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Industrial Waste Products in Pavements: Potential for Energy Conservation

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Criteria for evaluating the potential performance of industrial waste products as pavement materials are outlined. It is shown that a net energy saving is realized over a selected analysis period whenever the energy saved in the production of raw materials for a pavement that contains waste products (in comparison with a conventional pavement design) is equal to or greater than a function of the energy cost of resurfacing and the times required for both the conventional and waste-product pavements to reach a present serviceability index of 2.5. The "marginal waste product" is (a) in energy terms, that material for which the energy saved in production of raw material is just equal to the additional energy cost of resurfacing over the analysis period, and (b) in economic terms, that product for which the cost per unit of energy saved is equal to the current unit price of energy. Potentially useful industrial waste products can be ranked according to these criteria. A performance criterion for waste materials requires that data be available on which to base reasonable estimates of serviceability history. Several examples of waste products that are currently used as paving materials are discussed, and a statistical study of the compressive strength of pozzolanic concrete correlated with available data on pavement performance is examined.

Certain industrial waste products such as fly ash and blast-furnace slag have long been known to the construction industry as useful ingredients for paving mixtures and other purposes. The use of such products has generally resulted from a combination of their low cost and the high-quality products attainable. It is quite probable that such waste materials would be used in construction even in the absence of environmental or energy considerations.

Environmental enhancement has provided some incentive for greater use of industrial waste products in construction. Previous studies of the use of such waste products have generally focused on particular materials and have usually emphasized the environmental advantages of removing those materials from stockpiles. But, if any significant environmental advantage is to accrue from the use of industrial waste products, the material in question must exist in large quantities within a large geographic area. Otherwise, such environmental effects as enhancement of the landscape and pollution reduction are not sufficient to justify the expense of research and testing. The number of industrial waste products that offer real potential for environmental improvement and have properties suitable for use in construction is therefore quite limited.

Energy conservation has recently emerged as a specific consideration in the design and construction of pavement projects, and the potential of industrial waste products in relation to energy conservation has not been fully explored. The waste materials that result from essential industrial processes and that then exist in a form that makes them useful for incorporation into construction projects with little or no additional processing offer opportunities for substantial savings in the energy required to produce the raw ingredients of a paving mixture.

It is the purpose of this paper to outline criteria that could be used to evaluate the potential usefulness of industrial waste products as paving materials. The application of the criteria proposed here should make it easier to identify waste products that are usable for pavement construction and to rank such products on a quantitative scale according to the energy they save.

ENERGY CONSUMPTION IN PAVEMENT CONSTRUCTION

The energy required to construct and maintain a pavement can be summarized as follows:

$$E = M + T + C + R + A + S \quad (1)$$

where

- E = energy consumption per unit area of pavement for some analysis period in years;
- M = energy required to produce materials for a unit area of pavement;
- T = energy required to transport materials to the job;
- C = energy required to mix, place, and compact materials for a unit area of pavement;
- R = energy consumption by road users during the analysis period;
- A = energy required to construct overlay on a unit area of pavement; and
- S = energy required for maintenance of a unit area of pavement during the analysis period.

Subscripts c and w are used in the following discussion to denote terms in Equation 1 associated, respectively, with conventional materials and waste materials. If it is then assumed that the energy expenditures for transportation of material, mixing, placing, compacting, and maintenance are about equal for all

Figure 1. Vehicle operating costs on conventional pavement.

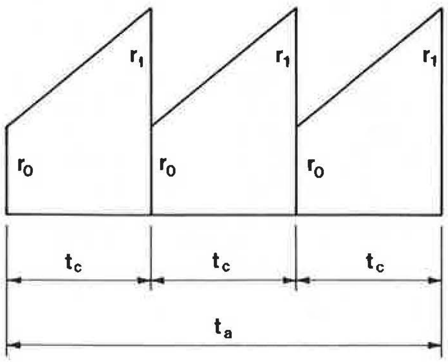
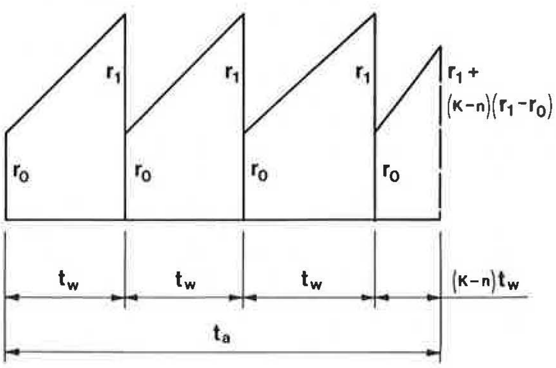


Figure 2. Vehicle operating costs on pavement that contains one or more waste materials.



types of pavement materials, Equation 1 becomes

$$(E_c - E_w) = (M_c - M_w) - (A_w - A_c) - (R_w - R_c) \quad (2)$$

The assumption that $T_c - T_w = 0$ is justified if two alternative designs are being considered that would originate from the same mixing plant, whether conventional or waste materials were used, and if sources of the respective materials are about equidistant. Significant differences in haul distance would require that the term $(T_c - T_w)$ be considered in computing energy costs.

ENERGY COST OF VEHICLE OPERATION

Haas and Hudson (1) have analyzed data from other sources and have concluded that the relation between pavement serviceability and average vehicle operating cost is reasonably approximated by a linear function. Translation of dollar costs into units of energy consumption should not significantly alter the linear relation as far as the problem under discussion is concerned as long as running speed remains constant.

Consider, therefore, a pavement constructed of conventional materials that requires a period of t_c years to reach a present serviceability index (PSI) of 2.5. In view of the approximate nature of the cost-serviceability relation, it is considered sufficient for the problem at hand to represent the serviceability history curve as a linear function also. Vehicle operating costs (in energy units) are therefore as shown in Figure 1. When the pavement is new and immediately after each resurfacing, vehicle operating cost is r_0 joules per vehicle kilometer. But after t_c years following construction and each subsequent overlay, the PSI has fallen to 2.5 and vehicle operating cost has risen to r_1 joules per vehicle kilometer.

If the analysis period of t_a years is taken to be an integral multiple of the resurfacing cycle time t_c, it is clear from Figure 1 that the average vehicle operating cost during the analysis period is

$$r_c = (r_0 + r_1)/2 \quad (3)$$

Now consider a pavement constructed by using one or more waste products, which requires a period of t_w years to reach a PSI of 2.5. Consider that $t_w < t_c$. Figure 2 shows the resurfacing cycle times and the analysis period t_a. Let n be the number of overlays placed during the analysis period and $K = t_a/t_w$. It can then be seen from Figure 2 that the average vehicle operating cost in this case is given by

$$r_w = 1/t_a\,[n \cdot (r_0 + r_1)/2\; t_w + 2r_0 + (K - n)(r_1 - r_0)/2 \cdot (K - n)t_w] \quad (4)$$

Equation 4 can be reduced to

$$r_w = (r_0/2K)\,[n + 2(K - n) - (K - n)^2] + (r_1/2K)\,[n + (K - n)^2] \quad (5)$$

The difference in the average energy cost of vehicle operation can thus be shown to be

$$r_w - r_c = \{[(K - n)^2 - (K - n)]/K\} \cdot [(r_1 - r_0)/2] \quad (6)$$

Since $(K - n) < 1$, it is clear from Equation 6 that $(r_w - r_c)$ is comparatively small in magnitude. But it also follows from Equation 6 and from the fact that $(K - n) < 1$ that $(r_w - r_c)$ is strictly negative.

The foregoing analysis depends, of course, on the assumption that overlays will be provided at the appropriate times and that such overlays will restore the PSI to a level approximately that of a new pavement. In view of the comparatively small magnitude of $(r_w - r_c)$ as given by Equation 6, it will be on the safe side to take account of the approximate nature of the analysis by concluding that

$$r_w - r_c \approx 0 \quad (7)$$

It therefore follows for a given traffic volume that

$$R_w - R_c \approx 0 \quad (8)$$

where R_w and R_c = the total energy expenditures by road users during the analysis period on the two respective types of pavement.

ENERGY COST OF RESURFACING

In the foreseeable future, it does not appear that a material will be available to take the place of asphalt as a binder for resurfacing courses. Consequently, the energy cost of an asphaltic concrete overlay (in joules per kilometer) will be the same for all types of pavements of a given width. Let a represent this unit energy cost of resurfacing. For a given thickness of overlay, a is constant; it then follows immediately that

$$A_w - A_c = an - a(t_a/t_c) = a[n - (t_a/t_c)] \quad (9)$$

where

A_w = resurfacing cost per kilometer in energy units for a pavement constructed with one or more waste materials over analysis period t_a years,

A_c = resurfacing cost per kilometer in energy units for a conventional pavement over analysis period t_a,

n = number of overlays required during t_a for a pavement constructed with one or more waste materials, and

t_c = period of years required for conventional pavement to reach a PSI of 2.5 after construction or overlay.

ENERGY CRITERION FOR SELECTION OF WASTE MATERIALS

Combining Equations 2, 8, and 9 gives

$$E_c - E_w = (M_c - M_w) - (A_w - A_c) = (M_c - M_w) - a[n - (t_a/t_c)] \quad (10)$$

Thus, a net saving in energy results from the use of waste products if

$$M_c - M_w \geq a[n - (t_a/t_c)] \quad (11)$$

Equation 11 can form the basis of a quantitative definition of the "marginal waste product" in terms of energy consumption and pavement performance. In those terms, the marginal waste product is that material for which the energy saved in raw material production is just equal to the additional cost of resurfacing over a selected analysis period.

For example, Wells (2) found that digested domestic wastewater sludge could be used in lieu of some fine aggregate or mineral filler in bituminous concrete and produce satisfactory results in terms of Marshall stability and air void content. But the biological stability of the dried sludge can only be ensured by heating it to 141°C (285°F) and premixing the sludge with hot asphalt cement before the binder is added to the hot aggregate.

An energy analysis of the use of digested wastewater sludge can be computed by using data developed by Barenberg and Thompson (3). The energy values used in the following discussion are based on the work of Barenberg and Thompson for typical job conditions but are for illustrative purposes only. Wells (2) showed that sludge solids could be incorporated into bituminous concrete to about 3 percent of the dry weight of aggregate. Since the digested sludge is a by-product, the energy required to make it available for pavement construction is essentially zero. If, then, the energy required to produce 0.9 Mg (1 ton) of aggregate for bituminous concrete is about 73.9 MJ (70 000 Btu), the gross energy saved by substituting 3 percent wastewater sludge should be about 2.44 MJ/Mg (2100 Btu/ton).

Let us consider only this gross energy saving for the moment and suppose that the sludge is to be evaluated for use in a 7.6-cm (3-in) thick bituminous concrete course that has a compacted density of 2307 kg/m^3 (144 lb/ft^3). Gross energy saving per unit area can thus be expressed as $M_c - M_w = (0.076)(2307)(2.44) = 0.429$ MJ/m^2 (340 Btu/yd^2). From data given by Barenberg and Thompson (3), the energy cost of a conventional bituminous concrete overlay 3.8 cm (1.5 in) thick is about 41.6 MJ/m^2 (33 000 Btu/yd^2). Application of Equation 11 then gives

$$M_c - M_w = 0.429 \geq 41.6[n - (t_a/t_c)] \quad (12)$$

or $[n - (t_a/t_c)] \leq 0.01$. Equation 12 indicates that digested wastewater sludge is a submarginal material for the application being considered unless bituminous concrete made with this waste material can serve just as long as conventional bituminous concrete before requiring an overlay $[n \approx (t_a/t_c)]$.

When the energy required for biological stabilization of wastewater sludge is included in the calculation, the value of $(M_c - M_w)$ becomes negative. In this case, the sludge is worthy of consideration in a paving application only if it provides substantially better service than conventional bituminous concrete—an unlikely condition.

Let us turn now to a hypothetical example at the other extreme. It is not likely that a material would be considered on nonenergy grounds for use in a pavement if that material resulted in a pavement that required resurfacing twice as often as its conventionally constructed counterpart. But, if energy conservation is taken into account, the following expression results from Equation 11:

$$M_c - M_w \geq 41.6 \cdot (t_a/t_c) \quad (13)$$

If the conventional pavement is resurfaced twice during an analysis period of 40 years, the minimum required energy saving for the hypothetical waste material to achieve marginality from the energy standpoint is about 83.2 MJ/m^2 (65 900 Btu/yd^2). An energy saving of this magnitude seems well beyond any saving potentially available, given the present state of the art.

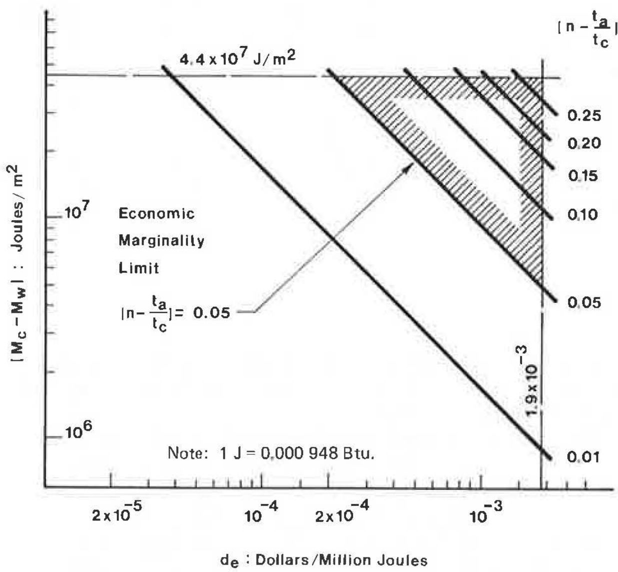
Hughes and Haliburton (4) investigated the use of zinc smelter waste as an aggregate component in bituminous concrete mixtures. The smelter waste required crushing and sorting or the addition of fine sand to meet specified gradation requirements so some expenditure of energy is required to prepare this waste material for use. According to Hughes and Haliburton (4), the highest proportion of fine sand added was 50 percent. If we use the data developed in a previous example, the gross energy saving that results from use of the zinc smelter waste can be estimated at about 50 percent of the energy expended in preparation of conventional aggregate, or about 40.7 MJ/Mg (35 000 Btu/ton).

For a 7.6-cm (3-in) thick bituminous concrete course with a compacted density of 2162 kg/m^3 (135 lb/ft^3), gross energy saving per unit area would be $M_c - M_w = (0.076)(2162)(40.7) = 6.69$ MJ/m^2 (5300 Btu/yd^2). If zinc smelter waste is to be at least marginal on an energy basis, Equation 11 (with a = 41.6) shows that the factor $[n - (t_a/t_c)]$ cannot exceed 6.69/41.6, or about 0.16. That is, bituminous concrete made with zinc smelter waste must be sufficiently serviceable to require resurfacing at intervals of not less than about 18.5 years if the corresponding period for conventional bituminous concrete is 20 years.

The examples presented here pertain to asphaltic concrete, but it should not be inferred from these illustrations that industrial waste products are potentially useful only in asphaltic mixtures. Furthermore, the examples have been selected to demonstrate a range in energy cost and are not intended to imply that a wide range of products can be used in asphaltic mixtures.

The foregoing examples tend to show that substitutions of waste products for conventional pavement construction materials are feasible from an energy standpoint only over a limited range of pavement performance. The zinc smelter waste may not be at the upper limit of this range, but it is difficult to conceive of a waste product or a combination of products so energy conserving that the factor $[n - (t_a/t_c)]$ could exceed about 0.25. In other words, for an analysis period of 40 years, it does not seem feasible to look for potential use of waste products as a pavement ingredient if the average frequency of resurfacing of such a pavement is expected to be more than once in 18 years compared with a standard

Figure 3. Cost of energy saved by use of waste products in pavement.



of once in 20 years. As the frequency of resurfacing of conventional pavements increases, the performance requirements for a waste material become more severe. For example, if $n - (t_a/t_c) = 0.16$, $t_c = 5$ years, and the analysis period $t_a = 40$ years, the marginal waste product must provide 4.9 years of service between overlays.

ECONOMIC CONSIDERATIONS

If the unit cost (present value) of an overlay is d dollars, the additional cost of a pavement in which one or more waste materials are used can be determined from the following equation, in terms of dollars per energy unit saved, in comparison with a conventional pavement:

$$d_e = d[n - (t_a/t_c)]/(M_c - M_w) \tag{14}$$

where d_e equals the cost per energy unit saved by the use of one or more waste products, which increase the required number of overlays per analysis period t_a from t_a/t_c to n.

The marginal waste product in economic terms can then be defined as that product that provides energy savings and pavement performance so that d_e is just equal to the current unit price of energy. Figure 3 shows the relation between d_e and $(M_c - M_w)$ for a unit cost of overlay equal to \$3.40/m^2 (\$2.84/yd^2). The current unit cost of energy, which is shown in Figure 3, has been estimated from the bulk rate for natural gas in Ohio and a heating value of 37.3 MJ/m^3 (1000 Btu/ft^3). The approximate bulk price of natural gas was estimated at \$0.071/m^3 (\$2/1000 ft^3). The values of the factor d in Equation 14 were computed by adding the present values of future overlays on the basis of a 40-year analysis period, 20 years between overlays for conventional pavement, and an interest rate of 10 percent.

Figure 3 also shows the approximate energy per unit area of pavement required to manufacture the material for a crushed aggregate layer that is 25.4 cm (10 in) thick: 44 MJ/m^2 (3870 Btu/ft^2). This value represents an upper bound on the energy saving for a 25.4-cm thick layer, since it implies the total substitution of waste material for conventional aggregate. The area in Figure 3 below this upper bound and to the left of the line that represents the current unit price of energy thus constitutes the "economic feasibility space" for the use of waste materials for the purpose of energy conservation.

It can be seen in Figure 3 that this economic criterion further narrows the practical range of the acceptable characteristics of waste materials for paving purposes. Materials that offer potential pavement performance as poor as that associated with $n - (t_a/t_c) = 0.25$ must provide a minimum energy saving of 34 MJ/m^2 (3000 Btu/ft^2) to meet the test of economic marginality, whereas materials that offer performance almost as good as that of conventional pavement [$n - (t_a/t_c) = 0.01$ or 0.05] can still be attractive from the economic standpoint if they offer only one-tenth as much energy savings.

MATERIALS REQUIREMENTS OR ENERGY CONSERVATION

The foregoing analysis provides some guidelines for a search for industrial waste products that are potentially useful for pavement construction. Although it is clear that materials that are capable of performing nearly as well as conventional materials are very much to be preferred, the field of potentially useful materials is not so narrow as it might seem at first glance.

First of all, if energy conservation and not environmental enhancement is the motivation for using waste products, it is not necessary that the materials in question be available in massive quantities over a wide geographic area. Although this may still be desirable, it is likely that materials that possess suitable characteristics and are available in sufficient quantities to satisfy local or regional needs exist in various localities. The zinc smelter waste mentioned earlier is one example of such a material. Stack dust from lime plants may be another example. Cement-kiln stack dust is both widely available and energy conserving.

Second, the energy crisis promises to be a continuing problem in our society. For the foreseeable future, the conservation of energy can be expected to become an increasingly vital concern in our national life. Even though the general public does not yet seem to take energy conservation very seriously, it is conceivable that energy could become such an overriding national concern as to affect both the attitudes and the lifestyles of many citizens. In such an event, public attitudes toward pavement rideability could change and thus modify the economic relations that have been shown to define the parameters of acceptable waste products for pavement use. Furthermore, it will become increasingly difficult to obtain high-quality conventional materials. It may well be necessary for both the traveling public and transportation officials to reevaluate pavement performance standards in the light of a threatened shortage of both materials and energy.

In anticipation of the increasing importance of energy conservation, it would be beneficial to investigate now the potential usefulness of waste products somewhat beyond the present limits of economic marginality. Priorities for the investigation of new materials can be established on the basis of potential energy saving and expected performance.

PERFORMANCE AND LABORATORY TESTS

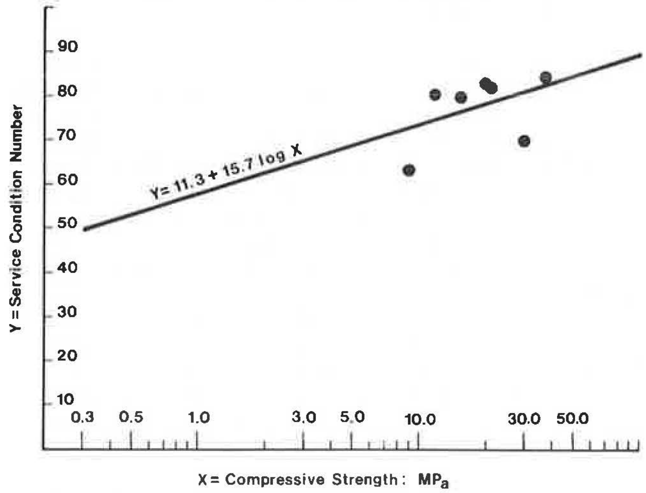
Use of a performance criterion for selected energy-conserving materials requires that data be available on which to base a reasonable estimate of the expected serviceability history of pavements that incorporate such materials. Laboratory tests can always be per-

Table 1. Pavement evaluation data for eight projects in Cook County, Illinois.

Street	From	To	Year Built	1978 Average Core Strength (MPa)	Present Condition Number	Surface Condition Index
Ela Road	Algonquin	Central	1974	11.89	81.0	84.0
Ela Road	Bradwell	Palatine	1968[a]	37.82	85.3	85.4
Ela Road	Dundee	Baldwin	1968	15.69	80.6	86.4
Ela Road	Freeman	Algonquin	1967	30.58	70.8	71.6
Howard	Gross Point	Frontage	1958	19.82	55.7	36.7
Plum Grove	Mecham	Old Plum Grove	1974	20.24	84.0	82.2
Potter	Golf	Ballard	1959	9.07[b]	65.0	65.0
Quentin	Palatine	Illinois	1964	21.59	82.6	76.9

Note: 1 MPa = 145 lbf/in².
[a]New surface, 1975.
[b]Core tested May 1977.

Figure 4. Service condition number versus current compressive strength for Cook County pavements (excluding Howard Street).



formed to determine physical properties of paving mixtures under controlled conditions. Test data such as modulus of rupture of concrete or Marshall stability of bituminous mixtures have long been used as indices of the probable performance of conventional pavements.

Of course, many variables other than the physical properties of paving materials affect the performance of any pavement. Traffic, subgrade, and environmental variables all influence pavement performance and thereby prevent a high correlation between the materials properties and the service life of a completed paving project. But effective use of an energy-conserving waste product does not require a precise statistical estimate of service life, at least not for the purpose of screening candidate materials for further research and development. It is only necessary at this stage to determine whether or not the expected service life of a pavement constructed by using the candidate material is close to that of a conventional pavement.

An example will show that such a determination can be made on the basis of laboratory data. Pozzolanic concrete pavement bases that contain lime and fly ash collected from the stacks of coal-burning utilities have been used for many years by various states. Some data are available on this material so that a comparison can be made between the compressive strength of cores and an independent measure of the expected remaining service life of pavements from which the cores were taken.

Table 1 gives data on eight pavements in Cook County, Illinois, that were constructed with pozzolanic concrete bases and have been included by the county in an extensive program of pavement evaluation. At the time this paper was written, these eight projects contained the only pozzolanic bases for which both core-test and evaluation data existed.

The surface condition index given in Table 1 is a number from 10 to 100 that summarizes a detailed visual evaluation of the pavement surface in which the number and severity of cracks and other surface anomalies are determined. This value decreases as the condition of the pavement surface deteriorates.

Service condition number, which also varies from 10 to 100, is a function of the expected service life of the pavement with which that number is associated. The service condition number is a weighted function of dynaflect observations, surface condition index, deflection number, and other data, including expected traffic. Values of 85 or more indicate an acceptable pavement with a service life of at least 10 years under expected traffic. Values from 80 to 85 indicate that a pavement service life of 10 years can be anticipated but that more maintenance must be expected and performance will be at a lower PSI. Values from 70 to 80 indicate that some reconstruction will be required within 10 years. Values of 60 or less indicate an expected service life of 5 years or less. As the service condition number drops below 60, the need for remedial action or reconstruction becomes more immediate.

Both surface condition index and service condition number, as used in this paper, are indices used by the Cook County Department of Highways and are principally based on data given by Chang, Phang, and Wrong (5, 6).

Although none of the pavements described in Table 1 is new, each pavement has an average compressive strength of core samples associated with pavement evaluation data taken at about the same time. It is thus possible to study the relation between the present compressive strengths of the pozzolanic concrete bases and the probable remaining service lives of the pavement systems of which such bases form a part. Howard Street has been omitted in most of the discussion that follows because its surface condition index is so poor that surface condition is clearly an overriding factor. The remaining pavements exhibit a much more limited range of surface condition values.

The relation between current compressive strength and service condition number was first studied at the ordinal level. For the seven pavements other than Howard Street, Spearman's rank correlation coefficient between present compressive strength and service condition number was found to be +0.57. The corresponding value with Howard Street included was +0.52. Calculations of Kendall's tau yield values of +0.43 without Howard Street and +0.36 with Howard Street. These correlation coefficients are all statistically significant at a level of confidence of about 0.15 and thus offer a fairly strong indication that a ranking of waste materials in accordance with laboratory compressive strengths reasonably approximates the ranking

by service lives of pavements that incorporate the waste material in question.

Regression calculations in which data given in Table 1 (omitting Howard Street) were used yielded the following:

$$Y = 11.3 + 15.7 \log X \quad (15)$$

where Y = service condition number and X = average compressive strength of cores (kPa). The equation and the associated data are shown in Figure 4. The coefficient of determination (R^2) is 0.21. This is not high enough to be statistically significant, but it does indicate a discernible positive relation between present compressive strength and expected service life.

The table below gives the relation between core compressive strength and expected remaining service life as developed from Equation 15 and the interpretation of service condition number used by Cook County (1 MPa = 145 lbf/in^2):

Anticipated Remaining Service Life to PSI = 2.5 (years)	Minimum Compressive Strength of Pozzolanic Concrete Base (MPa)
≥10	23
5-10	1
<5	<1

This table is illustrative only, since compressive strengths of pozzolanic bases vary in accordance with the properties of material used in different localities. Its purpose is to demonstrate that laboratory data can be used to develop an estimate of expected service lives of pavements that is adequate for at least a preliminary study of waste materials that offer potential energy savings in pavement construction.

CONCLUSIONS

The following conclusions are considered to be supported by the work presented in this paper:

1. The use of industrial waste products in pavement construction produces net energy savings whenever the energy saved in the production of raw materials (compared with some conventional design) exceeds a specified function of the energy cost of resurfacing and the time required for both the conventional pavement and the project that contains the waste product(s) to reach a PSI of 2.5.
2. Under existing conditions, waste products that do not provide a pavement service life nearly equal to the life that can be attained by using conventional materials are not feasible from the standpoint of energy conservation.
3. Comparing the cost of energy saved with the current price of energy, as an economic criterion, further restricts the range of feasible waste products under current standards of highway performance.
4. A deepening of the energy crisis would widen the range of waste products that are usable in pavement construction by increasing the cost of energy and thereby raising some new materials above the marginal level from the economic standpoint. It is also possible that energy shortages could bring about changes in public attitudes toward standards of highway performance. Changes in such standards could render many more industrial waste products feasible for the purpose of energy conservation.
5. Potentially useful waste products that are somewhat beyond the current limits of economic marginality should be investigated in anticipation of the increasing importance of energy conservation.
6. It has been demonstrated that it is feasible to use laboratory test data to develop an approximation of anticipated pavement service life in order to apply the criteria presented in this paper for evaluating the potential usefulness of waste products for energy conservation.

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