Analysis of Uniformly Loaded Floor Slabs Supported by Rammed Aggregate Pier Elements

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Abstract

Rammed Aggregate Pier soil reinforcing elements are commonly used to reinforce compressible soils below shallow spread footings to control settlement and increase allowable foundation bearing pressures. Rammed Aggregate Pier elements are also used to support concrete floor slabs in lieu of deep foundations or massive excavation and recompaction. The piers reduce total and differential settlements because of their high strength and high stiffness characteristics. Due to the variation in pier stiffness with respect to in-situ soil stiffness, the commonly-used assumption of uniform sub-grade support is invalidated. The dissimilar slab support conditions, consisting of high stiffness at the pier locations and relatively low stiffness between the piers, leads to the development of bending moments and shear stresses within the slabs under applied loads.

In an attempt to quantify the bending moment and shear stress conditions that develop in relatively thin structural slabs supported by Geopier Rammed Aggregate Piers, a series of finite element analyses were performed for various pier geometries and soil and pier stiffness conditions under uniform slab loading conditions. This paper presents the results of these analyses and provides design charts that may be used to estimate required concrete slab thicknesses for a uniformly distributed loading condition. Although it is recognized that a uniformly distributed loading analysis may not capture the critical load case for the design of the slab, this paper is of significance because it presents simple design charts that may be used to estimate preliminary floor slab thicknesses for a variety of span-to-depth ratios.

Introduction

For most buildings, ground floor slabs-on-grade are typically designed using empirical standards of practice that require little engineering effort and result in relatively thin and cost-effective slab sections. Analytical methods using nomographs are also available to designers that account for non-uniform loading conditions such as fork truck wheel loads and storage rack leg loads. Both empirical and analytical methods assume constant subgrade stiffness. When floor slabs are to be placed on deep fills, organic soils, and other compressible materials and excessive settlement is intolerable, slab design options usually consist of one of two choices:

1. Maintain the relatively thin concrete slab on grade design philosophy, but only if the unsuitable soils are excavated and recompacted or replaced with more qualified materials, or
2. Install deep foundations, such as driven piles or drilled caissons, that support a structural slab (i.e. a slab that is structurally designed and reinforced to be able to span between installed deep foundations).

Both of these options are costly when compared to a conventional slab on grade. A third option that has proven successful under these conditions is Geopier® Rammed Aggregate Piers (RAP reinforcing elements) to reinforce the compressible soils and allow for the construction of a relatively thin floor slab.

The RAP technique results in a subgrade that has a non-uniform stiffness distribution. The subgrade stiffness is very high at the RAPs and is relatively soft in its unmodified state between the RAPs. Therefore, the slab experiences shear and bending moment demands between that of a structural slab and a slab-on-grade. The structural design of slabs supported on RAPs can be accomplished through the use of a structural finite element program which can be tedious and is often viewed as "design overkill", especially for projects with lightly loaded slabs.

A series of numerical analyses performed to provide an improved understanding of slab behavior and some guidance on the design of RAP-supported slabs may be used as a design guide for uniformly loaded slabs. This paper does not address the design of floor slabs for other loading conditions, such as point loads or moving loads, line loads from aisles of tall storage racks, or discontinuous (hopscotch) uniform loads, which are all loading conditions that could govern the design of the floor slab.

Background

Most floor slabs for buildings constructed on-grade are designed using closed-form numerical solutions that represent the soil as linear elastic springs (Figure 1a), commonly known as the "Winkler" subgrade model. Using methods outlined by the Portland Cement Association and others (PCA 2001, ACI 1997), the design of the floor slab includes applying simulated loads to the slab and evaluating computed shear stresses and bending moments. Resulting designs can include slabs constructed from plain concrete and concrete reinforced with conventional rebar or post-tensioned strands. The design typically is based on an uncracked section and is focused on limiting the concrete tensile stress to a value that is much less than the concrete modulus of rupture or flexural cracking stress. The concrete modulus of rupture (f_r) is normally taken as: $f_r = 9 \sqrt{f'_c}$ where f'_c is the concrete compressive strength (psi) (PCA 2001). A factor of safety of about 1.7 is normally used in the design of a slab-on-grade (PCA 2001). Conventional slabs-on-grade are often four to six inches thick and are relatively inexpensive to construct.

At sites with soils that are deemed unsuitable for slab-on-grade support, the culprit soils are often excavated and replaced with suitable soils (Figure 1b). The floor slabs are then analyzed with the Winkler subgrade method presented above, which results in slab sections comparable to those on suitable soils. The added cost of this option is related to the cost of the earthwork, costs that can quickly become prohibitive at sites with deep cuts, contaminated soils, high groundwater, or adjacent structures that must be protected or underpinned. A pile-supported structural slab (Figure 1c) can cost as much or more than the excavation and replacement option. Because of the very high stiffness ratio between the piles and the natural soils, the piles are assumed to resist the entire load and the slab must be capable of structurally spanning between the pile supports. In this case, the stiffness of the in-situ soil is completely disregarded in the analysis.

A third option that has proven to be cost-effective for construction over soft and compressible soils is to improve the in-situ soil with Geopier RAP supported floor slab design (Figure 1d). For this third option, the piers are installed through the objectionable soils at a pier spacing that typically ranges between 8 and 15 feet on-center. Because the RAPs are stiffer than the surrounding soil, they attract floor slab loads forming a non-uniform support condition. Similar to pile-supported structural slabs, the floors must be designed to resist shear stresses and bending moments that develop as the applied loads attempt to span to the stiffer supports. However, these stresses are significantly lower than those resisted by structural slabs.

Geopier Rammed Aggregate Pier Construction

The construction of RAP reinforcing elements is well described in the literature (Lawton and Fox 1994, Fox and Cowell 1998) and consists of drilling a 24- to 36-in diameter cavity in the ground, constructing a bottom bulb by ramming a lift of open-graded stone into the bottom of the hole with a specially-designed beveled tamper, and constructing the pier shaft by ramming thin lifts of well-graded highway base course stone above the bottom bulb using the same high-energy hammer and beveled tamper foot (Figure 2). The beveled-shaped tamper foot forces the aggregate into the sidewalls of the drillhole and increases the lateral stresses around the pier (White et. al. 2000). The increase in lateral stress results in a decrease in the compressibility of the matrix soil (Handy 2001).

Unique to the process is the use of direct vertical ramming action on thin lifts of placed aggregate, resulting in piers of high strength and stiffness (Wissmann et al. 2001).

Numerical Analyses

To understand the development of shear stresses and bending moments in RAP-supported floor slabs, a suite of finite element analyses was performed that considered the response of the slab to uniformly distributed loading conditions. The model also accounted for subgrade support by using stiff springs at the RAP locations and relatively soft springs to represent the matrix soil between the piers. The analyses were performed for variations of:

- Applied uniform floor slab loading pressure (w, expressed in psf),
- Concrete compressive strength (f'_c, expressed in psi) and corresponding stiffness characteristics,
- RAP spring stiffness values (k_g, expressed in psi/in),
- Matrix soil spring stiffness values (k_m, expressed in psi/in),
- RAP spacing (L, expressed in feet), and
- Floor slab thickness (t, expressed in inches).

The results of each analysis were used to compare the computed bottom fiber tensile stresses against allowable values to establish the allowable value of applied slab pressure for the modeled slab geometry and spring support conditions. These results were used to evaluate the maximum allowable uniformly distributed load (prior to the development of limiting concrete tensile stress) for each value of normalized slab thickness (t/L). For simplicity, the analyses neglected stresses induced by concrete shrinkage and slab deformations, factors thought to be mitigated through the use of construction joints as described below.

Finite Elemental Model. A typical bay for a building with RAP foundation and floor slab support is shown in Figure 3. The piers are evenly spaced between the column bays with pier spacing determined from the characteristics of the matrix soils, floor slab loading, the thickness of the floor slab, and slab construction joint spacing. The piers are commonly located directly underneath the construction joints where the joint may transfer shear stresses but not bending moments. The hatched area shown in Figure 3 indicates the extents of the finite element model used in this study, bounded on two sides by slab joints and on the opposite sides by lines of symmetry.

RAM Concept software (RAM International 2005) was used to perform the finite element simulations. To model the response of the slab, hybrid shell elements that can accommodate in-plane axial and shearing stresses as well as out of plane bending and shearing stresses were modeled. A concrete 28-day compressive strength (f'_c) of 4000 psi (27,579 kPa) was used in the analyses. The RAP spacing was varied from 8 feet to 16 feet on-center in two foot increments. Figure 4 shows the finite element mesh that was used for the study.

Subgrade Support. Area springs were used to represent subgrade support. Stiff springs (k_g) were used to represent the 0.76 m (30-inch) diameter RAP elements and relatively soft springs (k_m) to represent the unimproved matrix soil response. A constant RAP spring stiffness value of 150 pci (40,740 kN/m^3) and matrix soil stiffness values ranging from 5 pci to 30 pci (1,358 kN/m^3 to 8,148 kN/m^3) were used.

The ratio of the spring constants is denoted by the stiffness ratio (R_s) and is a key determinant in the development of slab bending stresses (i.e. a stiffness ratio of infinity would result in a two-way structural slab design shown in Figure 1c; a stiffness ratio of unity would result in a conventional slab on grade design shown in Figure 1a). Table 1 presents a summary of stiffness constants and stiffness ratios used in the analyses. As noted above, the installation of the RAP elements increases the lateral stresses in the matrix soil which results in improved stiffness characteristics (Handy 2001). This soil improvement results in a transition from the high stiffness pier elements to the matrix soil elements. To capture this transition behavior the stiffness of the soil elements within a one foot radius from the edge of the piers was assumed to be the average stiffness of the piers and the matrix soil.

Table 1: Range of parameter values considered in this study

Parameter	Values considered in this study
RAP spacing (ft)	8, 10, 12, 14, and 16
RAP spacing (m)	2.4, 3.1, 3.7, 4.3, and 4.9
RAP stiffness, k_g (pci)	150
RAP siffness, k_g (kN/m^3)	40,740
Stiffness ratio, $R_s = k_g/k_m$	5, 10, and 20
Slab thickness, t (in)	4, 6, 8, and 10
Slab thickness, t (m)	0.10, 0.15, 0.20, and 0.25

Results

Figures 5 through 7 present the results of the numerical simulations for the 60 unique sets of geometry, subgrade support, and uniform loading conditions described in Table 1. The figures present contours of normalized thickness ratios (t/L) required to limit the tensile stress demands imposed by normalized slab pressures (w/f'_c) to within allowable values. The contours shown on the figures represent increasing pier spacing from 2.4 m (8 feet) on-center to 4.9 m (16 feet) on-center. A required floor slab thickness value for various applications of uniform slab pressure may be estimated by first establishing the appropriate pier to matrix soil stiffness ratio for the project site. The stiffness of the RAP element (k_g) is typically established through a site-specific modulus test performed in accordance with procedures found elsewhere (Fox and Cowell 1998). Next, the normalized loading parameter value (w/f'_c) is computed and a RAP spacing is selected. Figures 5 and 7 are then used to find the normalized required floor slab thickness (t/L) value. The required floor slab thickness (t) to appropriately resist the induced tensile stresses is then computed by multiplying the normalized floor slab thickness value (t/L) by the RAP spacing.

Conclusions

This paper presents the results of numerical studies performed to compute the response of uniformly loaded concrete floor slabs supported by RAP elements. The numerical simulations considered variable pier to matrix soil stiffness ratio values, variable pier spacing, and ranges of uniformly applied floor slab pressures. The results of the analyses are presented in normalized form in Figures 5 through 7, where the estimated floor slab thickness (t) is that which can adequately resist the applied pressures without developing tensile stresses that exceeds allowable capacity.

The results presented in this paper are subject to the following limitations:

1. Computed values of tensile stress in the floor slab on grade are developed for uniform loading conditions only. Other loading conditions and loading patterns, such as concentrated point loads, line loads, and “hopscotch” loading patterns will result in different tensile stress values that may be more critical to acceptable slab performance.
2. The modeled floor slabs included the assumption that a construction joint, which cannot transfer bending moments, is placed over the piers. Floor slabs with differing joint orientations should be evaluated separately.
3. The analyses presented herein are based on measured subgrade support conditions for Geopier Rammed Aggregate Pier elements. These results should not be extended to other types of foundation elements because of variations in stiffness ratios and differences in the radial soil stiffness function that results from differences in installation procedures.

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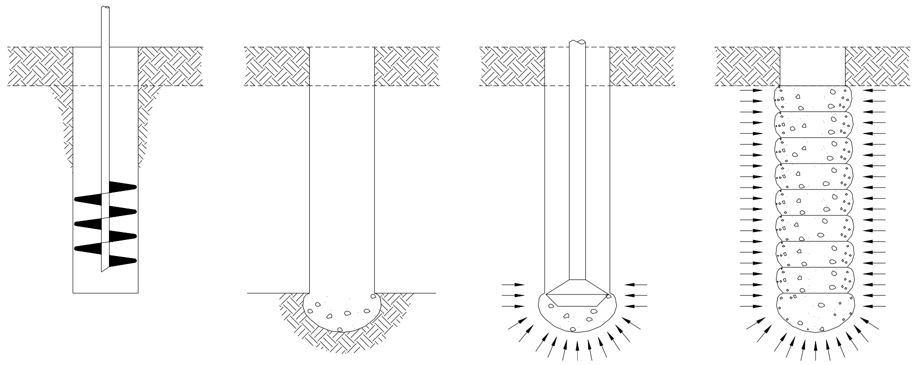

Figure 2: Rammed Aggregate Pier Construction

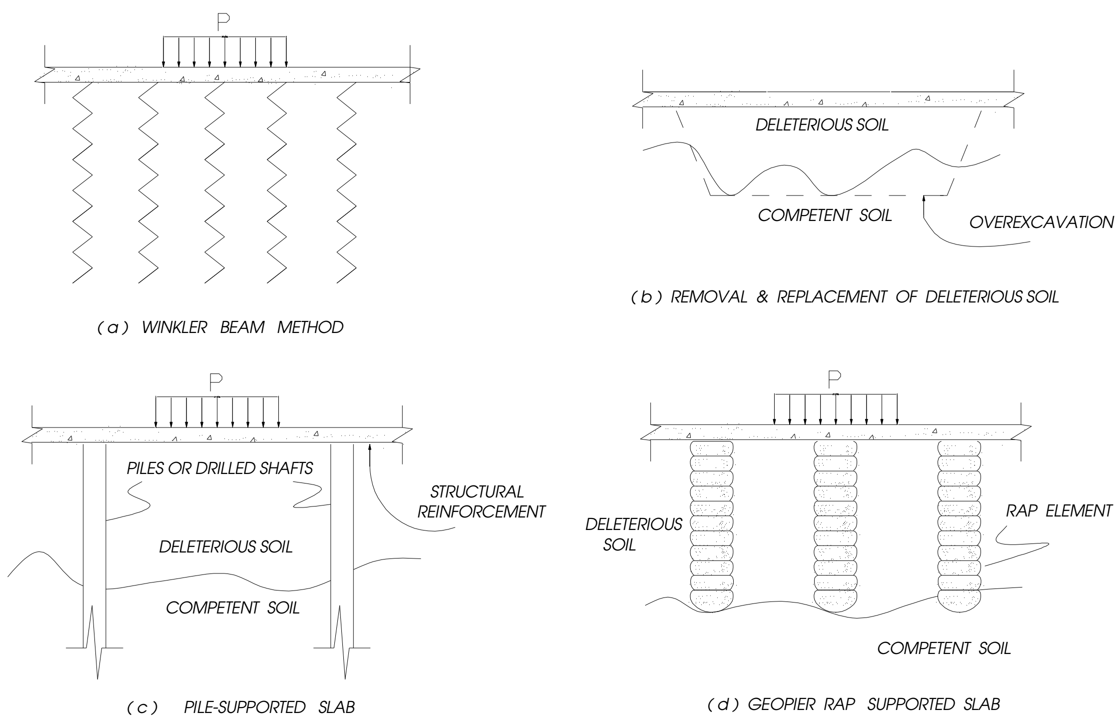

Figure 1: Floor Slab Support Options

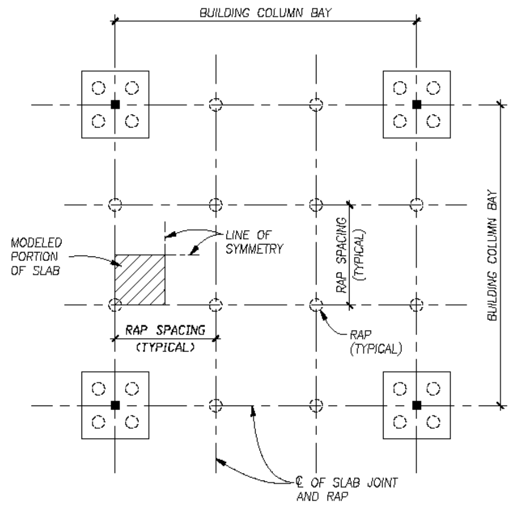

Figure3 - Typical Building Bay

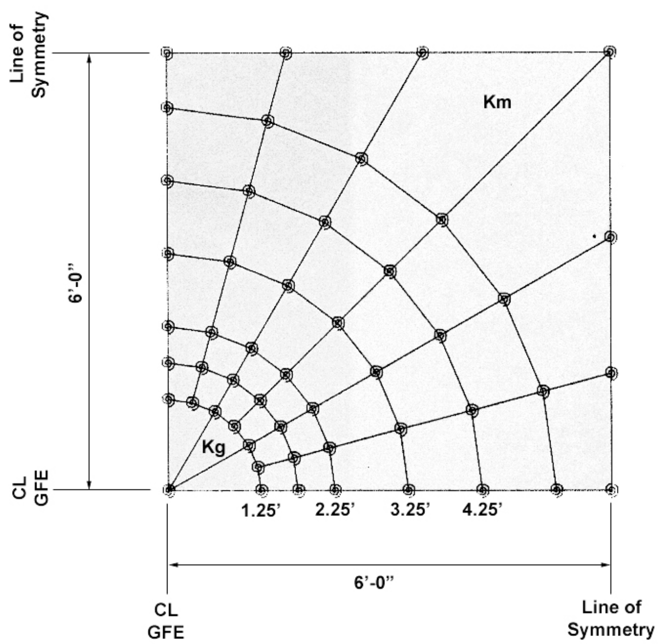

Figure 4: Finite Element Mesh

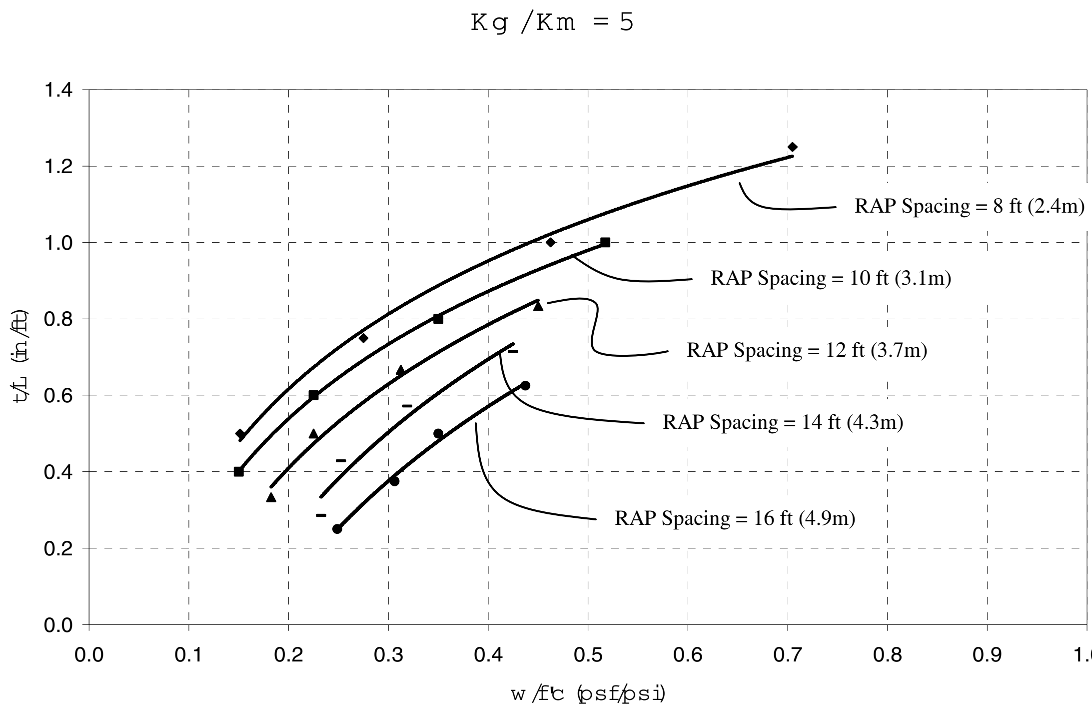

Figure 5: Kg/Km = 5 ; Normalized Thickness Required

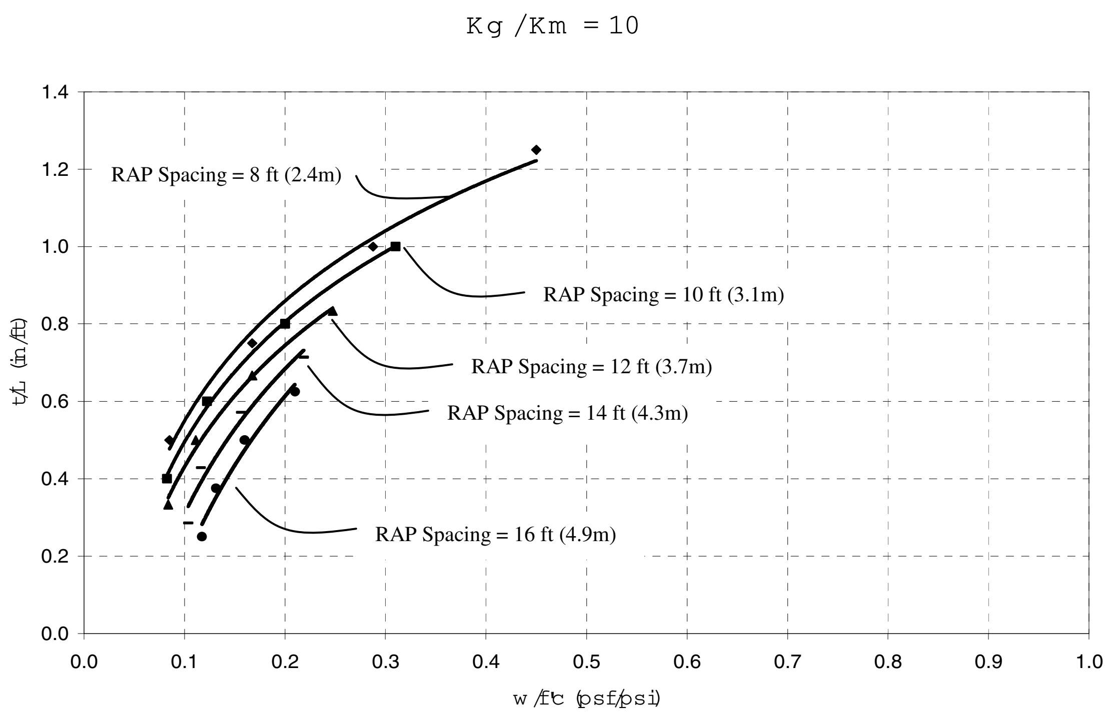

Figure 6: Kg/Km = 10 ; Comparison of Trendlines

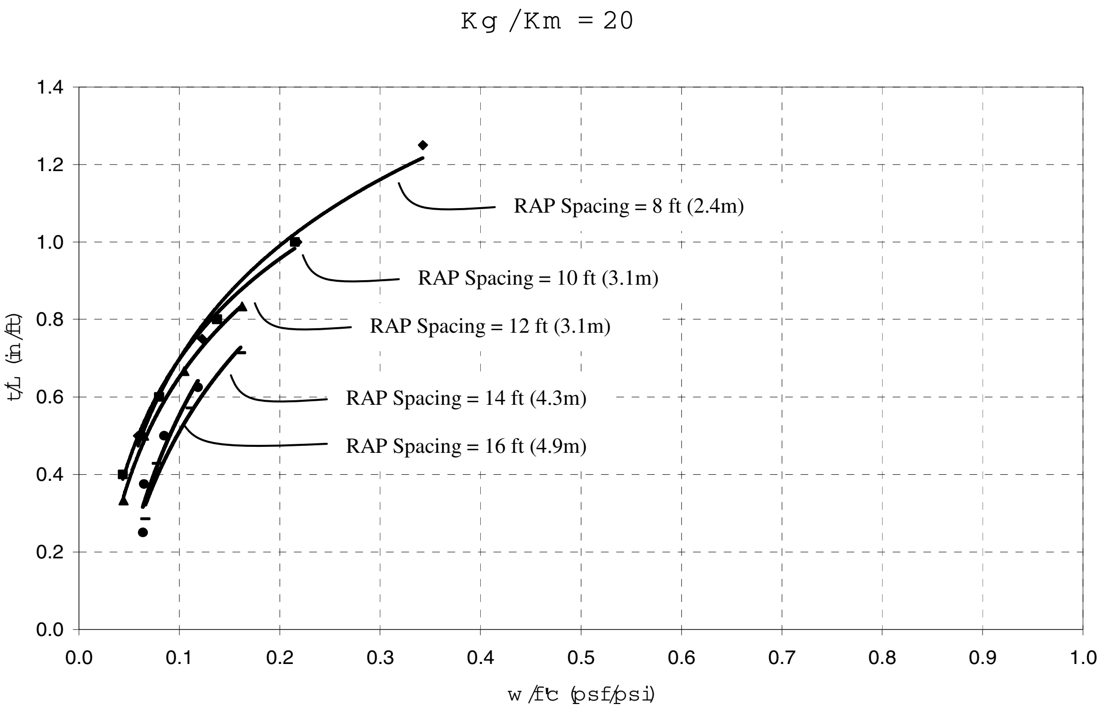

Figure 7: Kg/Km = 20 ; Normalized Thickness