Effectiveness of Cement Kiln Dust in Stabilizing Recycled Base Materials

Ali Ebrahimi, M.ASCE[1]; Tuncer B. Edil, F.ASCE[2]; and Young-Hwan Son[3]

Abstract: Effectiveness of cement kiln dust (CKD) in improving the stiffness of recycled base course materials was studied using both seismic modulus and bench-scale resilient modulus tests. Recycled materials included road surface gravel (RSG) and recycled pavement material (RPM). The modulus of RPM and RSG specimens mixed with CKD increased 5–30 times compared with untreated materials; however, the improvement was not as high as cement stabilization. Modulus generally increased with curing time with more hydration; however, decrease in the modulus of the RPM mixed with 15% CKD during curing is attributed to swelling potential of the CKD. Lower rate of increase in modulus of CKD mixtures compared with cement mixtures with curing time was attributable to the chemical composition of CKD, i.e., high free lime and sulfate contents. Freeze-thaw durability tests resulted in modulus reduction on the order of 0.5 to 0.8 for CKD mixtures and 0.5 for cement mixtures. Attributable to the combined effects of stiffness gain with continuing hydration and stiffness reduction with freeze-thaw cycles, the final modulus of the recycled materials mixed with CKD is 2 to 5 times higher than that of untreated RPM and RSG materials. This study also showed that modulus change of stabilized granular materials can be estimated from seismic Young's modulus. **DOI:** **10.1061/(ASCE)MT.1943-5533.0000472.** *© 2012 American Society of Civil Engineers.*

CE Database subject headings: Cement; Dust; Seismic tests; Resilient modulus; Durability; Recycling.

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Introduction

In situ recycling of roadway materials is both cost effective and environmentally friendly, resulting in reduced energy consumption, greenhouse gas emissions, and landfilling (Lee et al. 2010). One of the techniques to enhance strength, stiffness, and durability of highway materials is to mix the materials with chemical stabilizing agents such as cement, lime, cement kiln dust (CKD), and fly ash (Little 2009; Kootstra et al. 2010). The improvement technique is more critical when natural base course materials in highways are substituted with recycled materials. New mechanistic-empirical pavement design guide (MEPDG) (NCHRP 2006) requires the evaluation of the engineering properties of recycled materials with and without stabilization for further application in highway design and construction. The engineering properties of base course materials, including resilient modulus and long-term degradation of modulus attributable to frost action, should be evaluated.

The objective of this paper is to investigate the stiffness of two recycled roadway materials [recycled pavement material (RPM) and reclaimed road surface gravel (RSG)] and how they can be improved with an industrial byproduct, namely CKD as a binder. Resilient and seismic modulus of RPM and RSG blended with CKD and portland cement as a reference binder were determined. The modulus of recycled roadway materials mixed with the cementing agents was investigated as a function of curing duration and freeze-thaw cycles.

Application of Cement and CKD in Base Course Stabilization

Chemical stabilization using cement is a technique to enhance strength and durability of unsuitable soils for various geotechnical applications, e.g., highways. CKD is a cementitious byproduct and can be a cost-effective alternative binder. Highway materials, including base, subbase, and subgrade, have been treated with cement and CKD for decades (Guthrei et al. 2007; Kim and Siddiki 2004; Baghdadi et al. 1995; Collins and Emery 1982). CKD is a calcium base stabilizer that is an industrial byproduct from the production of portland cement and is collected by fabric filters or electrostatic precipitators. Solanki et al. (2007) showed the mixtures of silty soil with 15% CKD improve the resilient modulus (M_r) of mixtures approximately 35% to 425%. Miller and Zaman (2000) showed that CKD can be more effective than quicklime for stabilizing soil for road application. Their laboratory tests showed that CKD would reduce the plasticity index of soils and impart some resistance to freeze-thaw and wet-dry cycles.

Chemical Components of CKD and Related Problems

Chemical compositions of CKD widely vary with the source of raw materials used in cement production, type of operation, dust collection facility, and type of fuel. Chemical compositions of CKD influence the pozzolanic reactions while mixed with soil and consequently affect the mechanical properties of mixtures (Kim and Siddiki 2004; Solanki et al. 2007; Miller and Zaman 2000; Bhatty et al. 1996). Typically, cementing agents can be characterized based on their chemical compositions and physical properties (e.g., specific surface area) using performance tests (i.e., setting time, compressive strength, or modulus). Bhatty et al. (1996)

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and Miller and Zaman (2000) showed the significance of loss-on-ignition (LOI) content on the effectiveness of CKD for soil stabilization applications. Miller and Zaman (2000) described that CKD with high LOI retains higher percentage of bound water and less CaO available for pozzolanic reactions. Williams (2005) shows that the soil mixtures containing CKD with high LOI ($> 20\%$) never hardened. Peethamparan et al. (2008) showed that higher unconfined compressive strength was achieved with higher free-lime content attributed to the formation of ettringite [calcium-aluminate-sulfate-hydrate (C-S-H)] and secondary C-S-H during hydration. Peethamparan et al. (2008) did not report expansion due to formation of ettringite and concluded that the alkalis and sulfates present in the CKD may also play a significant function in the soil stabilization process by forming ettringite and syngenite in the hydrated CKD.

Free lime content of a cementing agent is limited relative to other chemical components to prevent destructive expansions that can damage cementitious bindings between aggregates (Kota et al. 1996; Taylor 1990). The amount of free CaO is controlled in cement industry by a compositional parameter called lime saturation factor (LSF) (Taylor 1990):

$$\mathrm{LSF} = \frac{\mathrm{CaO}}{2.8\,\mathrm{SiO_2} + 1.18\,\mathrm{Al_2O_3} + 0.65\,\mathrm{Fe_2O}} \tag{1}$$

Taylor (1990) stated that a cementitious substance with $\mathrm{LSF} > 1$ may undergo destructive expansion. This ratio provides an estimate of the required balance of lime and other oxide contents contributing to hydration and strength gain. A $\mathrm{LSF} < 1$ (0.92–0.98) provides the maximum attainable $C_3S(3CaO - SiO_2)$ contents in ordinary portland cement (Taylor 1990). Expansion occurs when all voids have been filled and there is still source of calcium hydroxide and water to produce more ettringite (Kota et al. 1996; Taylor 1996). Kota et al. (1996) showed that lime produces more heaving than cement in high sulfate soils because of formation of more ettringite in lime stabilization attributable to high free CaO content.

Excessive sulfate content (from soluble SO_3) can also lead to delayed expansion (Little 2009; Hunter 1988; Kota et al. 1996). Cement industry usually limits the sulfate content to 2.5–4% (Taylor 1990). Zhiming (2008) described that stabilizing high sulfate bearing soils with calcium-based stabilizers (such as cement or lime) is not recommended because of high potential of swell and low retained strength. The summary of problematic cases regarding the chemical composition of cementitious substances for soil stabilization is listed in Table 1.

Materials and Methods

Materials

Two recycled materials, recycled pavement material (RPM) and reclaimed road surface gravel (RSG), mixed with Type II portland cement and CKD were investigated for roadway application. RPM was an approximately equal mixture of a pulverized hot mix asphalt layer and a limestone base course layer from a roadway reconstruction project in Madison, Wisconsin. Aggregate in the RPM was mostly limestone and dolomite and was coated with 0.1- to 3-mm-thick of asphalt binder. The RPM had 4.7% asphalt content in accordance with ASTM D6307-05 (2010a). RSG was created by combining a conventional base course material with clay fines to meet the gradation and plasticity requirements for surface course materials as described in AASHTO M147 (1986). The properties of RPM and RSG are listed in Table 2. Particle size distributions of RPM and RSG are shown in Fig. 1.

The cementitious agents used in this study consisted of Type II portland cement and CKD. The CKD was provided by LaFarge Cement Plant in Alpena, Michigan. The chemical composition of the CKD, along with average chemical composition of 63 sources of CKD in the United States reported by Adaska and Haubert (2008), and Type II portland cement are presented in Table 3.

Specimen Preparation

A total of 18 specimens was prepared to study the hydration and freeze-thaw actions on the modulus of stabilized recycled materials. The RPM and RSG were tested with 0, 5, 10, and 15% by weight of CKD and 4% by weight of Type II portland cement. Tests were performed using portland cement as a reference binder to assist in evaluation of the effectiveness of CKD. The CKD and cement contents were selected to cover the range of typical dosages used in current practice of road construction. Cementing agents were added to the recycled materials and manually blended until they reached uniformity. Specimens were compacted within 1% of the maximum standard Proctor dry density and 0.5% of the optimal moisture content (NCHRP 2004), as listed in Table 4. Mixtures were compacted in six lifts of equal mass and thickness using a split mold with

Table 1. Problematic Cases of Cementitious Stabilization

Study	Issue	Reported problem
Little et al. (2009), Zhiming (2008), Kota et al. (1996) Taylor (1990), Hunter (1988), Mitchell (1986)	Sulfate content (from soluble SO_3)	There is a potential for excessive formation of expansive minerals, such as ettringite and thaumasite.
Zhiming (2008), Kota et al. (1996), Taylor (1996)	High free lime (CaO) content	Free lime caused excessive heaving.
Adaska et al. (2008), Williams (2005), Miller and Zaman (2000), Bhatty et al. (1996)	Loss of ignition (LOI)	The strength of soil mixed with CKD was not improved attributable to high LOI of CKD.

Table 2. Properties of Base Course Materials

Material	w_{opt} (%)	$\gamma_{d\,\max}$ ($\mathrm{kN/m^3}$)	LL (%)	PL (%)	Gravel content (%)	Sand content (%)	Fines content (%)	AASHTO symbol	USCS symbol
RPM	7.5	21.2	NP	NP	46	43	11	A-1-a	GW-GM
RSG	7.5	22.6	21	14	29	59	12	A-2-4	SC-SM

Note: Particle size analysis by ASTM D422 (2007b); maximum dry unit weight ($\gamma_{d\,\max}$) and optimum water content (w_{opt}) by ASTM D698 (2007c); Gravel, sand and fines contents and Unified Soil Classification System (USCS) classification by ASTM D2487 (2011); AASHTO classification by ASTM D3282 (2009a); asphalt content by ASTM D6307 (2010a); Atterberg limits [liquid limit (LL) and plastic limit (PL)] by ASTM D4318 (2010b); NP = not plastic.

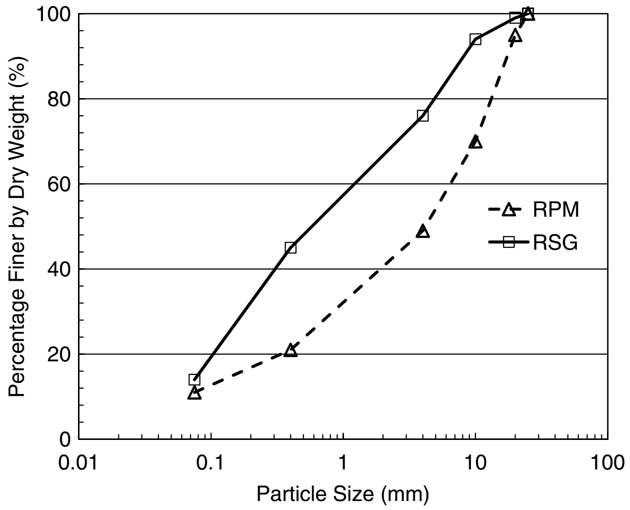

Fig. 1. Particle size distributions for RPM and RSG

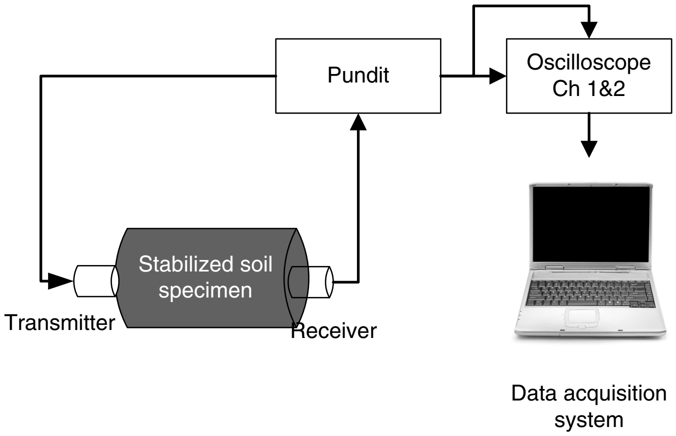

Fig. 2. Seismic test setup to monitor the modulus change of stabilized materials

152 mm in diameter and 305 mm in height. They were wrapped and moist cured for 28 days in a humidity room having 23°C and relative humidity of 95% (ASTM 2007a).

Seismic Wave Technique

Seismic wave technique [ASTM C597 (2009c)] is a nondestructive, accelerated, simple test procedure for concrete that can be adopted to determine the seismic (or lowstrain) Young's modulus (E_s) of stabilized base course materials. The seismic wave technique was used to follow the hydration process and durability of the CKD/cement mixtures. Velocity of the elastic wave propagated through a soil specimen is used to calculate the seismic modulus of the specimen. Change in the seismic modulus is attributed to hydration or effect of freeze-thaw actions. The E_s was calculated as described by Schuettpelz et al. (2010):

$$E_s = V_P^2 \rho \frac{(1+\nu)(1-2\nu)}{(1-\nu)} \tag{2}$$

where V_p = P-wave velocity calculated from the seismic test; ρ = mass density; and ν = Poisson's ratio (assumed to be 0.2 for stabilized materials). Elastic waves were generated by an ultrasonic transmitter and receiver with an operational frequency of 54 kHz. The ultrasonic probes were connected to the Pundit PLUS Ultrasonic Tester system. An oscilloscope captured the wave propagation traces and travel time. The test setup created reproducible results in the laboratory with a coefficient of variation approximately 10%. A schematic view of the test set up is shown in Fig. 2.

Table 3. Physical Properties and Chemical Composition of Type II Portland Cement, the Tested CKD, and Average of 63 CKD Sources

Parameter	Cement	CKD tested	CKD (average)[a]
Al_2O_3, %	5	4.6	4.5
Fe_2O_3, %	3	2.1	2.1
CaO, %	67	51.2	55.5
Lime saturation factor [LSF-Eq. (1)] %	0.97	1.26	—
Silica ratio (SR) $SiO_2/(Al_2O_3 + Fe_2O_3)$, %	2.75	1.79	—
MgO, %	1	1.6	1.3
SO_3, %	1	14.6	6.0
Free Lime	0.6	16.2	8.1
LOI	—	10.7	21.6
Specific gravity (G_s)	3.2	2.5	—

[a] From Adaska and Haubert (2008).

Table 4. Compaction Characteristics of RPM and RSG Mixed with CKD and Cement

Material mixture	CKD or cement %	w_{opt} (%)[a]	$\gamma_{d\,\max}$ (kN/m^3)[a]
RPM+CKD	5	7.0	21
RPM+CKD	10	7.7	21
RPM+CKD	15	8.5	19.8
RSG+CKD	5	7.5	21.3
RSG+CKD	10	9.2	20.8
RSG+CKD	15	10	20
RPM+Cement	4	7.0	20.7
RSG+Cement	4	7.5	20.9

[a] From standard Proctor test by ASTM D698 (2007c).

Bench-Scale Laboratory Resilient Modulus Test

Resilient modulus (M_r) is a fundamental mechanical property of base course materials for pavement design. Bench-scale resilient modulus (BSRM) tests were performed in accordance with the National Cooperative Highway Research Program (NCHRP) 1-28A test protocol (NCHRP 2004). All materials were tested under Procedure Ia, which applies to base and subbase materials. Internal linear variable displacement transducers (LVDTs) were mounted at the quarter points of specimens using clamps in accordance with NCHRP 1-28A specifications. Resilient moduli (M_r) was calculated by dividing the axial cyclic stress (σ_d) by respective recoverable (elastic) strain (γ_e) in each loading cycle. For a given state of stress (i.e., confining and deviator stress), M_r from the last 5 cycles of testing was averaged to obtain the M_r for that state of stress. The M_r data were fitted with the widely used power function given in Eq. (2) (Mosazadeh and Witczak 1981), where

$$M_r = k_1 \left(\frac{\sigma_b}{P_r} \right)^{k_2} \tag{3}$$

where σ_b = the bulk stress (= sum of three principal stresses, kPa); P_r = a reference stress (1 kPa in this study); and k_1 and k_2 = dimensionless fitting parameters. Parameter k_2 represents the stress dependency of the tested materials and falls in the range of 0.45 to 0.62 for typical granular materials. A summary resilient modulus

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(SRM) was also computed, as suggested in NCHRP 1-28A (NCHRP 2004). For base materials, the SRM corresponds to the M_r at a σ_b of 208 kPa in Eq. (2). The simpler power function instead of the more general relationship with more fitting parameters given in NCHRP 1-28A was preferred. Unstabilized RPM and RSG are essentially granular materials and Eq. (2) captures the behavior of granular materials properly.

Freeze and Thaw Tests

The change in modulus of the RPM and RSG mixtures attributable to the freeze-thaw (F-T) actions, i.e., freeze-thaw durability, was studied. There is no standard for conducting F-T cycles to study the effect of freeze-thaw on the mechanical property of soil mixtures. Investigators of F-T durability used different approaches to preconditioning of the stabilized specimens. Rosa (2006) performed F-T tests first soaking the specimens for 5 h and then isolating them from moisture (by wrapping them) during F-T cycles. Camargo et al. (2009) prevented the specimens from access to additional water during the freeze-thaw cycles. Baugh (2008) conducted F-T tests on specimens first exposed to water for 5 h and then allowed for 10-min drainage; freeze-thaw cycles were completed without further exposure to moisture. Rosa (2006) reported 7 to 50% reduction in the resilient modulus of fly ash stabilized subgrade materials. Camargo et al. (2009) reported 7% increase in the modulus of fly ash stabilized RPM and RSG after freeze-thaw tests. Baugh et al. (2008) showed up to 50% reduction in modulus of RPM stabilized with 10% CKD.

Freeze-thaw cycles in the laboratory must simulate the field conditions. Therefore, the following method was adopted from ASTM D6035-08 (2008) with some modifications. Specimens were wrapped in plastic and first cured for 28 days followed by soaking in water for 5 h and allowing to drain for 2 h. The 2-h draining approximately mimics the field condition (i.e., allowing drainage from the soils after a rainfall event before freezing period). After 2-h drainage, specimens were wrapped and frozen at −5°C for 24 h, followed by 24-h thawing at room temperature. During freeze-thaw cycles, no additional moisture was allowed into the specimens. The specimens were tested after 10 F-T cycles in the bench-scale laboratory resilient modulus test and during 10 F-T cycles in the seismic test. Ten F-T cycles were found to be enough since most changes take place within 5 freeze-thaw cycles (Rosa 2006).

Results and Discussions

Curing Time

The calculated seismic Young's modulus (E_s) of RPM and RSG mixed with 4% cement as a function of curing time is shown in Fig. 3(a). The E_s for both RPM and RSG mixed with 4% cement is approximately the same during the curing time and reflective of enhanced stiffness attributable to cement binding. E_s increases with curing time up to 21 days and remains constant thereafter. As cementitious agents become hydrated, a series of reactions occur, resulting in increased hardness and resistance to stresses. Needle-shape ettringite (calcium-aluminate-sulfate-hydrate) is the product of cement hydration. Ettringite forms a network between soil particles and strengthens the soil-cement mixtures. The hydration process continues during curing while sufficient water is available for generation of calcium silicate (Peethamparan et al. 2008; Miller and Zaman 2000; Miller and Azad 2000). In this study, the source of moisture for hydration was limited to the internal moisture of the specimens attributable to wrapping; therefore the strength gain associated with hydration is possibly limited because of unavailability of additional water.

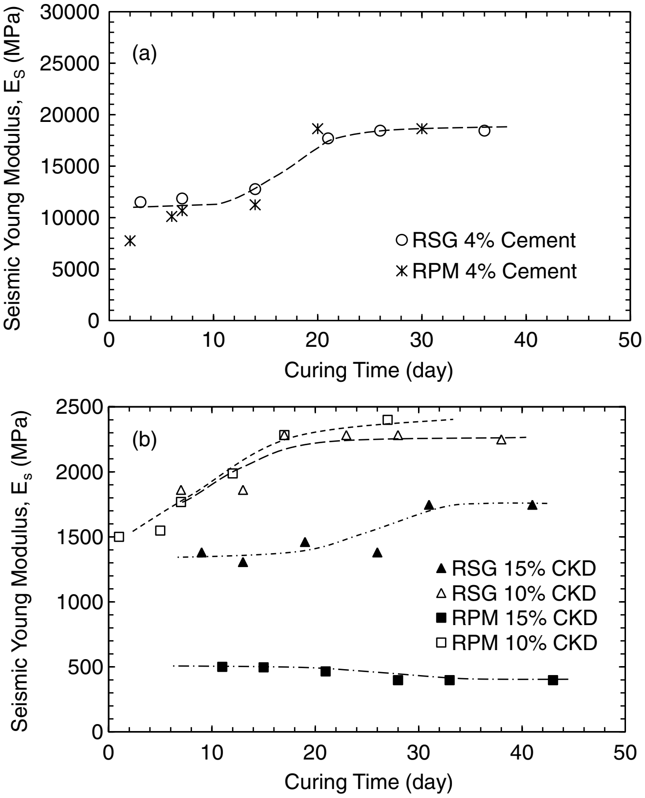

Fig. 3. Seismic Young's modulus as a function of curing time: (a) cement mixtures; (b) CKD mixtures for RSG and RPM

The E_s of RPM and RSG mixed with two different CKD contents is shown in Fig. 3(b). The calculated seismic moduli of CKD mixtures increase during curing in all the specimens, except RPM with 15% CKD. Hydration of CKD is expected to result in higher modulus for the stabilized RPM and RSG; however, the increase in modulus in CKD mixtures can be counteracted by the swelling potential of CKD attributable to free lime (attributed to LSF factor of 1.26) and SO_3 of 14.6%. The expansion of the CKD can damage the cementitious bonds generated from CKD hydration. The CKD used in this study has SO_3 and free lime content approximately 2.5 and 2 times higher than those of typical CKD (Table 3). High SO_3 and free lime content in CKD is reported to cause detrimental expansion, which adversely affects the stiffness of CKD mixtures and cementitious bonds between particles (Kota et al. 1996; Taylor 1996).

The normalized E_s and SRM with respect to the modulus after 7 days of curing are plotted as a function of curing time in Fig. 4. The normalized modulus after 21-day curing period is approximately 1.6 for cement mixtures but varies between 0.8 and 1.4 for CKD mixtures. The RPM with 15% CKD content has a reduction in modulus with time, more likely attributable to expansion of the specimens and hydrophobicity of the RPM particles.

Bench-Scale Resilient Modulus

The summary resilient moduli (SRM) of the RPM and RSG with and without cement or CKD stabilization calculated from the BSRM tests performed after 28 days of curing are presented in Table 5. The SRM of RPM and RSG without CKD is 310 and 230 MPa, respectively. The RPM and RSG with 4% cement has SRM of 20,200 and 22,120 MPa, respectively. After cement

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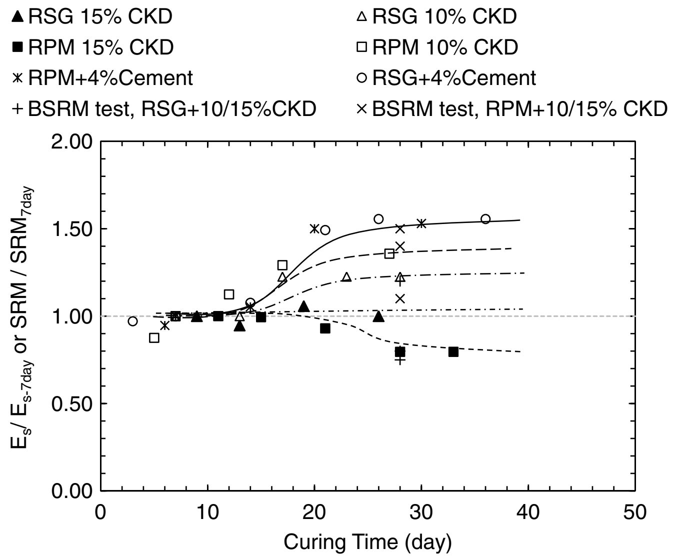

Fig. 4. Normalized modulus (based on 7-day modulus) as a function of curing time for RPM and RSG mixed with cement and CKD

stabilization both materials have comparable modulus, roughly 2 orders of magnitude higher. The SRM of the RPM with 5 to 15% CKD after 28 days of curing varies between 3,370 and 1,450 MPa. Thus, there are 5 to 10 times gain in modulus attributable to CKD stabilization. The SRM of RSG with 5 to 15% CKD after 28 days of curing varies between 1,200 and 7,170 MPa corresponding to roughly 6 to 30 times gain in modulus. The SRM of RPM and RSG specimens mixed with cement is 8 to 20 times higher than the SRM of RPM and RSG specimens mixed with CKD. Thus, CKD is not as effective binder as cement even at much higher dosages. This is attributed to chemical composition and swelling of CKD-stabilized materials.

Swelling Potential in CKD Mixtures

Swelling potential in CKD mixtures was captured in terms of the volume change calculated on CKD-stabilized specimens after 28-day curing and during F-T cycles, as given in Table 5. The specimens used for measuring volume change had an initial diameter of 100 mm and a height of 200 mm. Mixtures of RPM and RSG with 15% by weight of CKD resulted in 12 to 15% expansion after 28 days of curing. Swelling tests performed on pure CKD specimens after 28 days of curing showed 16% expansion, whereas CKD mixed with 50% by weight uniform sand exhibited 8% expansion, i.e., 50% reduction in swelling potential attributable to less CKD content as a source of expansion. In comparison with these results, the swelling potential of the CKD mixtures indicate that properties of the mixtures other than CKD content, such as strength of mixture, may impact the magnitude of expansion (12 to 15% expansion for RSG and RPM mixed with 15% CKD).

Increased CKD content from 5 to 15% in the RPM specimens resulted in 250% increase in volume expansion (i.e., from 6 to 15% expansion) and 60% decrease in summary resilient modulus (i.e., from 3,370 to 1,450 MPa), whereas the opposite behavior is observed for the RSG specimens (Table 5). Increased CKD content from 5 to 15% in the RSG specimens resulted in no increase in volume expansion (remained at 12% expansion) and 600% increase in the summary resilient modulus (from 1,200 to 7,170 MPa). This is likely attributed to the binder and/or base material characteristics as reported by Peethamparan et al. (2008) and Miller and Azad (2000). RPM specimens (with 4.6% asphalt content) may have weaker cementation between particles attributable to hydrophobicity of asphalt-coating on the aggregates, whereas the clay content in the RSG (~12.6% fines content) can enhance the pozzolanic

Table 5. Summary Resilient Modulus (SRM), Seismic Young's Modulus (E_s), and Volume Expansion for RPM and RSG Mixed with Cement and CKD

						Bench-scale resilient modulus test		
Material	CKD content (%)	Cement content (%)	Condition	Volume change[a] (%)	E_s[b] (MPa)	k_1[c]	k_2[c]	SRM[d] (MPa)
RPM	—	—	—	—	—	49.2	0.34	310
	5	—	28-day curing	6	—	2,510	0.5	3,370
	10	—		12	1,310	180	0.5	2,600
	15	—		15	700	100	0.5	1,450
	—	4		0	18,000	20,200	0	20,200
	5	—	10 F-T[e]	—	—	—	—	—
	10	—		15	410	79	0.5	1,150
	15	—		19	250	35	0.55	660
	—	4		0	8,800	16,900	0	16,900
RSG	—	—	—	—	—	21.6	0.44	230
	5	—	28-day curing	12	—	704	0.1	1,200
	10	—		12	1,320	5,625	0	5,630
	15	—		12	1,370	7,170	0	7,170
	—	4		0	20,700	22,120	0	22,120
	5	—	10 F-T[e]	12	—	505	0.15	1,110
	10	—		15	300	547	0.15	1,220
	15	—		15	470	2,055	0	2,060
	—	4		0	9,200	15,200	0	15,200

[a] Positive: Expansion.
[b] E_s: Seismic Young's Modulus.
[c] Fitting Parameters in Eq. (3).
[d] Summary Resilient Modulus (SRM) is calculated at a bulk stress of 208 kPa.
[e] F-T = Freeze-thaw cycles.

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Fig. 5. (a) Expansion of RSG mixed with 15% by weight of CKD after 28-day curing before testing; (b) bulging of the RSG mixed with 15% CKD after bench-scale resilient modulus testing; and (c) shear failure in RPM mixed with 15% of CKD after bench-scale resilient modulus testing (specimen diameter is 150 mm)

reaction of the CKD and balance the excess free lime content in the CKD (Miller and Zaman 2000; Baghdadi et al. 1995). Kota et al. (1996) also described that pozzolanic reaction would outweigh the damage attributable to formation of expansive minerals, when CKD is mixed with clay minerals.

The specimens of RPM and RSG mixed with 15% by weight of CKD after 28-day curing is shown in Fig. 5. Fig 5(a) shows the expansion of a RSG specimen (~15%) before BSRM test. The expansion can be observed by comparing the specimen diameter with the top platen as the initial diameter. Fig. 5(b) shows bulged shape of RSG mixed with 15% CKD after the BSRM testing. Fig. 5(c) shows the shearing failure of an RPM specimen mixed with 15% CKD after the BSRM test. Overall, the expansion of the specimens of RPM and RSG mixed with the CKD is significant (6 to 15%). This value is higher than suggested value by ASTM D2940-09 (2009b) "Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airports." For aggregates with hydrating components, volume expansion should be less than 0.50% after 7 days when tested in accordance with Test Method D4792. The expansion should be considered by design engineers in a specific project.

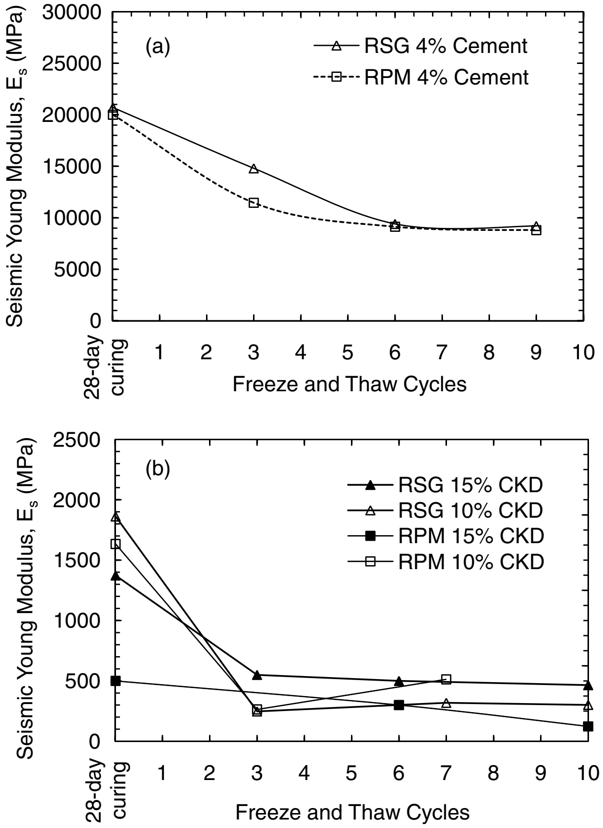

Fig. 6. Change of seismic Young's modulus as a function of freeze and thaw cycles for (a) cement and (b) CKD mixtures

Modulus Reduction of Cement/CKD Mixtures under Freeze-Thaw Cycles

The E_s of RPM and RSG specimens mixed with cement and CKD under 10 (F-T) cycles is shown in Fig. 6. The E_s of both cement and CKD mixtures decreases with increasing cycles of F-T and then stabilizes. Drop in modulus of cement mixtures occurred in first six F-T cycles and no significant change thereafter [Fig. 6(a)]. Drop in modulus of CKD mixtures occurred in first three F-T cycles and no significant change thereafter [Fig. 6(b)]. The SRM of the mixtures after 10 F-T cycles from the BSRM test is presented in Table 5. The RPM mixed with 10 and 15% CKD has SRM of 1,150 and 660 MPa, respectively, whereas RSG has SRM of 1,220 and 2,060 MPa, respectively.

To study the modulus reduction of the RPM and RSG mixtures with F-T cycles, the normalized E_s and SRM with respect to the modulus after 28 days of curing before F-T cycles was calculated and shown in Fig. 7. The modulus reduction factor (MRF = modulus after 10 F-T cycles/modulus after 28 days of curing) for RPM

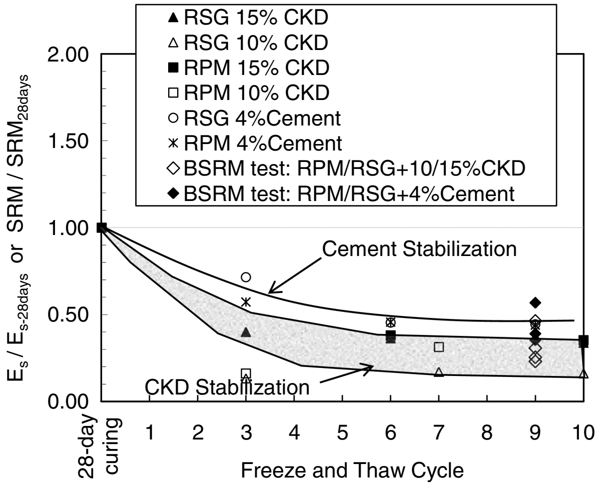

Fig. 7. Normalized modulus (based on 28-day modulus) as a function of freeze-thaw cycles for RPM and RSG mixed with cement and CKD

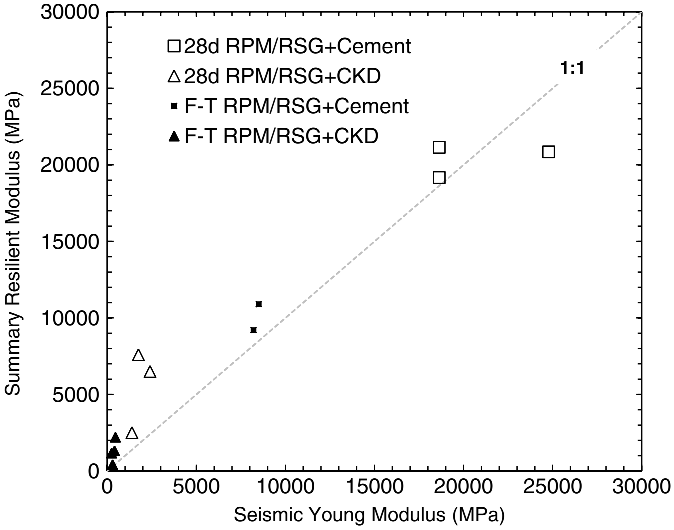

Fig. 8. Correlation between summary resilient modulus and seismic Young's modulus of RPM and RSG mixed with cement and CKD

and RSG mixed with 4% cement is 0.5. The MRF for the RPM and RSG mixed with 10 to 15% CKD is between 0.2 and 0.5 depending on the type of recycled materials and the CKD contents. The cement mixtures exhibit smaller modulus reduction (~50% reduction) compared with the CKD mixtures (~50 to 80% reduction) based on both the seismic and resilient modulus tests (Table 5 and Fig. 7).

Higher modulus degradation of CKD mixtures with F-T cycles is attributed to poor cementitious bonds between aggregates of recycled materials attributable to CKD hydration compared with cement. The F-T cycles impact the modulus of the stabilized materials depending on water content and mechanical characteristics of the specimens. During freeze-thaw cycles, water in the voids is converted to ice, and volume of water increases approximately 9%. This volume change potentially damages the cementitious bonds in the mixtures.

Correlation of Summary Resilient and Seismic Young's Modulus

Correlating seismic Young's modulus to resilient modulus requires corrections relating to the state of stress and strain amplitude for granular materials (Schuettpelz et al. 2010). Because the resilient modulus of stabilized materials (particularly cement stabilization) is less sensitive to the state of stress and strain amplitude unlike the granular materials, it may be possible to correlate it directly with low-strain seismic Young's modulus measured in unconfined state. Fig. 8 shows SRM versus E_s for all specimens stabilized with cement and CKD. The data indicate a good correlation and suggest that the much simpler seismic test can be used for assessing the modulus change of stabilized materials during curing time and under frost actions.

Conclusions

The seismic wave technique and bench-scale resilient modulus (BSRM) test were conducted to investigate the effectiveness of cement kiln dust (CKD) relative to Type II portland cement in improving the stiffness of two recycled materials: recycled pavement material (RPM) and reclaimed road surface gravel (RSG). The effects of curing time and freeze-thaw actions on stiffness were also investigated. The following observations and conclusions are advanced:

1. CKD stabilization improves modulus from 5 to 30 times depending on the CKD content and type of base material. However, the moduli (i.e., seismic Young's modulus and resilient modulus) of cement-stabilized materials were 5 to 20 times higher than those of CKD-stabilized materials.
2. Smaller increase in modulus of the CKD mixtures (ratio of 0.8 to 1.4) was observed during curing time, whereas this ratio was consistently 1.6 for cement-stabilized RPM or RSG. The variable response of CKD-stabilized materials to curing time is attributed to high free lime and sulfate content (from soluble sulfur trioxide) of the CKD.
3. Freeze-thaw cycles caused reduction in modulus but stabilized after 2–6 cycles, and the effect was more detrimental on the modulus of RPM and RSG mixed with CKD compared with the cement mixtures. Modulus reduction factors for freeze-thaw were 0.2 to 0.5 for CKD mixtures and 0.5 for cement mixtures.
4. Seismic modulus test is a convenient nondestructive test that correlates well with resilient modulus tests and can be used in determining the modulus change of stabilized materials during curing time and under frost actions.

CKD is recommended to be used in geotechnical applications with care by considering the expansion and modulus change during curing and under F-T cycles. Because of the combined effects of stiffness gain with continuing hydration and stiffness reduction with expansion and freeze-thaw cycles, the final modulus of the recycled materials mixed with CKD can be considered 2 to 5 times higher than that of untreated RPM and RSG materials.

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