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Creep behavior of recycled asphalt pavement backfill

Le comportement au fluage du remblai pavement d'asphalte recyclé

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ABSTRACT
Experiments were conducted to study the creep behavior of compacted recycled asphalt pavement (RAP), which is a backfill material that can be beneficially re-used in the construction of embankments and retaining structures. A series of constant stress, drained triaxial tests was performed on 100-mm diameter, compacted RAP specimens to assess its response under sustained shear stress. The test data displayed classic creep behavior, with clearly identifiable primary and secondary creep observed in all specimens. Tertiary creep and creep rupture were observed in specimens tested at shear stress ratios greater than 0.64. Fitting the RAP experimental data to a creep model developed for soils indicates that RAP displays creep behavior similar to clays. Models that predict the time to creep rupture were also successfully fit to the experimental data and showed that the time to creep rupture decreased with increasing shear stress ratio. In general, the creep potential of RAP is significant and should be considered in design. The developed creep models can be used to predict the time dependent deformation of projects utilizing RAP backfill.

RÉSUMÉ
Des expériences ont été entreprises pour étudier le comportement au fluage du trottoir réutilisé compact d'asphalte (RAP), qui est un matériel de remblai qui peut être avantageusement réutilisé dans la construction des remblais et des structures de retenue. Une série d'effort constant, les essais à trois axes vidangés ont été exécutés sur 100millimètre le diamètre, spécimens compacts de RAP pour évaluer sa réponse sous l'effort de cisaillement soutenu. Les essais ont montré le comportement classique au fluage, avec le fluage primaire et secondaire clairement identifiable observé dans tous les spécimens. On a observé le fluage tertiaire et la rupture de fluage dans les spécimens examinés aux rapports 0,64 plus grand que d'effort de cisaillement. Le raccord des données expérimentales de RAP à un modèle de fluage développé pour des sols indique que le RAP montre le comportement au fluage semblable aux argiles. Des modèles qui prévoient le temps à la rupture en fluage ont été également avec succès adaptés aux données expérimentales et ont prouvé que le temps à la rupture en fluage a diminué avec l'augmentation du rapport d'effort de cisaillement. En général, le potentiel de fluage du RAP est significatif et devrait être considéré dans la conception. Les modèles développés de fluage peuvent être employés pour prévoir que la déformation dépendante de temps des projets utilisant le RAP remblai.

1 INTRODUCTION

Recycled asphalt pavement (RAP) backfill is an attractive backfill alternative for new construction because pavement demolition materials can be re-used and material disposal is minimized. These issues are particularly important because of concerns regarding limited landfill space for construction demolition disposal. To date, RAP has been used in roadbase construction, retaining wall backfill construction, and embankment fill applications.

RAP is removed and/or reprocessed pavement material containing bituminous asphalt and aggregate. After removal and processing, the resulting RAP fill material is classified as well-graded gravel, with no fines and a maximum particle size of about 40 mm. Creep is a concern for RAP because of the viscoelastic-plastic behavior of the residual bitumen coating the aggregate particles. A series of constant stress, drained triaxial tests was performed on compacted RAP specimens. The specimens were tested at room temperature, at an effective confining pressure of 135 kPa, and at varying percentages of the failure deviator stress. The failure deviator stress was determined from a drained, strain-controlled triaxial test. Ten creep tests were performed at shear stress levels between 0.4 and 0.88. Axial strains were recorded with time during the creep tests until creep rupture occurred or until 1 week had elapsed.

2 CREEP BEHAVIOR

Deviatoric creep is a phenomenon where soils experience time-dependent shear deformations (Figure 1) under sustained shear stresses. Three distinct regions of creep behavior may be observed: primary creep, secondary creep, and tertiary creep

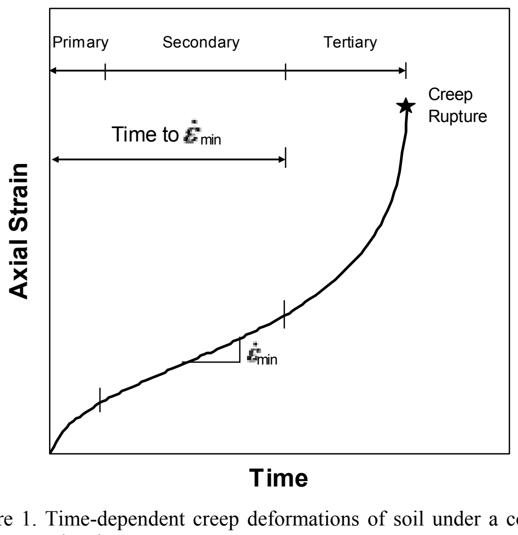

Figure 1. Time-dependent creep deformations of soil under a constant shear stress level.

followed by creep rupture (Mitchell 1993). Primary creep occurs immediately after application of the load; during this stage the strain rate decreases with time. During secondary creep, the strain rate is approximately constant and reaches a minimum value ($\dot{\varepsilon}_{\min}$). The strain rate again increases during tertiary creep until creep rupture occurs. At low stress levels only primary and secondary creep are observed.

2.1 *Strain rate behavior*

Singh and Mitchell (1968) describe a simple, three parameter model to describe the time dependent deformation behavior of soil during the primary and secondary stages of creep. This model describes strain rate as a function of stress level and time using:

$$\dot{\varepsilon} = A \cdot \exp(\alpha D) \cdot \left(\frac{t_1}{t}\right)^m \quad (1)$$

where $\dot{\varepsilon}$ is strain rate, D is the shear stress level ($D = \sigma_d / \sigma_{df}$, σ_d = principal stress difference, σ_{df} = principal stress difference at failure), t is time, t_1 is an arbitrary reference time, and A, α, and m are model parameters. The parameter m is important because it indicates the creep potential of the soil (Singh and Mitchell 1969). Soils with smaller values of m display larger creep strains, and therefore, have a larger creep potential. Mitchell (1993) indicates that typical values of m range from 0.7 to 1.3.

2.2 *Creep failure*

Creep failure can be defined as soil rupture at the end of tertiary creep. Alternatively, some researchers define creep failure as the time to reach the minimum strain rate at the end of secondary creep (Figure 1). Creep failure is critical for soils that display a value of m less than 1.0.

The time to creep rupture increases with decreasing stress level. Previous studies (Singh and Mitchell 1968, Campanella and Vaid 1974) have indicated a semi-logarithmic relationship between time to rupture ($t_{rupture}$) and D:

$$\log(t_{rupture}) = a - bD \quad (2)$$

where a and b are experimentally determined parameters. The time to rupture has also been related to the minimum strain rate achieved before the onset of tertiary creep (Saito 1965, Campanella and Vaid 1974):

$$\log(t_{rupture}) = c - d \cdot \log \dot{\varepsilon}_{\min} \quad (3)$$

Again, c and d are coefficients that are evaluated experimentally.

3 EXPERIMENTAL RESULTS

A series of constant stress, drained triaxial tests was performed on 100-mm diameter, compacted RAP specimens to assess its creep behavior. The material tested had particles up to 16 mm in size with no fines. Drained tests were performed because excess pore pressures typically will not develop in RAP in the field due to its large hydraulic conductivity. Specimens were compacted at a water content of 3% using an impact hammer and the Texas Department of Transportation 113-E standard compaction energy of 1,095 kN-m/m^3. The 3% water content was chosen because it represents the optimum water content for RAP (Rathje et al. 2001). The compacted specimens had a dry unit weight of 18.4 kN/m^3 and void ratio of 0.24, which represents a relative density of about 140%. This is a large relative density, but resulted from the large compaction energy. Tests were performed at an isotropic confining pressure of 135 kPa. This stress is representative of the stresses found in backfill applications (e.g., behind retaining walls). A series of monotonic, strain-controlled triaxial tests was performed to evaluate the drained strength of the compacted specimens in this range of confining pressure. These tests indicated Mohr-Coulomb shear strength parameters of c′ = 72 kPa and ϕ′ = 36 degrees. At a confining pressure of 135 kPa, the principal stress difference at failure (σ_{df}) was approximately 700 kPa and occurred at an axial strain of 6%.

The creep tests were performed at shear stress levels (D) between 0.4 and 0.88. Axial loads were manually adjusted during the tests to maintain a constant shear stress level. Axial strains and volumetric strains were recorded with time, and the tests were continued until creep rupture occurred or until approximately one week had elapsed. Although asphalt behavior is temperature dependent, all of the triaxial tests were performed at room temperature.

3.1 *Strain rate*

Axial strain is plotted versus the logarithm of time in Figure 2 for each of the tests. Tests performed at D ≥ 0.64 failed in creep rupture at times ranging from 15 minutes to almost 7,000 minutes. Tests performed at lower stress levels did not experience creep rupture during testing.

The data in Figure 2 were differentiated with respect to time to develop plots of axial strain rate (% per minute), as shown in Figure 3. These data indicate large initial values of strain rate (10^{-1} to 10^0 % per minute) that decrease with time. At larger stress levels, this behavior is followed by an increase in strain rate as creep rupture is approached. The creep model parameter m (equation 1) is represented by the slope of the linear portion of the curves in Figure 3. Based on these data, values of m range between 0.68 and 0.76 for the tests conducted at D ≤ 0.80. There was no discernable trend of m varying with stress level or time. At larger stress levels, tertiary creep initiated so quickly-that it was difficult to determine an accurate value of m. An average value of m was determined to be 0.7 for the tests conducted. This value is similar to values determined experimentally for clays in an undrained condition (Mitchell 1993), and indicates that RAP has a high creep potential.

Using the procedures described in Singh and Mitchell (1968) and assigning t_1 = 5 minutes, the model parameters A and α were found to be 6.1 and 2.7x10^{-3} % per minute, respectively. For soils, the typical range for A is 1.0 to 7.0, and for α is 2x10^{-8} to 4x10^{-3} % per minute (Kuhn and Mitchell 1993). The values for RAP fall near the upper range of the values determined for soil, again indicating high creep potential for RAP.

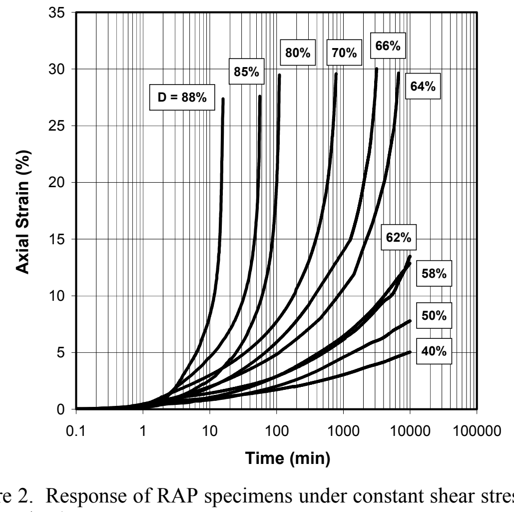

Figure 2. Response of RAP specimens under constant shear stress level ($D = \sigma_d / \sigma_{df}$).

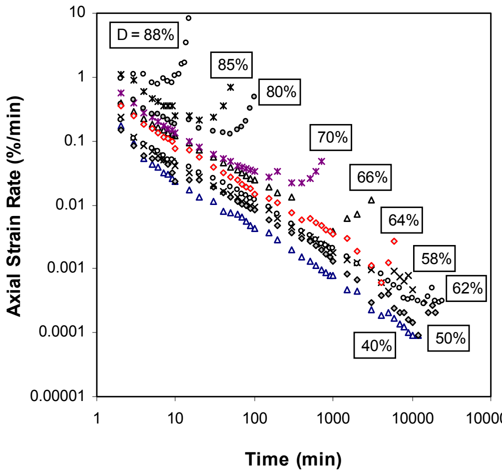

Figure 3. Axial strain rate of RAP specimens under constant shear stress level ($D = \sigma_d / \sigma_{df}$).

3.2 *Creep rupture*

Six of the creep tests, all performed at $D \geq 0.64$, experienced creep rupture within one week. These specimens initially exhibited a log-linear decrease in axial strain rate with time (Figure 3), followed by an acceleration in strain rate leading to creep rupture. The initiation of tertiary creep and imminent creep rupture can be identified in Figure 3 as the point where the axial strain rate reaches a minimum ($\dot{\varepsilon}_{\min}$) and starts to increase. Creep rupture was defined by the asymptotic point in the axial strain versus log(time) plots (Figure 2).

The time required to reach creep rupture ($t_{rupture}$) decreased at larger shear stress levels. For RAP, a linear relationship was observed between log($t_{rupture}$) and shear stress level, D (Figure 4). Fitting Equation (2) to the RAP data produces regression coefficients a = 10.15 and b = 10. Coefficient b indicates that $t_{rupture}$ increases by approximately one order of magnitude as the stress level decreases by 0.1.

For comparison, Figure 4 also shows rupture data from a series of undrained creep tests on Haney clay reported by Vaid and Campanella (1977). The stress levels for the Vaid and Campanella (1977) data were derived from the reported undrained shear strength, which was obtained from isotropically consolidated triaxial tests performed at a strain rate of 1% per minute. At a given shear stress level, the rupture life of Haney clay is longer than the rupture life of RAP (Figure 4). The RAP and clay data are parallel at larger stress levels, but the clay data start to deviate from a linear relationship at stress levels below about 0.8. Based on this nonlinear trend in rupture time, Vaid and Campanella (1977) define an upper yield stress, below which creep rupture does not occur (Figure 4). For Haney clay, the upper yield stress represents a stress level of about 0.77. For RAP, the nonlinear trend was not apparent at stress levels as low as 0.64; thus, an upper yield stress could not be determined in this manner. However, the RAP test performed at a stress level of 0.62 did not experience creep rupture after one week of testing, indicating that the upper yield stress ratio may lie between 0.62 and 0.64.

Other researchers have observed a linear relationship between the logarithm of $t_{rupture}$ and the logarithm of the minimum strain rate ($\dot{\varepsilon}_{\min}$) for various materials ranging from metals (Monkman and Grant 1956) to plastics (Pao and Marin 1952) to soils (Saito 1965). The time to rupture for RAP is plotted versus $\dot{\varepsilon}_{\min}$ in Figure 5 and fit with Equation (3). The data indicate a relationship that is close to linear. For comparison, the proposed relationships for clays by Saito (1965) and for Haney clay by Campanella and Vaid (1974) are also shown. The relationships are similar, but the range between the relationships indicates that $t_{rupture}$ can vary by about an order of magnitude for a given value of minimum strain rate. As a result, rupture relationships developed for one soil should not be used to predict the rupture of other soils.

The point of minimum strain rate signals the initiation of tertiary creep and impending creep rupture. Thus, the time to reach the minimum strain rate ($t_{\dot{\varepsilon}_{\min}}$) may be related to the time to rupture ($t_{rupture}$). Campanella and Vaid (1974) report that the ratio of $t_{rupture}$ to $t_{\dot{\varepsilon}_{\min}}$ for Haney clay was 2.5 to 3.5. For RAP, the ratio was about 1.5 to 2.5. These smaller values indicate that the tertiary stage of creep in RAP is shorter than for Haney clay, providing less warning of imminent rupture.

Although undrained creep tests on clay have indicated that the initiation of tertiary creep ($t_{\dot{\varepsilon}_{\min}}$) and creep rupture ($t_{rupture}$) depend on stress level (e.g., Figure 4), the data also indicate that the strain levels at $t_{\dot{\varepsilon}_{\min}}$ and $t_{rupture}$ are independent of stress level (Campanella and Vaid 1974, Figure 6). In the case of the axial strain at $t_{rupture}$, the strain level is approximately equal to the failure strain obtained in conventional, monotonic triaxial tests. This trend supports the concept that the rupture of soils during undrained creep is similar to the failure of soils in undrained shear, where failure occurs due to excess pore pressures and changes in effective stress that develop at a certain strain level.

For RAP, the cumulative axial strain at the minimum strain rate is plotted in Figure 6 as a function of stress level. In contrast to the data shown for Haney clay from Campanella and Vaid (1974), the axial strain at $t_{\dot{\varepsilon}_{\min}}$ varies considerably with stress level. Additionally, these strain levels are much larger than the axial strain at failure measured in a monotonic, strain-controlled triaxial test ($\varepsilon_f = 6\%$). This result indicates a different mechanism of creep failure for RAP.

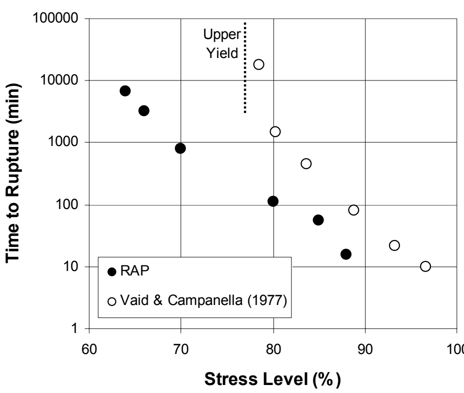

Figure 4. Time to creep rupture for RAP and Haney clay at different shear stress levels (σ_d / σ_{df}).

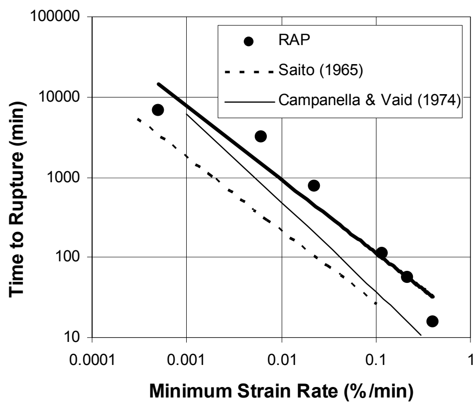

Figure 5. Relationships between time to creep rupture and minimum strain rate for RAP and two clays.

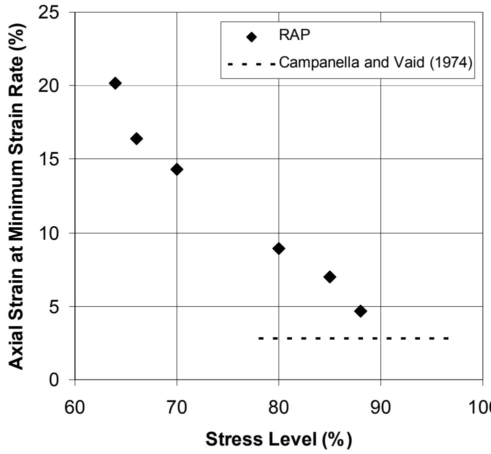

Figure 6. Axial strain at the minimum creep strain rate as a function of shear stress level (σ_d / σ_{df}).

4 DISCUSSION

For clays, most research on creep has focused on the behavior in an undrained condition. These studies have shown that the creep parameter *m* is generally less than 1.0 and creep rupture eventually occurs at larger stress levels due to increasing pore pressures generated by creep deformations. For the drained creep of clay, a creep parameter *m* less than 1.0 also has been reported (Bishop and Lovenbury 1969 and Tian et al. 1994 for normally consolidated clay, Tavenas et al. 1978 for overconsolidated clay). However, the observed strain rates in the drained condition are smaller than those observed in the undrained condition (~10^{-2} to 10^{-4} % per minute at the initiation of drained creep, ~10^{-1} to 10^{0} % per minute at the initiation of undrained creep). Additionally, rupture during drained creep has only been observed in overconsolidated clays, where a dilative response lead to an increase in water content and softening over time.

The drained creep behavior of RAP observed in this study is similar to the undrained creep behavior of clays, in terms of the large strain rates at the initiation of creep (~10^{-1} to 10^{0} % per minute) and the occurrence of creep rupture at larger stress levels. This behavior is unexpected for a gravel material, but is caused by the presence of the residual bitumen coating the particles. Most studies on the creep of bituminous asphalt have not presented the results in a form that can be compared with soil. Considering studies that have evaluated creep as a rate process (e.g., Mitchell et al. 1968, Herrin and Jones 1963), bituminous asphalt is inherently more susceptible to creep than soil.

5 CONCLUSIONS

A series of constant stress, drained creep tests was performed on compacted recycled asphalt pavement backfill. Tests were performed at shear stress levels (D = σ_d / σ_{df}) ranging from 0.40 to 0.88 and deformations were monitored for up to one week.

Classical creep behavior was observed in all specimens, with strain rates decreasing log-linearly with time after the load was applied. The strain rate increased with increasing stress level. The creep parameter *m* was observed to be about 0.7, which is similar to the value observed for clays. The creep parameters *A* and α were evaluated as 2.7x10^{-3} % per minute and 6.1, respectively. These values fall towards the upper range observed for clays, indicating RAP has a large creep potential.

Tests performed at shear stress levels (D) greater than 0.64 experienced creep rupture. The time to rupture decreased as the stress level increased. For a given stress level, RAP appears to rupture more quickly than clay. An upper yield stress ratio, below which creep rupture does not occur, may occur between 0.62 and 0.64 The time to rupture for RAP was also related to the minimum strain rate at the end of secondary creep. This log-linear relationship was slightly higher than similar relationships proposed for clay.

The creep potential of RAP appears to be at least as high, if not higher, than that of clay. When using RAP as backfill in projects that will induce large shear stresses, care should be taken to ensure that the creep deformations are not excessive.

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