Cold Recycling of Failed Flexible Pavements with Cement

William H. Alcoke, E. Guy Robbins, and James E. Taylor, Jr.,
Portland Cement Association, Skokie, Illinois

Recycling of failed pavements as a means of conserving materials and saving energy and money is examined. Documentation of the use of this method dates back to the 1940s. More recent experience with in-place cold recycling with cement in several states is outlined. Two theoretical pavement projects are used to demonstrate in detail the energy and cost requirements associated with this method of pavement rehabilitation. It is concluded that strengthening the existing pavement material in place by means of cold recycling, with cement as the binder, can produce substantial savings in energy and costs.

Conservation of aggregates and energy and cost savings are possible by means of rehabilitation and reconstruction of failing or failed old flexible pavements. The reuse of existing roadbed materials and surfacing by recycling in place with cement stabilization is one of many alternatives. Considerable engineering judgment is needed to arrive at the proper rehabilitation alternative. In-place cement stabilization is one of the processes available to the highway engineer to help solve paving problems. The process is not new. Examples can be cited that date back to the 1940s. In this paper, several estimates of today's energy use and costs are presented as a guide to those concerned with energy conservation.

PAVEMENT RECYCLING

A noted highway administrator said recently, "The byword of the future is conservation—conservation of money, energy, and materials." The benefits of recycling are easily identified when the tasks required to construct a pavement are considered: obtaining sources of raw materials such as aggregates and binder, production of materials, transportation, and disposal of the old pavement. When the pavement is recycled, all of these raw materials are conserved, transportation costs are greatly reduced, and disposal of the old pavement need not be an environmental problem.

The two broad categories of recycling are (a) surface recycling, in which the objective is to improve pavement roughness and skid resistance, and (b) base and surface recycling, in which the objective is to improve the load-carrying capacity of the pavement as well as to improve surface conditions. In many cases, surface distortion, rutting, and cracking are associated with inadequate load-carrying capacity of the base. The most probable causes are insufficient base thickness, increased traffic, age, and poor drainage. The most common failure with stone-and-gravel base occurs when the subgrade is saturated and traffic loadings force wet subsoil up into the base. Aggregate interlock is then lost, and the structural capacity of the base is appreciably reduced. The problem is how to correct a pavement with a stone-and-gravel base that has been structurally weakened by soil infiltration.

ALTERNATIVES

Several means of increasing the load-carrying capacity of pavements are readily available: (a) overlaying with a substantial thickness of asphaltic concrete, (b) reconstructing by hauling out the old base and surface material and building a new pavement, and (c) strengthening the existing material by cold recycling in place with any of several binder materials and placing a new surface.

COLD RECYCLING IN PLACE WITH CEMENT

One of the oldest and best-documented stabilization binders is portland cement. Soil-cement or cement-treated base was originally developed to use inexpensive in-place or nearby borrow materials. Cement stabilization is adaptable for a wide range of materials. The process is economical because only portland cement and water are hauled to the jobsite. One of the older applications of soil-cement is in the rebuilding or reconstruction of failing granular-base roads. This is the highly successful process now called recycling.

Many references on the subject date back to the 1940s (1-6). A 1960 article (7) describes a rather small street project [20 100 m^2 (24 000 yd^2)] on which cost savings were more than $1.73/$m^2$ ($1.45/$yd^2$) as a result of using in-place cement-treated base instead of hauling out failing street material and replacing it.

In more recent years, the state of Nevada has used in-place recycling with cement to rebuild more than 800 000 m^2 (1 million yd^2) of old, failing granular-base roads (see Figure 1). Reported construction costs have ranged from $1.20/$m^2$ ($1/$yd^2$) for a 127 000-$m^2$ (152 000-yd^2) project built in 1969 to $1.65/$m^2$ ($1.38/$yd^2$) for a 1975 project that involved 14.6 km (9.1 miles) and 155 000 m^2 (186 000 yd^2). The assistant district engineer for maintenance of the Nevada Department of Highways has said, "As Nevada's supply of good, cheaply produced aggregate becomes rarer, as asphalt prices continue to escalate, maximum utilization of the aggregate in existing pavements and bases through recycling and stabilization methods could become more and more an economic imperative" (8).

In Louisiana in 1977, some 33 projects totaling 1.8 million m^2 (2.1 million yd^2) were awarded for the recycling of old and wornout granular-based asphalt roads (see Figure 2). According to Harvey D. Shaffer of the Louisiana Department of Highways (9),

> Cement stabilization of existing base and surfacing represents our most common compromise between two extremes. . . . This has proved to be a very cost-effective method of improving the rideability and structural qualities of the pavement. Other advantages over a simple overlay include [the following]:
>
> 1. The width of the riding surface can be increased . . . with only a small percentage of increase in construction cost . . . with no changes in foreslopes and ditches.
> 2. The expensive . . . procedures for removing and replacing isolated sections of road that have had base failures are not necessary . . . .
> 3. From the standpoint of environmental and energy considerations, this method is better than providing an equivalent overlay, since less new material is required.
> 4. The safety and appearance aspects are improved . . . . With a thick overlay you noticeably decrease the shoulder width as well as increase the elevation difference between riding surface and ditch.
> 5. . . . corrections in cross slope, rutting, etc., can be made in shaping the base course.

Figure 1. Breaking up old mat with a preparizer on Nevada project.

Figure 2. Soil-cement mixing on Louisiana project.

Figure 3. Old mat broken up and recycled into soil-cement on Virginia street project.

Figure 4. Reconstruction with soil-cement on Virginia street project.

Another important consideration in using thick overlay rather than recycling existing materials is the transition at bridges. Either the old base and surface have to be removed or, if the overlay is placed full depth on the bridge, the load capacity must be checked.

States that have been plagued recently with major pothole maintenance brought on by low structural base support during freeze-thaw and wet-dry cycles are examining the merit of cement-base stabilization. Because cement-stabilized bases are semirigid and have high-impermeability properties that are designed to resist wetting and freeze-thaw, they maintain uniform load-carrying capacity through all seasonal temperature changes.

The state of Virginia started using cement stabilization to rebuild old flexible streets about 14 years ago and has been active in this work ever since (see Figures 3 and 4). The Virginia Department of Highways and Transportation took bids in May 1977 for a 200 000-m^2 (237 000-yd^2) street rehabilitation project in Fairfax County. The cost of the cement-stabilized base was \$2.25/m^2 (\$1.88/yd^2). In 1978, the department awarded three small maintenance restoration projects in Fairfax, Hanover, and Augusta Counties that call for 182 000 m^2 (218 000 yd^2) of cement stabilization.

ENERGY REQUIREMENTS IN PAVEMENT CONSTRUCTION

To determine the total energy required in the construction of pavements, it is necessary to consider the energy required to produce the materials; the energy if any in the materials being used; the energy required to haul the materials from their source to the construction project; the energy in the fuel used to operate the machinery to mix, haul, spread, compact, and finish the base; the energy in the curing compound or tack coat and its application; and the energy in the surfacing material and its application.

In this paper, the total energy requirements and costs associated with the rehabilitation of two theoretical projects are compared. The first project is a highway that shows distress from age and increased traffic. The energy required to rehabilitate this highway by cold recycling in place with cement is compared with an alternative solution of providing a substantial AC overlay with some base patching and bringing the shoulder area up to grade with additional aggregate material. The second project is a failing granular-base street with curb and gutter. The energy required to cement-stabilize this street and place a new surface is compared with the energy required to haul out the old base and surface material because of grade restrictions and haul in new base and surface material.

The basic energy units used in the project calculations are as follows:

1. Work = 2.69 MJ (0.746 kW·h) (10).

Table 1. Summary of energy requirements and costs for two projects.

Project	Process	Energy (MJ/m^2)	Estimated Cost Range ($\$/m^2$)
1	Recycling existing base and surface in place with cement and placing new surface	420	3.75-5.25
	Asphalt-concrete overlay with some base patching and new shoulder material	770	5.00-7.00
2	Recycling existing base and surface in place with cement and placing new surface	400	3.90-4.80
	Hauling out old base and surface and replacing with new base and surface	590	6.80-8.40

Note: 1 MJ/m^2 = 793 Btu/yd^2; $\$1/m^2$ = $\$0.8361/yd^2$.

2. Diesel fuel = 38.7 MJ/L (139 000 Btu/gal) (11).
3. Gasoline = 34.8 MJ/L (125 000 Btu/gal) (11).
4. Cement production = 7327 MJ/Mg (6.3 million Btu/ton) (12).
5. Asphalt = 44 000 MJ/m^3 (6.636 million Btu/bbl) or 44 MJ/L (158 000 Btu/gal) (5). This does not include drilling for crude oil, at X MJ/m^3 × X dry holes = X MJ/m^3, plus X MJ/m^3 for transportation from well to refinery, at 4 percent asphaltic content = X MJ/m^3, to be added to asphalt values.
6. Diesel truck haul = 2.55 km/L (6 miles/gal) (13).
7. Asphalt concrete in place = 6.46 $MJ/(m^2/m)$ [130 000 $Btu/(yd^2/in)$] (14, 15). This includes 683 MJ/Mg (587 000 Btu/ton) for asphalt cement manufacture; 44 000 MJ/m^3 (6.636 million Btu/bbl), the

Table 2. Calculations of materials required for project 1 (highway recycling in place with cement).

Material	Calculation	Quantity
Cement	216 kg/m^3 density ÷ 1.05 = 2057 kg soil material	
	2160 - 2057 = 103 kg/m^3 cement	
	1.2 km × 6.7 m × 150 mm = 1200 m^3 × 103 =	124.2 Mg
Water	2160 kg/m^3 × 1200 m^3 × 8 percent =	208 000 L
Water for cure	8040 m^2 at 0.68 L/m^2 =	5470 L
AC	8040 m^2 × 88 kg/m^2 =	707.5 Mg
AC aggregate	8040 m^2 × 88 kg/m^2 × 95 percent =	672.1 Mg

Note: 1 kg/m^3 = 0.062 lb/ft^3; 1 kg = 2.205 lb; 1 km = 0.62 mile; 1 m = 3.28 ft; 1 mm = 0.039 in; 1 m^3 = 35.3 ft^3; 1 Mg = 1.1 tons; 1 L = 0.264 gal; 1 m^2 = 1.196 yd^2; 1 kg/m^2 = 0.2 lb/ft^2.

Table 3. Energy calculations for project 1.

Process	Calculation	Amount of Energy (MJ)
Rip by using motor grader with scarifier teeth	110 kW × 10 h × 70 percent[a] =	2 800
Pulverize with one single-transverse-shaft rotary mixer	220 kW × 10 h × 70 percent[a] =	5 500
Reshape with same motor grader		
Haul cement using six cement tankers (total)	6 × 160 km × 2 at 2.55 km/L × 38.65 MJ/L =	29 000
Cement	124 200 kg at 7.3 MJ/kg =	907 000
Mix with two rotary mixers, and water and mix	2 × 220 kW × 8 h × 70 percent[a] =	8 900
One water pump	2 kW × 3 h =	20
Two water trucks, 11 000 L each (208 000 L required), 19 round trips	19 × 3 km × 2 at 2.55 km/L × 38.65 MJ/L =	1 700
Compact and finish		
One 50-kW tamping roller	50 kW × 8 h × 70 percent[a] =	1 000
One 110-kW motor grader	110 kW × 8 h × 70 percent[a] =	2 200
One 40-kW self-propelled pneumatic-tired roller	40 kW × 8 h × 70 percent[a] =	800
One 11 000-L water truck, two round trips	2 × 3 km at 2.55 km/L × 38.65 MJ/L =	90
Cure		
One 6000-L bituminous distributor	160-km haul × 2 at 2.55 km/L × 38.65 MJ/L =	4 900
Heat and distribute	5470 L × 280 J/L =	0
Bituminous material	5470 L × 44 MJ/L =	241 000
Surface		
One rotary broom pulled by 40-kW tractor	40 kW × 4 h × 70 percent[a] =	400
Produce AC aggregate	672 Mg × 58 J/Mg =	39 000
Haul AC and aggregate to plant	707.5 Mg at 20 Mg/trip = 35 trips × 160 km × 2 at 2.55 km/L × 38.65 MJ/L =	170 000
Produce and place 38-mm AC surfacing	38 mm × 8040 m^2 × 6458 $MJ/(m^2/m)$ =	1 970 000
Total		3 384 000[b]

Note: 1 MJ = 947.8 Btu; 1 kW = 1.34 hp; 1 km = 0.62 mile; 1 L = 0.264 gal; 1 kg = 2.205 lb; 1 Mg = 1.1 tons; 1 mm = 0.039 in; 1 m^2 = 1.196 yd^2; 1 $MJ/(m^2/m)$ = 20.13 $Btu/(yd^2/in)$.

[a]Does not operate at full power all of working time.

[b]Total ÷ 8040 m^2 = 420 MJ/m^2.

Table 4. Calculations of materials required for project 1 alternative (highway patching and new AC overlay plus new shoulder and turnout gravel).

Material	Calculation	Quantity
AC	100 mm × 6.7 m × 1.2 km plus 5 percent for patching =	840 m^3
	840 m^3 × 2320 kg/m^3 =	1 940 000 kg
AC aggregate	840 m^3 × 2320 kg/m^3 × 95 percent =	1 851 000 kg
Gravel	100 mm × 2 sides × 1.2-m width × 1.2 km plus 10 percent for turnouts =	320 m^3
	320 m^3 × 2160 kg/m^3 =	691 000 kg

Note: 1 mm = 0.039 in; 1 m = 3.28 ft; 1 km = 0.62 mile; 1 m^3 = 1.308 yd^3; 1 kg/m^3 = 0.062 lb/ft^3.

Table 5. Energy calculations for project 1 alternative.

Process	Calculation	Amount of Energy (MJ)
Produce AC aggregate	1851 Mg × 58 MJ/Mg	107 000
Haul AC and aggregate to plant	1949 Mg at 20 Mg/trip = 98 trips × 160 km × 2 at 2.55 km/L × 38.65 MJ/L =	473 000
Produce and place AC concrete	840 m^3 × 6458 MJ/(m^2/m) =	5 425 000
Produce gravel	691 Mg × 58 MJ/Mg =	40 000
Haul	691 Mg at 20 Mg/trip = 35 trips × 160 km × 2 at 2.55 km/L × 38.65 MJ/L =	168 000
Place and shape with motor grader	110 kW × 10 h × 70 percent[a] =	2 800
Compact with vibratory roller	75 kW × 8 h × 70 percent[a] =	1 500
Total		6 217 000[b]

Note: 1 MJ = 947.8 Btu; 1 Mg = 1.1 tons; 1 km = 0.62 mile; 1 L = 0.264 gal; 1 m^3 = 1.308 yd^3; 1 MJ/(m^2/in) = 20.13 Btu/(yd^2/in); 1 kW = 1.34 hp.

[a]Does not operate at full power all of working time.

[b]Total ÷ 8040 m^2 = 770 MJ/m^2.

Table 6. Calculations of materials required for project 2 (recycling in place with cement on a city street with existing curb and gutter).

Material	Calculation	Quantity
Cement	2160 kg/m^3 density ÷ 1.05 = 2057 kg soil material 2160 - 2057 = 103 kg/m^3 cement 360 m × 6.7 m × 150 mm = 360 m^3 × 103 =	37 Mg
Water	2160 kg/m^3 × 360 m^3 × 8 percent =	63 m^3
Cure	2400 m^2 at 0.68 L/m^2 =	1600 L
AC	2400 m^2 × 88 kg/m^2 =	211 Mg
AC aggregate	2400 m^2 × 88 kg/m^2 × 95 percent =	201 Mg

Note: 1 kg/m^3 = 0.062 lb/ft^3; 1 kg = 2.204 lb; 1 m = 3.28 ft; 1 mm = 0.039 in; 1 m^3 = 1.308 yd^3; 1 Mg = 1.1 tons; 1 m^2 = 1.196 yd^2; 1 L = 0.264 gal; 1 kg/m^2 = 0.2 lb/ft^2.

Table 7. Energy calculations for project 2.

Process	Calculation	Amount of Energy (MJ)
Rip with motor grader with scarifier teeth	110 kW × 2 h × 70 percent[a] =	600
Pulverize with one single-transverse-shaft rotary mixer	220 kW × 4 h × 70 percent[a] =	2 200
Reshape with same motor grader		
Haul cement in two cement tankers (total)	2 × 40 km × 2 at 2.55 km/L × 38.65 MJ/L =	2 400
Cement	37 Mg at 7300 MJ/Mg	270 000
Mix with one rotary mixer, and water and mix	220 kW × 6 h × 70 percent[a] =	3 300
Two water trucks, 11 000 L each (63 000 L required), three round trips each	6 × 0.8 km × 2 at 2.55 km/L × 38.65 MJ/L	150
Compact and finish		
One 75-kW vibratory steel-wheel roller	75 kW × 6 h × 70 percent[a] =	1 100
One 110-kW motor grader	110 kW × 8 h × 70 percent[a] =	2 200
One 40-kW self-propelled pneumatic-tired roller	40 kW × 5 h × 70 percent[a] =	500
One 11 000-L water truck, two round trips	2 × 0.8 km × 2 at 2.55 km/L × 38.65 MJ/L =	50
Cure		
One 6000-L bituminous distributor	40-km haul × 2 at 2.55 km/L × 38.65 MJ/L =	1 200
Heat and distribute	1600 L × 280 J/L =	0
Bituminous material	1600 L × 44 MJ/L =	70 400
Surface		
One rotary broom pulled by 40-kW tire tractor	40 kW × 4 h × 70 percent[a] =	400
Produce AC aggregate	201 Mg × 58 MJ/Mg =	11 700
Haul AC and aggregate to plant	211 Mg at 20 Mg/trip = 10 trips × 40 km × 2 at 2.55 km/L × 38.65 MJ/L =	12 000
Produce and place 38-mm AC surfacing	38 mm × 2400 m^2 × 6458 MJ/(m^2/m) =	589 000
Total		967 000[b]

Note: 1 MJ = 947.8 Btu; 1 kW = 1.34 hp; 1 km = 0.62 mile; 1 L = 0.264 gal; 1 Mg = 1.1 tons; 1 mm = 0.039 in; 1 m^2 = 1.196 yd^2; 1 MJ/(m^2/m) = 20.13 Btu/(yd^2/in).

[a]Does not operate at full power all of working time.

[b]Total ÷ 2400 m^2 = 400 MJ/m^2.

Table 8. Calculations of materials required for project 2 alternative (removal and replacement of existing base and surface).

Material	Calculation	Quantity
Existing (removed)	215 mm thick × 6.7 m wide × 360 m long × 2080 kg/m^3 =	1079 Mg
New		
Crushed stone	140 mm thick × 6.7 m wide × 360 m long × 2160 kg/m^3 =	729 Mg
Prime	2400 m^2 × 0.68 L/m^2 =	1600 L
AC	75 mm thick × 2400 m^2 × 2320 kg/m^2 =	418 Mg
AC aggregate	418 Mg × 95 percent =	397 Mg

Note: 1 mm = 0.039 in; 1 m = 3.28 ft; 1 kg/m^3 = 0.062 lb/ft^3; 1 Mg = 1.1 tons; 1 m^2 = 1.196 yd^2; 1 L = 0.264 gal; 1 kg/m^2 = 0.2 lb/ft^2.

energy content of the material; and a haul of 0-16 km (0-10 miles) from plant to job.

8. Aggregate base in place = 2.96 MJ/(m^2/m) [5950 Btu/(yd^2/in)] (14, 15).

9. Aggregate production = 58.26 MJ/Mg (50 100 Btu/ton) (14, 15).

Table 1 gives the summary results of the calculations.

The original roadway of project 1 is an old gravel-base road 200 mm (8 in) thick and 6.7 m (22 ft) wide, with a 25-mm (1-in) surface treatment and some extensively patched areas. The project consists of rehabili-

Table 9. Energy calculations for project 2 alternative.

Process	Calculation	Amount of Energy (MJ)
Scarify and shape with motor grader	110 kW × 10 h × 70 percent[a] =	2 800
Load with skip loader	110 kW × 10 h × 70 percent[a] =	2 800
Truck haul	1079 Mg at 20 Mg/trip = 54 trips × 40 km × 2 at 2.55 km/L × 38.65 MJ/L =	65 500
Shape and reroll subgrade with vibratory roller	75 kW × 3 h × 70 percent[a] =	570
New base	2400 m^2 × 140 mm × 296 MJ/(m^2/m) =	99 500
Tack coat		
One 6000-L bituminous distributor	40-km haul × 2 at 2.55 km/L × 38.65 MJ/L =	1 200
Heat and distribute	1600 L × 280 J/L =	0
Bituminous material	1600 L × 44 MJ/L =	70 400
Produce AC aggregate	397 Mg × 58 MJ/Mg =	23 000
Haul AC and aggregate to plant	418 Mg at 20 Mg/trip = 21 trips × 40 km × 2 at 2.55 km/L × 38.65 MJ/L =	25 500
Produce and place AC surface	75 mm × 2400 m^2 × 6458 MJ/(m^2/m) =	1 162 000
Total		1 405 000[b]

Note: 1 MJ = 947.8 Btu; 1 kW = 1.34 hp; 1 Mg = 1.1 tons; 1 km = 0.62 mile; 1 L = 0.264 gal; 1 m^2 = 1.196 yd^2; 1 mm = 0.039 in; 1 MJ/(m^2/m) = 20.13 Btu/(yd^2/in).

[a]Does not operate at full power all of working time.
[b]Total ÷ 2400 m^2 = 590 MJ/m^2.

tating a 1.2-km (0.7-mile) long, 6.7-m-wide, 150-mm (6-in) thick area with soil-cement and applying a 38-mm (1.5-in) thick asphaltic concrete (AC) surface. The project area totals 8040 m^2 (9600 yd^2). The basic project requirements are given below (1 km = 0.62 mile; 1 kg/m^3 = 0.062 lb/ft^3):

Item	Quantity
Production	1.2 km/10-h day
Cement haul	160 km one way
Water haul	3 km one way
AC materials haul	160 km to plant
Cement content	5 percent by weight
Soil-cement density	2160 kg/m^3
Optimum moisture content	10 percent
Moisture in soil material	4 percent
Moisture added for evaporation	2 percent

Details of the calculations for project 1 are given in Tables 2 and 3. Calculations for the alternate solution to project 1—base patching and provision of a new 100-mm (4-in) thick overlay, a new shoulder, and turnout gravel—are given in Tables 4 and 5.

The original roadway of project 2 is an old gravel-base street with double bituminous treatment. The project consists of rehabilitating an area two blocks [360 m (1180 ft)] long, 6.7 m (22 ft) wide (face to face of gutter) with 150 mm (6 in) of soil-cement and a 38-mm (1.5-in) thick AC surface. The project area totals 2400 m^2 (2870 yd^2). The project requirements are given below (1 m = 3.3 ft; 1 km = 0.62 mile; 1 kg/m^3 = 0.062 lb/ft^3):

Item	Quantity
Production	360 m/7-h day
Cement haul	40 km one way
Water haul from city hydrant	0.8 km one way
Materials for AC	40-km haul to plant
Cement content	5 percent by weight
Soil-cement density	2160 kg/m^3
Optimum moisture content	10 percent
Moisture in soil material	4 percent
Moisture added for evaporation	2 percent

The calculations for project 2 are given in Tables 6 and 7. Calculations for the alternate solution—removal and replacement of the existing base and surface and use of a 75-mm (3-in) AC thickness on 140 mm (5.5 in) of crushed stone—are given in Tables 8 and 9.

It is interesting to note that in each case only a few items make up the major portion of the energy required and all the other items are minor in comparison. Certain assumptions must be made in any such calculations. Included in these comparisons is the energy content of asphalt, 44 000 MJ/m^3 (6.636 million Btu/bbl). This value does not include the energy required to drill for crude oil (including dry wells) or to transport it to the refinery (prorating the oil for its asphalt content). The total energy required could be considerable. The 7300 MJ/Mg (6.3 million Btu/ton) for cement includes all of the energy used in quarrying, transporting raw materials, and producing the cement at the plant.

SUMMARY

Cold recycling of failing flexible-base pavements with cement is usually undertaken when the objective is to improve pavement load-carrying capacity and surface conditions such as roughness and skid resistance. The obvious alternatives are (a) overlaying with a substantial thickness of asphaltic concrete, (b) reconstructing by hauling out and replacing the old base and surface, or (c) strengthening the existing material by cold recycling in place and placing a new surface. The examples cited in this paper illustrate the savings in energy and costs that can result from judicious use of the third alternative with cement as the binder. Such comparisons are possible only if all factors are considered.

REFERENCES

1. Extensive Program of Street Improvement Made Possible in Lowell, Massachusetts, by Soil-Cement Method of Stabilization. American City, Vol. 55, No. 1, Jan. 1940, pp. 35-37.
2. H. H. Herzog. Building Soil-Cement Road in Kenosha County (Wisc.). Public Works, Vol. 74, No. 9, Sept. 1943, pp. 14-15, 32.
3. H. H. Herzog. Kenosha County (Wisc.) Soil-Cement Sample Mile Withstands Severe Test. Western Builder, June 3, 1943.
4. Cement-Stabilized Clay in New Mexico. Public Works, Vol. 77, No. 10, Oct. 1946, p. 58.
5. Kansas Salvages Old Road Base. Soil-Cement News, No. 24, June 1947.
6. Louisiana Salvages Old Road with S/C. Soil-Cement News, No. 23, March 1947.
7. W. J. Lockman. Utilization of Old Paving Materials and Cement Treatment Saves $35 000 for City. Southwest Builder and Contractor, Vol. 135, No. 1, Jan. 8, 1960, pp. 81-83.
8. B. M. Marsh. Nevada's Experience with Cement

in Recycling Asphalt Pavements. Presented at American Road Builders' Assn. /National Assn. of County Engineers National Conference on Local Transportation, Des Moines, Aug. 26, 1975.
9. H. D. Shaffer. Reconstruction and Rehabilitation. Presented at Region 2 AASHTO Design Committee Meeting, Orlando, FL, June 1976.
10. R. G. Hudson. The Engineer's Manual. Wiley, New York, 1950, p. 327.
11. Btu Content of Materials. U. S. Bureau of Mines, news release, March 13, 1974.
12. Voluntary Industry Conservation Progress Report 5. U. S. Department of Commerce and Federal Energy Administration, July 1977.
13. Truck Energy Data. American Trucking Assns., Inc., Washington, DC, 1977, pp. 8-9.
14. Energy Conservation in Construction of Pavements. Portland Cement Assn., Skokie, IL, 1978.
15. Fuel Usage Factors for Highway Construction. HRB, Highway Research Circular 158, July 1974.

Publication of this paper sponsored by Task Force on Optimizing the Use of Materials and Energy in Construction.

Abridgment

Characteristics and Performance of Low-Quality Aggregate in an Experimental Flexible Pavement

Kamran Majidzadeh and George Ilves, Ohio State University, Columbus

As a major component of pavement structures, aggregates directly affect structural integrity and durability. Under traffic and in rigorous climatic conditions, the quality, properties, and behavior of aggregate play crucial roles in pavement performance and service life. Aggregate degradation, whether caused by chemical interactions such as moisture and freeze-thaw or mechanical causes during construction and/or traffic loading, contributes to pavement distress mechanisms. Complex interactions among load, stresses, strains, and climate, as well as how and where aggregates are used, may influence the extent of the effect of aggregate quality on pavement performance.

Assuming that high-quality materials yield better performance, it is desirable but not always feasible to use quality aggregates in pavement construction. In some regions, supplies of quality aggregate are scarce and the costs of transporting such materials are high. Many other areas have abundant local supplies of lower-quality aggregates and, in some cases, as with certain ash wastes from power plants, so-called inferior materials can be substituted in paving mixtures with little or no adverse effect on pavement performance.

These considerations have stimulated research into low-quality aggregates and their influence on pavement performance. In two such studies recently completed at Ohio State University (1, 2), the characteristics of local low-quality aggregates and their influence on the performance of flexible pavement were evaluated. The first study focused on identifying the mechanisms of aggregate degradation by means of a detailed laboratory evaluation that simulated climate and loading conditions. The second study evaluated the performance of such materials under service conditions.

AGGREGATE QUALITY AND DEGRADATION MECHANISMS

Selection of Materials

The aggregates used in these studies were acquired from local suppliers in central Ohio where the research facilities are located. First, local sources of aggregate were reviewed for the availability of materials, past performance history, and compliance with specifications. Five sources, designated plants 1 through 5, were selected to provide samples of no. 67, no. 57, and no. 8 coarse gravels and sands, which are defined as low quality by state specifications based on content of deleterious material (shale, chert, etc.). These aggregates were used in the laboratory evaluation program; comparable materials were later used to construct an experimental section of flexible pavement for field analysis and laboratory verification.

Laboratory Test Programs

To analyze the properties and performance of local low-quality aggregates, materials obtained from the five sources were subjected to test programs that included environmental simulation, moduli response, indirect tensile strength, and structural simulation of pavement response. Standard procedures were used to determine material properties. Aggregates were oven dried, sieved, and tested for sodium sulfate soundness loss and Los Angeles abrasion loss.

Aggregate quality was expressed in terms of the weight of deleterious materials retained on a 4.75-mm (no. 4) sieve rather than by weight of the total sample. Each aggregate was tested by the Ohio Department of Transportation (DOT) and Ohio State University (OSU) laboratories. The Ohio DOT laboratory used standard procedures. The OSU research team used a subjective but more stringent criterion: