Comparative Study of Permanent Strain and Damping Characteristics of Coarse Grained Subgrade Soils with Resilient Modulus

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ABSTRACT
The resilient modulus (M_R) is used to represent the subgrade soil stiffness in the Mechanistic-Empirical Pavement Design Guide. The resilient modulus is typically estimated in the laboratory using a dynamic triaxial test. Dynamic triaxial tests can also be used to determine permanent strain and damping characteristics of subgrade soils. In addition to the resilient modulus, the permanent deformation and damping characteristic of subgrade soils also need to be studied to properly understand the subgrade soil behavior under dynamic traffic loading. Soils having good resilient modulus may or may not have small permanent strains and lower damping under repeated loading. Therefore, it is necessary to study resilient modulus with both permanent strain and damping characteristics of subgrade soils. In this study, repeated load triaxial tests were performed following AASHTO T307 on remolded soil samples collected from different regions of South Carolina. The samples were prepared at optimum moisture contents (w_{opt}) and ±2% w_{opt}. Resilient modulus, permanent strain and damping of subgrade soils were measured under different repeated deviatoric loads and confining pressures. Statistical models were developed to correlate resilient modulus model parameters (k_1, k_2, k_3), permanent strain model parameters (α_1, α_2, α_3, α_4) and damping model parameters (β_1, β_2, β_3) with soil index properties. Models were also developed to correlate permanent strain and damping with subgrade soils resilient modulus. Results showed that both permanent strain and damping decreases if resilient modulus increases for different South Carolina coarse grained soils.

Keywords: Resilient modulus, Moisture content, Permanent deformation, Damping, MEPDG.

INTRODUCTION

Permanent deformation (i.e., pavement rutting) is considered a structural distress that affects both the functional condition and structural health of flexible pavements. Different traffic (*1, 2*), materials (*3, 4, 5, 6, 7, 8*), and climate inputs (*9, 10*) have influence on pavement rutting in the Mechanistic Empirical Pavement Design Guide (MEPDG). Among these inputs, the subgrade soil resilient modulus (M_R) has the most significant effect on permanent deformation or pavement rutting (*11*). Typically, soils having higher M_R show less permanent deformation or permanent strain. However, some mixed soils (i.e., silty sands, sandy silts) exhibit high resilient characteristics and still yield significant rutting (*12, 13*). Therefore, it is necessary to correlate resilient modulus with permanent strain for mixed soils.

Numerous studies have been performed to establish test methods to measure the permanent deformation of soils (*14, 15, 16*). One of the most widely used methods is to estimate permanent strain potentials of soils from M_R test results (*17*). Permanent strain (ε_p) can be found directly in the laboratory using M_R tests or repeated load cyclic triaxial tests at different confining and deviatoric stresses. However, the M_R test is complex, time-consuming and expensive to perform. Therefore, correlations of M_R and ε_p to other parameters that are easier to obtain are often developed (*18*). Correlations between soil index properties and M_R model parameters have been developed in some previous studies (*19, 20, 21, 22, 23*). Some literatures also showed correlations between ε_p model parameters and soil index properties (*17, 24*). However, none of the previous studies simultaneously correlated M_R and ε_p model parameters with soil index properties. Therefore, there is a need to study both the M_R and ε_p with the soil index properties for the same set of soils.

Like permanent deformation, the damping characteristics of subgrade soils are also important to understand resilient behavior under repeated loading. The soil damping coefficient (ξ) is defined as the dissipation of energy due to dynamic loading and can be determined using cyclic triaxial tests or resonant column tests (*25*). Several studies have examined soil damping properties with shear modulus (*26, 27, 28, 29*) and a few studies have developed damping models using shear strain parameters (*30, 31*). Recently, the feasibility of estimating damping properties with resilient modulus were explored in a single study (*32*). In that study, damping models with resilient modulus model parameters were developed. There is still a need to develop damping models with cyclic stresses and confining pressures of repeated load triaxial tests, and to correlated damping model parameters with soil index properties.

In this study, repeated load triaxial tests were performed following AASHTO T307 on remolded soil samples collected from different regions of South Carolina for MEPDG local calibration. The samples were prepared at optimum moisture content (w_{opt}) and ±2% w_{opt}. M_R and ε_p of the subgrade soils were measured under different repeated deviatoric loads and confining pressures. Model coefficients were established for the resilient modulus model, the permanent deformation model, and the damping model using multiple linear regression. Statistical models were developed to correlate the M_R model parameters (k_1, k_2, k_3), ε_p model parameters (α_1, α_2, α_3, α_4), and ξ model parameters (β_1, β_2, β_3) with soil index properties. Correlations between M_R and ε_p, and M_R and ξ were also developed.

METHODOLOGY

Subgrade soils were collected from three different asphalt concrete (AC) pavement sections that were selected to represent different soil regions above and below the fall line in South Carolina (Figure 1). The selected pavement sections are US-321 (Orangeburg County, Coastal Plain, near fall line), US-521 (Georgetown County, Coastal Plain), and SC-93 (Pickens County, Piedmont Region). Bulk samples of subgrade soil were collected from the boreholes made in the center of the right lane at 1500 to 3000 ft spacing. Laboratory index tests were performed on the bulk samples: grain size analysis (ASTM D6913/AASHTO T311), Atterberg Limits (ASTM D4318/AASHTO T90), specific gravity (ASTM D854/ AASHTO T100), maximum dry density and optimum moisture content (ASTM D698/AASHTO T99), and moisture content tests (ASTM D2216/AASHTO T265). Soils from each borehole were classified according to USCS (ASTM D2488) and AASHTO (AASHTO M145).

M_R tests were performed in accordance with AASHTO T307. Specimens were prepared by compacting the soil in a CBR (California bearing ratio) mold (6 in. diameter and 7 in. height (without the disk spacer), compacted in 4 layers, 65 blows per layer) at moisture contents of ±%2w_{opt} and w_{opt}. After compacting the soil in the CBR mold, a 3 in. diameter Shelby tube was pushed into the soil to collect a 3 in. x 6 in. cylindrical specimen. The specimen was then extruded, inserted into a rubber membrane and subjected to a static confining pressure in a triaxial chamber. A repeated axial cyclic stress of fixed magnitude, load duration, and cycle duration was applied to perform the M_R tests.

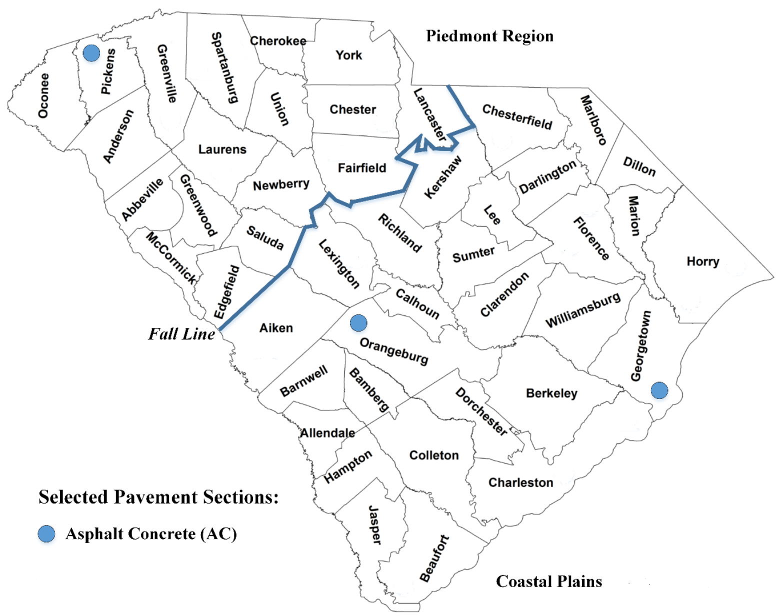

Figure 1. Selected Pavement Sections

M_R is defined as the ratio of the repeated maximum axial cyclic stress to the resultant recoverable or resilient axial strain and is used to represent the stiffness of the unbound layer subjected to repeated traffic loading. From different models developed to correlate M_R with stresses and fundamental soil properties, the generalized constitutive resilient modulus model is the most widely used (*33*):

$$M_R = k_1 P_a \left[\frac{\sigma_b}{P_a}\right]^{k_2} \left[\frac{\tau_{oct}}{P_a} + 1\right]^{k_3} \tag{1}$$

where P_a is atmospheric pressure, σ_b is bulk stress = $\sigma_1 + \sigma_2 + \sigma_3$, σ_1 is the major principal stress, σ_2 is the intermediate principal stress, σ_3 is the minor principal stress, τ_{oct} is the octahedral shear stress, and k_1, k_2 and k_3 are model parameters/material constants.

For permanent deformation, the following four-parameter permanent strain model formulation was used to explain individual effects of confining and deviatoric stresses on plastic strain (*13*):

$$\varepsilon_p = \alpha_1 N^{\alpha_2} \left[\frac{\sigma_{oct}}{P_a}\right]^{\alpha_3} \left[\frac{\tau_{oct}}{P_a}\right]^{\alpha_4} \quad (2)$$

where N is the number of load repetitions, σ_{oct} is the octahedral normal stress = $(\sigma_1 + \sigma_2 + \sigma_3)/3$, and α_1, α_2, α_3 and α_4 are model parameters of the formulation. A total of 2,500 load cycles were applied for the cyclic triaxial tests.

For damping coefficient, the following model formulation was developed to explain major principal stresses and confining pressures on damping coefficient. Damping was determined from the area of the hysteresis loop of the stress-strain curves of M_R tests stated on a previous literature (*25*).

$$\xi = \beta_1 \left[\frac{\sigma_1}{P_a}\right]^{\beta_2} \left[\frac{\sigma_c}{P_a}\right]^{\beta_3} \quad (3)$$

where P_a is atmospheric pressure, σ_1 is the major principal stress, σ_c is the confining stress, and β_1, β_2 and β_3 are damping model parameters.

INDEX TEST RESULTS

Table 1 shows the properties of the investigated soils. The samples listed represent one sample for each of the 8 different soils (considering both USCS and AASHTO) found at the pavement sites.

Table 1 Properties of Investigated Soils

Site	Bore-hole No.	% Passing No. 200 Sieve	*LL* (%)	*PL* (%)	*PI* (%)	G_s	w_{opt} (%)	$\gamma_{d,max}$ (kN/m^3)	Soil Classification	
									USCS	AASHTO
US-321	B-1	24.7	26	17	9	2.66	10.1	19.8	SC	A-2-4
	B-2	20.6	18	17	1	2.39	10.7	19.4	SM	A-2-4
	B-3	22.8	20	16	4	2.6	10.6	19.5	SC-SM	A-2-4
US-521	B-1	1.5	NA	NA	NA	2.65	9.3	19.5	SP	A-1-b
	B-2	0.8	NA	NA	NA	2.71	12.2	17	SP	A-3
SC-93	B-1	43.8	45	29	16	2.55	15.1	17.6	SM	A-7-6
	B-2	51.2	36	26	10	2.52	16.3	17.7	ML	A-4
	B-3	44	42	28	14	2.51	13.8	18.5	SC	A-7-6

Note: *LL* = liquid limit, *PL* = plastic limit, *PI* = plasticity index, G_s= specific gravity of soil, w_{opt}= optimum moisture content, $\gamma_{d,max}$= maximum dry unit weight, NA = not available.

RESILIENT MODULUS MODEL PARAMETERS

M_R model parameters were obtained for the generalized constitutive resilient modulus model (Equation 1) and are shown in Table 2 for three moisture conditions (dry, optimum, wet) for all 8 types of soils. Most of the test results show good coefficient of determination ($R^2 > 0.80$). These M_R values are representative of a bulk stress of 154.64 kPa and octahedral stress 13 kPa. Results indicate that specimens prepared on the dry side of w_{opt} have a higher M_R than those prepared at w_{opt}, and those prepared at w_{opt} have a higher M_R than those prepared on the wet side of w_{opt}.

Using multiple liner regression, the M_R model parameters $(k_1, k_2, and\ k_3)$ were correlated with soil index properties: soil dry density (γ_d), moisture content (w), maximum dry density

($\gamma_{d,max}$), optimum moisture content (w_{opt}), percent passing through No. 4 (P_4), No. 40 (P_{40}), and No. 200 sieve (P_{200}), D_{60}, D_{50}, D_{30}, D_{10}, uniformity coefficient (C_u), coefficient of curvature (C_c), liquid limit (LL), plastic limit (PL), plasticity index (PI), liquidity index (LI), specific gravity (G_s), and the percent sand, silt, and clay. All of the soils are classified as coarse grained soils (P_{200}>50%) except for SC-93 B-2 according to the AASHTO soil classification system (Table 1). However, according to the USCS soil classification system, US-321 and SC-93 soils are considered as mixed soil, and US-521 soils are classified as poorly graded sand. Table 3 shows the coefficients for the developed models. Coefficients of determination (R^2) of 0.43, 0.61 and 0.71 were found for k_1, k_2, and k_3, respectively. Table 3 shows the significance of different soil properties on the coefficients and overall model significance using p-value, where $p < 0.001$ indicates a statistically highly significant effect. $p < 0.01$ and $p < 0.05$ indicate statistically moderate and low significant effects, respectively. For the 8 soils tested, P_4, LI, w_{opt} and $\gamma_{d,max}$ showed a statistically significant effect on k_1, k_2 and k_3; w and γ_d showed a statistically significant effect on k_1 and w, γ_d, and G_s showed statistically significant effect on k_2.

Table 2 Resilient Modulus Model Parameters

Site	Soil	State	γ_d (lb/ft^3)	w (%)	k_1	k_2	k_3	R^2	M_R (MPa)
US-321	B-1	Dry	123.2	8.5	1219	0.5585	-1.8260	0.92	125
		w_{opt}	124.6	10.2	617	0.5820	-1.7710	0.70	65
		Wet	118.4	12.0	303	0.2642	1.6491	0.63	42
	B-2	Dry	117.7	7.0	955	0.6050	-0.7623	0.96	114
		w_{opt}	121.2	8.9	667	0.7167	-0.4379	0.97	87
		Wet	118.9	10.5	480	0.6250	0.5291	0.86	68
	B-3	Dry	123.8	8.0	879	0.8272	-2.1703	0.96	97
		w_{opt}	124.5	9.3	617	0.6108	-0.1492	0.82	79
		Wet	115.5	11.9	188	0.7616	-0.1470	0.81	26
US-521	B-1	Dry	121.0	7.8	1134	0.5054	-1.3099	0.97	121
		w_{opt}	122.6	9.5	777	0.3886	-0.3628	0.96	89
		Wet	119.3	11.2	449	0.3814	1.2511	0.79	62
	B-2	Dry	108.5	10.3	830	0.4098	0.5921	0.99	107
		w_{opt}	109.0	11.9	763	0.5265	0.4989	0.99	103
		Wet	104.2	13.7	694	0.4645	0.4067	0.99	90
SC-93	B-1	Dry	111.1	13.2	1047	0.4518	-3.0797	0.95	89
		w_{opt}	112.8	14.7	1147	0.4173	-4.4504	0.94	81
		Wet	110.7	16.7	292	0.4084	-4.7921	0.67	20
	B-2	Dry	98.0	16.9	1183	0.3862	-2.1402	0.87	109
		w_{opt}	103.4	18.1	1192	0.3151	-3.1520	0.90	94
		Wet	103.2	19.8	1037	0.4409	-5.1491	0.90	68
	B-3	Dry	116.2	11.2	1288	0.3607	-1.8520	0.85	122
		w_{opt}	117.5	13.2	1093	0.6480	-5.4391	0.94	76
		Wet	115.1	14.3	389	0.6976	-6.1519	0.87	25

Table 3 Developed Resilient Modulus Model Coefficients for South Carolina

Models	R^2	F value
$k_1 = -25340.939^{**} + 238.99P_4^{**} - 43.411LI + 12.77(w_{opt} \times \gamma_{d,max})^{***} - 92.557(\gamma_{d,max})^{**} + 559.692(\frac{w}{w_{opt}} \times \frac{\gamma_d}{\gamma_{d,max}})$	0.43	3.58*
$k_2 = +9.958^{**} - 0.075P_4^{*} + 0.037LI^{***} - 0.002(w_{opt} \times \gamma_{d,max})^{**} - 0.635(\frac{w}{w_{opt}} \times \frac{\gamma_d}{\gamma_{d,max}})^{***} - 0.613(G_s)^{*} + 0.839(\frac{\gamma_d}{\gamma_{d,max}})^{*} - 0.078$	0.61	6.06***
$k_3 = -63.2 + 0.682P_4^{*} - 0.235LI^{**} - 0.03(w_{opt} \times \gamma_{d,max})^{***}$	0.71	21.01***

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

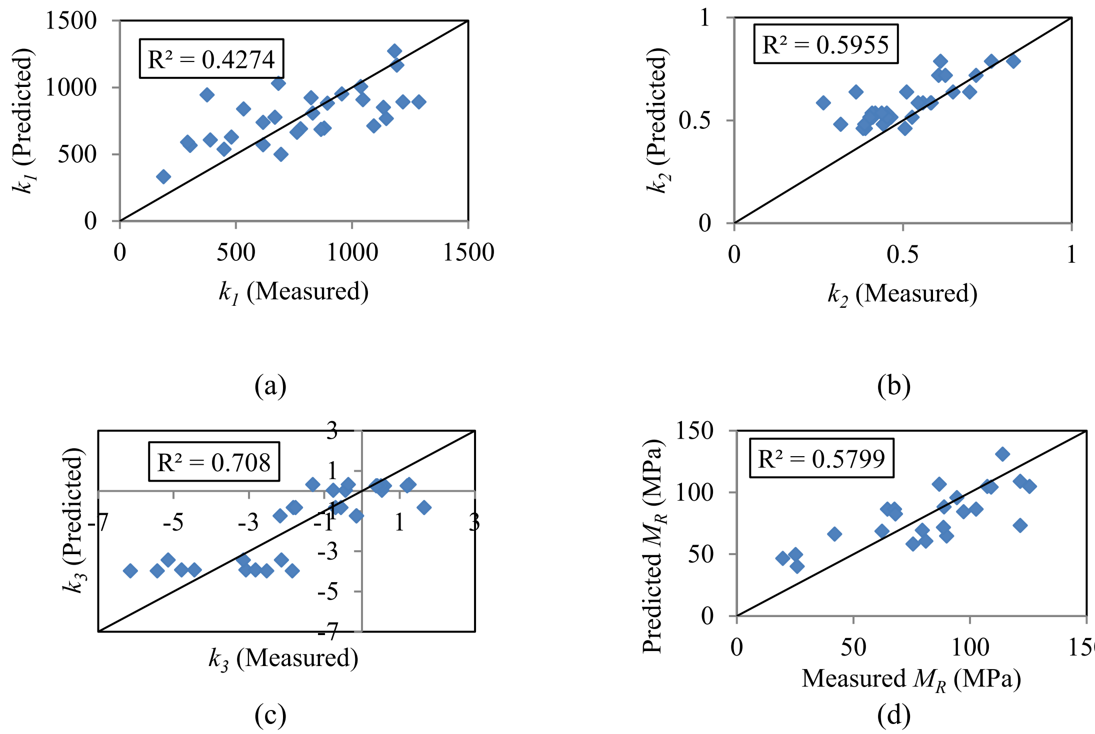

Figure 2 Measured and Predicted Resilient Modulus Model Parameters

Predicted and measured k_1, k_2, k_3, and M_R are shown in Figure 2(a), 2(b), 2(c) and 2(d), respectively. Model coefficients k_1, k_2, and k_3 are the regression constants of Equation 1, and therefore, these were measured from the applied bulk stresses, octahedral shear stresses, and the resultant resilient modulus values obtained from 15 different test sequences for each test using regression analysis. Most of the data points for all three models are observed close to the line of equity.

PERMANENT STRAIN MODEL PARAMETERS

Permanent strain model parameters were obtained for the four-parameter permanent strain model (Equation 2) and are shown in Table 4. Most of the test results show good coefficient of determination ($R^2 > 0.80$). These ε_p values are representative of the permanent strain after 2,500 number of load cycles. Results indicate that specimens prepared on the dry side of w_{opt} have a lower ε_p than those prepared at w_{opt}, and those prepared at w_{opt} have a lower ε_p than those prepared on the wet side of w_{opt}. Table 5 shows the coefficients for the developed models. Coefficients of determination (R^2) of 0.45, 0.60, 0.87 and 0.74 were found for α_1, α_2, α_3, and α_4, respectively. For the 8 soils tested, w, w_{opt} and $\gamma_{d,max}$ showed a statistically significant effect on all four model coefficients (α_1, α_2, α_3, and α_4); P_4 showed a statistically significant effect on α_1, α_2, and α_4; G_s, γ_d, *and LI* showed a statistically significant effect on α_2, α_3, and α_4; C_u showed statistically significant effect on α_1, and α_2. Other index properties did not show any significant effect on the permanent strain model parameters.

Table 4 Permanent Strain Model Parameters

Site	Soil	State	γ_d (lb/ft³)	w (%)	α_1	α_2	α_3	α_4	R^2	ε_p (%)
US-321	B-3	Dry	123.2	8.5	0.033	1.294	1.944	3.269	0.76	0.40
		w_{opt}	124.6	10.2	0.188	1.353	0.689	3.584	0.76	2.81
		Wet	118.4	12.0	1.439	1.192	1.265	3.275	0.70	7.63
	B-6	Dry	117.7	7.0	0.043	1.666	1.130	4.389	0.83	1.26
		w_{opt}	121.2	8.9	0.033	1.484	-1.158	4.294	0.88	1.63
		Wet	118.9	10.5	0.041	1.628	-0.760	4.120	0.92	3.40
	B-8	Dry	123.8	8.0	0.072	1.220	-0.164	4.128	0.76	0.56
		w_{opt}	124.5	9.3	0.041	1.716	-0.183	4.447	0.87	2.29
		Wet	115.5	11.9	0.854	1.173	-0.417	3.231	0.75	7.52
US-521	B-1	Dry	121.0	7.8	0.024	1.688	0.817	4.543	0.81	0.71
		w_{opt}	122.6	9.5	0.027	1.881	0.953	4.574	0.85	1.46
		Wet	119.3	11.2	0.071	1.679	-0.444	4.376	0.89	3.96
	B-4	Dry	108.5	10.3	0.018	1.779	-0.533	5.091	0.81	1.30
		w_{opt}	109.0	11.9	0.022	2.001	-1.331	6.048	0.86	1.97
		Wet	104.2	13.7	0.034	2.001	-1.331	6.048	0.89	2.79
SC-93	B-2	Dry	111.1	13.2	0.018	1.954	3.570	3.884	0.80	0.68
		w_{opt}	112.8	14.7	0.062	1.785	2.966	4.045	0.77	0.82
		Wet	110.7	16.7	2.007	1.390	0.803	3.828	0.84	3.18
	B-4	Dry	98.0	16.9	0.184	1.304	3.886	2.584	0.69	1.60
		w_{opt}	103.4	18.1	0.071	1.779	3.838	3.770	0.84	0.95
		Wet	103.2	19.8	1.898	1.527	1.567	5.213	0.87	1.77
	B-5	Dry	116.2	11.2	0.264	1.295	3.682	4.214	0.85	0.33
		w_{opt}	117.5	13.2	0.143	1.639	1.712	4.281	0.73	1.05
		Wet	115.1	14.3	0.943	1.200	0.731	3.319	0.77	2.88

Table 5 Developed Permanent Strain Model Coefficients for South Carolina

Models	R^2	F value
$\alpha_1 = 29.013 + 0.195w^{***} - 0.288P_4 - 0.011(w_{opt} \times \gamma_{d,max})^{*} + 0.000153C_u^{*}$	0.45	5.01**
$\alpha_2 = -53.424^{***} - 0.313w_{opt}^{**} + 0.388P_4^{***} - 0.176LI^{***} + 3.786G_S^{***} + 0.224(\gamma_{d,max} - \gamma_d)^{**} + 1.721\left(\frac{w}{w_{opt}} \times \frac{\gamma_d}{\gamma_{d,max}}\right)^{***} + 0.035(w_{opt} \times \gamma_{d,max})^{**}$	0.60	4.68**
$\alpha_3 = 21.952^{**} - 0.407w^{***} + 1.061w_{opt}^{***} + 0.138LI - 8.262G_S^{**} + 0.374(\gamma_{d,max} - \gamma_d) - 0.035(w_{opt} \times \gamma_{d,max}) + 0.0003C_u^{*}$	0.87	20.32***
$\alpha_4 = -254.632 + 1.191\gamma_d^{**} + 0.209w^{*} - 1.283w_{opt}^{*} + 1.623P_4^{**} - 0.638LI^{***} + 18.803G_S^{***} + 4.469\left(\frac{w}{w_{opt}} \times \frac{\gamma_d}{\gamma_{d,max}}\right)^{*} + 0.155(w_{opt} \times \gamma_{d,max})^{***}$	0.74	6.25***

$^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

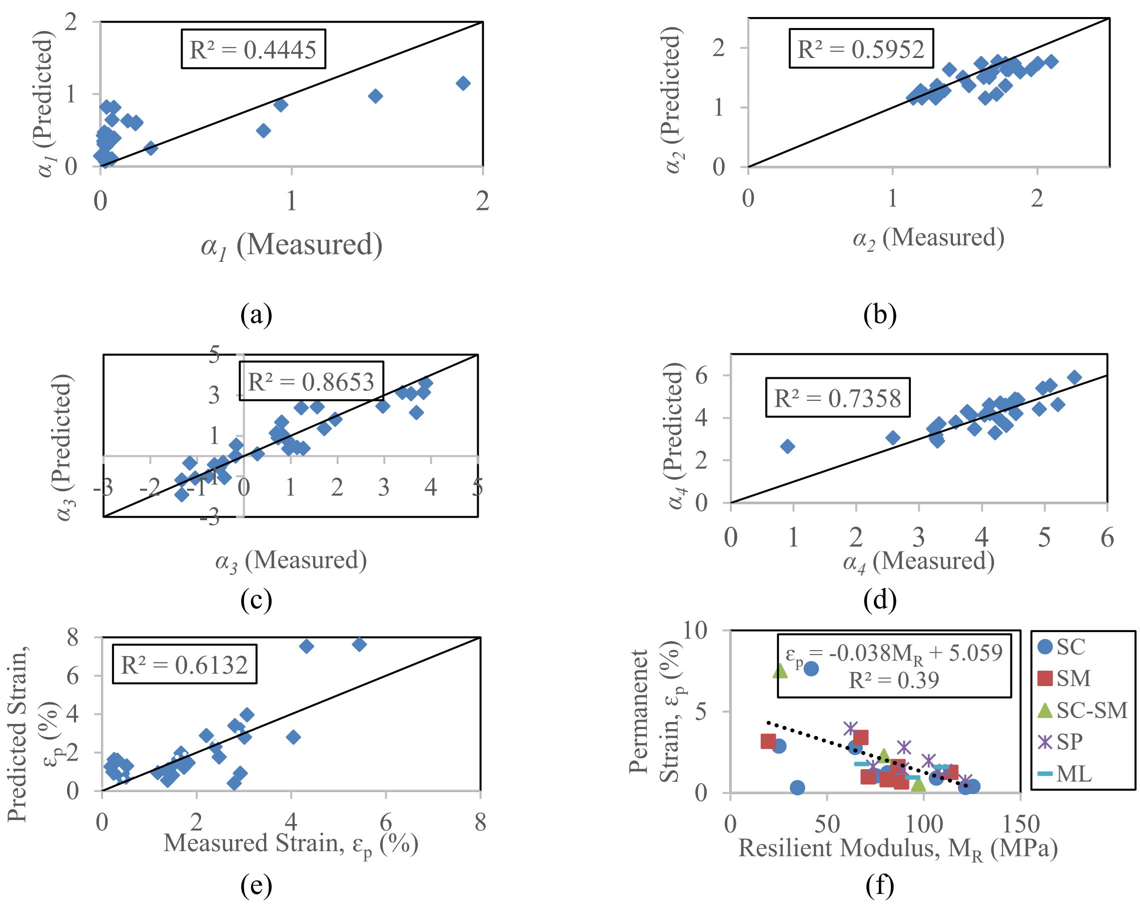

Figure 3 Measured and Predicted Permanent Strain Model Parameters

Predicted and measured $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ and ε_p are shown in Figure 3(a), 3(b), 3(c) 3(d), and 3(e), respectively. Model coefficients $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ are the regression constants of Equation 2, and therefore, these were measured from the load cycles, octahedral shear and octahedral normal stresses, and the resultant permanent strain values obtained after 15 different test sequences (2,500 load cycles) for each test using regression analysis. Most of the data points for all three models are observed close to the line of equity. Figure 3(f) shows the relation between resilient modulus and permanent strain for the five different types of soil (per USCS). Higher resilient modulus consistently showed lower permanent strain for mixed type soils (i.e., silty sands, clayey sands). This is unlike some previous studies (e.g., *12, 13*) that showed some mixed soils exhibit high resilient characteristics and still yield significant deformation. A relatively low coefficient of determination (R^2) was found because five different types of soils were considered at different moisture contents, thus work is ongoing to study additional soil types in South Carolina to further develop the coefficients. Although, the correlation between M_R and permanent strain has relatively, lower R^2 value, M_R explains permanent deformation or rutting characteristics for the South Carolina soils studied herein. For all different type of South Carolina coarse grained soils, permanent strain decreases due to increase in resilient modulus. Thus, permanent deformation for these soils can be predicted from soil index properties, or directly using the developed permanent strain model with soil resilient modulus.

Table 6 Damping Model Parameters

Site	Soil	State	γ_d (lb/ft^3)	w (%)	β_1	β_2	β_3	R^2	ξ (%)
US-321	B-1	Dry	123.2	8.5	18.6706	-3.4247	2.3277	0.75	4.86
		w_{opt}	124.6	10.2	4.8160	1.4255	-0.5538	0.50	4.91
		Wet	118.4	12.0	6.8021	0.7343	0.2023	0.23	6.17
	B-2	Dry	117.7	7.0	7.0501	-2.6195	1.8371	0.52	2.34
		w_{opt}	121.2	8.9	18.1081	-2.2052	1.8042	0.94	5.12
		Wet	118.9	10.5	7.1313	0.9394	0.6134	0.29	2.02
	B-3	Dry	123.8	8.0	1.5770	-0.9255	-0.0284	0.18	2.58
		w_{opt}	124.5	9.3	6.3756	-1.9893	1.8466	0.34	1.53
		Wet	115.5	11.9	7.4880	1.0138	-0.6993	0.40	11.30
US-521	B-1	Dry	121.0	7.8	35.6865	-3.0455	2.5617	0.76	5.69
		w_{opt}	122.6	9.5	13.5313	-2.8994	2.0653	0.75	3.83
		Wet	119.3	11.2	8.8713	-2.0615	1.9560	0.58	1.92
	B-2	Dry	108.5	10.3	18.9853	-1.3914	1.3181	0.81	6.77
		w_{opt}	109.0	11.9	20.9083	-1.0642	0.9351	0.87	10.45
		Wet	104.2	13.7	29.8248	-2.0438	1.7673	0.86	8.17
SC-93	B-1	Dry	111.1	13.2	2.7238	-3.5551	1.5654	0.49	2.03
		w_{opt}	112.8	14.7	2.9863	-1.3838	0.4976	0.11	3.08
		Wet	110.7	16.7	0.6835	4.3803	-3.8543	0.29	11.94
	B-2	Dry	98.0	16.9	5.4676	-3.8918	2.0071	0.48	2.71
		w_{opt}	103.4	18.1	7.6482	-2.3328	1.4602	0.43	3.60
		Wet	103.2	19.8	9.8637	0.9901	0.1414	0.21	5.05
	B-3	Dry	116.2	11.2	9.7185	-0.1843	0.0609	0.20	9.83
		w_{opt}	117.5	13.2	4.0739	0.9632	-0.5872	0.10	5.45
		Wet	115.1	14.3	4.7939	1.5332	-1.3095	0.39	12.40

DAMPING MODEL PARAMETERS

Damping model parameters were obtained for the three-parameter damping model (Equation 3) and are shown in Table 6. These ξ values are representative of the damping coefficient at 62.0 kPa major principal stress, and 27.6 kPa confining pressure. Results indicate that for most cases specimens prepared on the dry side of w_{opt} have a lower ξ than those prepared at wet side of w_{opt}. The coefficient of determination (R^2) varies widely depending on soil types and moisture content. Generally, higher value of coefficient of determination was found for poorly graded sands (US-521) than mixed sands (US-321, SC-93). That means developed damping model is more representative for poorly graded sands. Table 7 shows the coefficients for the developed models. Coefficients of determination (R^2) of 0.39, 0.60, and 0.52 were found for β_1, β_2, and β_3 respectively. For the 8 soils tested, w, w_{opt} and $\gamma_{d,max}$ showed a statistically significant effect on all three model coefficients (β_1, β_2, and β_3); G_s, *and* LI showed a statistically significant effect on β_2, and G_s, *and* P_4 showed a statistically significant effect on β_2. Other index properties did not show any significant effect on the permanent strain model parameters.

Table 7 Developed Damping Coefficients for South Carolina

Models	R^2	F value
$\beta_1 = 221.47 - 9.881\gamma_d^{**} - 4.719w^{***} + 29.797\left(\frac{w}{w_{opt}} \times \frac{\gamma_d}{\gamma_{d,max}}\right)^{*}$	0.39	5.43**
$\beta_2 = -94.158^{**} + 1.795\gamma_d^{*} + 1.072w^{***} - 1.409w_{opt}^{**} - 0.339LI^{**} + 15.283G_S^{*} + 0.106\left(w_{opt} \times \gamma_{d,max}\right)^{*}$	0.60	5.67***
$\beta_3 = -35.509 - 1.166\gamma_d^{***} - 0.545w^{***} + 0.765P_4^{*} - 5.453G_S + 2.467\left(\frac{w}{w_{opt}} \times \frac{\gamma_d}{\gamma_{d,max}}\right)$	0.52	5.28**

$^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

Predicted and measured β_1, β_2, β_3, and ξ are shown in Figures 4(a), 4(b), 4(c), and 4(d), respectively. Most of the data points for all models are observed close to the line of equity. Figure 4(e) shows the relation between resilient modulus and damping for the five different types of soil. A relatively low coefficient of determination (R^2) was found because five different type soils were considered at different moisture contents, thus work is ongoing to study additional soil types in South Carolina to further develop the coefficients. From Figure 4(e) it can be concluded that higher resilient modulus has lower damping for South Carolina coarse grained soils which conforms with another study (*32*).

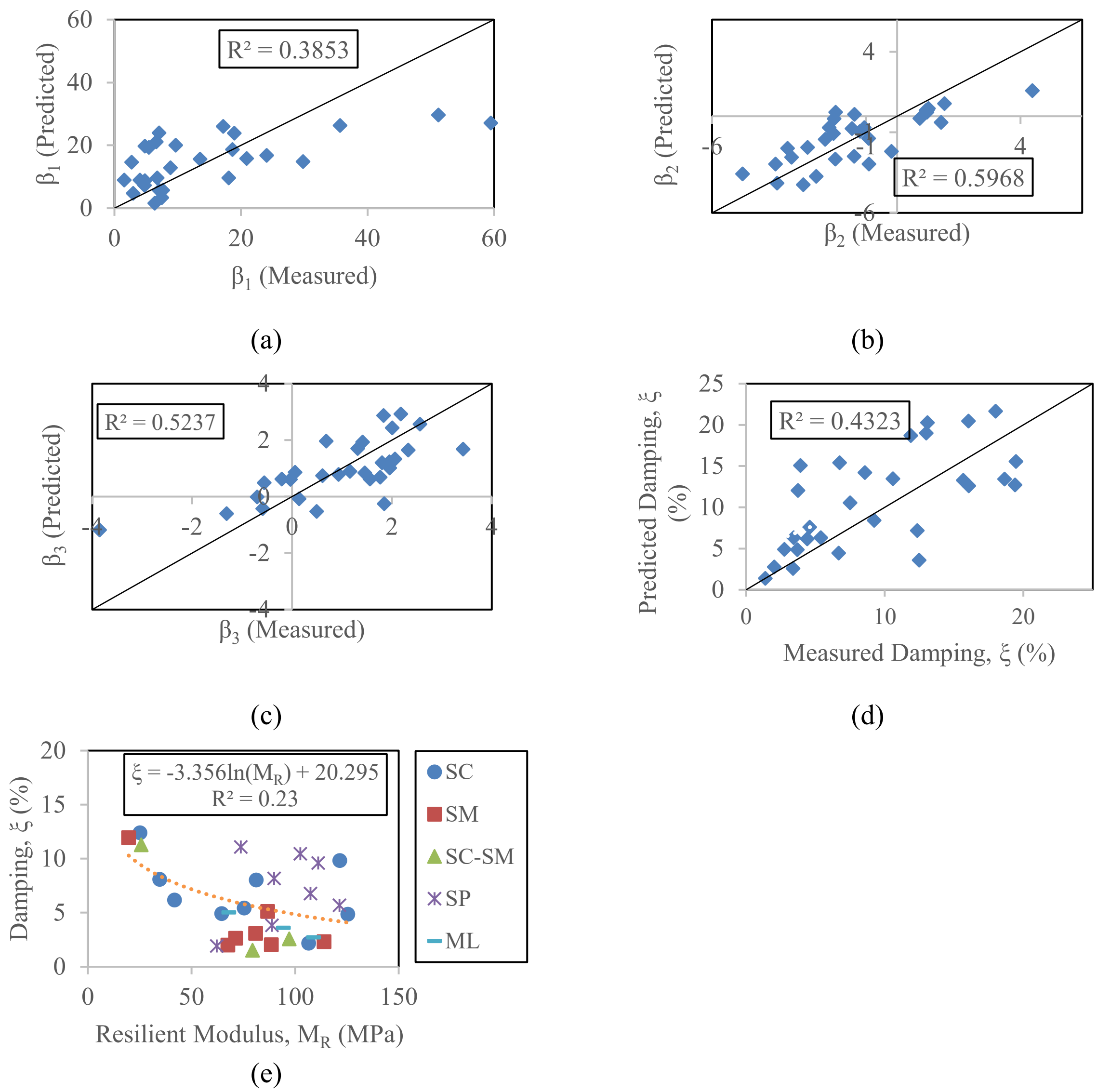

Figure 4 Measured and Predicted Damping Model Parameters

CONCLUSIONS

In this study, statistical models were developed to correlate resilient modulus model parameters (k_1, k_2, k_3), permanent strain model parameters (α_1, α_2, α_3, α_4), and damping model parameters (β_1, β_2, β_3) with soil index properties. Soils were collected from three sites in South Carolina and included poorly graded sands, silty sands and clayey sands. Results showed that P_4, LI, w_{opt} and $\gamma_{d,max}$ showed a statistically significant effect on all three resilient modulus model coefficients (k_1, k_2 and k_3), w, w_{opt} and $\gamma_{d,max}$ showed a statistically significant effect on all four permanent strain model coefficients (α_1, α_2, α_3 and α_4) and damping model parameters (β_1, β_2, β_3). Therefore, optimum moisture content and maximum dry density were found as the two most important soil index properties to predict resilient modulus, permanent strain, and damping. Fair correlations were developed for measured and predicted model parameters. Results showed that both permanent strain and damping decreases if resilient modulus increases for different South Carolina coarse grained soils.

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AUTHORS CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: M. M. Rahman, S. L Gassman; data collection: M. M. Rahman; analysis and interpretation of results: M. M. Rahman, K. M. Islam; draft manuscript preparation: M. M. Rahman, S. L. Gassman. All authors reviewed the results and approved the final version of the manuscript.

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