USE OF THE PARALLEL GRADATION TECHNIQUE TO ASSESS THE SHEAR STRENGTH OF RECLAIMED ASPHALT PAVEMENT IN DIRECT SHEAR

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Abstract: The demand for pavement construction aggregate is growing significantly. With a rise in aggregate consumption, the use of recycled materials has become an attractive solution in pavement construction from both economical and environmental perspectives. Use of recycled materials in the base course demands understanding of their properties including its shear strength and recognition of potential problems that may arise. The parallel gradation technique involves evaluating the parameters of a coarse material using a gradation that is finer but parallel to the prototype. It has been successfully used for estimating the shear strength parameters under certain conditions. The main objectives of this study are to: assess the applicability of the parallel gradation technique to estimate the shear strength of Reclaimed Asphalt Pavement (RAP) and determine the shear strength parameters of RAP in direct shear at two relative compactions.

Keywords: shear strength, parallel gradation, prototype, direct shear, relative compactions

1   Introduction

The demand for construction aggregate is growing significantly. In the United States, 2 billion tons of aggregate are produced each year and it is expected to increase to more than 2.5 billion tons annually by the year 2020 [1]. This growing need has raised concerns in the highway-related industries and there has been a push for finding alternative materials to replace quarried virgin aggregate.

The U.S. highway system includes nearly 4 million miles of public roads in the country [2]. Many of these roads are maintained by some form of reclamation be it partial or full depth. Removal of these pavements produces waste material. Rehabilitation for these pavements requires large quantities of aggregate. So if the waste material can be recycled for reuse as aggregate, it would reduce the need for virgin aggregate thereby preserving the environment in two ways: (1) reduce the need to quarry as much and (2) eliminate the need to dispose of the waste materials in landfills. Recycling of pavement materials date back as early as 1915 but its interest grew significantly in response to inflated construction costs [3]. However, there is a need for the recycled materials to perform well over the pavement life cycle. Therefore, there is a need to understand their engineering properties.

Some encouraging studies have shown that pavements constructed using recycled materials are as durable as those constructed with 100 percent virgin aggregate [3]. In this study, the shear strength of Reclaimed Asphalt Pavement or RAP having a gradation that is close to a base course gradation in Hawaii is estimated by conducting direct shear tests in conventional size equipment.

2   Literature review

2.1 Applications of recycled materials

The engineering properties of RAP are of particular interest to pavement and geotechnical engineers. They include gradation, shear strength, stiffness, etc. One way of assessing the quality of an aggregate for use as a road base or sub-base is by looking at its shear strength [4 & 5]. Two of the more common laboratory tests to measure a granular material's shear strength are the triaxial and direct shear tests

2.2 Reclaimed Asphalt Pavement (RAP)

RAP is obtained by milling or from full-depth removal of asphalt concrete. In the latter, a milling machine removes the asphalt concrete in a single pass. In full-depth removal, a rhino horn on a bulldozer and/or pneumatic pavement breakers are used to rip and break the pavement.

The properties of RAP are mainly dependent on the properties of the constituent materials used in the old pavement. The quality of RAP varies since it can be obtained from any number of pavement sources. RAP can be blended with virgin aggregate to produce a higher quality unbound material.

2.2.1   Shear strength of RAP

Several researchers have measured the shear strength of RAP, a summary of which is provided in Table 1. In the literature reviewed, the shear strength of RAP was measured either via consolidated drained (CD) or unconsolidated undrained (UU) triaxial tests. CD test friction angles (ϕranged from 37^0 to 57.5^0 with cohesion (c) ranging from 0 to 55.2 kPa.

2.3 Parallel gradation technique

The parallel gradation technique has been previously used for estimating the shear strength parameters of very coarse granular materials by testing the same material having a gradation that is parallel to the original. The main advantage is that without the oversized particles, conventional-size testing equipment can be used [6, 7, 8, 9, and 10] while at the same time maintaining the soil gradation relative to the original material. Several researchers have found that a finer parallel gradation gave similar friction angles to the same geological material with a coarser gradation provided the mineralogy, hardness of grains, particle shape, and particle roughness do not vary with particle size [10, 11, 12, 13, 14, and 15]. It can be an attractive alternative especially if the particle shape, particle surface roughness, hardness of grains and mineralogy are similar for all particle sizes [10].

3   Material characterization

3.1 Index properties and test gradation

The index properties of RAP are presented in Table 2. Of note are the very low absorption, very low optimum moisture content and very high maximum dry density.

To test the samples in a small shear box, the material was first dried in an oven at 60^0C. This temperature was selected to avoid softening the asphalt. If the RAP did soften, it can act as an adhesive and glue the particles together. The RAP was then sieved to various particle sizes for rebatching. Then, a gradation that is close to the State of Hawaii Department of Transportation's (HDOT) specification for 0.75-inch maximum nominal base course was selected as the target test gradation (Figure 1). This gradation contains little to no fines and is slightly more uniform than HDOT's base course. As such, it will provide conservative shear strength parameters.

Also shown in Figure 1 are two gradations that are parallel to but finer than the target test gradation. These two finer gradations were batched and tested in direct shear. The coarser of the two gradations (scalped on the 0.265-inch sieve) was tested in a 100-mm-square shear box while the finer (scalped on the 4.75 mm sieve) was tested in a 61.4-mm-diameter shear box.

Table 1: *Summary of RAP characteristics from the literature*

State	Aggregate type	Confining Stress/ kPa	Failure deviator stress/ kPa	USCS and AASHTO Symbol	G_s	w_{opt} (%)	γ_d (kN/m³)	$\gamma_{d\,max}$ (kN/m³)	Relative Compaction (%)	Test Type	Peak ϕ (°)	Peak c (kPa)	Reference Note
Texas	NK	34.5, 68.9, 137.9, 206.8, 344.7	NK	GW A-1-a	2.33	3	NK	18.4	NK	CD[1] Triaxial	37.0	55.2	Viyanant, (2006), Rathje et al. (2006[a]), and Rathje et al. (2006[b])
California	NK	0, 35, 70,105	NK	GW A-1-a		5.5	NK	22.9	95	CD[1] Triaxial	51.5	0	Bejarano, (2001)
									100		57.5	0	
Texas	NK	82.7, 117.2, 158.6, 255.1, 310.3	515, 642.6, 739.8, 1149.4, 1254.2	GW A-1-a	2.28	6.7 / 4.9 / 3.9 / 3.9 / 4.1	[a]18.3 / [a] 18.6 / [a] 18.9 / [a] 18.8 / [a] 18.7	NK	NK	CD[1] Triaxial	39.0	55.2	Carley (2001)
Florida-Hammermill	Lime rock	35,70, 105	NK	SW A-1-a	NK	5.5	[b] 18.5	NK	NK	UU[2] Triaxial	44.0	15.9	Cosentino and Kalajian, (2001)
Florida-Tubgrinder			NK	SP A-1-a	NK	6.6	[b] 19.0	NK	NK		35.0	46.2	
Illinois	NK	34.5, 68.9, 103.4, 137.8	NK	GW A-1-a	NK	7.2	NK	19.7	NK	UU[2] Triaxial	45.0	130.9	Garg and Thompson (1996)
Mississippi – OGDL[3]	Limestone		185, 283, 450	GP A-1-a	NK	6.3	NK	19.5	95	UU[2] Triaxial	38.5	28.8	Saeed (2008)
Louisiana – OGDL[3]		0, 34.5, 103	163, 261, 425	GP A-1-a	NK	5.4	NK	19.4	95		39.0	19.2	
Denver – finer DGBL[4]	Granite		77.2, 222, 441	GW A-1-a	NK	10.3	NK	19.8	95		41.0	14.3	

Note: (1) CD = consolidated drained; (2) UU= unconsolidated undrained; (3) OGDL= Open Graded Drainage Layer; (4) DGBL =Dense Graded Base Layer.
NK= not known; [a] Condition not given; [b] Modified proctor test

Table 2 *Summary of index properties*

Properties	RAP[1]	
LA Abrasion (%)[1]: Grading C	33	
LA Abrasion (%)[1]: Grading D	27	
	Fine[2]	Coarse[3]
Bulk Specific Gravity	2.17	2.54
Bulk Specific Gravity (SSD)[4]	2.31	2.61
Apparent Specific Gravity	2.52	2.72
Absorption (%)	6.3	2.5
Void Content (%)[5]	50.0	
Optimum Water Content (%)[6]	5.05	
Maximum Dry Density (kgm^{-3})[6]	1808	
Asphalt Content (%)[7]	5.8	

Notes
1) Per AASHTO T96.
2) Per AASHTO T84.
3) Per AASHTO T85.
4) SSD = Specific surface dry.
5) Per AASHTO TP56.
6) Per ASTM D1557 Method C (modified Proctor).
7) Per AASHTO T308.

Based on the gradations shown in Figure 1, the RAP can be classified as GW using the Unified Soil Classification System (USCS), and as A-1-a using the American Association of State Highway and Transportation Officials (AASHTO) classification system. Based on the parallel gradations with a maximum particle size of 4.75 mm, the RAP is classified as SP using the USCS, and as A-1-a using AASHTO.

3.2 Parallel gradation test results

A comparison of the Mohr-Coulomb failure envelopes for the small and large shear boxes are shown in Figure 2. The RAP samples were compacted to the same dry densities and moisture contents in both the large and small shear boxes. It can be seen that the Mohr Coulomb envelopes for the two shear box sizes are very similar.

One limitation of the parallel gradation technique is that if the original coarse material contains a significant amount of fines, a parallel gradation would contain even more fines and if excessive, the overall behavior of the material will be governed by the fines [8]. Since the sample contained little fines, the parallel gradation technique appears applicable for the RAP gradations tested as seen by the results in Figure 2.
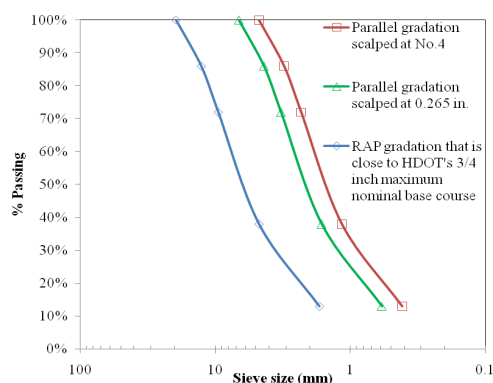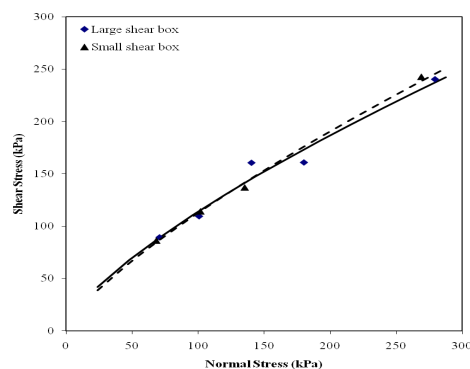

Figure 1: *Target and parallel gradations of RAP*

Figure 2: *Mohr-Coulomb failure envelop based on direct shear testing for large and small shear boxes on RAP*

3.3 Direct Shear Tests Results

For the direct shear testing program, "loose" and "dense" RAP samples were tested in the shear box at four different normal stresses. Details of the target sample densities and water contents are summarized in Table 3. All samples were 28.8 mm high.

Table 3: *Details of samples tested in direct shear*

Physical State	Dry Density (kg m^{-3})	Water Content (%)	Relative Compaction (%)
"Loose"	1722	4.76	95
"Dense"	1809	4.76	100

A summary of the direct shear results are provided in Figures 3 and 4 for "dense" and "loose" RAP, respectively. The test results are plotted in terms of shear stress (τ = horizontal shear force/initial area) normalized with the normal stress (σ = vertical load/initial area) versus shear strain (γ = horizontal displacement normalized by the original sample height) even though it is known that the shear strains are not uniform along the failure plane. Also, the volumetric strain (ε_v), equal to the change in height divided by the original sample height, is plotted versus γ. ε_v is positive for compression and negative for dilation.

Figures 3a and 4a provide an instant indication of the linearity (or nonlinearity) of the Mohr-Coulomb envelops at the peaks and at large strains. In figures 3b and 4b, the volumetric strain is plotted versus shear strain. Failure was defined when the shear stress peaked or at 20% shear strain if there was no peak in shear stress. Table 4 summarizes the shear strains at failure and at critical state.

From figures 3 and 4, the following observations are offered:
o The highest τ/σ occurs at the lowest normal stress and this ratio decreases with increasing σ. This is an indication that increasing σ reduces the brittleness. Also, increasing σ increases the strain to failure, and decreases the tendency to dilate.
o The strains at failure for "loose" RAP (16.5% to 20.0%) are higher than those for "dense" RAP (7.7% to 20.0%). For "loose" RAP, a τ/σ peak at shear strains less than 20% was obtained only at the lowest normal stress. On the other hand, "dense" specimens have peak τ/σ at shear strains less than 20% except for the highest normal stress. Therefore, brittleness is affected by both normal stress and relative density.
o It was interpreted that critical state occurred at a shear strain of 34.4%. Critical state is said to be reached when shearing occurs at constant volume. In this study, the shear strain at which critical state occurred was taken to be the strain at which the coefficient of variation of τ/σ is a minimum. Using this definition, values of τ/σ at critical state varied from 0.876 to 0.975.
o All the RAP samples were dilative at failure except for "loose" RAP at the two highest normal stresses.

3.4 Mohr-Coulomb envelop
Figure 5 presents a plot of the Mohr-Coulomb failure envelop for "dense" and "loose" RAP. The peak failure envelope was nonlinear with secant friction angles varying from 41.2^0 to 48.3^0 for "loose" RAP and 42.1^0 to 51.6^0 for "dense" RAP at the highest and lowest normal stresses, respectively. The friction angles for "dense" RAP are only slightly higher than those in the "loose" state. This is expected for poorly graded materials since the advantage of a higher relative compaction cannot be realized if there are insufficient fines available to fill in the voids. Critical state friction angles for "loose" RAP ranged from 41.2^0 to 43.3^0 and for "dense" RAP from 41.8^0 to 44.3^0.

For a cohesionless material, the Mohr-Coulomb failure envelope can be expressed as follows:
$$\tau = \sigma \tan\phi \qquad\qquad (1)$$
where τ = shear stress, σ = normal stress and ϕ = friction angle. The curvature of the envelop and the secant value of ϕ decreases as the normal stress increases due to increased particle breakage according to Duncan and Wright [16]. Secant values of ϕ with curved envelopes can be modeled as follows [16]:
$$\phi = \phi_0 - \Delta\phi\tan\frac{\sigma}{p_a} \qquad\qquad (2)$$

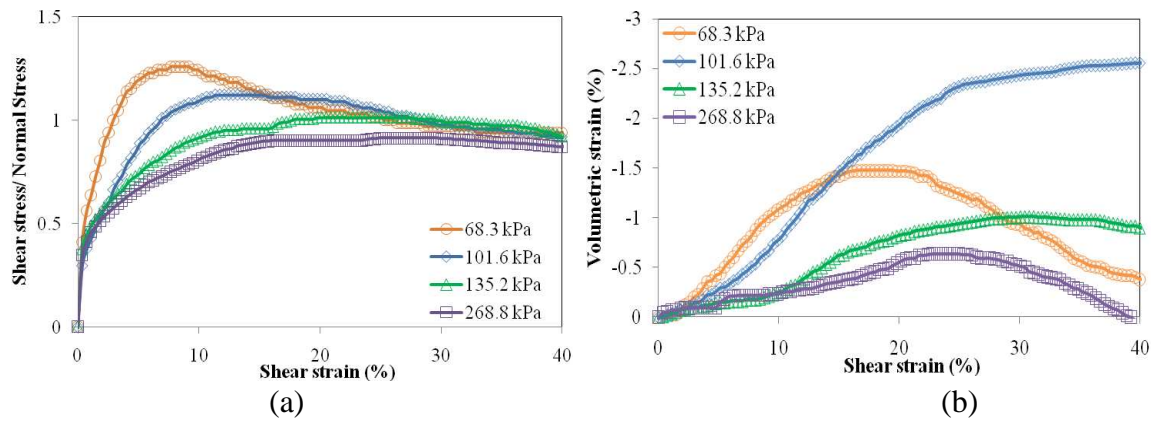(a)   (b)

Figure 3: *Direct shear test results for "dense" RAP scalped on the No. 4 sieve: (a) normalized shear stress and (b) volumetric strain versus shear strain. [Normal stresses shown in legend. Volume change sign convention: (+) for compression and (–) for dilation.]*

where ϕ_0 = friction angle at a normal stress = 1 atmosphere, p_a = atmospheric pressure, and $\Delta\phi$ = slope of ϕ versus $\log(\sigma/p_a)$ plot. Values of $\phi_0 = 45.7^0$ and $\Delta\phi = 11.2^0$ fitted the peak failure envelop well (R^2 =0.9384) for "loose" RAP and $\phi_0 = 48.3^0$ and $\Delta\phi = 15.9^0$ fitted well (R^2 =0.9707) for "dense" RAP.

(a)   (b)
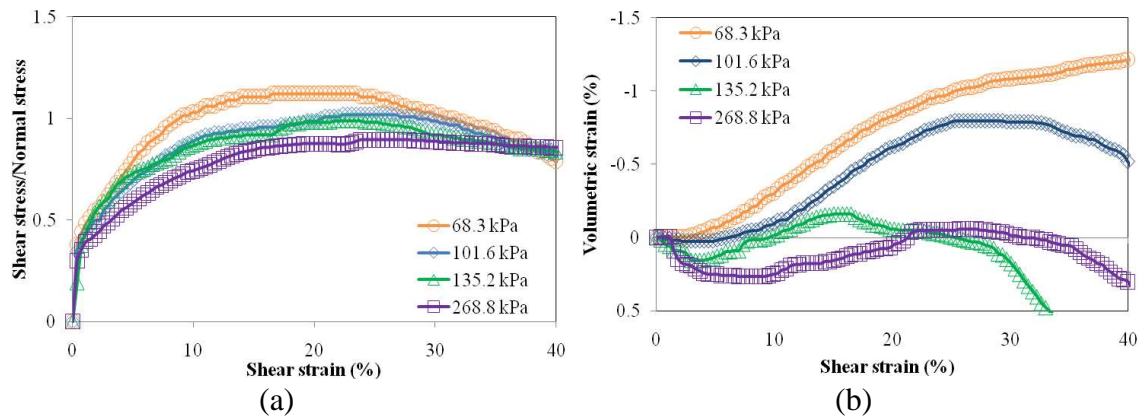
Figure 4: *Direct shear test results for "loose" RAP: (a) normalized shear stress and (b) volumetric strain versus shear strain. [Normal stresses shown in legend. Volume change sign convention: (+) for compression and (–) for dilation.]*

Table 4: Test results for "loose" and "dense" RAP

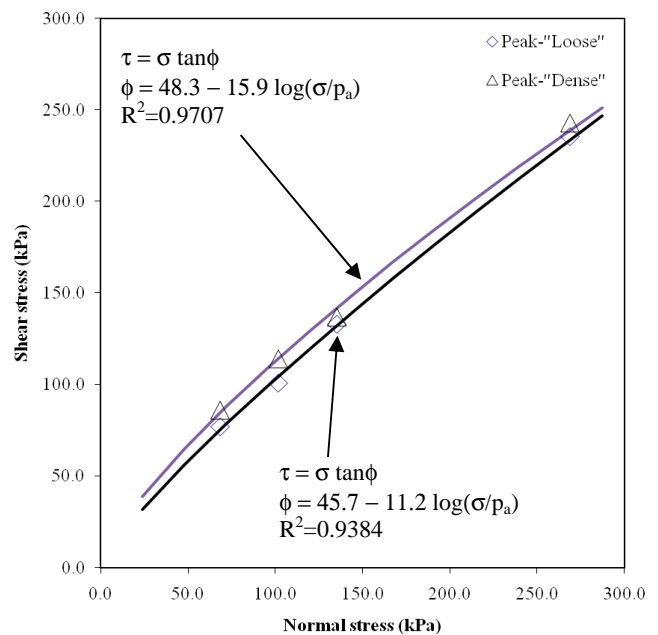| Relative Compaction[1] (%)	Normal Stress (kPa)	Failure[2]		Critical State	
		Friction Angle (degrees)	Shear Strain (%)	Friction Angle (degrees)	Shear Strain (%)
95	68.3	48.3	16.5	43.3	34.4
	101.6	44.7	20.0	42.6	34.4
	135.2	44.5	20.0	41.4	34.4
	268.8	41.2	20.0	41.2	34.4
100	68.3	51.6	7.7	43.3	34.4
	101.6	48.3	11.4	43.8	34.4
	135.2	45.4	19.8	44.3	34.4
	268.8	42.1	20.0	41.8	34.4

Figure 5: *Peak strength Mohr-Coulomb envelop based on direct shear testing for "Dense" and "Loose" RAP*

3.5 *Validity of Measured Friction Angle*

It is well known that the direct shear test suffers from many shortcomings. As a consequence, different friction angles and failure envelops can be obtained if the shear strength were to be measured using other types of tests. There is an interesting question as to how different the friction angles will be. The following equation [17] relates the friction angle from direct shear (ϕ_{ds}) with the friction angle from triaxial compression (ϕ_{tc}).

$$\dot{\phi}_{tc} = \frac{\tan^{-1}\left[\frac{\tan\phi_{ds}}{\cos\phi_{crit}}\right]}{1.12} \qquad (3)$$

where ϕ_{crit} = friction angle at critical state. Based on an average $\phi_{crit} = 42.7^0$ for RAP, Equation 3 suggests $\phi_{ds} \sim \phi_{tc}$ at 59.3^0. Above 59.3^0, $\phi_{ds} > \phi_{tc}$ and below 59.3^0, $\phi_{ds} < \phi_{tc}$. However, the difference between ϕ_{ds} and ϕ_{tc} is at most 3.3^0 for the range of measured ϕ_{ds} values at failure.

Many design problems are treated as plane strain in practice. It can be shown using Rowe's [18] equation below that the friction angle in plane strain testing (ϕ_{ps}) is at most 8.8^0 higher than in direct shear for the range of ϕ_{ds} measured and assuming $\phi_{crit} = 42.7^0$.

$$\tan \phi_{ds} = \tan \phi_{ps} \cos \phi_{crit} \qquad (4)$$

Thus for the RAP tested, ϕ_{ds} is at most 3.3^0 lower than ϕ_{tc} and the direct shear test provides a conservative value of ϕ compared with plane strain testing, which is not common in practice. Thus, it can be concluded that the results presented herein are appropriate for practical purposes.

4 Summary and conclusions

In this study, the shear strength of RAP having a gradation that is close to a base course gradation was estimated by conducting direct shear tests on a gradation that is parallel to it. This parallel gradation is finer and allows the use of conventional size test equipment (61.4-mm-diameter shear box). The following conclusions are offered:

- The peak Mohr-Coulomb failure envelope was nonlinear with secant friction angles varying from 41.2^0 to 48.3^0 for "loose" and 42.1^0 to 51.6^0 for "dense" RAP at the highest and lowest normal stresses, respectively. The friction angles for "dense" RAP are only slightly higher than those in the "loose" state indicating the effects of relative compaction are small for the range of values (95% to 100%) adopted and for this test gradation. Of note is that the values are not insignificant.
- The highest τ/σ occurred at the lowest normal stress and this ratio decreased with increasing σ. Also, increasing σ increased the strain to failure (ductility), and decreased the tendency to dilate.
- The strains at failure for "loose" RAP (16.5% to 20.0%) are higher than those for "dense" RAP (7.7% to 20.0%). Therefore, brittleness was affected by both normal stress and relative density.
- All RAP samples were dilative at failure except for the "loose" RAP tested at the two highest normal stresses.
- Critical state friction angles for "loose" RAP (41.2^0 to 43.3^0) are close to those for "dense" RAP (41.8^0 to 44.3^0). This is reasonable as the critical state friction angle is independent of the molding density.
- Based on theoretical equations relating the friction angle from direct shear (ϕ_{ds}) to the friction angle from triaxial compression (ϕ_{tc}) and to those from plane strain testing (ϕ_{ps}), it was found that the direct shear test provides conservative values of ϕ that are appropriate for practical purposes.

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