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Waste Management 26 (2006) 932–945
waste management
www.elsevier.com/locate/wasman

Geoenvironmental behavior of foundry sand amended mixtures for highway subbases

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Accepted 16 June 2005
Available online 18 August 2005

Abstract

The high cost of landfilling and the potential uses of waste foundry sands have prompted research into their beneficial reuse. Roadways have a high potential for large volume usage of the foundry sands. A laboratory testing program was conducted on soil-foundry sand mixtures amended with cement and lime to assess their applicability as highway subbase materials. The mixtures were compacted in the laboratory at a variety of moisture contents and compactive efforts and subjected to unconfined compression, California bearing ratio, and hydraulic conductivity tests. The environmental suitability of the prepared mixtures was evaluated by analyzing the effluent collected during hydraulic conductivity tests. Finally, required subbase thicknesses were calculated using the laboratory-based strength parameters. The results of the study show that the strength of a mixture is highly dependent on the curing period, compactive energy, lime or cement presence, and water content at compaction. The resistance of foundry sand-based specimens to winter conditions is generally better than that of a typical subbase reference material. Laboratory leaching tests indicated that if these mixtures later come in contact with water that has been discharged directly to the environment (e.g., drainage through asphalt pavement), the quality of water will not be affected.

1. Introduction

Foundry system sand, which is occasionally referred to as foundry sand, is widely used in the metal casting industry to create the mold into which molten metal is poured. The system sand is a blend of silica sand, organic additives, and bentonite as a binder. The properties of the foundry sand are determined by the relative amounts of binder and other additives, and are unique to each metal casting process. The continued addition of these binders and additives creates an excess volume that cannot be stored in the finite storage volume of the foundry sand system. The excess volume is typically landfilled even though it may have good engineering properties. For instance, the annual generation of foundry system sand is approximately 9 million and 12 million metric tons in Europe and the United States, respectively, and most of this sand is disposed in waste containment facilities (Abichou et al., 2004). At present, only 32% of foundry sand is beneficially reused in construction. This is mainly due to lack of information on its possible beneficial uses or due to regulatory requirements today in force across some countries that classify foundry sands among hazardous wastes (FEAD, 2001; SEPA, 2002). Unless alternative uses of this excess sand are introduced, an increase in landfilling costs is inevitable under present circumstances.

Significant efforts have been made in recent years to use foundry sand in civil engineering construction. Some of the application areas included highway bases and retaining structures (Kirk, 1998; Mast and Fox, 1998;

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0956-053X/$ - see front matter
doi:10.1016/j.wasman.2005.06.007

Goodhue et al., 2001), landfill liners (Abichou et al., 1998, 2004), asphalt concrete (Javed and Lovell, 1995), flowable fill (Bhat and Lovell, 1996), and pavement bases (Kleven et al., 2000). Other studies have shown that the thermal or biological remediation of the foundry sands provides an opportunity for their land applications (Leidel and Novakowski, 1994; Reddi et al., 1996).

Existing research has shown that foundry sand can be effectively used in geotechnical construction due to its comparable properties with sand-bentonite mixtures (Abichou et al., 2004). However, limited information exists about the use of foundry sand as a component in base or subbase layers of highway pavements. Roadway applications provide an opportunity for high volume reuse of the excess material. Moreover, the effect of different factors on the mechanical properties of the subbase layers constructed with foundry sand need to be evaluated. These factors are mainly due to differences in constructional operations (e.g., compaction conditions), material homogeneity, and the selection of different materials amended with foundry sand.

The objective of this study was to investigate the beneficial reuse of foundry sand amended mixtures for subbase layers in highways. To achieve this objective, a battery of tests was conducted on foundry sand and rock-foundry sand mixtures amended with lime or cement. Unconfined compressive strength (q_u) and California bearing ratio (CBR) tests as well as scanning electron microscopy (SEM) analyses were conducted to investigate the effect of cement and lime addition, curing time, molding water content, and mixture gradation on geotechnical parameters. The effect of winter conditions was examined by performing hydraulic conductivity and unconfined compression tests on the specimens after a series of freeze–thaw cycles. Finally, the environmental suitability of the prepared mixtures was evaluated through leaching tests.

2. Materials

The foundry sand used in this study was obtained from Toprak Foundry located in Bilecik, Turkey. The foundry sand had approximately 24% particles passing the US No. 200 sieve (<0.074 mm) and was classified as nonplastic silty sand (SM) according to the Unified Soil Classification System (USCS) and A-2-4 according to the American Association of State Highway and Transportation Officials (AASHTO) Classification System. The physical and chemical properties of the foundry sand used in this study are provided in Table 1. These values fall in a range of values reported by the previous researchers (Abichou et al., 1998; Kleven et al., 2000; Goodhue et al., 2001). Type I Portland cement (ASTM C-150), which is a commonly used agent in soil stabilization projects mainly due to its low cost, was used as a binder in this study. High calcium (95%) quicklime from Afyon Lime Corporation, Inc., Turkey, was used as an alternative binder. In order to investigate the performance of relatively permeable foundry sand/stone subbases, 18 mixtures were prepared with crushed rock addition. The crushed rock was obtained from Kutludag Mining Corporation located in Seyitgazi, Turkey. The rock was mainly formed of calcschist and did not contain any reactive limestone (i.e., CaO). Abrasion resistance (Los Angeles abrasion) of rock was determined as 29 following the procedures listed in ASTM C-131. This value was considered satisfactory since it was lower than 50, an upper limit generally considered for highway subbase applications (AASHTO T-96). The debris and large size particles in the crushed rock were pulverized until they passed through a 19-mm sieve. Additionally, small size sand particles in the rock were eliminated by sieving through 0.425-mm mesh sieve (US Sieve size #40).

Two samples of materials currently used in base and subbase construction by the Turkish Highway Administration were selected as reference materials. The base contained approximately 20.5% fines, had a plasticity index of 6 and was classified as clayey gravel (GC) according to the USCS and A-1-a according to the

Table 1
Physical properties and chemical composition of the foundry sand used in the current study

Physicochemical properties	Notation/value
Classification (USCS)	SM
Classification (AASHTO)	A-2-4
G_s	2.45
C_u	5.5
Fines content (<74 μm) (%)	24
Active clay content (<2 μm) (%)	5
Moisture content (%)	3.25
pH	9.1
Organic content (%)	4.3
Chemical composition	**% value**
Silica (as SiO_2)	98
Aluminum (as Al_2O_3)	0.8
Iron (as Fe_2O_3)	0.25
Potassium (as K_2O)	0.04
Calcium (as CaO)	0.035
Magnesium (as MgO)	0.023
Nickel	0.004
Chromium	0.003
Lead	0.003
Zinc	0.003
Copper	0.002
Cadmium	0.001
Sulphur	–
Trace elements	0.836

Note. G_s: specific gravity, C_u: coefficient of uniformity ($=D_{60}/D_{10}$). Fines content and grain size diameters (for C_u calculations) are based on ASTM D 422. Active clay content was determined following the procedures in ASTM C 837.

Table 2
Particle size distribution of materials and mixtures used in the testing program

Specimen name	Particle size (mm)							
	D_{10}	AASHTO M147 limits	D_{30}	AASHTO M147 limits	D_{60}	AASHTO M147 limits	D_{85}	AASHTO M147 limits
F	0.002	0.06–0.08	0.15	0.1–0.4	0.25	0.25–2	0.4	0.9–11
F-L5	0.002	0.06–0.08	0.075	0.1–0.4	0.25	0.25–2	0.4	0.9–11
F-C5	0.002	0.06–0.08	0.075	0.1–0.4	0.25	0.25–2	0.4	0.9–11
F-R73	0.1	0.06–0.2	0.7	0.4–3	6	3.5–12	15	9–25
F-R55	0.07	0.06–0.2	0.2	0.4–3	6	3.5–12	11	9–25
F-R73-C5	0.08	0.06–0.2	0.7	0.4–3	6	3.5–12	15	9–25
B	0.2	0.06–0.2	1.9	0.4–3	7	3.5–12	23	9–25
D	0.0035	0.06–0.08	0.3	0.1–0.4	1.5	0.25–2	3	0.9–11
R	–	NA	5.5	NA	8.3	NA	15	NA

Note. L: lime; C: cement; R: crushed rock; F: foundry sand; B: reference subbase; D: reference base; NA: not available.

AASHTO Classification System. Furthermore, the material contained about 1% organic matter. The fines content of the nonplastic, inorganic subbase material was 8%, and it was classified as light brown silty sand (SM) and A-2-4 according to the USCS and AASHTO, respectively. The final gradations of the materials used in the testing program are provided in Table 2.

3. Test procedures

The procedure outlined in ASTM D 4318 was followed to measure the liquid and plastic limits of each foundry sand sample. The only deviation from ASTM D 4318 procedure was the hydration period. Based on the suggestions of Kleven et al. (2000), the hydration period was extended to one week to ensure the hydration of the thermally degraded bentonite in the foundry sand. Mechanical sieving and hydrometer analyses were conducted following ASTM D 422. The obtained particle size distributions (PSD) indicated that mixtures, in general, satisfied the AASHTO M 147 subbase PSD limits (Table 2).

The specimens were compacted at the optimum moisture content as well as at 2% wet and 2% dry of optimum, to examine the effect of the molding water content on the strength parameters. As with Atterberg limit tests, the foundry sand samples were hydrated for one week prior to compaction. This was necessary, since developed compaction curves (not presented herein) indicated that the dry unit weight changes significantly past $\sim\pm 3\%$ optimum moisture contents (OMC) due to moisture-sensitive nature of the foundry sand.

Two different compactive efforts were studied: standard Proctor (ASTM D 698) and modified Proctor (ASTM D 1557). Crushed rock was added as 55% and 73% of the total weight to some mixtures to determine its effect on the engineering performance of the mixtures. Cement and lime were added as binders to 18 mixtures. These binders are commonly used in highway subbase or subgrade construction to increase the bearing capacity of soils. Table 3 provides a summary of the 40 mixtures used in this study. Table 3 also provides the optimum moisture contents (OMC) and maximum dry unit weights (γ_{dm}) of the mixtures based on compaction tests. The nomenclature represents the compaction effort, percentages of rock and binders used and the compaction moisture conditions, respectively (e.g., F-M-R73-C5(+2) is a mixture comprised of foundry sand, 73% rock, and 5% cement compacted at 2% wet of optimum moisture content using a modified Proctor effort). Unconfined compression, CBR, and hydraulic conductivity tests were performed on the mixtures to evaluate the effect of selected factors on subbase performance. Triplicate tests were conducted on each mixture as quality control and the averages of these three tests are reported as results. The coefficient of variation (ratio of standard deviation to the mean) was less than 25% in hydraulic conductivity tests and less than 15% in the remaining tests.

3.1. Geomechanical tests

The unconfined compressive strength (q_u) is a common measure of the strength of a mixture design in roadways and is often used to determine the structural layer coefficients of the subbase layers for designing pavements. Strength testing followed the procedures outlined in ASTM D 1633. A strain rate of 1%/min was maintained during the unconfined compression tests. The specimens prepared with foundry sand, crushed rock, cement, and lime were compacted at two different compactive efforts. After compaction, the specimens were extruded with a hydraulic jack, sealed in plastic wrap, and cured for 1 and 7 days at 100% relative humidity and controlled temperature (21 ± 2 °C) before testing. The specimens for CBR testing were prepared following the procedures listed in AASHTO T-193 and ASTM D 1883. The specimens were compacted at the optimum moisture content (OMC) using the standard Proctor effort and were cured for 1 and 7 days at

Table 3
Legend and the composition for the mixture designs

Specimen name	Foundry sand, %	Crushed rock, %	Lime, %	Cement, %	W/C	Compactive effort	Water content during compaction	γ_{dm} (kN/m^3)	OMC, %
F	100	–	–	–	–	Standard	OMC	17.03	12.3
F(+2)	100	–	–	–	–	Standard	OMC+2		
F(−2)	100	–	–	–	–	Standard	OMC−2		
F-M	100	–	–	–	–	Modified	OMC	18.83	9.0
F-M(+2)	100	–	–	–	–	Modified	OMC+2		
F-M(−2)	100				–	Modified	OMC−2		
F-L5	100	–	5	–	2.9	Standard	OMC	16.09	14.7
F-L5(+2)	100	–	5	–	3.3	Standard	OMC+2		
F-L5(−2)	100	–	5	–	2.5	Standard	OMC−2		
F-M-L5	100	–	5	–	2.5	Modified	OMC	17.56	12.5
F-M-L5(+2)	100	–	5	–	2.9	Modified	OMC+2		
F-M-L5(−2)	100	–	5	–	2.1	Modified	OMC−2		
F-C5	100	–	–	5	2.5	Standard	OMC	16.96	12.5
F-C5(+2)	100	–	–	5	2.9	Standard	OMC+2		
F-C5(−2)	100	–	–	5	2.1	Standard	OMC−2		
F-M-C5	100	–	–	5	2.0	Modified	OMC	17.84	10
F-M-C5(+2)	100	–	–	5	2.4	Modified	OMC+2		
F-M-C5(−2)	100	–	–	5	1.6	Modified	OMC−2		
F-R73	27	73	–	–	–	Standard	OMC	20.95	7.5
F-R73(+2)	27	73	–	–	–	Standard	OMC+2		
F-R73(−2)	27	73	–	–	–	Standard	OMC−2		
F-M-R73	27	73	–	–	–	Modified	OMC	21.34	5.6
F-M-R73(+2)	27	73	–	–	–	Modified	OMC+2		
F-M-R73(−2)	27	73	–	–	–	Modified	OMC−2		
F-R55	45	55	–	–	–	Standard	OMC	20.22	7.7
F-R55(+2)	45	55	–	–	–	Standard	OMC+2		
F-R55(−2)	45	55	–	–	–	Standard	OMC−2		
F-M-R55	45	55	–	–	–	Modified	OMC	20.65	6.1
F-M-R55(+2)	45	55	–	–	–	Modified	OMC+2		
F-M-R55(−2)	45	55	–	–	–	Modified	OMC−2		
F-R73-C5	27	73	–	5	1.5	Standard	OMC	20.98	7.7
F-R73-C5(+2)	27	73	–	5	1.9	Standard	OMC+2		
F-R73-C5(−2)	27	73	–	5	1.1	Standard	OMC−2		
F-M-R73-C5	27	73	–	5	1.1	Modified	OMC	21.40	5.7
F-M-R73-C5(+2)	27	73	–	5	1.5	Modified	OMC+2		
F-M-R73-C5(−2)	27	73	–	5	0.7	Modified	OMC−2		
B						Standard	OMC	22.25	8.3
B-M						Modified	OMC	23.22	6.5
D						Standard	OMC	20.77	7.0
D-M						Modified	OMC	21.88	6.0

Note. L: lime; C: cement; R: crushed rock; F: foundry sand; M: modified Proctor energy; B: reference subbase; D: reference base; OMC: optimum moisture content; γ_{dm}: maximum dry unit weight; W/C: water-to-cementing agent ratio.

100% relative humidity and controlled temperature (21 ± 2 °C) before testing. The swell during soaking was measured using a dial gauge. Penetration was conducted using a metal piston with a diameter of 4.96 cm per ASTM D 1883. Corrections in the penetration curves were made as described in the selected procedures. A strain rate of 1.27 mm/min was used to describe the penetration curve.

3.2. Hydraulic tests

The hydraulic conductivity of the reference base material was determined using the constant-head method in accordance with ASTM D 2434. The procedure described in ASTM D 5856 was followed for the hydraulic conductivity test conducted on subbase material and foundry sand-base specimens. Specimens of 101.6 mm in diameter and 116.4 mm in height were compacted at their OMC in five layers with the standard Proctor energy and were then cured for 7 days at 100% relative humidity and at 21 ± 2 °C following the compaction. The specimens were left overnight to achieve equilibrium inside the rigid-wall cells before initiating the tests. The influent was prepared from a stock solution that contained rain water. The feed solution had an electrical conductivity (EC) of 0.1 mS/cm and a pH of 7.2, comparable with the properties of water in the natural environment (Tuncan et al., 2000; Lee et al., 2004). Table 4 provides a list of chemical constituents present in the feed solution. The applied hydraulic

Table 4
Chemical properties of feed solution used in column tests

Chemical composition	Value (mg/L)
Calcium (as CaO)	8.0
Chloride	7.4
Potassium (as K_2O)	3.5
Sulphate	2.6
Magnesium (as MgO)	1.2
Nickel	ND
Chromium	ND
Lead	ND
Zinc	ND
Copper	ND
Cadmium	ND

Note. ND: not detected.

gradient was 3 for the crushed rock amended specimens, while a hydraulic gradient of approximately 4–5 was selected for the specimens without crushed rock. Each test was terminated after ensuring the stabilization of flow and following the criteria given in ASTM D 5084. The effluent from the column test (leachate) was collected on a regular basis and the samples were stored for chemical analysis. US EPA (Environmental Protection Agency) standard methods were used to store and analyze the leachates.

3.3. Climatic tests

To observe the effect of winter conditions on geotechnical engineering parameters, some of the mixtures were subjected to strength and hydraulic conductivity tests after a series of freeze–thaw cycles. Specimens with varying cement, lime, and crushed rock contents were compacted at their optimum moisture contents using procedures outlined in ASTM D 698. After 7 days of curing, the specimens were frozen in a temperature chamber at -23 ± 1 °C for 24 h and then thawed in a humidity chamber for 23 h per ASTM D 560. Specimens were frozen and thawed at zero overburden stress. The weight loss, water content, hydraulic conductivity, and unconfined compressive strength were measured at the end of 1, 4, and 8 freeze–thaw cycles.

3.4. Environmental tests

The pH of selected mixtures was measured using the Cole Parmer 39000-50 pH meter following the procedures given in U.S. EPA Method 9045. Electrical conductivity (EC) measurements were performed using Omega CDB-70 conductivity meter. Each specimen was left for 1 h and 24 h at room temperature (20 ± 3 °C) before conducting the pH and EC measurements, respectively. Cation concentration analyses were conducted using atomic absorption spectroscopy (AAS) and following the procedure outlined in SW 846 EPA Method 6010B.

3.5. Microscopy analysis

Undisturbed specimens of 7-day cured specimens were prepared for scanning electron microscopy (SEM) analysis by the critical point drying technique as outlined in Bennett et al. (1977). The specimens were initially treated with acetone and a critical point drying apparatus was utilized to replace the acetone with CO_2. The specimens were held on an aluminum sample holder with adhesive tape. Later, they were coated with gold to minimize any charge build-up. The microstructure and chemical composition of the samples were examined under LEO 440 Model SEM using the energy dispersive X-ray (EDX) technique.

4. Results and discussion

4.1. Influence of crushed rock content and molding water content

It is a common practice to prepare highway subbases with crushed rock or rock amended mixtures. As part of this study, two different percentages by weight of crushed rock, 55% and 73%, were selected such that the PSD of each mixture satisfied the AASHTO M 147 gradation limits. Fig. 1 shows the unconfined compressive strength (q_u) of the specimens compacted at their optimum, 2% wet of optimum, and 2% dry of optimum moisture contents. Unconfined compression tests were not conducted on the reference subbase material (B) since it was cohesionless. The results presented in Fig. 1 indicate that the strength of specimens compacted at optimum or 2% dry of optimum moisture content increases with addition of crushed rock; however, the strength seems to be insensitive for rock contents above

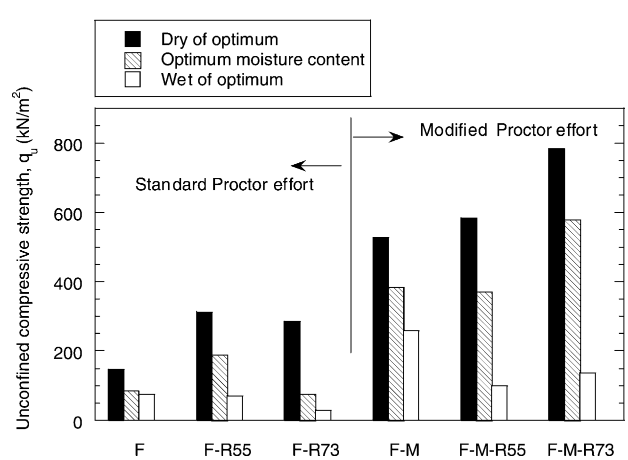

Fig. 1. Effect of compaction moisture content and crushed rock content on strength (*Note.* F: foundry sand; M: modified Proctor; R55 and R73 designate the specimens with 55% and 73% crushed rock, respectively. Each specimen was cured for 1-day before the test).

55% when the standard Proctor compaction effort was utilized. Additionally, high rock contents are needed to observe an increase in q_u when the modified Proctor compaction is performed. On the other hand, the measured strength values of crush rock-amended mixtures are higher than those observed for foundry sand. This trend is clearer for the specimens compacted at dry of optimum. For instance, q_u is 313 kPa for the mixture including 55% crushed rock (F-R55), which is almost twice the strength determined for the foundry sand (F) when standard Proctor effort compaction and dry-of-optimum conditions are considered.

Fig. 1 also suggests that the molding water content at compaction can significantly affect the q_u of the mixture design. An increase in molding water content generally leads to a decrease in strength of the specimens compacted with the same effort. The effect of water content on strength can be explained on the basis of suction theory. Specifically, the decreased pore water pressures due to the lack of water on the dry-of-optimum side of the compaction curve led to higher strength values. Similar conclusions were made by previous researchers that the dry-of-optimum moisture conditions generally increases the strength of highway bases and compacted soils (Benson and Daniel, 1990; Aydilek and Arora, 2004).

4.2. Influence of compactive effort, curing period, and binder addition

The effect of compaction energies on q_u and CBR are presented in Fig. 2. For the specimens cured for the same period of time, higher q_u and CBR are observed with modified Proctor compaction effort. This is mainly due to higher maximum dry unit weights of the specimens that result from the increased compaction energy. For instance, the γ_{dm} of foundry sand (F) increased from 17.03 to 18.83 kN/m^3 with increasing compactive energy. A similar increase in maximum dry unit weights is evident for all mixtures with varying degrees of change in their q_u and CBR (Table 3 and Fig. 2). The unconfined compressive strengths of specimens compacted with modified Proctor effort are 96% to 675% higher than those compacted using the standard Proctor effort when a 1-day curing period is considered. An increase of 75% to 1050% in CBR can also be observed for the specimens compacted at a higher compaction effort (i.e., modified Proctor effort).

Fig. 2 also shows that the q_u and CBR of cement or lime amended mixtures increase with increasing curing time despite the fact that only two curing periods were evaluated in this study. On the other hand, a significant increase is not evident for the remaining mixtures. The postulated mechanism is that the delayed release of calcium hydroxide ($Ca(OH)_2$) by Portland cement or free lime (CaO) by quicklime caused these increases and the temperature of the curing chamber and availability

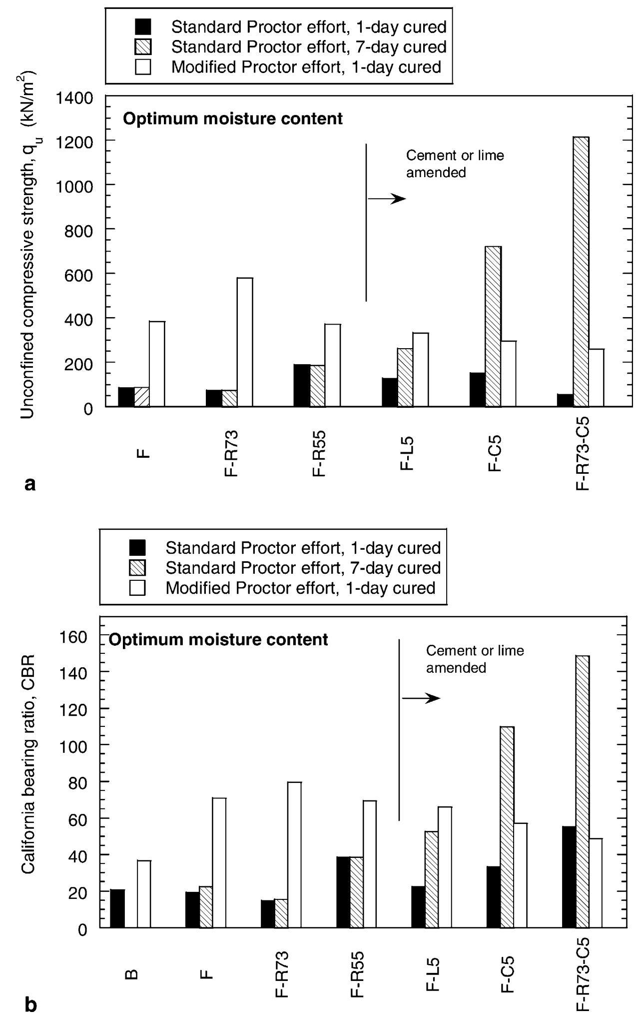

Fig. 2. Effect of compaction effort, curing period, and cement or lime addition on (a) strength; and (b) CBR (*Note*. F: foundry sand; B: reference subbase; R55 and R73 designate the specimens with 55% and 73% crushed rock, respectively; L5 and C5 designate the specimens with 5% lime and cement, respectively).

of 100% relative humidity also enhanced these cementitious reactions. It is believed that the specimens did not significantly hydrate after 1 day of curing and, thus, the increase is relatively small. On the other hand, the strength increase is more evident for the 7-day cured specimens. For instance, the 1-day strength of F-C5 increased almost five times after 7 days of curing from 150 to 720 kPa when it was compacted at OMC. Similar increases in strength with increasing curing period were reported by previous researchers (Vishwanathan et al., 1997).

It can be observed in Fig. 2 that the CBR of foundry sand-based specimens is either comparable or higher than that of the reference subbase material when similar curing period or compaction effort is considered. The CBR generally increases with addition of cement or lime and this increase is clearer when cement was the binder. The CBR of specimens compacted with modified

Proctor effort exceeds 50, a generally accepted limit for subbase applications (Asphalt Institute, 2003). Furthermore, the cement or lime amended specimens (L5, C5, and R73-C5) compacted with standard Proctor effort exhibits CBR values higher than 50 after 7 days of curing. The SEM photographs in Fig. 3 show the agglomeration of foundry sand as a result of cement or lime addition, which may be an indicator of an increase in CBR. Relatively higher amounts of calcium are evident as a result of the addition of lime, as shown in the EDX plots of Fig. 4. The same figure also suggests that most of the silica in the foundry sand was consumed to form calcium silicate hydrates, which in turn hardened the specimen. Additionally, oxygen (i.e., air) present in the pores of the foundry sand decreased, possibly due to a decrease in the hydraulic conductivity.

Fig. 5 shows that the compaction moisture content plays a major role in the q_u and CBR of the cement or lime amended mixtures. Wet-of-optimum conditions reduce the q_u and CBR significantly, and this is the case when the specimens are compacted with standard or modified Proctor effort. The effect of water content on strength can be explained by the characteristics of cementitious reactions. The water-to-cementing agent ratio (W/C) is important in these reactions, even though it cannot always be optimized in solidification/stabilization work. Cement or lime doubles its volume upon hydration, which creates a network of small gel pores (Conner, 1990). When W/C reaches the range of 0.22–0.25, the binder starts to fully hydrate which leaves free water (pore water), gel water, and air voids. Very high W/C ratios leave "bleed water", which is water that appears as standing water on the surface of the solid mass. This starts to occur at a W/C ratio of about 0.48 or greater (Conner, 1990). The observed decrease in unconfined compressive strength with increasing molding water content may be attributed to relatively high W/C ratios for the specimens used in the current study (the ratio W/C was greater than 0.48, even for the mixtures compacted at optimum moisture content using the standard Proctor effort).

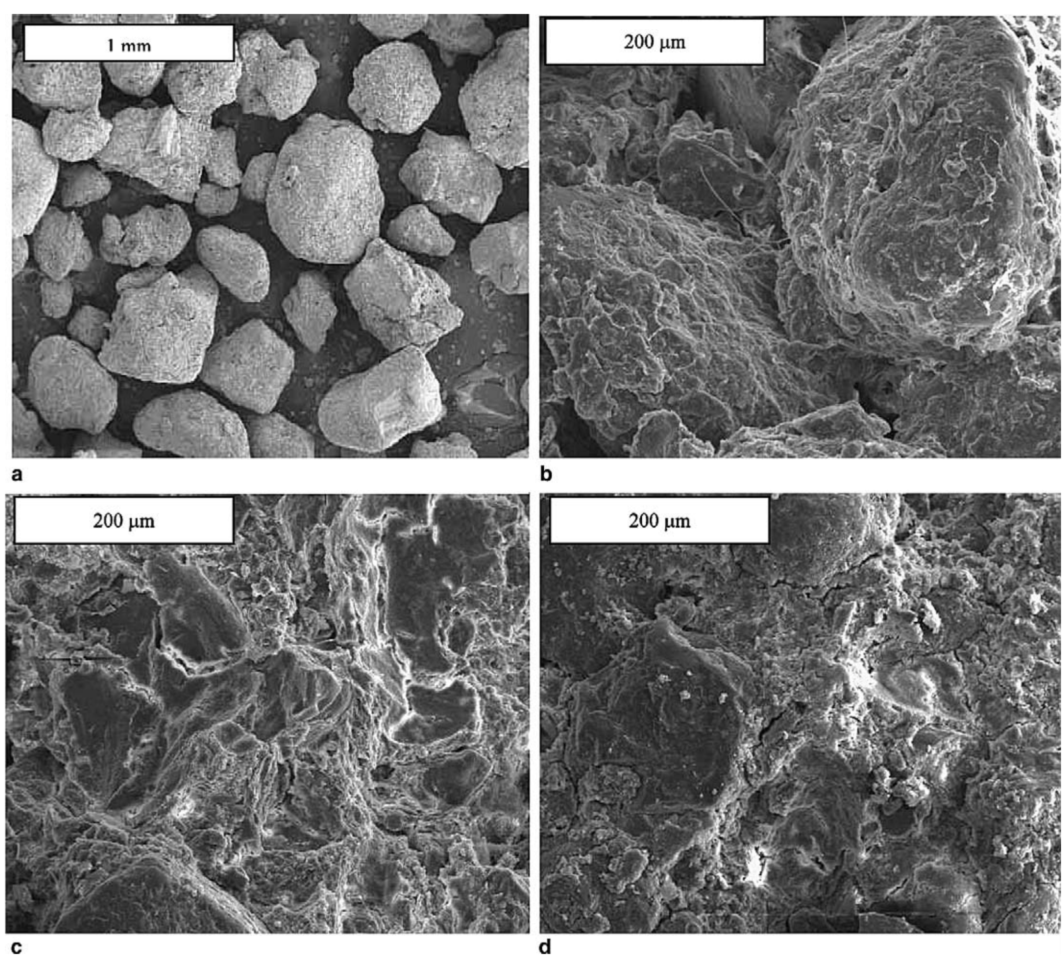

Fig. 3. SEM photograph of (a) foundry sand prior to compaction, (b) compacted foundry sand, (c) lime amended foundry sand, and (d) cement amended foundry sand (specimens were compacted with standard Proctor effort and cured 7 days).

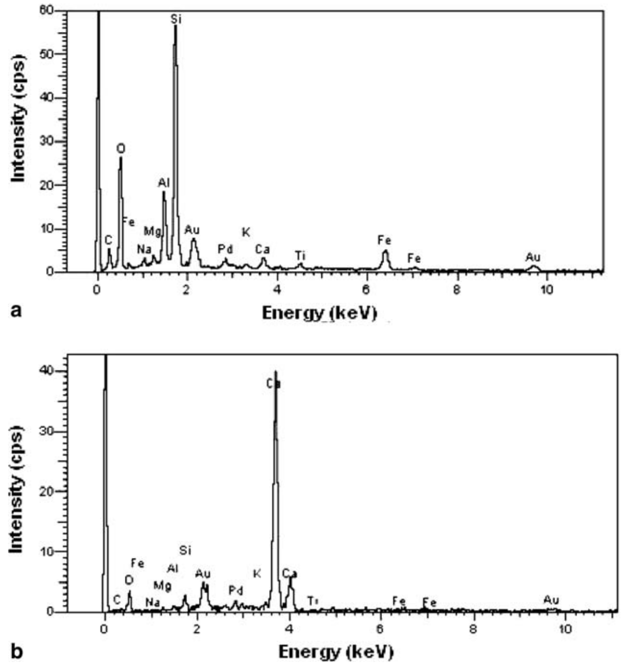

Fig. 4. EDX plot of the SEM photograph of (a) compacted foundry sand (F) and (b) 7-day cured lime amended foundry sand (F-L5).

A significant amount of swell was not observed when the specimens were kept submerged for four days; hence, the mixtures do not appear to have long-term swell potential. As seen in Fig. 6, a maximum swell value of 0.5% was obtained for foundry sand when it was compacted at optimum water content using standard Proctor effort. The other mixtures resulted in swell values ranging from 0.05% to 0.4%. Compacting the specimens at wet of optimum would have resulted in lower swell values (Kleven et al., 2000) even though this was not studied herein.

4.3. Influence of winter conditions

In any stabilization application, the stabilized material should be able to withstand climatic stresses, particularly freeze–thaw cycles (TFHRC, 2002). Subjecting the specimens to strength tests after freeze–thaw (F–T) cycles and recording the change in weight have been reported as indicators of durability; however, it has been noted by Kalankamary and Donald (1963) that the evaluation of durability by weight loss as a result of freeze–thaw cycles (ASTM D 560) is overly severe, and this test procedure does not totally simulate field conditions. Therefore, some of the U.S. highway agencies currently require unconfined compression tests in lieu of durability testing. Previous research indicates that 8–12 cycles of freezing and thawing could be considered adequate in investigating the effect of F-T cycles on various engineering parameters including strength (Zaman and Naji, 2003).

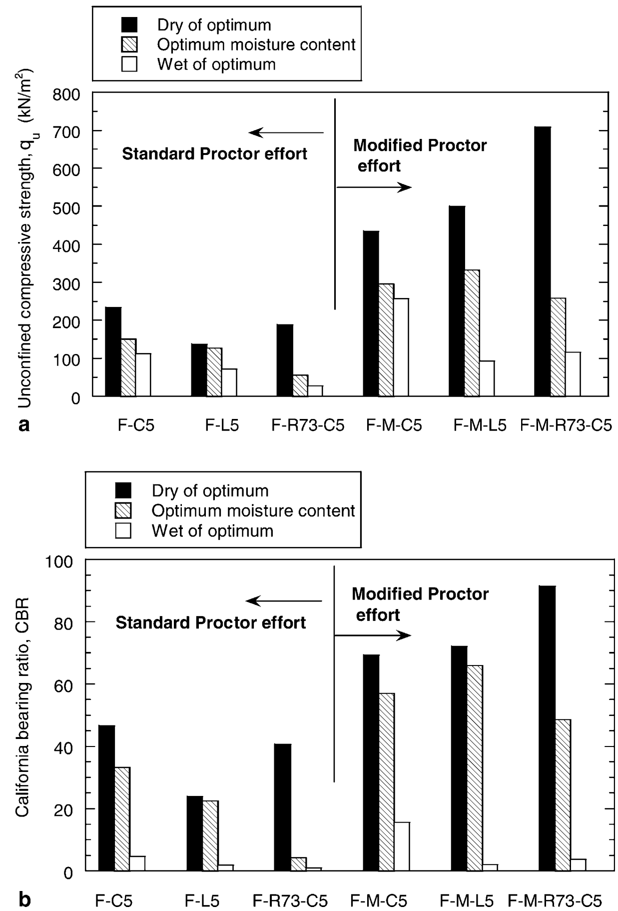

Fig. 5. Effect of moisture content on (a) strength; and (b) CBR of cement or lime amended foundry sand mixtures (*Note.* F: foundry sand; M: modified Proctor effort; R73 designate the specimens with 73% crushed rock; L5 and C5 designate the specimens with 5% lime and cement, respectively. Each specimen was cured for 1-day before the test).

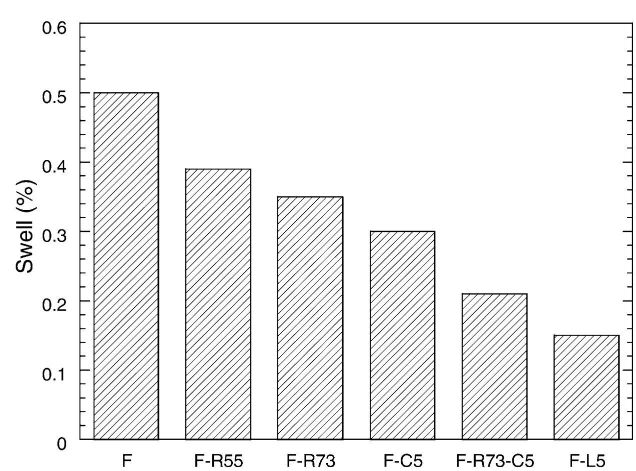

Fig. 6. Swell test results (*Note.* F: foundry sand; R55 and R73 designate the specimens with 55% and 73% crushed rock, respectively; L5 and C5 designate the specimens with 5% lime and cement, respectively. All specimens were compacted with standard Proctor effort).

In the current study, the specimens were cured for 7 days as normally practiced in pavement construction. Unconfined compression and hydraulic conductivity tests were conducted on the mixtures after each freeze–thaw cycle and the results are summarized in Figs. 7 and 8. The unconfined compressive strength ratio ($q_{ur} = q_{un}/q_{ui}$) and hydraulic conductivity ratio ($K_r = K_n/K_i$) in Figs. 7 and 8 are ratios of hydraulic conductivity and unconfined compressive strength after n freeze–thaw cycles (K_n or q_{un}) to the initial hydraulic conductivity and strength (K_i or q_{ui}). Fig. 7 indicates that the q_{ur} of all foundry sand-based specimens stays nearly constant between the first and the eighth freeze–thaw cycles even though they lost 40–50% of their initial strength after the first cycle. The effect of freeze–thaw on strength can be explained in terms of the retardation or acceleration of the cementitious reactions. Freezing action retards the cementitious reactions, which causes a reduction in strength; conversely, thawing action contributes to the increase in strength via accelerating the cementitious reactions. Evidently, the freezing temperature and period are dominant in the first cycle of the mixtures. It is believed that between cycles of 1 and 8, both freezing and thawing compensated each other and hence the observed variation in q_{ur} is minimal. A larger change can be observed in the strength of specimens including crushed rock, probably due to their relatively higher porosity and susceptibility to frost action.

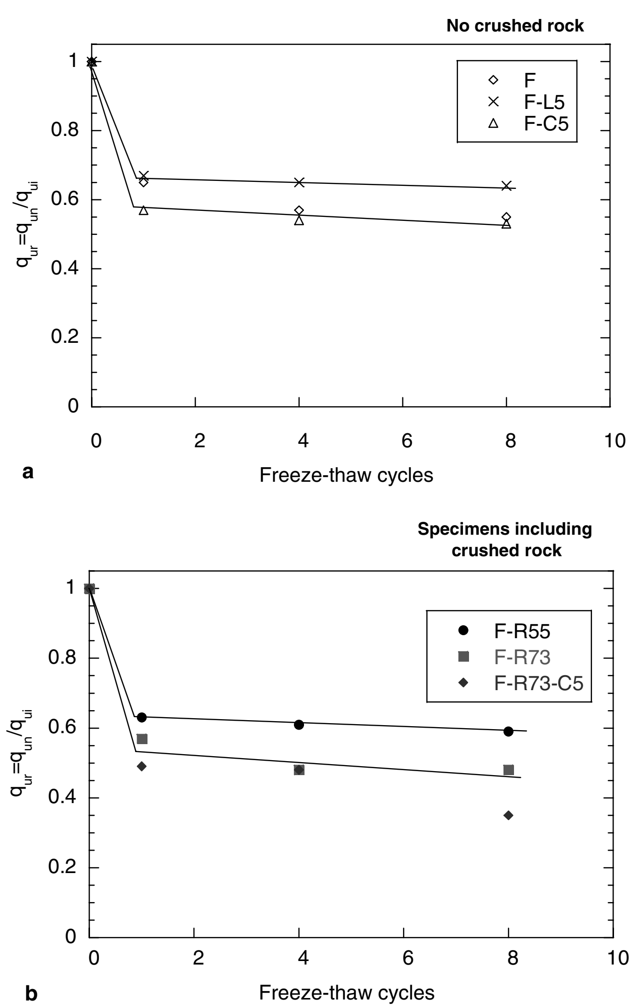

Fig. 7. Effect of winter conditions on unconfined compressive strength (*Note*. F: foundry sand; R55 and R73 designate the specimens with 55% and 73% crushed rock, respectively; L5 and C5 designate the specimens with 5% lime and cement, respectively).

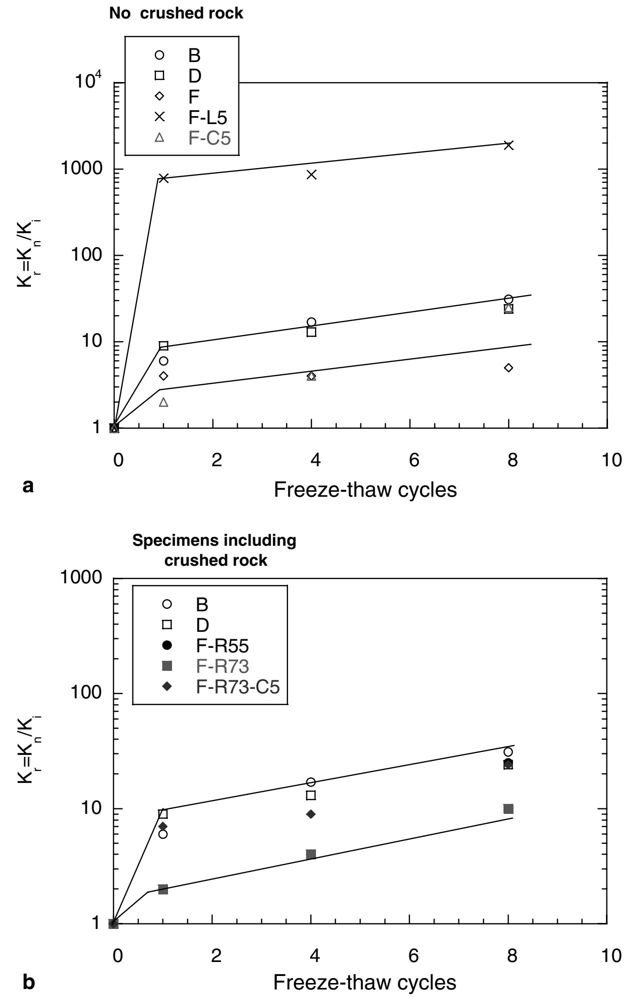

Fig. 8. Effect of winter conditions on hydraulic conductivity (*Note*. F: foundry sand; B: reference subbase; D: reference base; R55 and R73 designate the specimens with 55% and 73% crushed rock, respectively; L5 and C5 designate the specimens with 5% lime and cement, respectively).

Fig. 8 shows the effect of freeze–thaw cycles on the hydraulic conductivity of the mixtures. The resistance of foundry sand-based specimens to winter conditions is generally better than that of the two reference materials. For instance, the K_r stays in a range 6–32 for the two reference materials whereas the same ratio ranges from 2 to 24 for the foundry sand-based mixtures. The only exception to that phenomenon is lime amended specimens, which experience more than a three order of magnitude increase in their hydraulic conductivities, i.e., $K_r > 1000$. Visual observations after the eighth cycle also indicated that these specimens were at the verge of disintegration. The measured weight loss for all of the mixtures was in a range of 2% to 30% after eight cycles of freeze–thaw (not shown herein), and lime amended specimens and the foundry sand experienced the greatest weight loss. On the other hand, the weight losses for the cement amended specimens were less than 14%, a generally accepted limit for cement-treated bases. Visual observations of these mixtures did not reveal cracks or degradation. Therefore, it was assumed that the volume of pores was capable of accommodating the formation of ice lenses during freezing without causing noticeable damages. However, it is important to note that the laboratory simulated freezing and thawing conditions are harsher than the normally encountered winter conditions (e.g., including the conditions in Turkey), and most of the mixtures are likely to exhibit better performance in the field.

4.4. Environmental suitability

To evaluate the characteristics of leachate from foundry sand used in this study, effluent was collected for chemical analyses during the hydraulic conductivity tests. The pH and electrical conductivity (EC) measurements conducted on the specimens are given in Fig. 9. As expected, the pH increases when lime or cement is added. The release of $Ca(OH)_2$ or CaO in these binders increases the pH, and the measured values are comparable at different times. Furthermore, the encapsulation process, a common phenomenon observed during cement stabilization, decreases the EC of the cement-amended mixtures (Tuncan et al., 2000). The encapsulation process usually occurs in the first day of the mixing process due to the fast hydration of Portland cement, which may be a reason for the relatively higher EC observed at 24 h. Effluent collected from the specimens during the tests was initially grayish and cloudy; however, the color and cloudy appearance of the effluent began to diminish after about 8 h. This improvement in clarity is consistent with the small decrease in electrical conductivity observed between 24 and 72 h, as shown in Fig. 9 (i.e., from 0.5–20 to 0.3–17 mS/cm).

One drawback of using compacted foundry sand as a highway subbase material is potential leaching of toxic constituents. Several studies have been conducted in the past to evaluate the characteristics of leachate from foundry sand (Ham et al., 1981; Lovejoy et al., 1996; Naik et al., 2001). Most of this work showed that foundry sand did not cause groundwater or surface water contamination since the measured concentrations were significantly below the US EPA maximum concentration limits. Furthermore, Freber (1996) indicated that

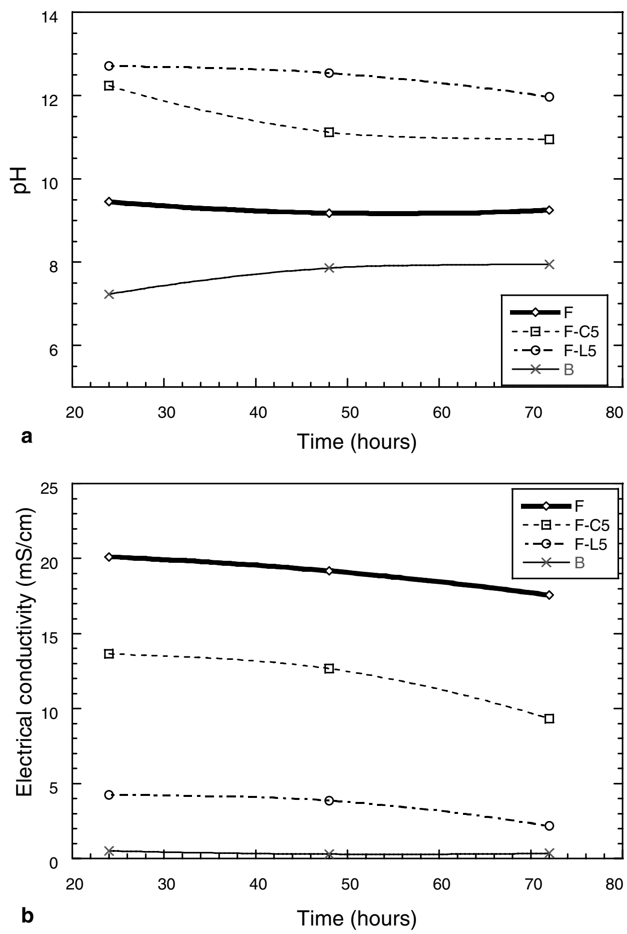

Fig. 9. (a) pH; and (b) electrical conductivity of foundry sand-based mixtures (*Note*. F: foundry sand; B: reference subbase; L5 and C5 designate the specimens with 5% lime and cement, respectively).

the concentrations of metals in groundwater underlying highway embankments are comparable with those encountered in the natural environment, i.e., embankments built with natural soils. On the other hand, Lee and Benson (2002) and Coz et al. (2004) showed that the concentrations of zinc, lead, chromium, and iron leaching from foundry sand may exceed the US EPA limits; however, they concluded that the difference is only 10%, which may be considered acceptable.

In the current study, measurements were conducted on the effluent specimens for selected metals only (nickel, chromium, lead, copper, zinc, and cadmium) due to the low organic content of the foundry sand used in this study. The results of the chemical analyses given in Fig. 10 and Table 5 indicate that the leachate is not significantly contaminated with metals. The metals were likely leached from either fresh constituents added to the system sand circuit in the foundry or cooling of the molten metal in the mold. For all metals, the concentration decreases gradually and relatively lower concentrations are measured at later stages (i.e., 48 and 72 h), which indicates that the construction stage of the subbase may be the most

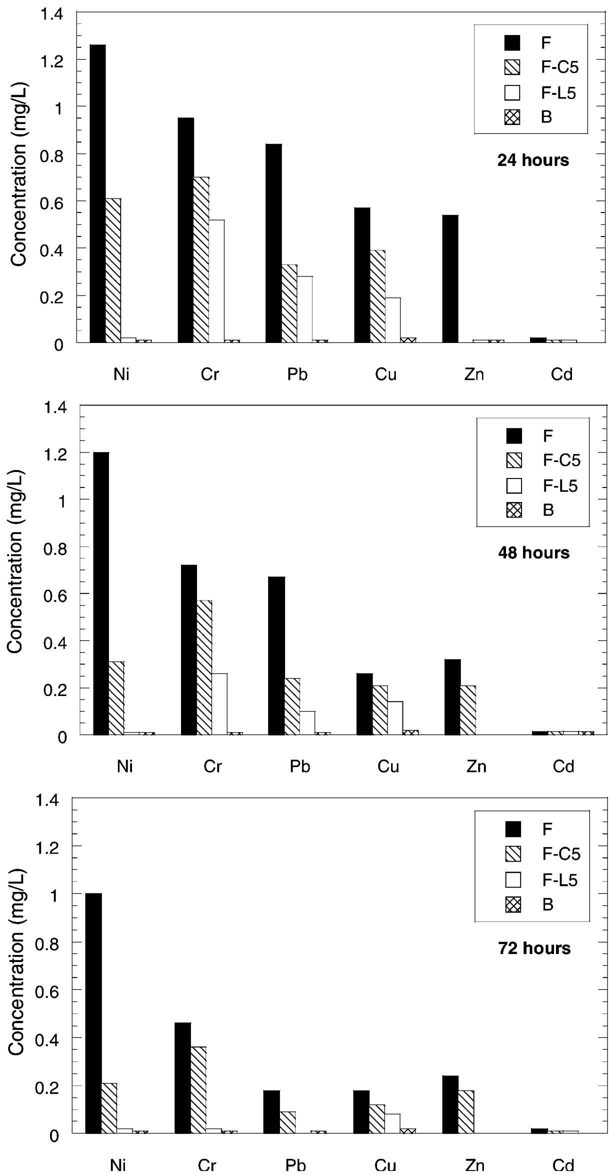

Fig. 10. Amount of leached constituents from foundry sand-based mixtures during column tests (*Note*. F: foundry sand; B: reference subbase; L5 and C5 designate the specimens with 5% lime and cement, respectively).

critical one and mass loading of the groundwater may happen during this phase. The results also indicate that the lime or cement amended mixtures result in lower metal concentrations, possibly due to decreased solubility of these constituents at high pH values or decreased hydraulic conductivities as a result of agglomeration capacity of cement and lime. Nickel concentrations are higher than those measured for other metals at all times; however, drinking water standards are not exceeded for any of the measured constituents (Davis and Cornwell, 1998). From these analyses, it is evident that water passing through foundry sand or foundry sand-based mixtures will not become contaminated with metallic compounds, since the measured concentrations were lower than the US EPA limits. Thus, if these mixtures later come in contact with water that has been discharged directly to the environment (e.g., drainage through asphalt pavement), the quality of water will not be affected with leaching metals. Other elements occasionally present in foundry sands, such as cyanide and fluorides, may also leach into surface or groundwater (West Virginia Department of Environmental Protection, 2000; South Australian Environment Protection Authority, 2003); however, such a study was not conducted herein.

5. Subbase thickness design

Unconfined compression and CBR test results can be used to estimate the thickness of the subbase layer in a flexible pavement, and the procedures defined in the AASHTO Guide (1993) were followed herein to design the subbase thicknesses. First, the structural numbers (SN) were calculated using a design serviceability loss (Change in the Present Serviceability Index, ΔPSI) of 1.9 and a roadbed material effective resilient modulus (M_R) of 34.5 MPa, which was selected based on previous literature (Huang, 1993). Equivalent single-axle loads (ESALs or W_{18}) of 5 million and 50 million were used in the analyses to simulate low traffic (Case I) and high traffic (Case II) conditions, respectively. The over-

Table 5
Mass of leached constituents from foundry sand-based mixtures at the end of testing (at 72 h)

Constituent	F		F-C5		F-L5		B	
	L/S (L/kg)	Mass leached (mg/kg)	L/S (L/kg)	Mass leached (mg/kg)	L/S (L/kg)	Mass leached (mg/kg)	L/S (L/kg)	Mass leached (mg/kg)
Ni		0.47		0.09		0.009		0.004
Cr		0.22		0.16		0.009		0.004
Pb	0.55	0.08	0.56	0.04	0.57	ND	0.44	0.004
Cu		0.08		0.05		0.04		0.008
Zn		0.11		0.08		ND		ND
Cd		0.009		0.005		0.005		ND

Note. F: foundry sand; B: reference subbase; L5 and C5 designate the specimens with 5% lime and cement, respectively; ND: not detected; L/S: volume (in L) of influent percolated/mass (in kg) of dry material.

all standard deviation (S_o) and reliability (Z_R) were assumed to be 0.35% and 95%, respectively. Eq. (1) was used to back calculate the structural numbers (SN) for two traffic conditions:

$$\log(W_{18}) = Z_R \cdot S_0 + 9.36 \cdot \log_{10}(SN+1) - 0.20 + \frac{\log_{10}[\Delta \mathrm{PSI}/(4.2-1.05)]}{0.4 + 1094/(\mathrm{SN}+1)^{5.19}} + 2.32 \cdot \log_{10}(M_R) - 8.07 \quad (1)$$

The top layer of asphalt (D_1) was fixed as 102 mm for Case I and 152 mm for Case II. The M_R of asphalt was assumed to be 2965 MPa, which corresponds to a structural coefficient of $a_1 = 0.44$ according to the AASHTO Guide (1993). An M_R of 207 MPa (corresponding to a structural coefficient of $a_2 = 0.14$) and a thickness of 152 mm (D_2) were assumed for the base layer for both cases based on AASHTO road tests (Huang, 1993). The structural coefficient of the subbase layer (a_3) was calculated for its corresponding CBR values of 7-day cured specimens compacted with standard Proctor effort and 1-day cured specimens compacted with modified Proctor effort. Additionally, the M_R values were estimated using the procedure given in the AASHTO Guide (1993) and they were also used to calculate a second series of a_3 values. Finally, the subbase thicknesses were determined using the following formula:

$$D_3 = \frac{\mathrm{SN} - a_1 D_1 - a_2 D_2 m_2}{a_3 m_3}, \quad (2)$$

where m_2 and m_3 are the drainage coefficients for the base and subbase layer, respectively. They were chosen as 1.2 which assumes excellent drainage conditions within the pavement system (Huang, 1993).

Table 6 shows the required subbase thicknesses for Cases I and II. Layer coefficients of F-R73-C5 could not be interpreted from the CBR test results because the CBR exceeded 100. The calculated thicknesses are relatively large as compared to generally practiced ones in highway construction, and greatly exceed the minimum limit of 152 mm recommended in the AASHTO Guide (1993). Nevertheless, the results clearly indicate that the use of foundry sand-based mixtures requires a comparable or lower subbase thickness than those obtained for reference subbase material, when same compaction effort is considered. Thicknesses of the subbase layers based on CBR and M_R are generally comparable. Additionally, an increase in compaction energies and decrease in traffic load decreased the required thicknesses.

The calculations indicated that the compaction moisture content has a significant effect on the calculated subbase thicknesses due to the moisture-sensitive nature of the foundry sand. Table 7 is given as an example to demonstrate this phenomenon. An increase in moisture content beyond OMC leads to a significant increase in thicknesses, and in most cases measurements were not possible on the nomographs given in the AASHTO Guide (1993) due to the low CBR. On the other hand, dry-of-optimum conditions required lower subbase thicknesses. As discussed before, winter conditions generally lead to a decrease in strength of cement-treated mixes. This would indicate larger subbase thicknesses, even though not presented herein. However, it should be noted that the climatic stresses may have unexpected effects on the mixtures even in the short-term (i.e., during construction), and therefore precautions should be taken to protect specimens from in-situ freezing conditions in harsh environments (e.g., insulation).

Table 6
Required subbase thickness for different mixture designs for two traffic conditions (all thickness values are in mm)

Specimen name	CBR		M_R	
	Case I	Case II	Case I	Case II
F	478	860	477	858
F-M	355	639	356	642
F-L5	371	668	365	656
F-M-L5	365	656	357	642
F-C5	327	589	327	589
F-M-C5	368	663	368	662
F-R73	526	947	546	983
F-M-R73	349	629	352	633
F-R55	395	712	408	735
F-M-R55	361	650	359	646
F-R73-C5	<334	<334	<334	<334
F-M-R73-C5	375	675	380	683
B	515	926	520	937
B-M	455	820	468	843

Note. L: lime; C: cement; R: crushed rock; F: foundry sand; M: modified Proctor energy; B: reference subbase. Minimum thickness requirement (AASHTO Guide 1993) for ESALs greater than 5,000,000 is 152.4 mm.

Table 7
Effect of compaction moisture content on subbase thicknesses of selected mixtures (all thickness values are in mm and were calculated based on CBR considering Case I traffic conditions)

Specimen Name	Dry of optimum	Optimum	Wet of optimum
F	444	478	>787
F-M	354	355	709
F-L5	483	371	>787
F-M-L5	355	365	>787
F-C5	380	327	>787
F-M-C5	362	368	525
F-R73	369	526	NA
F-M-R73	323	349	>787
F-R55	372	395	>787
F-M-R55	346	361	>787
F-R73-C5	388	<334	NA
F-M-R73-C5	343	375	>787
B	488	515	NA
B-M	411	455	>787

Note. L: lime; C: cement; R: crushed rock; F: foundry sand; M: modified Proctor energy; B: reference subbase. Minimum thickness requirement (AASHTO Guide 1993) for ESALs greater than 5,000,000 is 152.4 mm. NA: not available since the specimen failed during testing.

6. Conclusions

Foundry system sand is a blend of silica sand, organic additives, and bentonite as a binder. Continued addition of binders and additives to the foundry system sand creates an excess volume that cannot be stored in landfills. Highway subbases are one of the largest application areas, and reuse of the foundry sand can provide significant cost savings. A battery of tests including unconfined compressive strength (q_u) and California bearing ratio (CBR) tests, as well as scanning electron microscopy (SEM) analyses, were conducted to investigate the effect of cement and lime addition, curing time, molding water content, and mixture gradation on the geotechnical properties of foundry sand-based highway subbases. The effect of winter conditions were examined by performing hydraulic conductivity and unconfined compression tests on the specimens after a series of freeze–thaw cycles. Finally, the environmental suitability of the prepared mixtures was analyzed through leaching tests. The observations are summarized as follows:

1. An increase in strength can be obtained in the field by compacting the foundry sand-based mixtures using higher compactive efforts (i.e., energy simulating modified effort). The test results showed that the water content at compaction could affect the q_u of the mixture design considerably. The performance of the foundry sand-based mixtures can be significantly increased by preventing the intrusion of excess water in the field. It is recommended that the subbase layer be compacted at dry of optimum for higher strength. Alternatively, compaction may be performed at optimum moisture content; however, engineers should be careful about rain or any other addition of unwanted water at the time of compaction.
2. Lime or cement treatment had a beneficial effect on the strength of the mixtures. Addition of lime or cement increased the q_u and CBR of the fully hydrated (i.e., cured for 7 days) specimens. Furthermore, addition of cement increased the q_u and CBR of the rock-foundry sand mixtures.
3. For all mixtures, the q_u decreased and the K_r increased with an increasing number of freeze–thaw cycles. The decrease in strength with the number of cycles was more prominent for mixtures that contained crushed rock owing to their relatively higher porosity and frost susceptibility. The resistance of foundry sand-based specimens to winter conditions was generally better than that of the two reference materials as observed in relatively lower increases in their hydraulic conductivity during freeze–thaw cycles.
4. Laboratory leaching tests indicated that water passing through foundry sand-based mixtures will not become contaminated with undesirable compounds. Thus, if these mixtures later come in contact with water that has been discharged directly to the environment (e.g., drainage through asphalt pavement), the quality of water will not be affected.
5. Lower subbase thicknesses would be required if foundry sand-based mixtures were used in lieu of a reference subbase material. The calculations also indicated that the compaction moisture content has a significant effect on the calculated subbase thicknesses partly due to the moisture-sensitive nature of the foundry sand. Additionally, an increase in compaction energies and decrease in traffic load decreases the required thicknesses.
6. The results indicated that the foundry sand utilized in this study satisfies the geomechanical as well environmental limits and can be safely used as a component in highway subbases. The physical and chemical properties of this particular foundry sand are similar to the foundry sands that exist in many locations; therefore, the reported trends may be considered for future studies. On the other hand, the effects of organic additives and other elements (e.g., cyanides, fluorides) on surface water or groundwater were not analyzed herein, and such tests should be conducted if the trends reported in the current study will be adopted.

Acknowledgements

The funding for this project was provided by Anadolu University, Turkey, through contract No. 03-210. This support is gratefully acknowledged. Dr. Yucel Guney was the principal investigator (PI) in this project.

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