# Iowa Thickness Design Guide for Low Volume Roads Using Reclaimed Hydrated Class C Fly Ash Bases

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This paper is intended to provide flexible pavement thickness design parameters and a design method for low volume roads and streets utilizing Iowa reclaimed hydrated Class C fly ashes as artificial aggregates for a base material. AASHTO design guidelines are presented for using these materials untreated, or if higher strengths are needed, stabilized with raw fly ash or hydrated lime. Hydrated Class C fly ashes in Iowa are produced at sluice pond disposal sites at generating stations burning western sub-bituminous coals. They may be formed by dozing raw ash into the sluice pond where it hydrates to form a cementitious mass or they may be constructed as an engineered fill (above the sluice pond level) by placing the raw ash in lifts, followed by watering, compaction and subsequent hydration. The hydrated ash is typically mined by using conventional recycling-reclaiming equipment to pulverize the material where it is stockpiled on-site for use as an artificial aggregate. Research has been conducted on these materials, on an on-going basis, under the Iowa Fly Ash Affiliate Research Program since 1991. Test roads have been constructed using reclaimed fly ash as an aggregate base in Marshalltown (1994) and near Ottumwa (1995). They have been, and are, performing well. Based on extensive laboratory testing, this paper presents layer coefficients for reclaimed hydrated Class C fly ash bases for use in AASHTO thickness design for low volume roads and streets. Key words: fly ash, hydrated fly ash, bases, AASHTO design, layer coefficients.

## OBJECTIVE

This guide is intended to provide flexible pavement thickness design parameters and a design method for low volume roads and streets utilizing Iowa reclaimed hydrated Class C fly ashes as artificial aggregates for a base material. Design guidelines are presented for using these materials untreated, or if higher strengths are needed stabilized with raw fly ash or hydrated lime. The complete report containing all of the data used in development of this guide is available on request (*11*).

## BACKGROUND

Hydrated Class C fly ashes in Iowa are produced at sluice pond disposal sites at generating stations burning western sub-bituminous coals. They may be formed by dozing raw ash into the sluice pond where it hydrates to form a cementitious mass or they may be constructed as an engineered fill (above the sluice pond level) by placing the raw ash in lifts, followed by watering, compaction and subsequent hydration.

The hydrated ash is typically mined by using conventional recycling-reclaiming equipment to pulverize the material where it is stockpiled on-site for use as an artificial aggregate.

Research has been conducted on these materials, on an on-going basis, under the Iowa Fly Ash Affiliate Research Program since 1991 (*1*,*2*). Test roads have been constructed using reclaimed fly ash as an aggregate base in Marshalltown (1994) and near Ottumwa (1995). They have been, and are, performing very well (*3*,*4*).

## PAVEMENT THICKNESS DESIGN BY AASHTO METHODS

The following formula controls selection of layer thicknesses in the low volume AASHTO design method (*5*).

Equation (1):

$$SN = a_1D_1 + a_2D_2 + a_3D_3$$

where

SN = Structural Number

$a_1,a_2,a_3$ = layer coefficients representative of surface, base, and subbase courses, respectively

$D_1,D_2,D_3$ = actual thicknesses (in inches) of surface, base, and subbase courses, respectively

The AASHTO Design Guide also provides correlations from common laboratory tests such as the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) to layer coefficients. Once a layer coefficient is selected for each layer, pavement layer thickness may be determined from the SN equation. There is no unique solution, therefore, the one which is the most economical should prevail.

The AASHTO Design Guide also suggests a simplified procedure for the design of low-volume roads. The simplified variables for this design procedure are basically the same as in the standard design:

- U.S. Climatic Regions
- Relative Quality of Subgrade Soil
- Traffic Level
- Inherent Reliability

## CORRELATION OF STANDARD TESTING AND MATERIAL TYPE TO LAYER COEFFICIENT

There is limited information on the correlation of standard testing results to layer coefficients for flexible pavement design. This sec-

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**TABLE 1 Correlations of Standard Tests to Layer Coefficients ($a_i$) from the AASHTO Design Guide**

| $a_i$ | CBR, % | Unconfined Compressive Strength, psi |
|---|---|---|
| 0.10 | 25 | [a]0 |
| 0.11 | 35 | 100 |
| 0.12 | 40 | 175 |
| 0.13 | 70 | 225 |
| 0.14 | 100 | 300 |
| 0.15 | - | 390 |
| 0.16 | - | 425 |
| 0.17 | - | 500 |
| 0.18 | - | 575 |
| 0.19 | - | 610 |
| 0.20 | - | 675 |
| 0.21 | - | 750 |
| 0.22 | - | 800 |

tion will summarize suggested layer coefficients based on UCS, CBR, and material description. Surface, base, and subbase layer coefficients $a_1$, $a_2$, and $a_3$, are all measured on the same scale, so in the following discussion any layer coefficient will be designated $a_i$.

*The AASHTO Guide For Design of Pavement Structures* (*5*) offers a fairly comprehensive correlation between CBR and $a_i$ for granular layers, and between unconfined compressive strength and $a_i$ for cement treated layers. The CBR correlation, derived from work in Illinois, is non-linear and does not account for CBR values in excess of 100. The correlation for UCS, from work in Illinois, Louisiana, and Texas, is approximately linear. The UCS is typically used in assigning layer coefficients where CBR values are in excess of 100 percent. Table 1 summarizes AASHTO correlations.

The National Asphalt Paving Association published *A Guide to Thickness Equivalencies For the Design of Asphalt Pavements* in 1984. They determined and suggested layer equivalencies based on the AASHTO Road Test results and AASHTO committee judgment (*6*). The unique quality of their assignations is that they are relative values, with no specific layer coefficient given. Table 5 shown on Figure 5 shows the coefficients resulting from the assumption that the coefficient for dense graded crushed stone is 0.14.

The most interesting approach to the assignment of layer coefficients for pozzolanic pavements was presented in a paper by Walter Morris (*7*). Morris' paper focused on the fact that pozzolanic and cement treated bases were not really considered in the AASHTO Road Test. Morris then cites the finding by the Pennsylvania DOT that structural coefficients change with layer thickness. Layer coefficients of semi-rigid to rigid bases increase as the layer thickness increases. He then presents a correlation of UCS to layer coefficient for differing thicknesses of pozzolanic base as shown on Table 2.

Fly ashes are pozzolanic materials and Class C fly ashes are both self-cementitious and pozzolanic. The reclaimed hydrated Class C ashes although hydrated and hard still contain an abundance of unreacted pozzolanic materials. When used untreated and compacted into a base layer they slowly develop strength over time due to continued pozzolanic reactions. The addition of a calcium source to the reclaimed hydrated ashes serves to activate additional pozzolanic reactions and results in dramatic increases in strength. Development of layer coefficients for design considers this in addition to adjustments of coefficients based on Morris' work.

**TABLE 2 Layer Coefficients for Pozzolanic Bases from Morris, 1989**

| | Thickness of Pozzolanic Base, inches | | | | | |
|---|---|---|---|---|---|---|
| Design Strength, psi | 6 | 7 | 8 | 9 | 10 | 12 |
| 600-800 | .20 | .22 | .24 | .26 | .28 | .34 |
| 800-1100 | .23 | .26 | .29 | .32 | .35 | .41 |
| 1100-1500 | .28 | .32 | .35 | .38 | .41 | .44 |
| 1500 & above | .32 | .36 | .40 | .44 | .44 | .44 |

**TABLE 3 Typical CBR Values for Different Materials**

| **Description of Material** | **CBR, %** |
|---|---|
| Well-graded crushed aggregates | 100 |
| Well-graded natural gravels | 80 |
| Gravelly sands (predominately sand) | 20-50 |
| Silty or clayey sands | 10-40 |
| Fine clean sands | 10-20 |
| GW: gravel or sandy gravel | 60-80 |
| GP: gravel or sandy gravel | 35-60 |
| GM: silty gravel or silty, sandy gravel | 40-80 |
| GC: clayey gravel or sandy, clayey gravel | 20-40 |
| SW: sand or gravelly sand | 20-50 |
| SP: sand or gravelly sand | 10-25 |
| SM: silty sand | 20-40 |
| SC: clayey sand | 10-20 |
| CL: lean clays, sandy clays, gravelly clays | 5-15 |
| ML: silts, sandy silts | 5-15 |
| OL: organic silts, lean organic clays | 4-8 |
| CH: fat clays | 3-5 |

## DEVELOPMENT OF LAYER COEFFICIENTS FOR RECLAIMED FLY ASH

In order to develop layer coefficients for reclaimed fly ash, CBR tests were utilized in conjunction with UCS tests. Tests were conducted on untreated reclaimed ash and reclaimed ashes activated with raw fly ash and hydrated lime (*11*).

### California Bearing Ratio

The CBR was developed by the California Highway Department, and is one of the leading flexible pavement design procedures in the world (*8*). It can be conducted in the laboratory, or on field samples, and although it is most appropriate for fine-grained soils, it is also used to characterize aggregates for road base applications. The CBR test is most effectively used in the case where layers of the pavement increase in strength from the subgrade to the surface (*9*). It is important to realize that while CBR gives an index of strength, it is not a strength measurement. Table 3 is condensed from Rollings and Rollings (*8*), and gives some typical CBR values.

**TABLE 4 Range of specific gravity and absorption for reclaimed fly ash materials**

| Bulk Specific Gravity of Coarse Material (+#4) | Bulk Specific Gravity of Fine Material (-#4) | Absorption of Coarse Material (%) |
|---|---|---|
| 1.45 - 1.53 | 1.99 - 2.26 | 24 - 37 |

Care should be taken in the assignment of a CBR value to a highly cemented granular material, as strain induced by traffic may break the cementitious bonds (*9*). Factors affecting CBR value include maximum aggregate size, gradation, aggregate shape and texture, and plasticity. The American Society for Testing and Materials (ASTM) Standard Test Method ASTM D1883 for CBR suggests that materials containing a substantial fraction larger than the #4 sieve will yield more variable results (*10*).

### Unconfined Compressive Strength

The UCS has long been used to evaluate the strength of soils and stabilized materials.

## MATERIALS

For development of this guide the following material sources were used.

Reclaimed hydrated Class C fly ashes were obtained during 1995 and 1996 from the following generating stations: Ottumwa, Port Neal 3, Prairie Creek, and Council Bluffs. Raw fly ash used to activate the reclaimed ashes were obtained from the respective generating stations during 1996 and 1997. UCS and CBR tests were conducted using 10, 15 and 20 percent raw ash. Little additional benefit was obtained from reclaimed ash activated with 15 percent and 20 percent raw ash. Reagent grade hydrated lime was also used as an activating agent. Cement kiln dust (CKD) and Atmospheric Fluidized Combustion Residue (AFBC) have also been used as activating agents. Chemical composition and test data are included in reference 11.

## RECLAIMED FLY ASH ENGINEERING PROPERTIES

### Particle Size Distribution

The reclaimed ash stockpile typically contains 10 to 15 percent plus 3/4 inch material. This material is crushed to pass the 3/4 inch sieve and reincorporated into the sample prior to testing. The results of particle size analysis conducted according to ASTM C136 is shown on Figure 1.

Figure 1 shows that all the reclaimed ashes are reasonably well graded. The Council Bluffs and Neal 3 material have nearly identical gradation, and are the coarsest of the four, with about 15 percent passing the #200 sieve. The Ottumwa material is the finest, with about 25 percent passing the #200 sieve. The Prairie Creek material falls halfway between the others, at about 20 percent passing the #200 sieve. These results are typical of numerous other samples that have been tested under previous Affiliate research (*1*,*2*).

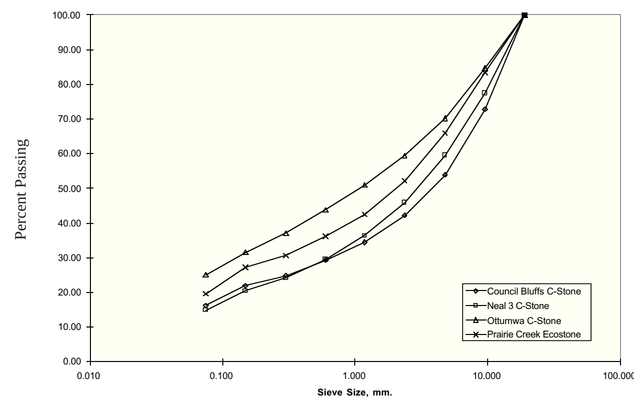


**FIGURE 1 Particle size distribution of reclaimed fly ashes.**

### Specific Gravity and Absorption

Specific gravity and absorption of the coarse fraction of the reclaimed ash was conducted according to ASTM C127, Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate. The specific gravity of the fine fraction (material passing the #4 sieve) was determined by the Iowa State Materials Analysis and Research Laboratory (MARL) using a helium pycnometer. The range of results of the specific gravity testing are shown in Table 4. The specific gravity of the materials is in the range of a lightweight aggregate. The high porosity is evidenced by the high absorption values.

### Moisture/Density Relationships

Moisture/Density relationship of the reclaimed fly ash was determined according to ASTM D698, Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort. Tests were conducted using molds 6 inches in diameter by 4.584 inches high. Specimens were formed in three equal layers, with each layer being compacted with 56 blows from a 5.5 pound hammer dropped twelve inches. Specimens were weighed to the nearest gram, and a moisture sample was taken from each. One curve was developed for each combination of reclaimed fly ash and additive. All additive levels are based on the oven dry weight of reclaimed fly ash. Table 5 summarizes the range of moisture/density relationship for all the materials tested.

**TABLE 5 Range of ASTM D698 Test Results for Reclaimed Fly Ash Materials**

| Material | Optimum Moisture (%) | Maximum Dry Density (pcf) |
|---|---|---|
| Untreated | 27 - 37 | 79 - 88 |
| Raw Fly Ash, activated 10% | 26 - 38 | 75 - 91 |
| Lime, activated 2-1/2% | 27 - 39 | 77 - 87 |

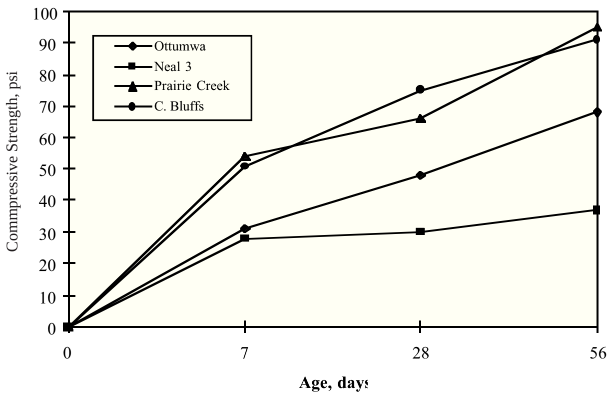


**FIGURE 2 Untreated reclaimed ash strength gain.**

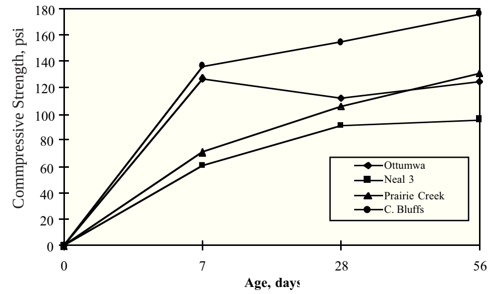


**FIGURE 3 10% Raw fly ash activated reclaimed ash strength gain.**

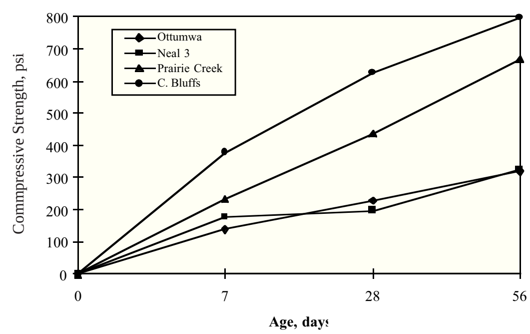


**FIGURE 4 2-1/2% Lime activated reclaimed ash strength gain.**

## Strength Development Characteristics

### *Untreated reclaimed ash - laboratory results*

When moistened and compacted, untreated reclaimed fly ash materials gain strength as a function over time due to pozzolanic reactions. Figure 2 illustrates this for the 4 reclaimed ashes used in this study. As long as water is available it is believed that this pozzolanic strength development continues to occur over a long period of time (years) and the material is believed to be able to heal itself following crack development (autogenous healing). Untreated ash bases perform primarily as a flexible base.

### *Calcium activated reclaimed ash - laboratory results*

The addition of an external source of calcium to the reclaimed ash during base construction can dramatically in-crease strength development. The calcium activates additional pozzolanic reactions among the aggregate particles thereby cementing them together. Strength gains can be dramatic and are long-term. Figure 3 illustrates strength gain characteristics of 10% raw fly ash activated reclaimed ash. Fly ash activation transforms the material into a semi-flexible base.

Figure 4 illustrates strength gain characteristics of 2-1/2 % hydrated lime activators and shows the strong increase in strength being developed from pozzolanic activity. Lime activation transforms the material into a semi-rigid base for heavy load applications.

## DESIGN PARAMETERS

### Range of Test Results

Numerous CBR and UCS tests were conducted on untreated and stabilized materials used in the development of this guide.

### Layer Coefficients

The coefficients for a 6 inch base have been developed using 7 day CBR values in the cases where the CBR is less than 100 percent and using UCS values at 56 days of age in the cases where the CBR's were in excess of 100 percent. The coefficients have then been modified for greater base thicknesses using Morris's data for pozzolanic bases.

Based on the testing data the suggested layer coefficients for use in preliminary design are given in Table 6 shown on Figure 5 as a function of base thickness. These coefficients are believed to be conservative. Testing should be conducted on project specific materials to confirm or increase the design coefficients.

**DESIGN METHODOLOGY**

**The AASHTO method suggested for low volume pavement thickness design using reclaimed fly ash follows.**

**SUBGRADE RATING**

**Determine the average quality of the project subgrade soil from Table 1.**

**Table 1. Subgrade soil quality.**

| Rating (%) | Modulus of Subgrade Reaction (k, pci) | CBR Value |
|---|---|---|
| Very Good | Greater than 550 pci | > 55 |
| Good | 400 to 550 pci | 40 - 55 |
| Fair | 250 to 350 pci | 20 - 35 |
| Poor | 150 to 250 pci | 6 - 20 |
| Very Poor | Less than 150 pci | < 6 |

**TRAFFIC LEVEL**

**From estimated traffic projections determine the traffic level anticipated from Table 2.**

**Table 2. Traffic levels for the low-volume design method.**

| Traffic Level | ESAL's |
|---|---|
| High | 700,000 to 1,000,000 |
| Medium | 400,000 to 600,000 |
| Low | 50,000 to 300,000 |

**STRUCTURAL NUMBER (SN)**

**Estimate the structural number from Table 3.**

**Table 3 Recommended ranges of Structural Number (SN) flexible pavement design catalog for low-volume roads.**

| Relative Quality of Subgrade Soil | Traffic Level | 75% Level of Inherent Reliability (SN) |
|---|---|---|
| Very Good | High | 3.0 - 3.2 |
| | Medium | 2.7 - 3.0 |
| | Low | 2.0 - 2.6 |
| Good | High | 3.3 - 3.4 |
| | Medium | 3.0 - 3.2 |
| | Low | 2.2 - 2.8 |
| Fair | High | 3.4 - 3.5 |
| | Medium | 2.7 - 3.3 |
| | Low | 2.3 - 2.9 |
| Poor | High | 3.7 - 3.0 |
| | Medium | 3.4 - 3.6 |
| | Low | 2.5 - 3.2 |
| Very Poor | High | 3.8 - 4.0 |
| | Medium | 3.5 - 3.7 |
| | Low | 2.6 - 3.3 |

**MINIMUM THICKNESS**

**Establish the minimum thicknesses of the asphalt surface course and base from Table 4.**

**Table 4. Recommended minimum pavement layer thicknesses (inches).**

| Traffic, ESAL's | Asphalt Concrete | Aggregate Base |
|---|---|---|
| Less than 50,000 | 1.0 (or surface treatment) | 4 |
| 50,001 - 150,000 | 2.0 | 4 |
| 150,001 - 500,000 | 2.5 | 4 |
| 500,001 - 2,000,000 | 3.0 | 6 |
| 2,000,001 - 7,000,000 | 3.5 | 6 |
| Greater than 7,000,000 | 4.0 | 6 |

**SUBBASE**

The need for a subbase should be determined by the designing engineer based on the quality of the subgrade soil.

If the subgrade is so soft that stabilization (lime, fly ash, cement) is required, CBR tests should be conducted on the stabilized soil and the subgrade soil quality then determined from Table 1, before proceeding with the design.

**RECLAIMED ASH BASE**

**Determine source and type available (described under layer coefficients).**

**LAYER COEFFICIENTS**

- **Assign layer coefficients**
  - → HMA Surface Course ..........................($a_1$) - Table 5
  - → Reclaimed Fly Ash Base ......................($a_2$) - Table 6
  - → Other Bases ..........................................($a_2$) - Table 5
  - → Subbase ..............................................($a_3$) - Table 5

**Table 5. Layer coefficients ($a_i$) derived from thickness equivalencies, developed by National Asphalt Pavement Association, 1984.**

| Layer | Thickness Equivalency | $a_i$ |
|---|---|---|
| **HMA surface, binder, leveling and base courses** | | |
| mixes containing crushed coarse aggregate | 3.00 | 0.42 |
| mixes containing uncrushed coarse aggregate | 2.75 | 0.39 |
| mixes containing no coarse aggregate (sand asphalt) | 2.50 | 0.35 |
| **Cement-treated base courses** | | |
| 650 psi compressive strength or more | 1.50 | 0.21 |
| 400 to 500 psi compressive strength | 1.25 | 0.18 |
| less than 400 psi compressive strength | 1.00 | 0.14 |
| **Other base courses** | | |
| portland cement concrete | 3.00 | 0.42 |
| untreated dense-graded crushed aggregate | 1.00 | 0.14 |
| lime/fly ash treated, plant mix | 1.00 | 0.14 |
| lime/fly ash treated, road mix | 0.75 | 0.11 |
| soil cement | 0.75 | 0.11 |
| crusher run aggregate | 0.75 | 0.11 |
| **Subbases** | | |
| gravel | 0.50 | 0.07 |
| sand | 0.50 | 0.07 |

**Table 6. Suggested layer coefficients for reclaimed fly ash bases for preliminary design as a function of thickness.**

**A. Base Thickness ≈ 6 inches**

| Source | Untreated | 10% Raw Fly Ash | 2-1/2% Lime |
|---|---|---|---|
| Ottumwa | 0.12 | 0.13 | 0.14 |
| Neal 3 | 0.13 | 0.14 | 0.15 |
| Prairie Creek | 0.13 | 0.14 | 0.17 |
| Council Bluffs | 0.13 | 0.14 | 0.19 |

**B. Base Thickness ≈ 8 inches**

| Source | Untreated | 10% Raw Fly Ash | 2-1/2% Lime |
|---|---|---|---|
| Ottumwa | 0.14 | 0.15 | 0.16 |
| Neal 3 | 0.14 | 0.16 | 0.17 |
| Prairie Creek | 0.15 | 0.16 | 0.19 |
| Council Bluffs | 0.15 | 0.16 | 0.21 |

**C. Base Thickness ≈ 10 inches**

| Source | Untreated | 10% Raw Fly Ash | 2-1/2% Lime |
|---|---|---|---|
| Ottumwa | 0.16 | 0.17 | 0.18 |
| Neal 3 | 0.17 | 0.18 | 0.19 |
| Prairie Creek | 0.17 | 0.18 | 0.21 |
| Council Bluffs | 0.17 | 0.18 | 0.23 |

**D. Base Thickness ≈ 12 inches**

| Source | Untreated | 10% Raw Fly Ash | 2-1/2% Lime |
|---|---|---|---|
| Ottumwa | 0.18 | 0.19 | 0.20 |
| Neal 3 | 0.19 | 0.20 | 0.21 |
| Prairie Creek | 0.19 | 0.20 | 0.23 |
| Council Bluffs | 0.19 | 0.20 | 0.25 |

**DESIGN PROCESS**

- The design process for reclaimed ash bases is trial and error. A design thickness is assumed to establish a layer coefficient. A design thickness is then calculated. If they agree within ± 1 inch, the design is satisfactory. If not a new thickness is assumed and a design thickness recalculated.

**CALCULATIONS**

- Using the SN and layer coefficients determine the various layer thickness in inches ($D_1$, $D_2$, $D_3$) from the AASHTO equation:
  $SN = a_1D_1 + a_2D_2 + a_3D_3$
- When assigning layer thicknesses, economics and minimum layer thicknesses should be considered.

**IOWA FLY ASH AFFILIATE RESEARCH PROGRAM - IOWA STATE UNIVERSITY**

- Kenneth L. Bergeson P.E., Program Director - 515-294-9470
  Thickness Design Report ISU-ERI-Ames Report 98401 , January 1998

**FIGURE 5 Pavement thickness design guide using reclaimed fly ash.**

## PAVEMENT THICKNESS DESIGN GUIDE USING RECLAIMED FLY ASH

### Design Methodology

The AASHTO method suggested for low volume pavement thickness design using reclaimed fly ash is shown on Figure 5.

### DESIGN COMMENTS

The layer coefficients assigned to the reclaimed fly ash are believed to be conservative considering their long term strength gain properties, so if the designing engineer has other experience on similar materials, a less conservative correlation, may be considered. It should be noted that bases with a high unconfined compressive strength (>800 psi) are considered as rigid bases and may contribute to reflective cracking in the asphalt surface layer (*9*).

The need for a subbase should be determined by the designing engineer based on the quality of the subgrade soil.

If the subgrade is so soft that stabilization (lime, fly ash, cement) is required, CBR tests should be conducted on the stabilized soil and the subgrade soil quality then determined from Table 1 shown on Figure 5 before proceeding with the design.

Determination of layer coefficients for similar base materials not included in this study may be made through simple laboratory testing, as described in the following steps.

a. If the material is not to be stabilized, or if its design unconfined compressive strength is expected to be less than 300 psi, determine the CBR value and select a layer coefficient from Table 1, page 3.

b. If the material is stabilized with lime or similar activator (expected strength greater than 300 psi) determine the 28 day unconfined compressive strength and select a layer coefficient from Table 1.

c. If the material is stabilized with Portland cement (expected strength greater than 300 psi) determine the 7 day unconfined compressive strength and select a layer coefficient from Table 1.

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### REFERENCES

1. Bergeson, K.L. et al. *Reclaimed High Calcium Fly Ash Use as a Highway Base Material*. Final Report, ISU-ERI-Ames 92-402, Iowa State University, Ames, Iowa, 1991.
2. Bergeson, K., and R. Lapke. Use of Fly Ashes and AFBC Residues as a Synthetic Aggregate Material. *Thirtieth Annual Power Affiliate Report*,

ISU-ERI-Ames 93-087, Iowa State University, Ames, Iowa, 1993.

3. *IES Utilities Ottumwa-Midland Landfill Access Road.* Field Demonstration Project Report, ERI Project 3009, ISU, Ames, Iowa, April 1996.
4. *IES Utilities Sutherland Power Plant Access Road.* Field Demonstration Project Report, ERI Project 3009, ISU, Ames, Iowa, April 1996.
5. *AASHTO Guide For Design of Pavement Structures*. American Association of State Highway and Transportation Officials, Washington, DC, 1993.
6. *A Guide to Thickness Equivalencies for the Design of Asphalt Pavements*. National Asphalt Paving Association, Washington, D.C., 1984.
7. Morris, W. L. *Design Guidelines for Pozzolanic Pavements.* Pozzolanic Soil Stabilization Workshop, Council Bluffs, Iowa, 1989.
8. Rollings, M. P., and R. S. Rollings, Jr. *Geotechnical Materials in Construction*, McGraw-Hill, New York, 1996.
9. Hausmann, M. R. *Engineering Principles of Ground Modification*, McGraw-Hill Publishing Company, New York, 1990.
10. ASTM D 1883, Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils, *Annual Book of ASTM Standards*, Vol. 4.08, ASTM, Philadelphia, Pennsylvania, 1993.
11. Bergeson, K.L. and A. Barnes. *Iowa Thickness Design Guide for Low Volume Roads Using Reclaimed Hydrated Class C Fly Ash Bases*, ISU-ERI-Ames 98401, Iowa State University, Ames, Iowa, January 1998.