Figure 7. Areas of isolated alligator cracking.

Figure 8. Closeup of alligator cracking in isolated areas.

extensive (54 000 yd^2) lime and fly ash pavement project (10-in thick LFA base, a 3-in thick asphalt concrete surface) is documented. The structural capacity of the pavement has not decreased since construction. The pavement performance as of summer 1981 has been good. A major attribute of the LFA base course pavement was the extensive use of by-product materials (10 000 tons of fly ash, 30 000 tons of slag) in the project.

ACKNOWLEDGMENT

We wish to thank Terry Wells of CIPS and Anthony Georgeff, Superintendent of Highways for Montgomery County, for their assistance and support of this project.

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Evaluation of Heavily Loaded Cement-Stabilized Bases

S.D. TAYABJI, P. J. NUSSBAUM, AND A.T. CIOLKO

A field evaluation was carried out to determine performance of heavily loaded cement-stabilized bases. Ten projects, located in Oregon, Idaho, and British Columbia, were surveyed. Bases at six projects were used as log-sorting yards and at the other four projects as container-port storage areas. Stabilized base thickness ranged from 6 to 18 in. Cement content of the stabilized base generally varied from 5 to 8 percent. Log-sorting yards carried wheel loads that exceeded 80 kips. Wheel loads at container ports ranged from 10 to 25 kips. Performance was evaluated visually. Properties of base and subgrade materials were determined in the laboratory from samples obtained at each project site. Pavement analysis was conducted to determine stresses in the base. Also, required base thickness was computed for each site. Thickness was chosen to just sustain the estimated number of wheel loads up to the time of survey. It was found that base thickness computed from existing design procedures was generally more than as-constructed thickness. Since bases at all project sites are performing well, it is concluded that present design procedures for conventionally stabilized materials are conservative for heavily loaded high-quality cement-stabilized bases investigated in this study.

Since 1935 thousands of miles of cement-stabilized bases have been constructed. Extensive laboratory and field testing has been done on stabilized bases that meet criteria for soil-cement. These bases ranged in thicknesses from 5 to 9 in (1). Compressive strength was generally 400-500 lb•f/in² (2-4).

Very little information has been reported for stabilized bases that have thicknesses of 12 in or greater and have compressive strength in excess of 1000 lb•f/in². Information is available on limited full-scale traffic tests conducted by the U.S. Army Corps of Engineers on soil-cement pavements 21 and 25 in thick (5).

Use of high-quality thick-cement-stabilized bases has been increasing for heavily loaded facilities such as log-sorting yards, container ports, and log-haul roads. However, present methods for design of such pavements are based on extrapolations of results from laboratory testing and field evaluations of 5-9 in thick soil-cement pavements. To improve design of future heavily loaded high-quality cement-stabilized bases, a field evaluation of several such facilities was conducted. Information obtained included data on materials, design, construction, performance, and maintenance. This information was analyzed to determine the feasibility of using high-quality cement-stabilized bases for very heavily loaded roadways. The adequacy of existing thickness design procedures for such bases was also evaluated.

Table 1. Project features.

Location	Use	Thickness (in)		Base Cement Content (% by Weight)	Subgrade	
		Stabilized Base	Asphalt Surface		Type	CBR
Lynterm[a]	Container port	15.0	2.0	7	Gravelly sand	15
Vanterm[a]	Container port	18.0	1.5	8	Gravelly sand	15
Seaboard[a]	Container port	8.0	2.0	7	Gravelly sand	15
Frazer[a]	Container port	8.0	2.0	6	Sand	9
Caycuse[b]	Log-sorting yard	14.0	None	8-13	Clayey silt	6
Sweethome[c]	Log-sorting yard	12.0	3.0	5	Silty clay	2
Tomco[c]	Log-sorting yard	12.0	3.0	5	Sandy gravel	40
Bauman[c]	Log-sorting yard	12.0	3.5	5	Silty clay	5
Foster[c]	Log-sorting yard	12.0	5.0	5	Silty clay	4
Cascade[d]	Log-sorting yard	18.0	3.0	8	Gravelly sand	8

[a] Vancouver.
[b] Vancouver Island.
[c] Oregon.
[d] Idaho.

Figure 1. Representative stabilized base materials.

Table 2. Base material test data.

Location	Density (lb/ft^3)	Compressive Strength (lb·f/in^2)	Modulus of Rupture (lb·f/in^2)	Modulus of Elasticity (000 000s lb·f/in^2)
Lynterm	152	4690	630	4.2
Vanterm	148	2520	420	3.9
Seaboard	148	2120	380	2.0
Frazer	150	2900	450	2.5
Caycuse	149	4210	585	2.5
Sweethome	136	1600	320	1.3
Tomco	144	2420	484	0.7
Bauman	144	1690	338	0.6
Foster	144	2090	418	0.5
Cascade	130	1340	268	0.4

OBJECTIVE AND SCOPE

The objective of the project was to determine the feasibility of using high-quality cement-stabilized bases for facilities where very heavy loads would be applied for a limited number of applications. Objectives were accomplished by conducting field surveys of 10 facilities to obtain information on design, materials, cost, construction, loading, performance, and maintenance. Compressive strength and modulus of elasticity were determined from tests on cores taken at project sites. California bearing ratios (CBRs) were determined from tests on subgrade soils taken at project sites. An analysis was conducted to determine application of existing thickness design procedures to heavily loaded stabilized roadways.

FIELD INSPECTIONS

Field inspections were made at 10 facilities that have stabilized bases that carry heavy wheel loads.

Project Features

Project location, use, and design features are shown in Table 1. Projects were located in British Columbia, Oregon, and Idaho. Stabilized bases at these locations were used as storage areas for container ports or for log-sorting yards. The facilities were constructed between 1971 and 1980.

Lean concrete bases were used at projects in Oregon and Idaho. At Caycuse on Vancouver Island a zero-slump roller-compacted lean concrete was used. This high-quality base was selected to minimize operational surface abrasion. Excessive abrasion was anticipated at Caycuse due to operation of fork lifts that have prongs lowered for pushing logs across the yard.

Design features of thickness and cement content are listed in Table 1. Base thickness varied from 8 to 18 in. Where base thickness exceeded 12 in, base materials were placed in two or three lifts of about 6 in each. Asphalt-wearing surface thickness varied from 0 to 5 in. No asphalt was placed on the roller-compacted concrete used at Caycuse. Cement content generally varied from 5 to 8 percent. However, at Caycuse percentages as high as 13 percent were used.

Materials

Materials used at the surveyed facilities can be classified into three categories. At facilities located in the Vancouver area, roller-compacted concrete was used. At facilities in Oregon and also at some facilities in the Vancouver area, lean concrete made with crushed aggregate was used. Soil-cement bases made with gravelly sand were used in Idaho. Core specimens shown in Figure 1 illustrate texture and particle-size distribution of stabilized materials representative of those used at projects in Idaho, Oregon, and Vancouver. These specimens are from 4-in diameter cores taken at each project.

Cores were tested in the laboratory to determine compressive strength, modulus of elasticity, and density. Tests were made in accordance with ASTM C 42-77 and ASTM C 469-65. Test results are listed in Table 2. There was general correspondence between compressive strength, density, and modulus of elasticity. Largest values were obtained from Vancouver cores. The strength values are substantially higher than those usually obtained for conventional cement-stabilized materials.

Lengths of cores obtained from the Bauman project site were insufficient for determining modulus of elasticity. A modulus of elasticity value for Bauman bases was estimated based on the relation between compressive strength and modulus of elasticity obtained for cores from the other three Oregon projects.

Modulus of rupture values listed in Table 2 were computed from compressive strength. For the high-strength Vancouver bases, the relation between flexural and compressive strength for concrete shown in Neville's Figure 5.4 (6) was used to determine modulus of rupture values. Remaining values were computed by using the relation between compressive and flexural strength for soil-cement presented in Figure 14 of Felt and Abrams (7).

Subgrade samples obtained from each project were tested at Construction Technology Laboratories to determine CBRs. Tests were conducted in accordance with ASTM D 1883-73. Values obtained and soil identification are listed in Table 1.

Construction Cost Data

Costs associated with construction of stabilized bases were obtained during interviews conducted at each project site. Cost information is reported in the table below.

Location	Base Cost (cents/yd²/in of thickness)	Year Constructed
Lynterm	52	1977
Vanterm	40	1975
Seaboard	NA	1971
Frazer	NA	1972
Caycuse	58	1976
	67	1979
Sweethome	49	1976
Tomco	39	1976
Bauman	65	1980
Foster	54	1978
Cascade	38	1976

Cost varied from \$0.38 to \$0.67/yd²/in of thickness. No clear price trend is apparent because many interacting factors varied at each site. Some factors that influence cost are project size, project location, material availability, year constructed, cement content, site conditions, construction procedures, and equipment availability.

Construction

Construction equipment and procedures varied at each project. Procedures used with roller-compacted base at Caycuse are typical of projects in Vancouver. At Caycuse, a Barber-Greene continuous-flow plant was established at the aggregate stockpile about 2 miles from the log-sorting area. The mixture was produced at a rate of about 300 tons/h.

The mix was transported to the job site in dump trucks. There it was placed with a Barber-Greene SA-190 asphalt paver equipped with electronic grade control. The newly placed mix was then compacted by a Dynapac 25- to 30-ton self-propelled vibratory roller. About three passes were required to achieve specified density. A Hyster rubber-tired roller was used to tighten the surface.

At Tomco in Oregon, a central mix two-shaft pugmill plant with a vane-type cement feed was used. Belt scales measured and controlled aggregate and cement feed. Production rate of the plant was about 500 tons/h. The plant is shown in Figure 2.

Laydown equipment at Tomco was a Blaw Knox spreader on a 380 Michigan dozer. A vibratory single-drum roller with a load of 200 lb/linear in was used for compaction of 6-in-thick base lifts. About four coverages were required to achieve specified compaction. The blade of a CAT 14-E controlled from a string line was used for trimming.

Curing generally consisted of keeping exposed surfaces wet for seven days or until covered with additional lifts or surfacing. Sprinklers or water trucks were used for wetting.

Loads

Six of the projects surveyed carried wheel loads that exceeded 80 kip. These six were all log-sorting yards. A tire of the type used on log-handling equipment is shown in Figure 3. This tire is capable of carrying a load of 100 kip. At container ports, wheel loads ranged from 10 to 25 kip.

Loading details for all projects are given in Table 3. The number of axle applications listed in Table 3 was estimated from average daily operations, working days per year, and pavement age.

Performance

A subjective rating of performance was made based on visual observations of cracking, rutting, and repairs. Data obtained from performance observations are listed in Table 4. This table shows that only limited cracking, rutting, or patching were observed. All projects, with the exception of Caycuse, had an asphalt surface. Therefore, extent of base cracking is not known. However, extensive cracking that would have resulted in loss of base support would have been apparent at the asphalt surface.

Figure 2. Batch and mix plant for cement-stabilized base materials.

Figure 3. Tire for log-handling equipment.

Table 3. Loads.

Location	Axle Load (kip)	Wheel Load (kip)	Load Configuration (in)			Tire		Estimated Axle Applications (000s)
			Between Axles	Wheel Base	Between Duals	Width (in)	Area (in^2)	
Lynterm	100	25	120	100	20	15	300	45
Vanterm	56	28	66	144		13	310	350
Seaboard	40	10	100	100	13	8	130	90
Frazer	40	10	100	100	13	8	130	24
Caycuse	200	100	360	183		30	888	90
Sweethome	162	81	276	127		16	742	30
Tomco	162	81	276	127		30	742	67
Bauman	162	81	276	127		30	742	10
Foster	162	81	276	127		30	742	36
Cascade	170	85	312	127		30	850	48

Table 4. Performance indicators.

Location	Pavement Rating	Cracking Extent ($ft/100\ ft^2$)	Crack		Rutting (in)	Patching (% of Area)
			Width (in)	Spacing (ft)		
Lynterm	5.0	0.01	3/16	250	None	0.01
Vanterm	5.0	0.8	1/8-3/16	100	None	None
Seaboard	3.5	0.2	1/8-3/16	Random	3/4	0.3
Frazer	5.0	0.01	1/8-1/4	500	None	None
Caycuse	4.0	1.0	1/2	120	1/4	0.3
Sweethome	4.3		None		None	1.0
Tomco	3.8		None		None	0.25
Bauman	4.5	None	None		None	None
Foster	5.0	None	None		None	None
Cascade	5.0	1.7	3/16-1/2	60	None	None

Table 5. Maintenance.

Location	Age (years)	Repair Activity	Cost ($)	Comments
Lynterm	3.5	Patching	None	Patching at time of construction
Vanterm	5.0	None	None	
Seaboard	12.0	Additional asphalt layers near dock	3500/year	To correct settlement due to subgrade subsidence
Frazer	8.0	None	None	
Caycuse	4.0		1700 First year 5200 Second year	To replace areas damaged by fork lift prongs
Sweethome	4.0	Asphalt resurfacing	2000 Total	
Tomco	4.5	Asphalt patching	1000 Total	
Bauman	0.5	None	None	1980 construction
Foster	2.0	None	None	
Cascade	4.0	None	None	

Performance was rated on a scale of 0-5, where 4-5 is very good, 3-4 is good, and 2-3 is fair. Eight of the 10 projects were rated very good. The lowest rating of 3.5 was assigned to the pavement at Seaboard, where 0.75-in-deep rutting was observed in a localized area of subgrade subsidence.

Maintenance

Maintenance activities and costs for each project are listed in Table 5. A regular maintenance budget is established at Seaboard. Other operators indicated there has been no need to allocate maintenance funds in yearly budgets.

ANALYSIS

A thickness design procedure was used to determine required base thickness for each project surveyed. Rated wheel loads obtained from manufacturers' literature and estimated number of load applications to the time of the field survey were used for computation. Thus, theoretical base thickness is the thickness that would just sustain the estimated number of load applications. Theoretically, any more applications would result in base failure.

The design procedure used was based on concepts given by the Portland Cement Association (1). In the procedure that was used, maximum flexural stress for a given base thickness is computed for placement of interior wheel loads. A fatigue curve is used in conjunction with modulus of rupture values to determine allowable load applications. The thickness that results in allowable load applications equal to the estimated load applications is the required pavement thickness. At projects where an asphalt surface exists, base thickness was obtained by subtracting an equivalent asphalt surface thickness from the required pavement thickness. It was assumed that 1 in of asphalt surface is equivalent to 0.5 in of stabilized base.

Fatigue models are not available for good-quality stabilized base material subjected to a limited number of heavy loads. Data are available for concrete or for soil-cement material subjected to large numbers of low-magnitude load applications. Because of the high compressive-strength values obtained from cores at the sites investigated, the fatigue curve for concrete was used for design computations.

Theoretical required base thicknesses are plotted versus as-built thicknesses in Figure 4. For 8 of

Figure 4. Theoretical versus actual base thickness.

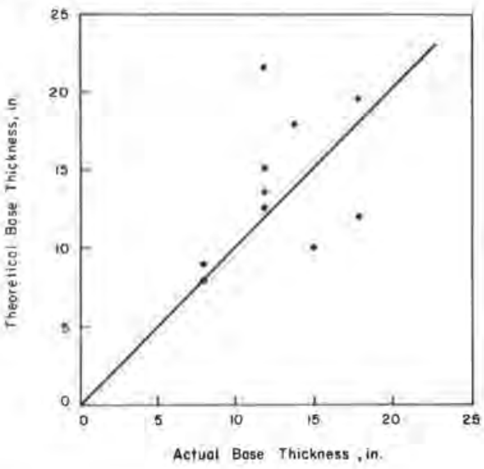


Table 6. Analysis results.

Location	Wheel Load (kip)	Base Thickness (in)	Subgrade Modulus (lb/in^3)	Maximum Deflection (in)	Maximum Stress ($lb{\cdot}f/in^2$)
Lynterm	25	15	220	0.015	237
Vanterm	28	18	220	0.007	103
Seaboard	10	8	220	0.020	359
Frazer	10	8	180	0.020	387
Caycuse	100	14	160	0.037	450
Sweethome	81	12	80	0.076	505
Tomco	81	12	420	0.037	330
Bauman	81	12	140	0.073	397
Foster	81	12	130	0.082	384
Cascade	85	18	160	0.051	205

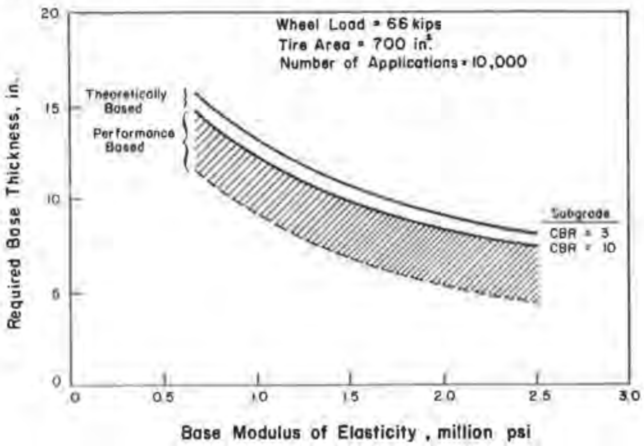
the 10 projects, as-built base thickness was equal to or less than the required computed thickness. However, stabilized bases at all surveyed sites were performing well. Computed required thickness values obtained by using a fatigue relation for soil-cement were even larger than those obtained by using a fatigue curve for concrete. Therefore, present thickness design procedures can be considered very conservative for the type of conditions encountered at the sites investigated. These conditions included heavy loadings, generally less than 100 000 load applications, and good-quality stabilized base materials.

Analysis was also conducted to determine maximum flexural stress and deflection at each project site. A finite element computer program for analysis of slab on elastic foundation was used. Pavement details, material properties, and rated single axle load placed at an interior location were used as input. Results are presented in Table 6. Maximum computed pavement deflections range from 0.007 to 0.082 in and maximum flexural stress in the base ranged from 103 to 505 $lb{\cdot}f/in^2$.

CONCLUSIONS

Survey and analysis results show that high-quality cement-stabilized bases perform well under very heavy loading. Results also indicate that present design procedures for high-quality cement-stabilized bases are very conservative. For example, theoretical design considerations would indicate that 8 of the 10 surveyed pavements should have failed. However, even though 8 pavements are thinner than required by theory, their performance was rated good to very good.

Figure 5. Thickness versus modulus of elasticity.



Optimized thickness design procedures for high-quality cement-stabilized materials can be developed if realistic performance criteria and fatigue models are available. For example, for pavements, use of initial cracking as failure criteria for fatigue loading may be too severe. Pavements continue to perform satisfactorily even after cracks have appeared. Also, there is a need to investigate the fatigue behavior of high-quality cement-stabilized base material.

Development of an optimized design procedure could result in significant cost savings. An example is shown in Figure 5. The solid lines represent design thicknesses as a function of stabilized base modulus of elasticity. The two solid lines are for subgrades that have CBR values 3 and 10. Performance-based design thicknesses are within the shaded area below the solid lines. Thus, thickness reductions of up to 3 in may provide satisfactory performance.

ACKNOWLEDGMENT

Work was performed by the Transportation Development Department of the Construction Technology Laboratories under a research contract with the U.S. Air Force. The contract was administered by TRW, Inc., and Karagozian and Case. Work was conducted under the direction of Bert E. Colley, director, Transportation Development Department and W.G. Corley, divisional director, Engineering Development Division.

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Coal Refuse and Fly Ash Compositions: Potential Highway Base-Course Materials

W.J. HEAD, P.V. McQUADE, AND R.B. ANDERSON

The necessity of using waste products in construction is becoming both evident and crucial as waste disposal continues to have a negative impact on the environment, disposal costs escalate, and traditional materials become scarce and expensive. Two by-products of the coal industry—coal refuse and fly ash—show promise for use in highway base-course applications. The already abundant supplies of these materials are expected to increase. Summarized in this paper are results of studies of the physical and engineering properties of both unstabilized and stabilized mixtures of coal refuse and fly ash. In addition, comparisons of performances of several hypothetical pavement systems are presented. The base courses of the pavements were either a crushed stone or coal refuse and fly ash mixtures. Findings indicate that stabilized coal refuse and fly ash mixtures are technically feasible base-course materials. In-service feasibility of the mixtures should be established by appropriate field testing. Unstabilized mixtures appear unsuitable for base-course applications because of questionable wet-dry and freeze-thaw durability. Both traditional substances and waste products should be considered as candidate construction materials. Technology for assessing competitive materials is available for many applications.

Waste use continues to concern engineers and others responsible for construction, environmental protection, and energy conservation. Waste products may be feasible alternatives to expensive or scarce conventional construction materials. Waste use obviates disposal problems. In addition, proper use of waste is an energy-conservation practice.

Two waste products that can be combined with appropriate stabilizing agents to yield potentially useful construction materials are coal refuse and fly ash. This paper deals with laboratory development and characterization of mixtures of these substances. Included are assessments of potential use of selected mixtures as highway base-course materials.

According to McQuade and others, (1, pp. 8-12):

> Coal mine refuse is usually comprised of clays, claystone, and/or shales which occur immediately above and below the coal or are interbedded in the coal seam itself. The exact nature of the refuse is a function of the geologic development of the coal seam....The automated [mining] equipment may extract portions of the mine floor and roof, in addition to interbedded impurities, with the coal. This results in the production of larger volumes of refuse material which are rejected in the [coal] cleaning process....Fly ash is a by-product of the coal combustion process. It is a very fine, light dust which is collected from stack gases....It is primarily comprised of rock detritus which collects in fissures of coal seams. The chemical composition of fly ash is highly variable....

Production of both coal refuse and fly ash exceeds use by huge margins. Refuse production is estimated to approach 200 000 000 tons annually (1, pp. 8-12). Most of the refuse is deposited in disposal sites. Annual production of fly ash approaches 50 000 000 tons. Approximately 8 400 000 tons were used in 1978 (2); excess ash remains in disposal sites.

The nature of both coal refuse and fly ash is complex; thus, general material characterization for design purposes is not possible. In addition, supply of these materials far exceeds demand. Consequently, significant use must at least accompany or indeed supplant disposal of the materials, given the finite extent of disposal sites and the general negative environmental impact associated with such sites. In light of these principles, the research reported here was undertaken for the following purposes: (a) to determine strength and durability characteristics of selected mixtures of coal refuse and fly ash, (b) to demonstrate that coal refuse and fly ash can be combined to yield potentially useful construction materials, and (c) to assess the feasibility of using mixtures of coal refuse and fly ash in pavement construction. The scope of the research effort was restricted to assessments of potential utility of selected mixtures as highway pavement base courses through the use of a computer-based pavement-performance-simulation program. Matters that deal with availability of refuse and ash and economic feasibility related to conventional construction materials were addressed in the research program and reported elsewhere (1, p. 8-12; 3); they are not considered here.

This paper is divided into four parts. A summary of the engineering characteristics of coal refuse and fly ash samples is presented followed by strength, durability, and environmental quality assessments of selected blends of coal refuse and fly ash. Next, the effects of various stabilizing agents on the strength and durability of the blends is presented. Finally, performances of four hypothetical highway pavements are compared with the aid of a pavement-performance-simulation program. The base courses of the pavements were a crushed stone aggregate, an unstabilized coal refuse and fly ash mixture, a lime-stabilized refuse and ash mixture, and a portland-cement-stabilized refuse and ash mixture. Base-course thicknesses, ambient temperatures, and subgrade support conditions were variables in the simulation program.

CHARACTERISTICS

Coal Refuse and Fly Ash Samples

Samples of coal refuse were obtained from 18 loca-