Bitumen Coating for Downdrag Mitigation in Cohesionless Soils

KAMAL S. TAWFIQ AND JOSEPH A. CALIENDO

Effectiveness of bitumen coating in mitigating downdrag in cohesionless soils was investigated using direct shear apparatus and a rod shear test. Tests on soft and stiff bitumen sheared with sand and crushed limestone showed that changes in temperature, shear-strain rate, and normal stress significantly affected the shearing characteristics of bitumen coating. Increasing the normal stresses caused an increase in the soil-particle penetration layer into the bitumen and altered the viscous behavior of the material. High friction resistance was recorded when crushed limestone was used to shear the bitumen layers. Stiff bitumen coating provided better protection against soil penetration than soft bitumen. However, at high temperatures, both bitumens lost their protective capabilities, resulting in a significant soil penetration into the bitumen coating. Bitumen-coated samples tested with sand exhibited the lowest friction. The effectiveness of bitumen coating in this case was 98 percent; it dropped to 54 percent when crushed limestone was used.

Proprietary mechanically stabilized earth (MSE) walls are commonly constructed at bridge abutments in Florida and many other states. Before wall construction, end-bent concrete piles are driven behind the proposed wall. Subsequently, as the wall is constructed, backfill is placed adjacent to the piles and compacted to the desired density. If compressible soil deposits are encountered at the site, relative settlement of the soil surrounding the piles might take place. Accordingly, part of the weight of the soil transfers to the piles, thereby, exerting downdrag forces against the pile shafts. This downdrag effect is commonly termed "negative skin friction," since downward shear stresses are mobilized along the shaft. Observations have indicated that a relative downward movement of about 1 percent of the pile diameter of the soil with respect to the pile is sufficient to fully mobilize the negative skin friction (*1*).

Various methods have been suggested to predict downdrag forces on piles. These methods are based on different assumptions of the behavior of soils adjacent to the pile shaft, and on the distribution of the negative skin friction in the settling zone.

In most cases, the predicted or measured settlement of the soil surrounding a pile shaft is clear indication of a potential downdrag problem within pile foundations. Unless some action is taken to mitigate its effect, the downdrag force could detrimentally affect the economy of the project, and it should be included in the design as an additional axial load.

Small downdrag forces on piles are often neglected in the design. For higher values, the downdrag can be resisted either by

- Providing additional piles;
- Using a preloading method;
- Using bentonite slurry; or
- Using bitumen coating to ease the effect of relative settlement.

K. S. Tawfiq, Department of Civil Engineering, Florida Agricultural Mechanical University/Florida State University College of Engineering, Tallahassee, Fla. 32316-2175; J. A. Caliendo, Department of Civil Engineering, Utah State University, Logan, Utah 84322.

According to Machan and Squier (*2*), benefit/cost studies of each of these alternatives have suggested that bitumen coating is the most cost-effective approach for reducing downdrag in piles.

Several investigators have studied the effectiveness of bitumen coating in mitigating downdrag in piles (*3–6*). Baligh et al. (*7*) suggested a simplified method for determining downdrag loads on bitumen coated piles. For fine-grained soils, the skin friction can be estimated by the following expression:

$$\tau_s = m\left(\frac{\dot{\gamma}}{\dot{\gamma}_o}\right)^n \quad (1)$$

$$\dot{\gamma} = \frac{\dot{\rho}_{av}}{a} \quad (2)$$

where

$\dot{\gamma}$ = average shear strain rate in the bitumen,
$\dot{\rho}_{av}$ = average settlement rate in the soil layer,
a = in situ bitumen coating thickness,
$\dot{\gamma}_o$ = reference shear rate chosen arbitrarily to be 10^{-5} sec^{-1}, and
m, n = temperature-dependent bitumen parameters.

For coarse-grained soils, the maximum value of τ_s can be estimated using the beta (β) method and a reduction parameter ranging from 0.5 to 1.

Fellenius (*8*), on the other hand, stated that one can either rely on actual field tests, if reliance is justified by time and economical considerations, or use the conservative assumption that a properly applied bitumen coat can reduce the negative skin friction to a value of about 200 lb/ft^2. According to Fellenius, this value will adequately predict the downdrag load.

Based on pile-uplift test results, Machan and Squier (*2*), measured 90 percent reduction in downdrag forces on bitumen-coated piles. When downdrag was predicted using bitumen viscosity, the forces were lower than the field measurements. For a precise estimate of downdrag forces of bitumen-coated piles, Machan and Squier emphasized the need for refinement of existing prediction techniques.

STUDY OBJECTIVES

The purpose of the study was to evaluate the effect of temperature, particle size, shearing rate, and normal stresses on the shearing characteristics of bitumen coating and to conduct a thorough investigation in order to refine existing approaches for estimating the negative skin friction, τ_s, on bitumen-coated piles—taking into account the shearing properties of the bitumen-soil matrix. To meet these objectives, concrete blocks coated with two types of bitumens were tested in the laboratory using two different cohesionless soils and a direct shear apparatus. Additional tests were performed in the laboratory using concrete rods coated with bitumen and sheared in a steel mold under loading and ambient conditions similar to those applied in the direct-shear test.

TESTING PROGRAM

In this study, two different particle sizes of cohesionless soils were tested. The first soil was reddish-brown sand with some fines. The second soil was coarse-grained, crushed, Florida limestone. These two types of soils were selected to suit the size of the direct-shear box and the steel mold of the rod-shear test and to fit within the backfill range of MSE walls proposed by the Florida Department of Transportation. Grain-size analysis showed that the first soil was a well-graded sand with 2 percent fines, and the second one was a well-graded gravel with less than 1.3 percent fines. In the study soil, 8 percent of the particles were larger than the thickness of the bitumen coating used in the investigation, whereas 70 percent of the soil particles in the crushed limestone were larger than that thickness.

For bitumen coating, AC-5 and AC-30 bitumens were selected. AC-5 has a minimum penetration grade of 212 at 25°C, whereas AC-30 has a minimum penetration grade of 70 at 25°C. The flash points for the first and the second bitumen were 268°C (515°F) and 257°C (495°F), respectively.

SAMPLE PREPARATION AND PROCEDURE

Direct-Shear Test

To simulate the shearing mechanism between the pile shaft and the coating material during downward movement of the soil, concrete blocks were prepared to model the pile surface. These blocks were also used to replace the lower half of the shear box in the direct-shear apparatus. The blocks were 12.7 cm × 12.7 cm × 1.25 cm and were reinforced with wire mesh to avoid any cracking during load application and to expedite the distribution of temperature during testing. A large number of these blocks was prepared and cured before coating them with bitumens. The following two sets of samples were prepared for direct-shear testing: (*a*) concrete-bitumen-soil samples and (*b*) concrete-soil samples without bitumen coating.

A typical coated concrete sample was prepared for direct-shear test by heating the bitumen to 150°C and then pouring the emulsion in a 6-cm × 6-cm steel mold to adepth of 0.32 cm. This depth was in accordance with the Florida Department of Transportation's requirements for the thickness of bitumen coating (*9*). Before pouring the bitumen, the steel mold was lubricated using high-vacuum grease, to facilitate the detachment of the mold upon bitumen solidification. The bitumen layer was positioned on the concrete block so that it coincided with the soil sample in the upper half of the shear box. To avoid any distortion during the storage period, the cured bitumen remained in the steel mold until minutes before it was transferred to the direct shear apparatus. After setting the coated block in the direct shear container, the upper half of the shear box was then lubricated and carefully lowered on the bitumen layer to a distance of about 1 mm from the concrete surface. A preweighed soil specimen was then placed in the shear box and carefully tamped to the desired density.

Figure 1 shows a schematic of the shear box used in testing. In this investigation, the normal stresses varied from 18.85 kPa to 40.64 kPa. Shearing stresses on the samples were applied at a constant rate of deformation. In this study, three rates of deformation were used. These rates varied from 0.0025 mm/min to 1 mm/min. Accordingly, the rates of shear strain, $\dot{\gamma}$, ranged from 1.3×10^{-5} sec^{-1} to 5.25×10^{-3} sec^{-1}. The shear strain rate, $\dot{\gamma}$, in the bitumen coating equals the deformation rate of the upper half of the shear box divided by the coating thickness.

The concrete-bitumen-soil samples were tested at 25°C (77°F), 56°C (133°F), and 5°C (41°F). During testing, measurements of vertical deformation, horizontal deformation, and shear load were recorded for further analysis. After testing, the samples were visually examined to assess the amount of disturbances in the bitumen layers and to evaluate the effect of the shear stresses, temperature, and normal stresses on the soil-particle penetration into the bitumen coating.

Rod Shear Test

A rod shear test was devised in the laboratory to simulate the negative skin friction induced by the relative movement between the pile and the soil (Figure 2). A similar testing approach was used by Bush et al. (*10*) except that the coated rod was sheared against the steel mold.

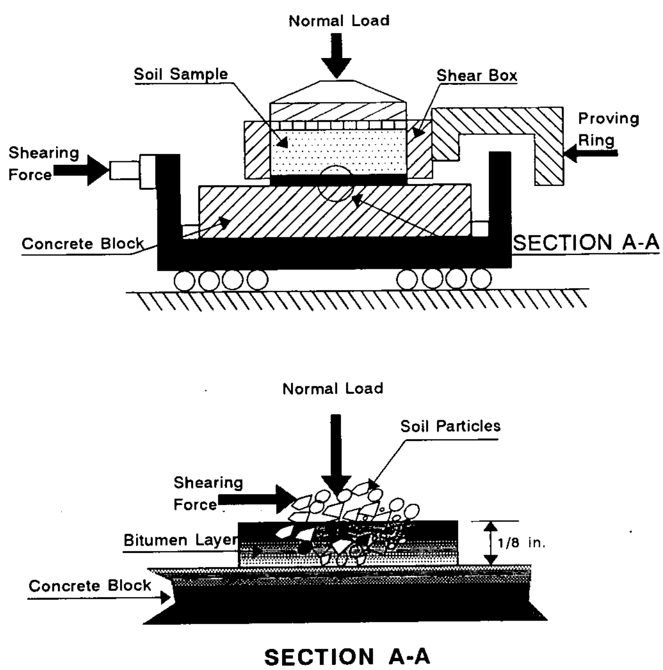

FIGURE 1 Schematic of direct shear test.

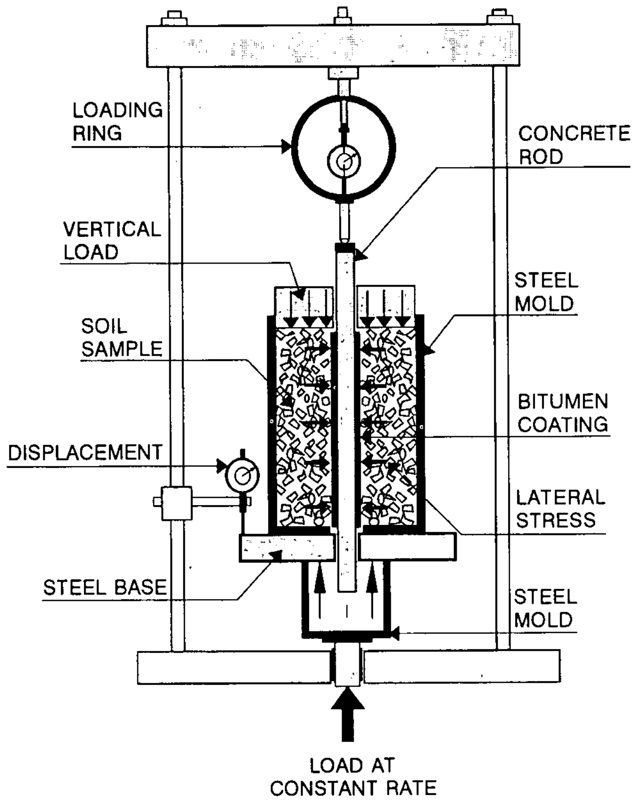

FIGURE 2 Schematic of rod shear test.

In the rod shear test, a concrete rod, 30 cm in length and 3 cm in diameter, was coated with a 3.2-mm bitumen layer. The rod was placed vertically in a steel mold 15.2 cm in diameter and 17.8 cm high. A hole with a 3.7-cm diameter was drilled in the base of the mold so that the rod could advance through it during testing. After centering the rod in the mold, a soil sample was placed adjacent to the coated portion of the rod. The entire length of the coated part (16 cm) was in contact with the soil. The soil samples used were the same as for the direct shear tests. The setup was placed on a loading frame, and a predetermined vertical load was then placed on the soil surface to produce lateral effective stresses, $\overline{\sigma_h}$, which ranged from 2 kPa to 5 kPa. These stresses were obtained as follows:

$$\overline{\sigma_h} = \overline{\sigma_v} \cdot k_o \quad (3)$$

where $\overline{\sigma_v}$ is vertical effective stress and k_o is $1 - \sin \phi$. It was not possible to obtain higher lateral stresses because of the limited number of dead loads that could be added to the setup. Vertical loading was applied on the concrete rod under controlled rate of displacement.

Testing a typical rod was initiated by driving the steel mold upward using a stepping motor while the bitumen-coated rod was kept in place by the loading ring. The shear resistance induced by the relative displacement was recorded from the loading ring, and the rate of deformation was measured from the dial gage attached to the mold base. Shear-strain rates used in the rod shear testing ranged from 1.3×10^{-5} sec^{-1} to 5.25×10^{-3} sec^{-1}. At the end of each test the coated rod was removed from the mold and visually inspected to evaluate the severity of the soil-particle penetration into the bitumen.

DISCUSSION OF RESULTS

Test results from 96 samples showed that the ambient temperature and the shear-strain rate have a significant effect on the shearing behavior of bitumen-coated blocks. The normal stress σ_h and the grain size affected the penetration of the soil particles into the bitumen layers. The unavoidable penetration caused a significant increase in the friction resistance of the bitumen-soil matrix. Figures 3 to 5 depict the shearing behavior of the samples at different shearing rates, temperatures, and normal stresses. These relationships are plotted in terms of shear-stress ($\log \tau_s$) versus shear-strain rate ($\log \dot{\gamma}$). Similar representations for the shearing behavior of different bitumens were followed by Baligh et al. (7). The shear strain rate $\dot{\gamma}$ equals the horizontal displacement rate of the upper shear box divided by the bitumen coating thickness, *d*. These plots constituted liner relationships in which the slopes and the points of intersection of the lines represent the values of *m* and *n* parameters in Equation 1.

For the AC-5-bitumen-coated samples sheared with sand (less than 5 percent of the particles were larger than the coating thickness), the shear resistance τ_s was the highest at 5°C. As the temperture increased, the shear resistance decreased until it reached the lowest value at 56°C. This increase in the ambient temperature decreased the viscosity of the bitumen to a level at which the bitumen functioned as a lubricant material to the sand particles. The shear resistance, τ_s, at 56°C was significantly lower than the resistance at 5°C. The effect of the soil-particle penetration on the shearing of the bitumen-coated samples was apparent at all the temperatures used in testing. Increasing the normal stresses caused an increase in the shear resistance. However, the shearing behavior of the bitumen (without soil penetration) should be independent of normal stresses.

The same behavior was observed in the AC-30-bitumen-coated samples sheared with both types of soils. As the ambient temperature increased, the shear resistance of the bitumen coating decreased. At 56°C, the shear resistance, τ_s, of the crushed limestone samples (70 percent of the particles were larger than the bitumen-coating thickness) increased abruptly once the normal stress was increased to 40.64 kPa, and it exceeded the shear resistance obtained at 25°C. This mobilization of the shear stresses was a clear indication that full-particle penetration was attained at this normal stress. At 25°C and 5°C, a gradual increase in the values of the shearing resistance, τ_s, with the increase of the normal stresses was recorded.

This increase was also caused by the built-up friction between the soil particles and the concrete surface. At this stage, the bitumen functioned as a visco-frictional material. Measurements of the vertical deformation proved that full soil penetration had taken place during direct shear testing. These measurements showed that the amount of vertical deformation exceeded the thickness of the bitumen coating. In addition, a visual inspection after testing ascertained that a substantial penetration by the large particles occurred in the bitumen coating.

Results from the rod shear testing corresponded with those obtained from the direct shear tests. The shear-stress versus strain-rate relationships of the rod shear tests (Figures 3 to 5) exhibited the same slopes, *n*, as they had for the direct shear lines. However,

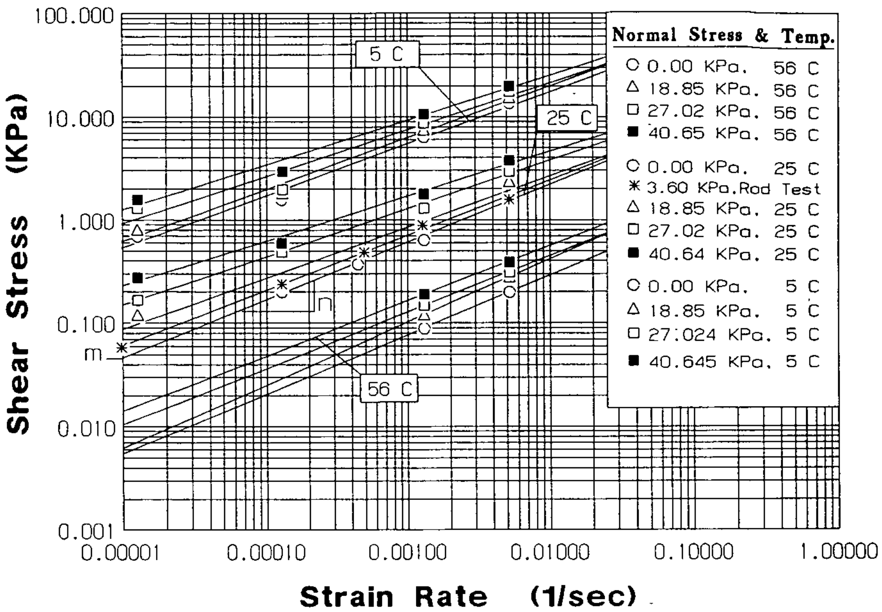

FIGURE 3 **Shear stress versus shear strain rate of concrete-bitumen-soil samples, AC-5 bitumen and sand.**

the effect of the sand-particle penetration on the shear resistance of bitumen coating in the rod shear test was less insignificant. This is because the magnitudes of the normal stresses that could be attained in this method were too small to induce considerable soil penetration. However, the induced lateral stresses were sufficient to produce full penetration of the limestone particles into the bitumen layer.

Characterization of Shear Resistance in Bitumen Coating

The magnitude of the downdrag forces in bitumen-coated piles is governed by the viscoelastic behavior of the bitumen material, which, in turn, is dictated by the ambient temperature and the rate of shear strain, $\dot{\gamma}$, in the bitumen coating. The strain rate in the

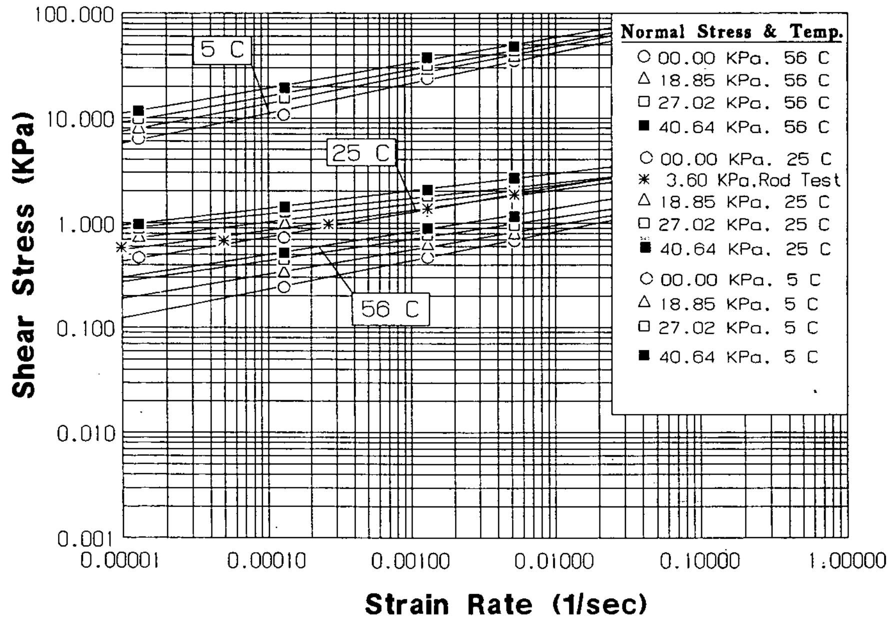

FIGURE 4 **Shear stress versus shear strain rate of concrete-bitumen-soil samples; AC-30 bitumen and sand.**

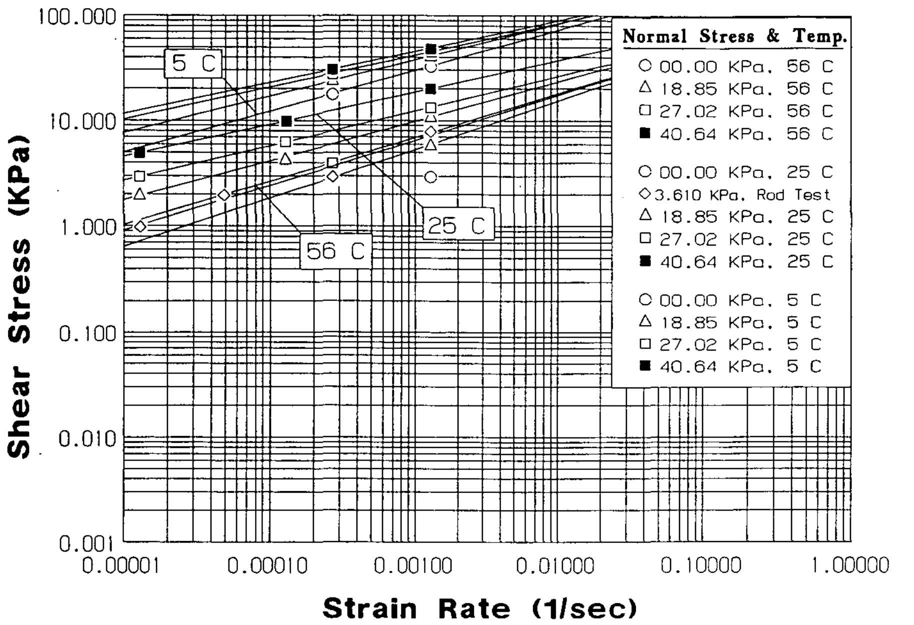

FIGURE 5 Shear stress versus shear strain rate of concrete-bitumen-soil samples; AC-30 bitumen and crushed limestone.

bitumen is proportional to the rate of settlement of the soil layers surrounding the pile shaft. The downdrag on a bitumen coated pile can be determined from

$$F_s = \tau_s (P \cdot L) \tag{4}$$

where

F_s = downdrag force,
τ_s = shear stress in the bitumen coating,
L = length of the embedded portion of the coated pile, and
P = perimeter of the pile.

The shear stress in bitumen coating is proportional to the shear strain rate $\dot{\gamma}$, and it can be expressed as follows:

$$\log\tau_s = \log m + n \cdot \log\left(\frac{\dot{\gamma}}{\dot{\gamma}_o}\right) \tag{5}$$

where

$\dot{\gamma}_o$ = a reference strain rate equal to 10^{-5} sec^{-1},
m = shear stress at the reference strain rate,
n = slope of the $\log\tau$ versus $\log\dot{\gamma}$ relationship.

The magnitude of m and n parameters can also be obtained from the following relationships:

$$m = m_o\ 10^{-\alpha_m T} \tag{6}$$

$$n = n_o + \alpha_n T \tag{7}$$

where

m_o and n_o = values of m and n at T = 0°C;
α_m = slope of the relationship of m parameter versus temperature; and
α_n = slope of the relationship of n parameter versus temperature (Figures 6 to 9).

In the present study, these parameters were found to be dependent on the effective normal stress and on the type of soil used to shear against the bitumen coating.

Considering the effect of soil-particle penetration on the shearing behavior of bitumen coating, Equations 5–7 alone may not be sufficient to characterize the shear resistance in the bitumen-soil matrix. The results of this investigation showed that the viscous behavior of the bitumen must be modified to accommodate the friction resistance associated with the presence of the soil particles in the bitumen layer. On the basis of the parameters used in this study, Equations 6 and 7 were modified to model the effect of soil-particle penetration on the shear resistance between the bitumen-soil matrix and the pile surface. The following expressions can be used to describe the effect of temperature and normal stress on the soil-particle penetration and, thus, on the shear stresses of bitumen-coated piles:

$$m = m_o\ 10^{\Delta\sigma_n(\tan\phi_o + T\tan\zeta) - \alpha_m T} \tag{8}$$

$$n = (n_o + \alpha_n T) - \Delta\sigma_n\ (\tan\psi + T\tan\theta) \tag{9}$$

where

$\Delta\sigma_n$ = effective normal stress increment,
ϕ_o = angle of friction of the bitumen-soil matrix at T = 0°C and $\dot{\gamma}_o = 1 \times 10^{-5}$ sec^{-1},
ξ = variation in α_m with respect to $\Delta\sigma_n$,
$\psi = \tan^{-1}(n_o - n_T)/\Delta\sigma_o$, and
θ = variation in α_n with respect to $\Delta\sigma_n$.

These parameters depend on the soil and bitumen type. For materials used in this study, the values of these parameters can be obtained from Table 1 along with the values of m_o, n_o, α_m, and α_n. Parameters for samples coated with AC-30 bitumen and tested with crushed limestone were almost similar to those obtained from

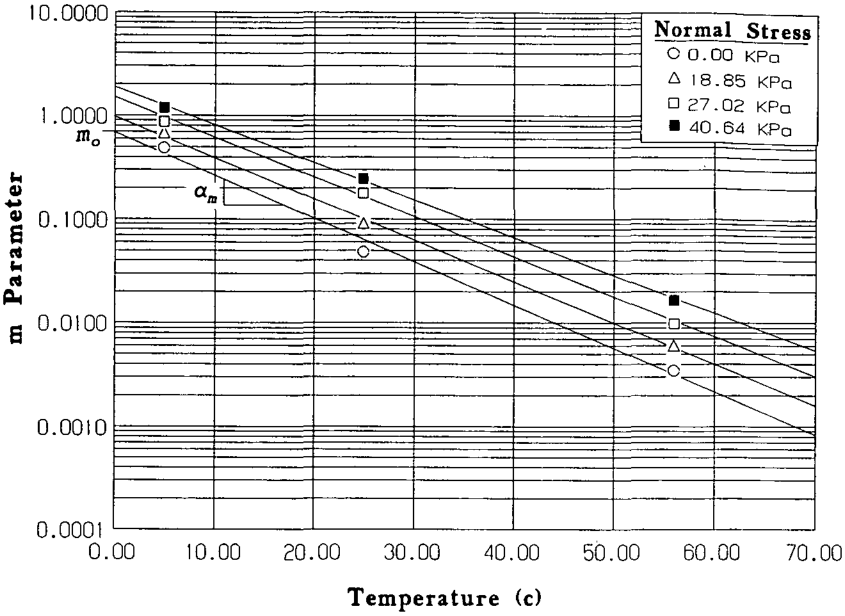

FIGURE 6 **Shear parameter *m* of AC-5 bitumen and sand.**

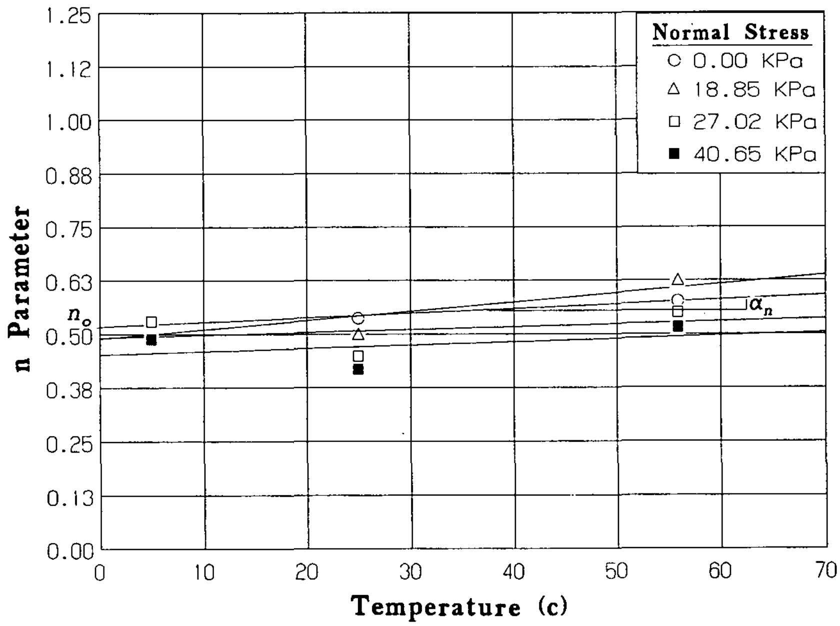

FIGURE 7 **Shear parameter *n* of AC-5 bitumen and sand.**

samples coated with the same bitumen and tested with sand at 5°C and 25°C. However, the considerable penetration of the crushed limestone particles into the bitumen layer at 56°C and 40.6 kPa caused the friction resistance to exceed the values of the shear resistance obtained at 25°C. This sudden increase in the friction complicated the prediction of the shearing behavior of the these samples at 56°C. Therefore, the shear parameters presented in Table 1 for the crushed limestone samples should be used for predicting shear stresses only at temperature levels lower than 56°C.

Other ranges of values can also be obtained for different bitumens and soils. The variation in these values might not be very significant, especially for ϕ_o and ξ, which influence the *m* parameter. However, ϕ_o and ξ were found to have more impact on the shear resistance, τ_s, than ψ and θ parameters.

Illustrative Example

Consider a typical 0.61-m (24-in.) square bitumen-coated pile in a 6-m (18.3-ft) cohesionless backfill behind a proprietary MSE

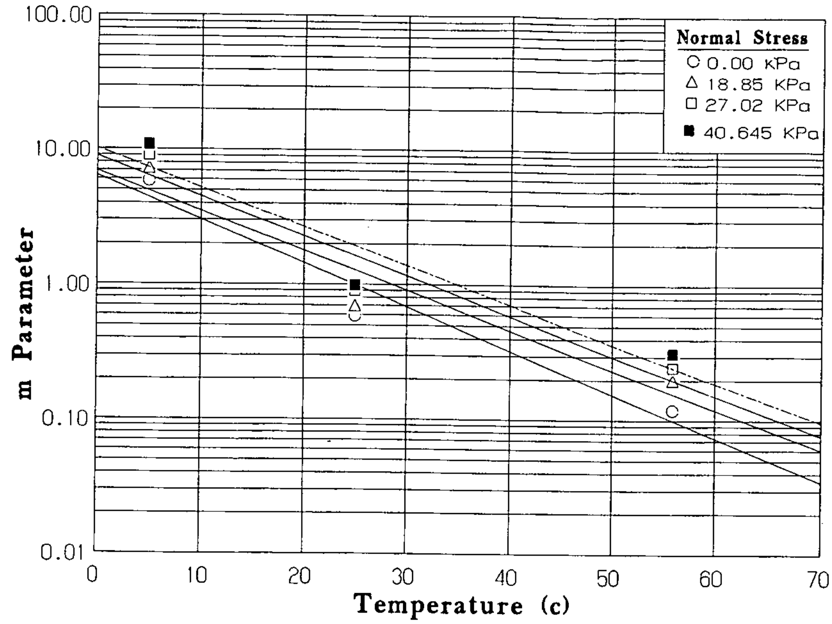

FIGURE 8 Shear parameter *m* of AC-30 bitumen and sand.

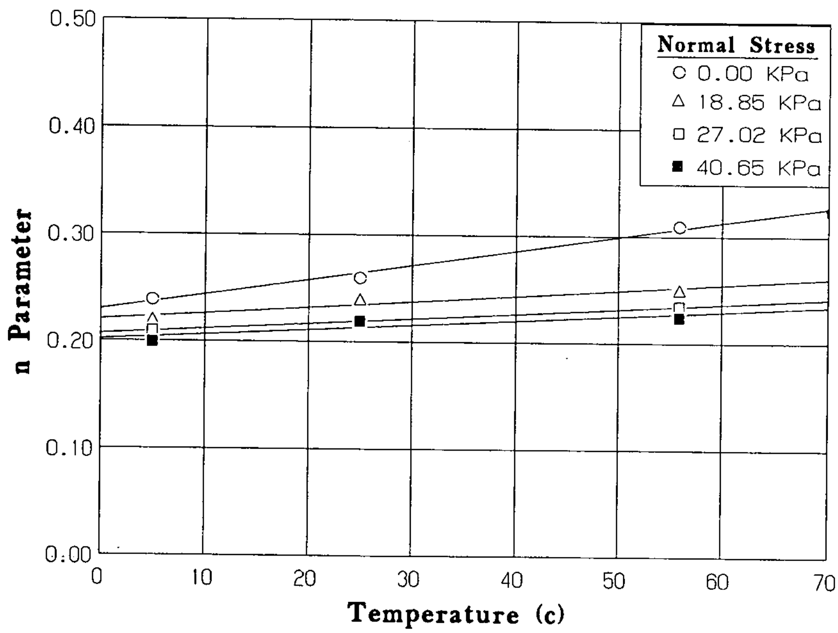

FIGURE 9 Shear parameter *n* of AC-30 bitumen and sand.

wall. The temperature at the site varies during the year from 38°C (100°F) to 0°C (32°F). The ground settlement rate, $\dot{\rho}$, is 12.7 mm/day (½ in. per day). This rate corresponds to the maximum settlement reported by Machan and Squier (*2*) for the Mocks Bottom bridge. Two bitumens, AC-5 and AC-30, are to be used to coat the pile with a 3.2-mm (⅛-in.) layer. Based on the rate of settlement, the value of the strain rate, $\dot{\gamma}$, in the bitumen coating is 4.6×10^{-5} sec^{-1}.

From Table 1, substitute the shear parameters of AC-5 and AC-30 bitumens into Equations 7 and 8 to obtain *m* and *n*, and consider that the subsurface temperature is about 5°C lower than the air temperature at the site. Using Equation 1 for shear-strain rate of 4.6×10^{-5}, the magnitude of the unit friction, τ_s, and the downdrag forces of both bitumens are presented in Table 2. The downdrag force, F_s, on pile without coating is about 138.5 kN (14 tons).

If crushed limestone is to be used as a backfill and AC-30 bitumen for coating, the downdrag load, F_s, on the pile will be equal to 65.88 kN (6.6 tons). This signifies a 54 percent reduction in downdrag. It is clear from Table 2 that the most effective con-

TABLE 1 Shear Parameters of the Concrete-Bitumen-Soil Samples

BITUMEN TYPE	ϕ_o	ξ	ψ	θ	α_m	α_n	n_o	m_o
AC-5-SAND	0.642	0.007	0.102	0.0015	0.042	0.0016	0.526	0.70
AC-30-SAND	0.623	0.005	0.05	0.001	0.0324	0.0014	0.233	6.5
AC-30-LIMESTONE	0.624	0.006	0.062	0.001	0.0324	0.0015	0.35	6.5

TABLE 2 Downdrag on Bitumen-Coated Pile in Cohesionless Soil

BITUMEN TYPE	T = 35° C	T = 25° C	T = 0.0° C
AC-5	m = 0.065	m = 0.17	m = 0.9
	n = 0.54	n = 0.52	n = 0.51
	τ_s = 0.149 kPa	τ_s = 0.373 kPa	τ_s = 1.93 kPa
	F_s = 1.1 kN	F_s = 2.73 kN	F_s = 14.13 kN
	Effectiveness= 98%	Effectiveness= 97%	Effectiveness= 89%
AC-30	m = 0.80	m = 1.8	m = 6.2
	n = 0.26	n = 0.22	n = 0
	τ_s = 1.127 kPa	τ_s = 2.52 kPa	τ_s = 8.47 kPa
	F_s = 8.25 kN	F_s = 18.43 kN	F_s = 62 kN
	Effectiveness= 94%	Effectiveness= 86%	Effectiveness= 54%

dition for mitigating downdrag forces on piles is for piles to be adjacent to sand backfill (particle sizes less than the coating thickness) and coated with AC-5 bitumen (or any bitumen with high-penetration grade).

CONCLUSION

This study evaluated experimentally the effect of temperature, particle size, shearing rate, and normal stresses on the shear resistance of bitumen coating. The study indicated that at certain temperatures the effectiveness of bitumen in mitigating downdrag in cohesionless soils is governed by the bitumen's characteristics and the particle size of the soil. The larger the soil particles, the higher the soil penetration into the bitumen coating. The presence of the soil particles in the bitumen could adversely affect its efficiency in mitigating negative skin friction. For the same bitumen, changing the temperature, the strain rate, and the normal stress influences the amount of skin friction on piles. Stiff bitumens such as AC-30 provide better penetration resistance. However, the viscosity of this bitumen is rather high; consequently, the downdrag forces are also high.

To account for the presence of the soil particles in the bitumen coating and for the build up in friction from the increase in the normal stresses, equations were introduced to modify the shear parameters of the bitumen, *m* and *n*. The new shear parameters ϕ_o, ξ, ψ, and θ were suggested to model the visco-frictional behavior of the bitumen-soil matrix. Use of these equations in a parametric analysis showed that as these parameters increase, the downdrag force decreases.

On the basis of the analysis, it was found that the reduction in downdrag could attain 98 percent with soft bitumen coating and sand backfill. The larger the soil particles, the lower the bitumen coating's effectiveness. Finally, it should be noted that the effectiveness of any friction reducer in mitigating downdrag forces should not be ruled out based on the shearing characteristics of the friction reducer acting alone. Rather, the effectiveness of the total matrix (concrete-reducer-soil) should be evaluated under different temperatures and loading conditions.

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