of the land reclamation projects are ongoing.

Mine hazard attenuation. Historical mining left substantial underground mine voids connected to the surface by thousands of vertical mine shafts and drill holes. These penetrations are immediate safety hazards. Many are in various stages of collapse, representing a danger of future subsidence. This project closes mine shafts that are open to the surface, fills subsidences, and creates more detailed maps of the undermined areas. To date, substantial effort is being expended in a subsidence abatement mapping effort. Over 30 shafts have been identified for closure and work has begun on several of them.

Chat utilization. Extensive use of chat as aggregate in road and driveway construction, concrete foundations, buildings, and even recreational facilities (i.e., sandboxes and playing fields) historically helped to spread contamination problems outside the mining area. In recent years, chat use guidelines have been established by the state. However, lead dust potentially generated by uncontrolled chat piles and chat-covered roads represents a health risk for local residents. By utilizing chat-based asphalt to pave these roads, overall volumes of chat will be reduced, lead dust generation will be suppressed, health risks will be mitigated and local transportation infrastructure improved. Chat will also be used extensively in mine hazard attenuation and land reclamation activities.

Land reclamation. Chat piles, chat bases (the material remaining after a chat pile is removed), and flotation tailings ponds pose human health and ecological risks and limit options for productive land use. Land reclamation projects under the OPTC remove chat bases and re-vegetate these features in the perimeter areas. In the Picher/Cardin area, targeted chat piles and mill ponds located close to residences are addressed. Approximately 14 acres of chat base have been removed and over 400 acres are scheduled for reclamation in 2005.

Stream channel restoration. Over time, portions of chat and other mine wastes have washed into stream channels, contributing to degradation of water quality, loss of habitat and exacerbating flooding during rainfall events. In conjunction with chat utilization and land reclamation activities, several stream channels have been identified for restoration.

Conclusions

The Tar Creek Superfund Site is one of the most challenging hard rock abandoned mine sites in the United States. Comprehensive remediation efforts require innovative solutions, due to the massive areal extent of disturbance and contamination; volumes of contaminated waters, sediments, waste materials, and soil; proximity to several communities; and inclusion of sovereign Native American lands. The remediation demonstration projects of the Oklahoma Plan for Tar Creek represent a first step toward launching comprehensive, sustainable and forward-thinking strategies for remediation of these disturbed mined lands. The long-term success of any remediation solution will depend on a solid foundation of quality science and engineering, coupled with local cooperation.

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