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SYNOPSIS Hydrologic Consultants, Inc. was contracted to undertake the closure of a former pesticide facility. While pesticide compounds were present on the site, they were located primarily in the top two feet of soil. Five remedial action alternatives for the site were reviewed; the remedial action selected was to cap the site. Because of the expense of obtaining clay in sufficient quantities, a less costly alternative to clay was adopted: a high-bitumen-content hydraulic asphalt concrete (HAC) pavement. For preliminary design purposes, a performance assessment was conducted utilizing the Hydraulic Evaluation of Landfill Performance (HELP) model to compare the relative performance of clay and asphalt capping material. The results of model simulations indicated that the asphalt pavement design with a permeability value of 10^{-8} cm/s and a cover thickness of 4 inches, would perform better than a clay cap in terms of the total annual volume of water infiltrating through the capping surface.

The results of permeability testing at the conclusion of site remediation indicated that the actual in-place cap exceeded the design requirements and was superior in performance to compacted clay. The use of chemical pathway analyses and performance modeling enabled an alternative design to be adopted, and saved approximately $500,000 over the projected cost of a compacted clay cap.

DESCRIPTION OF THE SITE AND HISTORY OF SITE INVESTIGATIONS

Hydrologic Consultants, Inc. (HCI) was contracted by Southern Pacific Transportation Company (SPTCo) in August 1988 to complete an engineering design and specifications for the remediation of the Aggie Chemical property, located approximately 2.7 miles northeast of the center of the city of San Antonio, Texas. The site is a 1.3-acre parcel that is roughly triangular in shape, and is bounded on the north by Old Seguin Road, on the east and south by Edgar Street, and on the west by private residential property (Figure 1). A little-used spur track of the Southern Pacific Railroad parallels the boundary of the site to the south, and an open grassy area lies to the southwest. Property in the vicinity of the site is currently occupied primarily by residential and light industrial structures.

Buildings that had been present on the site were demolished in 1982, so that at the commencement of remedial activities in 1989, the site consisted of an open lot covered with a dense stand of brush and undergrowth, and a few small trees (Figure 2). The parcel was level and at grade with Edgar Street and Seguin Road along its northern, eastern and southern boundaries; however, the land surface fell off steeply towards the west, down a three-foot embankment, to bordering residential property.

The property had been leased from SPTCo by Aggie Chemical Industries for a period of about 40 years, and was the former location of a facility for mixing and distributing pesticides. Pesticides were received in bulk at the facility, and were mixed into stock solutions for subsequent distribution to end users.

The first known site investigation activities were conducted by personnel of the Texas Water Commission (TWC) in 1983. Composite soil samples were collected from five locations on the property, and were analyzed for a suite of pesticide compounds, including aldrin, BHC (lindane), chlordane, DDD, DDT, dieldrin, methoxychlor, PCP, Silvex, and toxaphene. The results of analyses indicated that elevated concentrations of pesticides were present in soils at some locations on the property; the highest detected concentration of chlordane was 16,600 milligrams per kilogram (mg/kg). Accordingly, the TWC requested that SPTCo develop a plan for remediation of the property. During subsequent site investigation work, conducted during the period 1984 through 1988, surface soil samples were collected, shallow soil borings were drilled and sampled, and three monitoring wells were installed. The results of surface-soil sampling were used to assess the lateral distribution of pesticide compounds

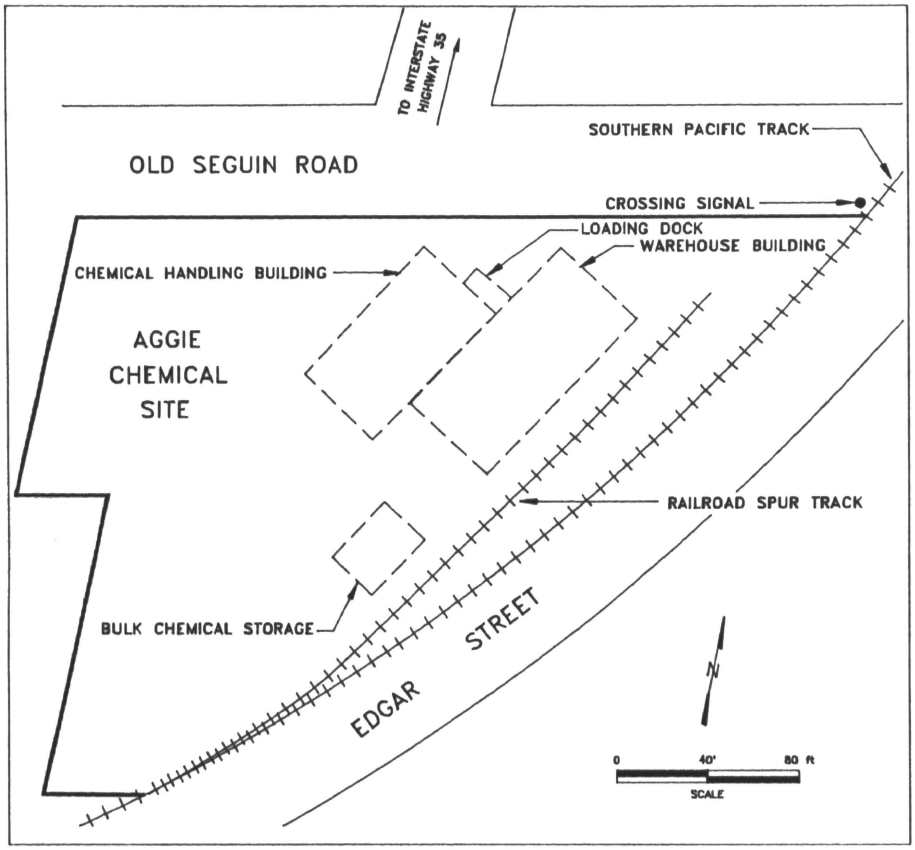

Figure 1. General Layout of the Aggie Chemical Site. Buildings were demolished in 1982, and the spur track had been removed at the commencement of remedial activities.

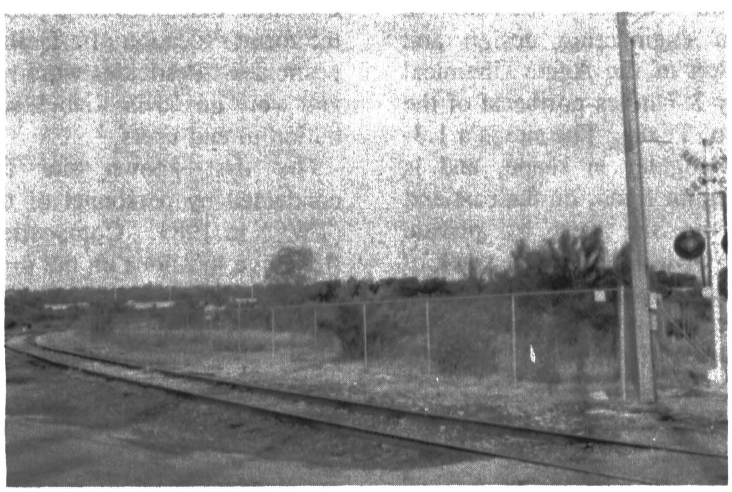

Figure 2. The Aggie Chemical Site in January 1989, Looking West

(primarily chlordane) in shallow soils on the site. The shallow soil borings were used to assess the lateral and vertical distribution of pesticide compounds at selected locations in soils beneath the site.

The sampling results suggested that while chlordane was present in surface soils on the property, soils that contained chlordane at concentrations in excess of about 150 mg/kg were restricted to the areas around the previous locations of the mix building and storage buildings, and to topographically-low areas on the site that received surface drainage (Figure 3). The results of analyses of samples collected from soil borings suggested that chlordane was probably not present in soils on the site at depths greater than about 10 feet below land surface. Furthermore, the shallow groundwater table was not encountered by the monitoring wells, indicating that ground water occurred at depths greater than 40 feet below land surface (HCI, 1991).

As a result of site investigations (HCI, 1991) it was concluded that:

- the pesticide compound of primary environmental concern on the site was chlordane;
- the bulk of pesticide compounds on the site occurred within the uppermost two feet of soil;
- the chemical properties of the pesticides rendered them relatively immobile;
- pesticide compounds on the site were probably degrading with time; and
- pesticide compounds in soils at the site probably were not adversely affecting the water resources of San Antonio.

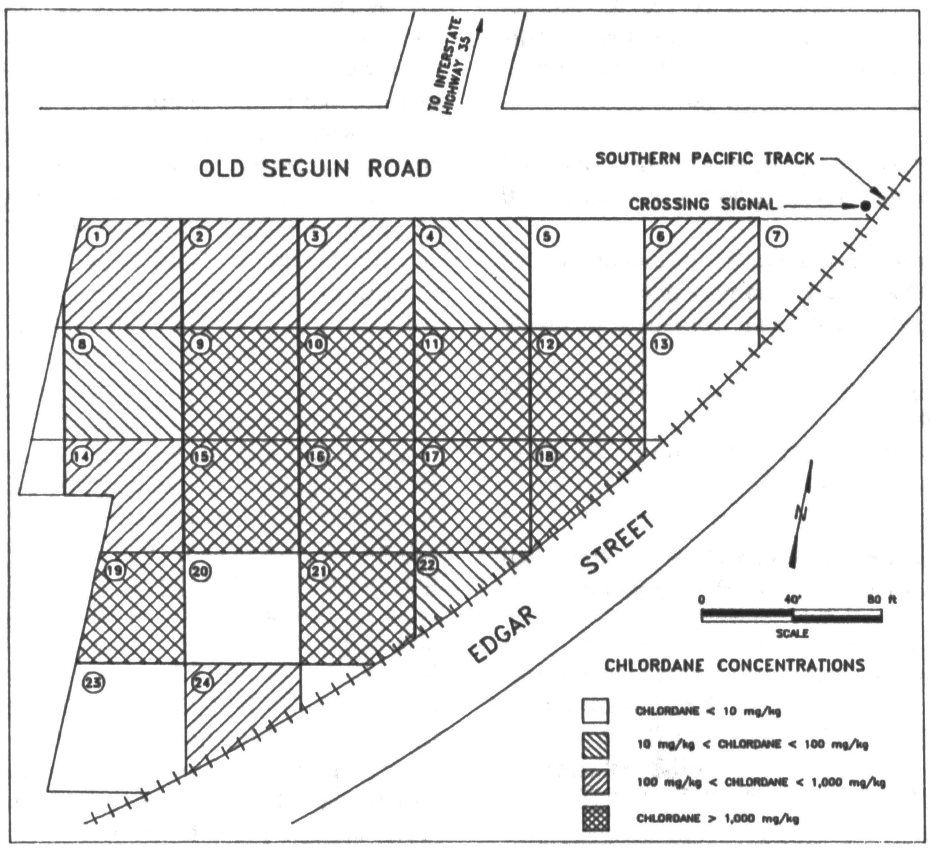

Figure 3. Approximate Distribution of Chlordane in Shallow Soils

REMEDIAL ACTION PLAN AND DEVELOPMENT OF REMEDIAL DESIGN

Following the completion of site investigation activities, it was necessary to examine and assess the data that had been collected and to use those data to develop a formal Remedial Action Plan (RAP) to address potential environmental concerns at the site. The RAP would serve to establish remediation guidelines, compare several possible remedial-action strategies, and recommend a conceptual remedial-action plan based on the comparative evaluation of remedial-action strategies. The RAP would be presented to the TWC for review; following acceptance of the document, the RAP would then be used as the basis for preparing detailed specifications for site remediation.

The potential for adverse effects to human health resulting from exposure to pesticide compounds on the site was examined using standard risk assessment techniques (U.S. EPA, 1986), and it was concluded that because pesticides in soil on the site were relatively immobile, the primary route of exposure to pesticides would be via ingestion of soil that contained pesticide compounds (S.S. Papadopulos & Associates, 1988). In light of this result, several remedial alternatives were then examined to evaluate their relative potential for application at the Aggie Chemical site. The alternatives that were evaluated included:

- no action;
- excavation and off-site disposal of soil that contained pesticide compounds at concentrations in excess of 10 mg/kg;
- excavation and on-site enhanced bioremediation of soils that contained pesticide compounds;
- on-site incineration of soils that contained pesticide compounds;
- grading the site and capping it with a low-permeability material.

The projected costs associated with each of these alternatives are presented in Table 1.

Table 1. Cost Estimates Associated with Remedial Alternatives Examined for the Aggie Chemical Site

REMEDIAL ALTERNATIVE	ESTIMATED COST (1988 dollars)
No action	--
Excavation and off-site disposal	$ 1,500,000
Excavation and on-site bioremediation	$ 2,400,000
Excavation and on-site incineration	$ 2,600,000
Grading and capping the site with 3 feet of compacted clay	$ 950,000

Upon completion of the formal evaluation of alternatives, it was concluded that the most effective and feasible option was to grade the site, install a cap of compacted clay with a perimeter fence, and monitor the site for a ten-year period (S.S. Papadopulos & Associates, 1988). The cap would serve to isolate the soils that contained pesticide compounds from human contact, and to reduce the potential for pesticide compounds to be transported from the site in surface runoff. Periodic monitoring would ensure that the integrity of the cap was regularly checked, and would allow assessments to be made of the degradation of pesticide compounds in the subsurface over time. The RAP also proposed that monitoring should cease and possible temporary deed restrictions might be relaxed once sampling evidence indicated that the concentrations of pesticide compounds on the site had declined to concentrations less than those found in typical agricultural applications.

Once the preferred conceptual remedial alternative had been identified, a closure plan could be developed in greater detail. The plan that was developed had to address requirements for remediation that were appropriate to the site, according to the waste classification that was assigned by the Hazardous and Solid Waste Division of the TWC for the soils on the Aggie Chemical site that contained pesticide compounds - Class I (industrial). The design performance criteria that would be applied by the TWC were that the site remediation, as implemented, would isolate soil materials that contained pesticides from access by humans, and that the closure design would significantly reduce the infiltration of moisture from the land surface. The essential provisions of the Technical Guidelines of the State of Texas for closure of a landfill containing Class I waste required that the site be graded, and then capped with a 3-foot thick cap of compacted clay and a one-foot layer of vegetated topsoil (31 Texas Administrative Code, §335.3 et seq.). However, during development of design specifications it became apparent that the large quantity of suitable clay that would be required (approximately 8,000 cubic yards) would not be available in the San Antonio area. We therefore examined alternative cap designs that might be capable of achieving design performance similar to the clay cap that had initially been proposed. To be considered for implementation, an alternative design had to be resistant to weathering, had to be durable, yet flexible enough to resist cracking, and had to reduce infiltration of moisture to extremely small quantities. Published information (MATRECON, 1988) indicated that a design incorporating asphalt might be capable of achieving the required performance. A series of water storage projects that had been constructed during the 1960s and 1970s had been designed using seepage barriers consisting of a high-bitumen-content asphaltic concrete (hydraulic asphalt concrete; HAC). Reviews of post-construction performance suggested that HAC was resistant to degradation, and was effective in preventing the percolation of water (Asphalt Institute, 1976; MATRECON, 1988). A sample of the HAC liner of the Luddington pumped-storage project in Michigan was therefore obtained for testing so that the hydraulic performance of the material could be assessed. Cores were taken from the liner sample, and were tested in a geotechnical laboratory to determine values for saturated hydraulic conductivity. Laboratory testing was conducted according to the protocols of ASTM D5084 (EPA Method 9100). The results of laboratory analyses indicated that the saturated hydraulic conductivity of the HAC samples was less than 5×10^{-11} centimeters per second (cm/s).

The relative effectiveness of asphalt and clay capping designs in reducing infiltration of precipitation were next evaluated using an infiltration model, the Hydraulic Evaluation of Landfill Performance (HELP) model, developed at the U.S. Army Corp. of Engineers Waterways Experiment Station (Schroeder and others, 1984a; ibid., 1984b.; ibid., 1990). The HELP model can be used to estimate the infiltration of percolating water through one (or several) soil layer(s) of specified properties. The HELP model has been extensively documented and tested (Schroeder and Peyton, 1987), and has been accepted by the U.S. Environmental Protection Agency.

Infiltration simulations were conducted using default climatologic information for San Antonio, Texas, and using soil properties corresponding to soil types that were found at the site or properties of asphalt and granular base material as they had been determined by laboratory testing (Table 2). Note that the hydraulic conductivity of the asphalt cap was conservatively assumed to be 1×10^{-8} cm/s - nearly three orders of magnitude greater than the hydraulic conductivity determined by laboratory testing.

Table 2. Properties and Characteristics of Capping Materials Used in HELP Model Simulations

	CAPPING DESIGN			
PROPERTY/ CHARACTERISTIC	**COMPACTED CLAY**		**ASPHALT CONCRETE**	
	Layer 1	Layer 2	Layer 1	Layer 2
Description	Vegetated cover	Compacted clay	Asphalt pavement	Granular base
USCS classification	SM	CH	--	GW
Thickness	12 in.	36 in.	4 in.	6 in.
Total porosity	0.453	0.430	0.030	0.318
Field capacity	0.191	0.367	0.021	0.039
Hydraulic conductivity	7×10^{-4} cm/s	1×10^{-7} cm/s	1×10^{-8} cm/s	5×10^{-4} cm/s
Peak daily infiltration	0.005 in.		< 0.0005 in.	

NOTE: Unified Soils Classification System (USCS) designations are as follows: SM - silty sand; CH - high-plasticity clay; GW - well-graded gravel.

The total mean annual infiltration or the peak daily infiltration (Table 2) through alternative cap designs was taken to represent the anticipated design performance; performance was estimated by model simulations. The anticipated design performance for a 4-inch thick asphalt cap, having a saturated hydraulic conductivity of 1×10^{-8} cm/s was estimated to be about 0.003 inches of water infiltrating per year, corresponding to a peak daily infiltration rate less than 0.0005 inches (Table 2) - considerably better performance than could be achieved with most compacted clays. An engineering design, specifying the materials and methods to be used in achieving remediation and closure of the Aggie Chemical site, and incorporating a capping surface of HAC was therefore prepared. The engineering design for remediation and closure adhered in most respects to the initial conceptual site closure plan that had been proposed in the RAP, and contained the following elements:

- Vegetation on the site would be removed and disposed at a municipal landfill, and the three existing monitoring wells would be abandoned. The site would then be graded to provide a smooth surface, incorporating controlled drainage across the site from northeast to west and southwest.
- After the site had been cleared and graded, the subgrade material (native soil) would be compacted to provide a firm foundation for installation of the pavement. Compaction specifications for the subgrade soils were developed based on the results of Proctor compaction tests.
- A compacted granular base course would then be installed over the compacted subgrade. Compaction specifications for the granular base course material were developed based on the results of Proctor compaction tests.
- A 4-inch thick surface paving course of HAC would be installed over the site, and would be covered with an asphaltic seal coat after the paving course had cured.
- A riprap drainage-control structure would be installed at the southwest corner of the site to control runoff from the southwest corner of the site, and to prevent erosion of the pavement or underlying subgrade.
- After the pavement had been completed, a fence would be installed around the perimeter to restrict access to the site.
- Three new monitoring wells would then be installed through the pavement to allow samples to be collected of the shallow ground water (if any) beneath the site.

The closure specifications required that an emulsified asphalt surface sealant would be installed on the completed pavement, to protect the pavement and reduce the hydraulic conductivity of the HAC surface course. Following completion of the HAC pavement, the asphaltic surface course was allowed to cure for a period of nine months prior to application of the specified surface sealant. The emulsified asphalt surface sealant was installed over a three-day period in June 1990. With the application of the surface sealant, remedial construction on the Aggie Chemical site had been completed as specified.

ACCEPTANCE AND PERFORMANCE SPECIFICATIONS

The compacted subgrade, base course, and HAC surface course were tested in the field as remediation proceeded, and the results of tests were compared to acceptance criteria to ensure the quality of the final constructed project. A sample of the asphalt concrete mix was collected and analyzed, and the test results were compared to the required job-mix specifications. Finally, cores were taken from the completed HAC surface course, and were tested to compare the properties of the completed pavement with specified acceptance and performance standards.

The acceptance criteria for the HAC surface course that had been established in the engineering design included:

- gradation specifications for the HAC mix;
- bitumen content for the HAC mix;
- compaction and density specifications for the completed HAC surface course;
- minimum thickness for the completed HAC surface course; and
- maximum voids for the completed HAC surface course.

A sample of the HAC mix was taken as the surface course was laid. The sample was then analyzed in the laboratory for representative design parameters (bitumen content, Marshall stability, flow, and aggregate gradation) and compared with the specified job-mix formula. The mix as supplied met or exceeded all design specifications (Table 3), except that the percentage of fine-grained aggregate (passing No. 100 and No. 200 sieves) appeared to be slightly lower than had been specified. However, the apparent divergence may be a result of removal of some of the fine-grained material from the mix sample during the laboratory bitumen-extraction process. This slight deviation from specifications was therefore neglected.

Table 3. Laboratory Test Results for HAC Mix as Supplied

Asphalt Concrete Parameter	Design Specifications	Test Results
Bitumen Content, % by weight	7.0 to 8.0	7.8
Marshall Stability, lbs	1,000 minimum	1,750
Flow	30 maximum	21
Aggregate Gradation, % by weight		
passing 3/4-inch sieve	100	100
passing 1/2-inch sieve	100	100
passing 3/8-inch sieve	86 to 100	95
passing No. 4 sieve	62 to 75	71
passing No. 8 sieve	41 to 53	46
passing No. 16 sieve	27 to 40	32
passing No. 30 sieve	21 to 31	24
passing No. 50 sieve	13 to 22	16
passing No. 100 sieve	10 to 16	7 (see text)
passing No. 200 sieve	8 to 14	5 (see text)

After the HAC surface course had been placed and compacted, the in-place field density of the HAC was measured in four locations using nuclear density methods (ASTM D2922). The field testing results were compared with the maximum laboratory density of compacted HAC, determined in the laboratory using the mix sample that had previously been collected. The test results from all four locations successfully met the specified compaction criteria of 97 percent of the laboratory maximum density (Table 4).

Table 4. Field Compaction Test Results for HAC Surface Course

Compaction Test Location	Maximum Laboratory Density (lb/ft^3)	Tested Field Density (lb/ft^3)	Relative Percent Compaction
1	146.1	142.8	97.7
2	146.1	143.5	98.2
3	146.1	143.9	98.5
4	146.1	144.2	98.7

Figure 4. The HAC Mix is Placed On the Primed Granular Base Course

Figure 5. The Completed Pavement, Looking Southwest from the Intersection of Edgar Street and Old Seguin Road

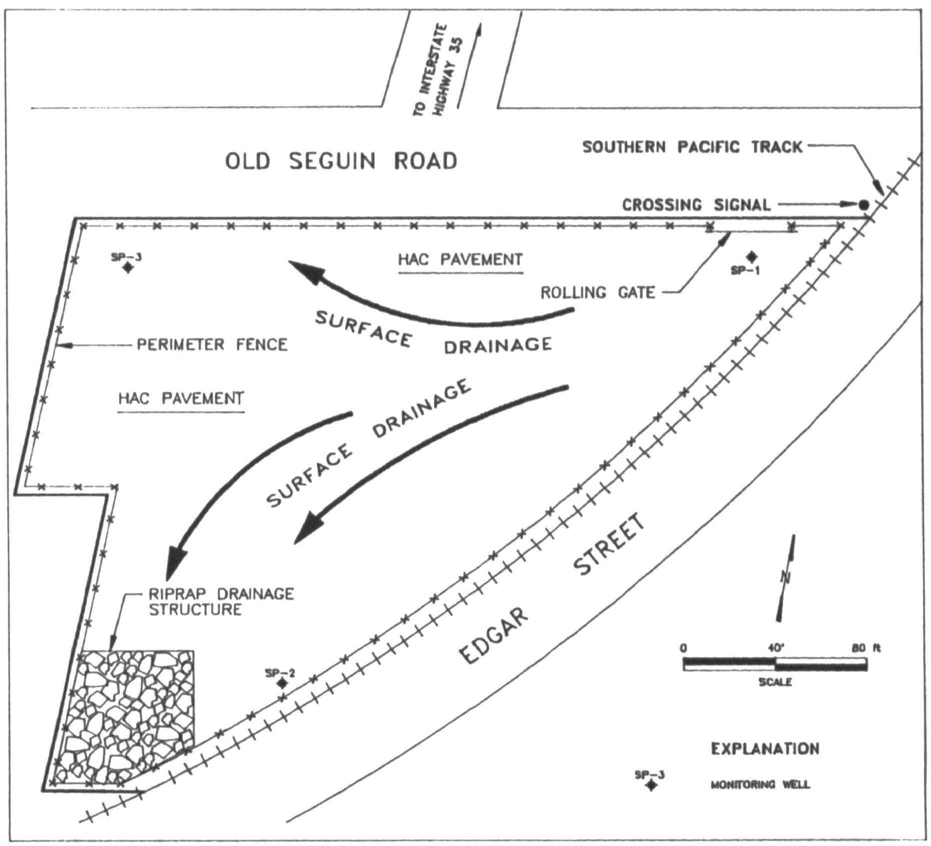

Figure 6. As-built Remedial Construction on the Aggie Chemical Site

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A sample of the HAC mix was taken as the surface course was laid. The sample was then analyzed in the laboratory for representative design parameters (bitumen content, Marshall stability, flow, and aggregate gradation) and compared with the specified job-mix formula. The mix as supplied met or exceeded all design specifications (Table 3), except that the percentage of fine-grained aggregate (passing No. 100 and No. 200 sieves) appeared to be slightly lower than had been specified. However, the apparent divergence may be a result of removal of some of the fine-grained material from the mix sample during the laboratory bitumen-extraction process. This slight deviation from specifications was therefore neglected.

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passing 1/2-inch sieve	100	100
passing 3/8-inch sieve	86 to 100	95
passing No. 4 sieve	62 to 75	71
passing No. 8 sieve	41 to 53	46
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4	146.1	144.2	98.7

Cores of nominal 8-inch diameter were removed from three locations on the HAC surface course prior to installing the three required new monitoring wells. The cores were transported to the laboratory, where core thickness and field density were measured, and the percent relative compaction and percent total voids of all three cores were determined (Table 5). The measured core thicknesses were all greater than the required 4-inch minimum, and the percent relative compaction of all three cores exceeded the specified 97 percent minimum compaction. The slight deviation of measured average percent total voids (3.1 percent) from the specified average of three percent total voids was judged to be not significant and was neglected.

Table 5. Test Results for HAC Surface Course as Installed

Core Number	Hydraulic Asphalt Concrete Property: Thickness (inches)	Field Density of Cores (lb/ft^3)	Relative Percent Compaction	Percent Total Voids
SP-1	4 1/2	144.1	98.6	2.5
SP-2	4 1/4	143.3	98.1	3.0
SP-3	4 3/4	142.2	97.3	3.8
Acceptance Specification	**4 minimum**	--	**97.0 minimum**	**3 percent average**

While acceptance specifications had been established so that the quality of the work could be monitored, the sole performance criterion required by the TWC specified a maximum hydraulic conductivity for the HAC surface course. Accordingly, after the emulsified asphalt surface sealant had been allowed to cure for ten months, cores were removed from three locations on the pavement. The cores were tested for saturated hydraulic conductivity according to the protocols established in ASTM D5084 (equivalent to EPA Method 9100): cores were placed in triaxial compression cells, were saturated, and were subjected to a constant differential pressure of one pound per square inch (1 psi; equivalent to standing water ponded to a depth of 2.3 feet on the pavement surface). The cells were closed as the constant differential pressure was maintained, and the test was continued over a period of three weeks. At the end of the test, the total volume of water that had passed through each core was measured and the corresponding hydraulic conductivity was calculated for each core.

The results of permeability testing (Table 6) indicate that the average hydraulic conductivity of the three samples is less than 5×10^{-9} cm/s, so that the required performance standard was met.

Table 6. Results of Permeability Testing for Closure Verification

CORE SAMPLE LOCATION	SATURATED HYDRAULIC CONDUCTIVITY (cm/s)
1	1.8×10^{-10}
2	5.2×10^{-10}
3	1.3×10^{-8}
Average of 3 Samples	**4.6×10^{-9}**

CONCLUSIONS

The Aggie Chemical site was officially closed in the spring of 1992, and has been declared by the TWC to be acceptable for use as a parking lot. Design performance assessment using the HELP model was sufficient to demonstrate that an innovative closure design, utilizing a high-bitumen-content asphalt pavement, could achieve the required performance. Detailed design specifications enabled the contractor to construct a high-quality paving surface, and acceptance specifications allowed the quality of the work to be monitored as remediation proceeded. Verification testing of the pavement at the conclusion of remedial construction demonstrated that the required acceptance and performance criteria had been met. The total cost of site remediation, including site investigation, preparation of a remedial action plan and engineering design, remedial construction, construction oversight, and closure verification testing, was approximately $500,000, or about $9.50 per square foot to remediate the 53,000 square foot site. This figure is considerably less than costs estimated for any of the other remedial alternatives that were considered. Furthermore, as a parking lot the property remains useful. No practical use of the property could have been realized if a clay cap had been installed.

REFERENCES

American Society for Testing and Materials (1989), "Annual Book of ASTM Standards, Vol. 4.08: Soil and Rock; Dimension Stone; Geosynthetics", American Society for Testing and Materials, Philadelphia, Pennsylvania.

Asphalt Institute (1974), "Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types", The Asphalt Institute, College Park, Maryland, MS-2.

_________ (1976), "Asphalt in Hydraulics", The Asphalt Institute, College Park, Maryland, MS-12.

Hydrologic Consultants, Inc. (1992), "Remediation and Closure of the Aggie Chemical Site, San Antonio, Texas", unpublished report submitted to the Texas Water Commission, dated January 31, 1992.

MATRECON, Inc. (1988), "Lining of Waste Impoundment and Disposal Facilities", U.S. Environmental Protection Agency, Contract No. EPA/600/2-88/052 (formerly SW-870).

Schroeder, P.R., Morgan, J.M., Walski, T.M., and A.C. Gibson (1984a), "Hydrologic Evaluation of Landfill Performance (HELP) Model: Vol. I. User's Guide for Version 1", U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, Ohio, Contract No. EPA/530-SW-84-009.

Schroeder, P.R., Gibson, A.C., and M.D. Smolen (1984b), "Hydrologic Evaluation of Landfill Performance (HELP) Model: Vol. II. Documentation for Version 1", U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, Ohio, Contract No. EPA/530-SW-84-010.

Schroeder, P.R., McEnroe, B.M., Peyton, R.L., and J.W. Sjostrom (1990), "Hydrologic Evaluation of Landfill Performance (HELP) Model: Vol. IV. Documentation for Version 2", U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, Ohio, Interagency Agreement No. DW21931-425-01-3.

Schroeder, P.R., and R.L. Peyton (1987), "Verification of the Hydrologic Evaluation of Landfill Performance (HELP) Model using Field Data", U.S. Environmental Protection Agency, Cincinnati, Ohio, Technical Resource Document EPA 600/2-87-50, 163 pp.

S.S. Papadopulos and Associates, Inc. (1988), "Remedial Action Investigation, Southern Pacific Transportation Company, Aggie Chemical Site, San Antonio, Texas", unpublished report dated March 7, 1988.

U.S. Environmental Protection Agency (1986), "Superfund Public Health Evaluation Manual", Office of Emergency and Remedial Response, U.S. Environmental Protection Agency, Contract No. EPA/540/1-86/060.