Integrated strategy for beneficial use of dredged materials in Great Lakes commercial ports

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16. Abstract:

This report describes efforts to facilitate beneficial use of dredged materials (DM) from Great Lakes ports and harbors as an alternative construction material in transportation-related earthwork applications. Activities described here constitute Phase II of a Phase I effort previously described in CFIRE Final Report 07-06 "Beneficial Use of Dredged Materials in Great Lakes Commercial Ports for Transportation Projects." The overall objective is to link together the following components: 1) identify applications for use of DM in transportation-related projects, 2) summarize required geotechnical properties in specific transportation applications, 3) identify available geotechnical test methods to determine those properties, 4) identify specific values of required geotechnical material properties for specific uses, and 5) identify locations within the Great Lakes region where dredged materials meeting these specifications may be sourced. This report summarizes results from a suite of laboratory tests designed to characterize dredged materials obtained from select confined disposal facilities (CDF) in Wisconsin, efforts to enhance web-based tools for dredged material management, and efforts to disseminate this information to a targeted audience of stakeholders in the region. The index and engineering properties of raw dredged material (RDM) and RDM stabilized with self-cementing Class C fly ash (FA) were evaluated systematically. RDM samples were obtained by near-surface grab sampling of material placed in a confined disposal facility located at the south end of Milwaukee (MKE) Harbor in Wisconsin. RDM was blended with 10%, 20%, and 30% FA and cured for 2 hours, 7 days, and 28 days. Results showed that blending RDM with FA reduced the plasticity and improved its engineering properties. Increasing FA content increased the maximum dry unit weight and reduced the optimum water content of the stabilized dredged material (SDM). For any curing time, the undrained shear strength of SDM increased linearly with increasing FA content. The improvement in strength increased significantly as the curing time increased. Freeze-thaw cycles only slightly reduced the strength of the SDM specimens (by 4% on average), indicating that SDMs are durable to freeze-thaw processes likely encountered in field beneficial use applications. California bearing ratio (CBR) values for SDM cured beyond seven days varied between 10-20, and were comparable to those of compacted silty sand or sand. Results from CBR testing indicate that the SDM rates as "fair" to "good" for subgrade construction applications. The resilient modulus values for all SDMs increased significantly with increasing FA content. Resilient modulus values for SDM specimens after seven days of curing varied between 35-83 MPa. These values are comparable to those of gravel and crushed stone, and places the SDM in "good" to "excellent" rating categories for subgrade applications. Results of this study indicate that dredged materials stabilized with Class C fly ash show mechanical characteristics viable for beneficial use as subgrade or embankment fill.

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Integrated strategy for beneficial use of dredged materials in Great Lakes commercial ports

Final Report

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Disclaimers

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Chapter 1: Introduction

1.1 Background and Motivation

Dredging of harbors and channels is an indispensable part of maintaining marine transport and supporting multi-modal freight transport systems. Dredged material (DM) management options for Great Lakes commercial ports, particularly those involving confined disposal facilities (CDF) or other long term or permanent placement facilities are diminishing. Many existing disposal facilities serving these ports are at or near capacity. High costs plus limited new site availability make prospects for new or expanded disposal capacity increasingly unlikely. According to a February, 2012 analysis by the U.S. Army Corps of Engineers (USACE), at least six of the Great Lakes largest cargo-handling ports – Duluth/Superior, Calumet Harbor, Saginaw, Toledo, Lorain and Cleveland – are in "critical" status, meaning that dredged material management issues could "severely restrict channel availability within 5 years." Another six ports – Green Bay, Sheboygan, Port Washington, Milwaukee, Rouge River and Ashtabula – have "pressing" needs that could restrict channel availability in ten years.

Implications of these restrictions to freight movement in the North American mid-continent are serious. Some 175 million to 200 million tons of bulk commodities – including iron ore, coal, stone, petroleum products, chemicals and grain – are moved annually on the Great Lakes St. Lawrence Seaway system. The marine mode has been well documented as the most fuel efficient, least air toxic and safest mode for movement of this cargo, and Great Lakes marine transportation supports some of North America's most important core industries including steel manufacturing, automotive, construction and agriculture. For many Great Lakes bulk cargo movements, sheer volume precludes shifts to other surface transportation modes.

Beneficial use (BU) of dredged materials as an alternative source of material for habitat restoration, earthworks, and transportation-related construction (e.g., structural fills, embankments) is emerging as a potentially attractive approach to sustainable material management in the region. A recent CFIRE-funded "Summit on the Beneficial Use of Dredged Materials" held March 14-15, 2013 in Louisville, KY presented strategies, technologies, case studies and policy discussions aimed at promoting beneficial use as a smarter, more sustainable approach to dredged material management approach in the Great Lakes and around the country (see inset). The Summit was targeted specifically for state departments of transportation (DOTs) as potential users of clean construction material dredged from Great Lakes harbors and navigation channels.

A recurring topic of discussion at the recent summit and an important issue that must be addressed prior to widespread beneficial use of dredged materials is the fact that dredgings can vary widely in their physical characteristics and that these characteristics remain largely unknown. Some dredged materials are granular and therefore are most appropriate for high-strength applications such as pavement base material or structural fill. Other dredged materials are fine-grained and therefore may be most appropriate for other applications such as habitat restoration material, hydraulic barriers, or non-structural fill. Existing disposal facilities, which serve as potential sources for "mining" alternative construction material, remain largely uncharacterized and can be highly heterogeneous with respect to the physical properties of available materials. There is a need to address the current disconnect between the wealth of potential construction materials that are available and potential users of these materials. Effectively addressing this need could have a major impact toward solving the disposal capacity crisis for DM management, reducing construction costs, and reaping the sustainable environmental advantages of a sustainable material resource.

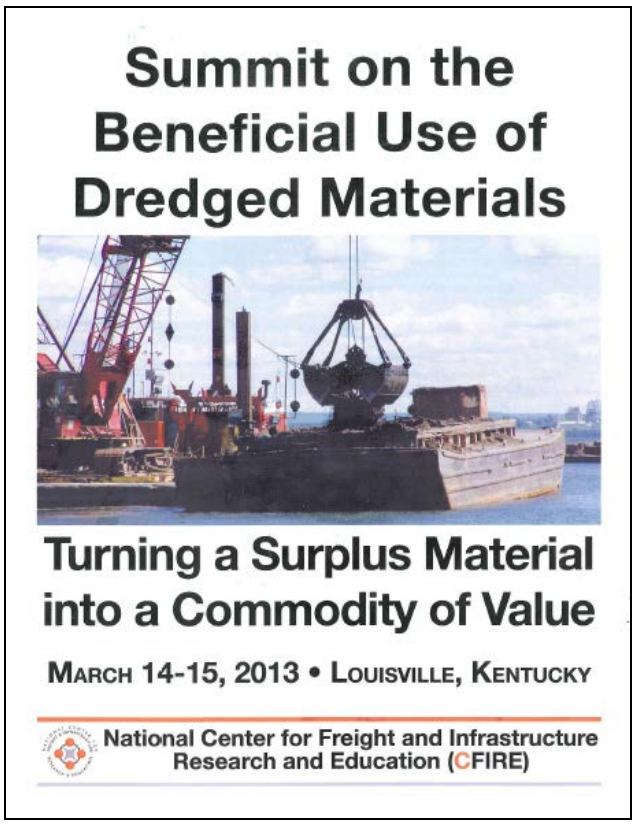


Figure 1.1 Promotional material from 2013 summit on the beneficial use of dredged materials.

1.2 Research Objectives

The objective of this project is to advance the beneficial use of dredged materials as a sustainable material resource for construction operations in the Great Lakes region. The plan builds directly upon previous efforts funded under CFIRE RI-8: "Beneficial Use of Dredging Materials from Harbors and Channels." These previous efforts include planning of the recent beneficial use summit by project Co-PIs Gene Clark and David Knight and development of a beneficial use technical framework by project PI Bill Likos. The work plan is a natural extension of those previous efforts and involves collaboration between three different researchers at three different institutions, including two CFIRE partner institutions.

Emphasis of the current effort is placed on laboratory characterization of dredged materials from select confined disposal facilities (CDF) in Wisconsin, using this information to enhance web-based tools for dredged material management, and disseminating this information to a targeted audience of stakeholders in the region. This project focuses on beneficial use of DM as an alternative material for earthwork construction applications in the transportation sector (e.g., embankments, pavement base, etc.).

The long term objective of the effort is to contribute to sustainable construction by facilitating use of DM instead of natural mined materials. The immediate objective, as described here and summarized in Figure 1.1, is to produce a set of guidelines that explicitly links together: 1) applications for the use of DM as construction materials in transportation-related earthwork projects, 2) required geotechnical properties of materials for specific construction applications, 3) geotechnical laboratory and field test methods available to determine these properties, 4) specifications (values) of these properties required for specific transportation-related projects, and 5) locations within the Great Lakes from which dredged materials having properties meeting these specifications may be sourced. The project is intended to build upon existing and more general frameworks for beneficial use of DM from the Great Lakes region (Great Lakes Commission, 2004) but within the specific context of using DM in the transportation construction sector. Emphasis is placed entirely on suitability in terms of physical characteristics. Suitability in terms of toxicity or environmental characteristics of the material is assumed.

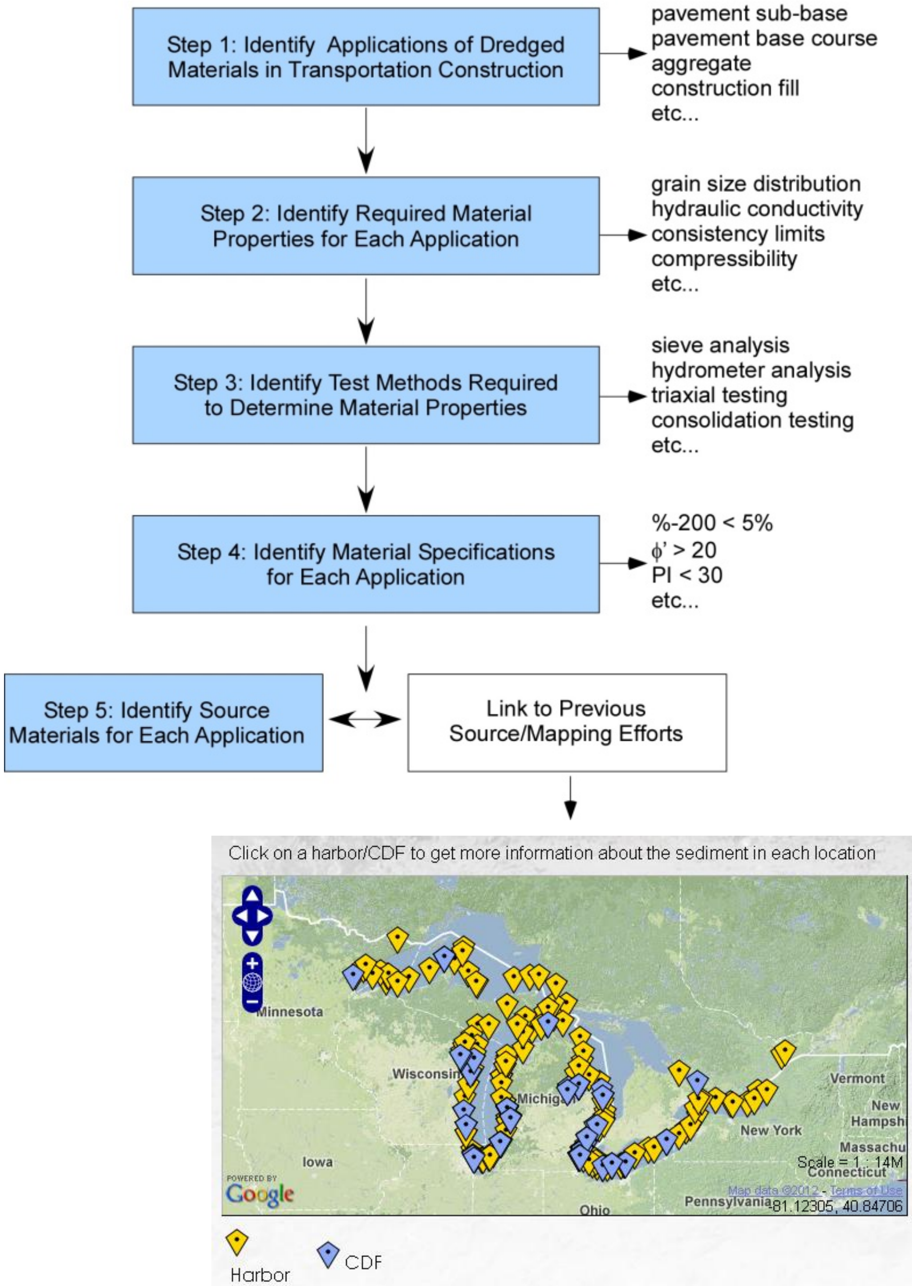


Figure 1.2 Summary of Phase I and Phase II project scope for beneficial use of dredged materials in the Great Lakes region
(map from http://www.glc.org/rsm/mapholder.html)

Chapter 2:

Engineering Properties of Raw and Stabilized Dredged Material

2.1 Chapter Summary

The index and engineering properties of raw dredged material (RDM) and RDM stabilized with self-cementing Class C fly ash (FA) were evaluated systematically. RDM samples were obtained by near-surface grab sampling of material placed in a confined disposal facility located at the south end of Milwaukee (MKE) Harbor in Wisconsin. RDM was blended with 10%, 20%, and 30% FA and cured for 2 hours, 7 days, and 28 days. Results showed that blending RDM with FA reduced the plasticity and improved its engineering properties. Increasing FA content increased the maximum dry unit weight and reduced the optimum water content of RDM-FA mixtures, referred to herein as stabilized dredged material (SDM). For any curing time, the undrained shear strength (c_u) of SDM increased linearly with the increasing FA content. The improvement in c_u increased significantly as the curing time increased. The effect of curing time on c_u was more significant as the FA content increased. Freeze-thaw cycles only slightly reduced the strength of the SDM specimens (by 4% on average) indicating that SDMs are durable to freeze-thaw processes likely encountered in field beneficial use applications. California bearing ratio (CBR) values for SDM cured beyond seven days varied between 10-20, and were comparable to those of compacted silty sand or sand. Results from CBR testing indicate that the SDM rates as "fair" to "good" for subgrade construction applications. The resilient modulus (M_R) values for all SDMs increased significantly with increasing FA content. A significant increase in M_R was obtained until seven days of curing with a small additional increase beyond seven days. M_R values for SDM specimens after seven days of curing varied between 35-83 MPa. These values are comparable to those of gravel and crushed stone, and places the SDM in "good" to "excellent" rating categories for subgrade applications. Results of this study indicate that dredged materials stabilized with Class C fly ash show mechanical characteristics viable for beneficial use as subgrade or embankment fill.

2.2 Introduction

Approximately 300-million cubic yards of sediments must be dredged from US ports, harbors, and waterways each year to maintain or deepen navigation channels, anchorages or berthing areas for the safe passage of boats and ships (Mchergui et al. 2014; Capra et al. 2015; Childs 2015; Katsiaras et al. 2015). Disposal of this volume of dredged material is the single greatest challenge for most dredging projects (Alcorn 2002; Morgan et al. 2002; Ringeling and Rienks 2002; Estes et al. 2012; Brils et al. 2014). Traditional dredging methods discharge sediments into oceans, rivers, lakes, wetlands, estuaries, or confined disposal facilities (CDFs). Particularly, in

Great Lakes Region (including the states of Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin), about 2-3 million cubic yards of sediments are dredged annually, half of which are placed in CDFs. Meanwhile, many existing CDFs that serve ports are at or near their capacity (Clark and Knight 2013).

Beneficial use of raw dredged materials (RDMs) has become a viable alternative to traditional "dredge and dispose" methods (Childs 2015). RDMs can be used for beach nourishment, capping, land creation and improvement, habitat creation or restoration, replacement fill, construction fill, and for topsoil enhancement (Winterhalter 1990; Limeira et al. 2012; Mchergui et al. 2014; Clark and Knight 2013). However, the frequency of beneficial use of RDMs in the US at present is only about 20%. The estimated range of beneficial use is between 33-73% indicating that the beneficial use of RDMs has great potential (Childs 2015). Use of RDMs can take various forms depending on their geotechnical and chemical characteristics. Potential applications for beneficial use of RDMs in construction of transportation facilities include use in pavement systems (e.g., embankment, subgrade, base and sub-base), structural fills, and backfills behind retaining walls

Knowledge of the engineering properties of RDMs (e.g., grain size distribution, Atterberg limits, compaction characteristics, durability to freeze-thaw, shear strength, and hydraulic conductivity) are needed for essentially all earthwork applications in the transportation sector. Pavement design applications require additional assessment of resilient modulus (M_R) and durability characteristics. Design of structural fills or retaining wall backfill requires evaluation of shear strength and hydraulic conductivity.

RDMs in CDFs are typically classified as low plasticity silt (ML), high plasticity silt (MH), high plasticity organic (OH), and high plasticity clay (CH) soil by the Unified Soil Classification System (USCS) indicating that RDMs are among the poorest earthwork materials (USBR 1963; Grubb et al. 2006). Therefore, to improve the engineering properties of RDMs, pozzolanic materials such as lime, cement, and fly ash (FA) may be blended with RDMs to produce stabilized dredged materials (SDMs). The engineering properties and general feasibility of using RDMs stabilized with different cementitious materials have been demonstrated through laboratory tests (Watabe et al. 2000; Maher et al. 2004; Maher et al. 2006a; Chrysochoou et al. 2010; Grubb et al. 2010; Kim et al. 2010; Gui et al. 2012; Malasavage et al. 2012) and field tests (Sadat Associates Inc. 2001; Maher et al. 2006b).

The New Jersey Department of Transportation (NJDOT) used 81,000 cubic yards of RDMs stabilized with 8% Type II cement as embankments fills in two roadways. Results of the geotechnical investigation suggested that the two roadway embankments have a fairly high factor of safety against slope failure and the settlement in the SDM sub-grade was not significant over the course of one year (Sadat Associates Inc. 2001). Approximately 600,000 cubic yards of

RDMs stabilized with cement, cement kiln dust, and lime kiln dust were also used in the construction of a parking lot for the Jersey Garden's Mall, which also demonstrated the feasibility of using SDMs as structural fill (Sadat Associates Inc. 2001). However, there is limited information in the literature on the use of FA to stabilize RDMs. Maher et al. (2006a) evaluated geotechnical properties of RDMs stabilized with Portland cement and FA and indicated that SDM is a viable material for embankment fill. Grubb et al. (2010) suggested that stabilizing RDMs with lime, cement kiln dust, high alkali and slag cements, and FA, improves strength and compressibility of the RDMs for beneficial use in high volume embankment fill and subgrade improvement applications.

The use of FA as a binder is attractive because FA is an industrial by-product that is relatively inexpensive compared with cement and lime (Tastan et al. 2001). About 50-million tons of FA is produced annually in the United States, out of which over 20-million tons are used in engineering applications (ACAA 2014). Self-Cementing Class C FA, which has relatively high CaO content (compared with Class F FA), has been shown to significantly improve the engineering properties of both inorganic soils (Ferguson 1993; Cokca 2001; Prabakar et al. 2004; Edil et al. 2006) and organic soils (Tastan et al. 2011). Therefore, FA is considered as an effective stabilizing agent for a large quantity of construction applications (Mackiewicz and Ferguson 2005; Kate 2005).

This chapter herein describes a systematic investigation of index and engineering properties of RDMs stabilized with self-cementing Class C FA for potential use as highway embankment fill. Such high volume application can potentially use the majority of RDMs. Grain size distributions, specific gravities, Atterberg limits, compaction properties, California bearing ratio (CBR), shear strength, resilient modulus, and durability of RDMs and SDMs were evaluated systematically at different FA contents and curing times. Practical recommendations were made from the test results.

2.3 Materials

2.3.1 Raw Dredged Material (RDM)

Bulk RDM samples were obtained by near-surface grab sampling from a CDF located at the south end of Milwaukee Harbor in Wisconsin. Representative RDM sample had in-situ water content of 67.3%, which was obtained per ASTM D2216. A representative RDM sample consisted of 96.6% fine particles and 3.4% sand-size particles. Atterberg limits including the plastic limit (PL) and liquid limit (LL) were measured following ASTM D4318, and are respectively 42.2% and 61.5%. According to USCS, the RDM sample classifies as high plasticity silt (MH). The organic content for the RDM sample obtained per ASTM D2974 was 9.8%.

Specific gravity (G_s) measured according to ASTM D854 is 2.59, which is within the typical range of G_s for fine-grained soils with organic contents (Huang et al. 2009).

Compaction properties of the RDM sample were obtained using a Harvard Miniature compactor following the standard compaction method per ASTM D698. Maximum dry unit weight (γ_{dmax}) is 12.9 kN/m^3 and the optimum water content (w_{opt}) is 30%. The CBR value measured per ASTM D1883 is as low as 1.5 and the unconfined compressive strength (q_u) measured following ASTM D2166 is 27.7 kPa. Shear strength parameters were obtained from consolidated undrained (CU) triaxial compression test following ASTM D4767 with pore water pressure measurement. The shear strength parameters corresponding to total stresses include c=53 kPa, ϕ=21.5°. Values corresponding to effective stresses include c'=20 kPa, ϕ'=35.4°. These values indicate that the RDM is a relatively poor earthwork material and that its engineering properties must be improved by amendment or stabilization prior to most beneficial use applications in earthwork construction.

2.3.2 Fly Ash

The self-cementing FA sample to stabilize RDM for this study was obtained from the Oak Creek power plant located in Oak Creek, Wisconsin. The fly ash is classified as Class C according to ASTM C618. Table 2.1 summarizes the approximate chemical composition of typical Class C fly ash.

Table 2.1. Range of Chemical Composition of Class C Fly Ash

Parameter	Content (%)
SiO_2 (amorphous silica)	20- 60
SiO_2 (crystalline silica)	0- 10
Fe_2O_3	4-33
Al_2O_3	10-33
CaO	1- 30
MgO	0- 4
TiO_2	0- 3
Na_2O	0- 10
K_2O	0- 3
Carbon	0- 50
Trace Metals	< 0.1

2.4 Methods

According to ASTM D7762, testing procedures for mechanical properties of stabilized dredged materials (SDMs) using Class C FA include CBR, resilient modulus, unconfined compressive strength, and freeze-thaw tests. The RDM sample was stabilized with 10%, 20%, and 30% by weight of FA. Stabilized samples were respectively designated as SDM-10FA, SDM-20FA, and SDM-30FA, where 10, 20, and 30 indicate fly ash content by mass. Effects of curing times on Atterberg limits, compaction properties, undrained shear strength, freeze-thaw durability, unconfined compressive strength, CBR, and resilient modulus of the SDM specimens were also evaluated.

For a given FA content, after thoroughly mixing FA with RDM, each mixture was subdivided into three groups to evaluate the effect of curing time on the index and engineering properties (i.e. curing after 2 hours, 7 days and 28 days). A summary of the testing program on SDM specimens including the number of specimens for each test and the corresponding ASTM or AASHTO testing standard followed is presented in Table 2.2.

Table 2.2 Summary of Testing Program (values indicate the number of replicate samples used)

Testing Program	Standards	Numbers of Samples									
		Curing Time: 2 h*				Curing Time: 7 d			Curing Time: 28 d		
		RDM	SDM 10FA	SDM 20FA	SDM 30FA	SDM-10FA	SDM 20FA	SDM 30FA	SDM-10FA	SDM 20FA	SDM 30FA
Atterberg Limits	ASTM D4318	1	1	1	1	1	1	1	1	1	1
Compaction	ASTM D698	1	1	1	1	-	-	-	-	-	-
Triaxial UU Test	ASTM D2850	3	3	3	3	3	3	3	3	3	3
Freeze-thaw test	ASTM D560	3	3	3	3	-	-	-	-	-	-
UC strength Test	ASTM D2166	3	3	3	3	-	-	-	-	-	-
CBR	ASTM D1883	1	1	1	1	1	1	1	1	1	1
Resilient Modulus	AASHTO T307	1	1	1	1	1	1	1	1	1	1

* h=hour, d=days

2.4.1 Atterberg Limits

Atterberg limits tests are conducted to obtain basic index information about the fine-grained fraction of soils, or to indirectly estimate strength and compressibility characteristics. Common Atterberg limits including the liquid limit (LL) and plastic limit (PL), and can be used to assess the amount of dewatering needed before RDM can be handled and processed. The LL, PL, and corresponding plasticity index (PI = LL – PL) are commonly used when investigating DM in harbors and CDFs or for evaluating suitability of any raw construction material in roadway construction.

Following ASTM D4318, air-dried RDM samples passing through the #40 sieve (0.475 mm opening size) were used for Atterberg limits tests. Different amounts of tap water were separately added to the RDM, SDM-10FA, SDM-20FA, and SDM-30FA specimens to approximately achieve optimum water content based on Proctor compaction tests (Section 2.4.2). After thoroughly mixing the samples in sealed plastic bags, each sample was divided into three groups and allowed to cure for 2 h, 7 d, and 28 d in a room maintained at 100% relative humidity and 25 °C. Additional tests were conducted using samples tested immediately after mixing. The 2-h curing time was selected to more accurately represent field construction conditions (Senol et al. 2006). Specimens cured for 7 d and 28 d were selected to represent early and relatively long-term curing conditions in roadway construction applications.

2.4.2 Proctor Compaction

Compaction tests were conducted to obtain compaction characteristics of the RDM and SDMs, including the γ_{dmax} and w_{opt}, and to prepare compacted specimens for subsequent mechanical tests. The compaction tests were conducted using a Harvard miniature compaction apparatus (Humboldt 2003). RDM samples were air-dried and sieved through sieve #4 (4.75 mm opening size). Fractions of the RDM samples passing through sieve #4 were blended with different FA contents (i.e., 10%, 20%, and 30% by weight). Five subsamples of each blend were mixed with different water contents (ranging from 10% to 40%) and compacted into the steel Harvard miniature compaction mold (diameter of 33 mm and height of 71 mm) using a Harvard compactor. This produced a compaction effort equivalent to the modified Proctor effort according to ASTM D698.

2.4.3 Unconsolidated Undrained Strength

Shear strength obtained from the unconsolidated-undrained (UU) triaxial test is used to evaluate stability of embankment fills in an undrained (e.g., rapid loading) condition. In the UU test, specimens are sheared in compression without permitting pore water drainage by applying constant axial strain rate (ASTM D2850). For each FA content, three replicate specimens were prepared for the UU tests. All specimens were prepared using the Harvard miniature compaction method, wrapped and sealed immediately with plastic sheeting to minimize possible moisture change, and cured in the moisture room (with 100% relative humidity at 25 °C) for 2 h, 7 d, and 28 d. Cured specimens were tested for undrained shear strength according to ASTM D2850 under 100 kPa isotropic confining pressure.

2.4.4 Freeze-Thaw Cycling

To evaluate durability of RDM and SDM samples under cycles of freezing and thawing in the field, the freeze-thaw (F-T) cycling tests were conducted following ASTM D560. Specimens were compacted at γ_{dmax} and w_{opt} using a Harvard compactor. After sealing with plastic sheeting, the specimens were placed for 24 h in a freezing cabinet that maintained a constant temperature of -23 °C. Following the freezing stage, all specimens were placed in the moisture room (with the relative humidity of 100% and temperature of 25 °C) for 24 h. Twelve F-T cycles were considered in this study.

2.4.5 Unconfined Compressive Strength

To investigate how cycles of freezing and thawing and the percentage of FA affect unconfined compressive strength of the SDM specimens, two groups of cured specimens were tested for unconfined compressive (UC) strength: one group was not subjected to F-T cycles and one group was subjected to F-T cycles. For the first group, specimens compacted using a Harvard compactor at optimum water content and maximum dry unity weight were sealed and then placed in moisture room for 24 d. For the second group, samples that had undergone 12 F-T cycles (24 d) were tested. Strain rate in both cases was 1 %/min according to ASTM D 2166.

2.4.6 California Bearing Ratio

The California Bearing Ratio (CBR) test is a penetration test that can be used to evaluate the strength of materials for potential use as pavement subgrade, subbase, and base course material. Following ASTM D1883, air-dried RDM passing through the sieve #4 and blended with different FA contents (i.e., 0%, 10%, 20%, and 30% by weight) were compacted at γ_{dmax} and w_{opt} in a steel mold with a height of 152 mm and diameter of 117 mm. Materials were compacted in five layers with 25 blows per layer. Compacted specimens were then sealed with plastic sheeting and placed in the moisture room for 2 h, 7 d, and 28 d. Cured specimens were then placed in a water bath for 96 h for soaking to simulate the worst-case scenarios under which pavements may perform (Mallick and El-Korchi 2009). After soaking, a standard CBR piston penetrated the specimens at a constant rate of 1.27 mm (0.05 in) /min.

2.4.7 Resilient Modulus

Resilient modulus is a measure of soil stiffness under dynamic loading (AASHTO 1986). The resilient modulus test simulates the field stress conditions for pavement systems. The mold used to prepare resilient modulus specimens in this study had a diameter of 102 mm (6 in) and height of 203 mm (12 in). Specimens were compacted at w_{opt} in the mold in five layers with 25 blows per layer using a modified compaction hammer to achieve the γ_{dmax}. All specimens were then extruded from the mold after compaction, sealed with plastic sheeting, and cured in the moisture room for 2 h, 7 d, and 28 d. Procedures described in AASHTO T307 were followed using the loading sequence for cohesive soils.

2.5 Results

2.5.1 Atterberg Limits

Fig. 2.1 shows the results of Atterberg limits tests in the form of the Casagrande Plasticity Chart that plots PI versus LL. The RDM specimen and SDM specimens with FA contents less than 20% are classified as MH, while the SDM specimens with FA content of 30% are classified as ML. In general, as FA content increases, both LL and PI decrease for all the specimens. There is a linear relationship between LL and PI for the entire suite of RDM and SDM materials having different FA contents and curing times (R^2 = 0.93). The slope of trend line of RDM–FA mixtures chart is 0.70, which indicates this trend line is approximately parallel to the A-line (the slope of A-line is 0.73).

When FA is blended with soil and water, a series of reactions lead to dissociation of lime (CaO) and the formation of cementitious and pozzolanic gels (Tastan et al. 2011). During the hydration process, free lime reacts pozzolanically with the clay, and this reaction reduces clay plasticity (Little and Nair 2009). The Linear relationship between the LL and PI may not be a unique characteristic for SDM. Other stabilized fine-grained soils in the literature show similar response. Fig. 2.1 also illustrates the linear relationship between PI and LL of high plasticity clay (CH) and low plasticity clay (CL) stabilized with different FA contents ranging between 5-15% (Eskioglou 2008).

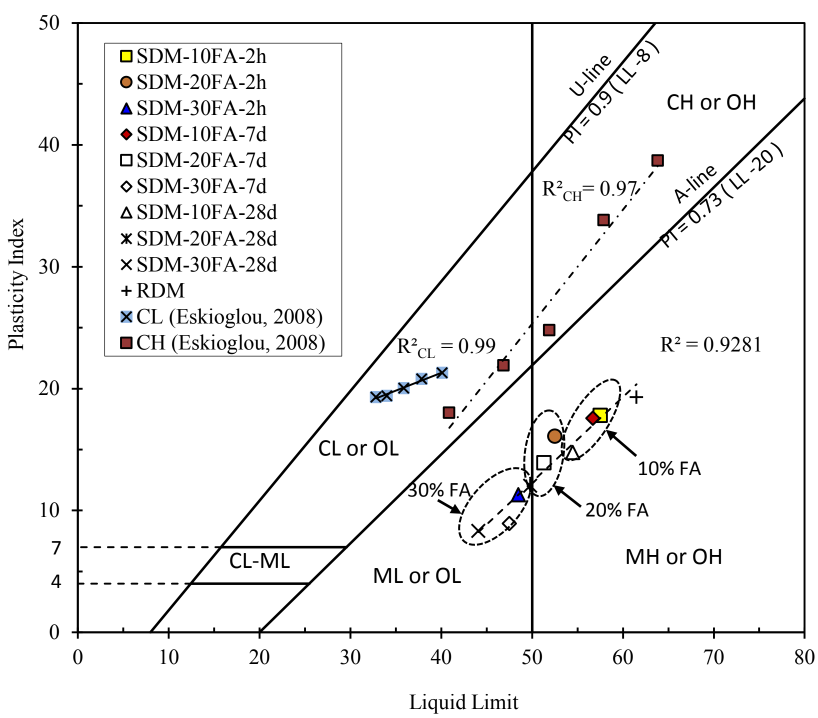


Fig. 2.1. Atterberg limits for RDM and SDM specimens

Figs. 2.2 and 2.3 show the variations of LL and PI versus FA content and curing time more clearly. Fig. 2.2 shows that at a given curing time, both LL and PI decrease with increasing FA content. Blending RDM with FA immediately reduces the LL and PI. As the SDM specimens cure longer, the rate of reduction of LL and PI with FA content increases. On average, increasing the FA content by 10% reduces the LL by 5% and the PI by 3%. Fig. 2.3 shows that for a given FA content in the SDM specimens, the LL and PI decrease with increasing curing time. The majority of LL reduction occurs after 2 h of curing, after which LL only slightly reduces LL over the 28 d curing period. For example, for RDM stabilized with 20% FA, the LL is reduced by 15% from 62% to 53% after curing for 2 h. The LL is reduced to 53% (only by another 5%) after 28 d curing. PI also decreases with increasing curing time, as shown in Fig. 2.3(b). Reduction in PI occurred immediately after curing until 7 d, after which PI only reduced slightly before 28 d.

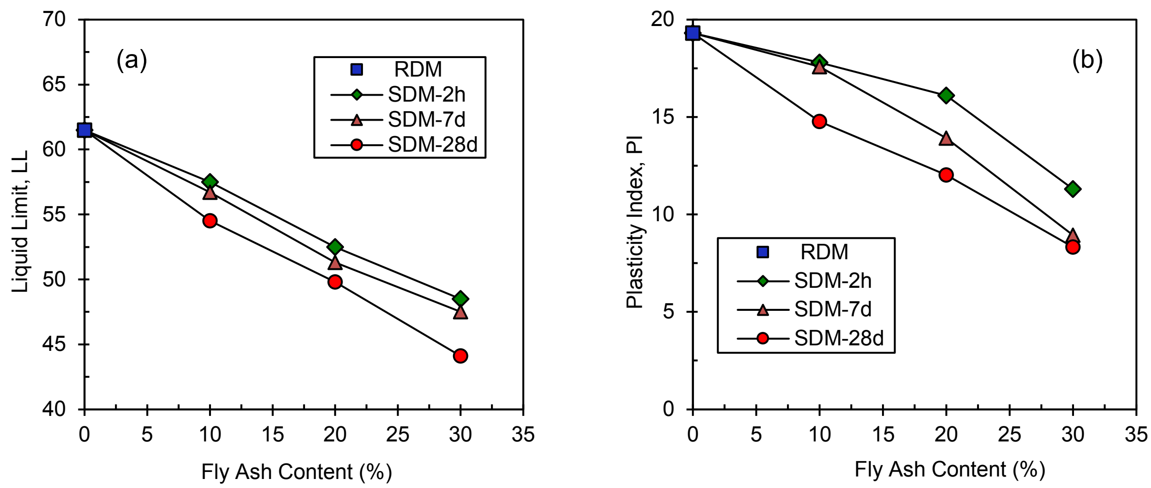
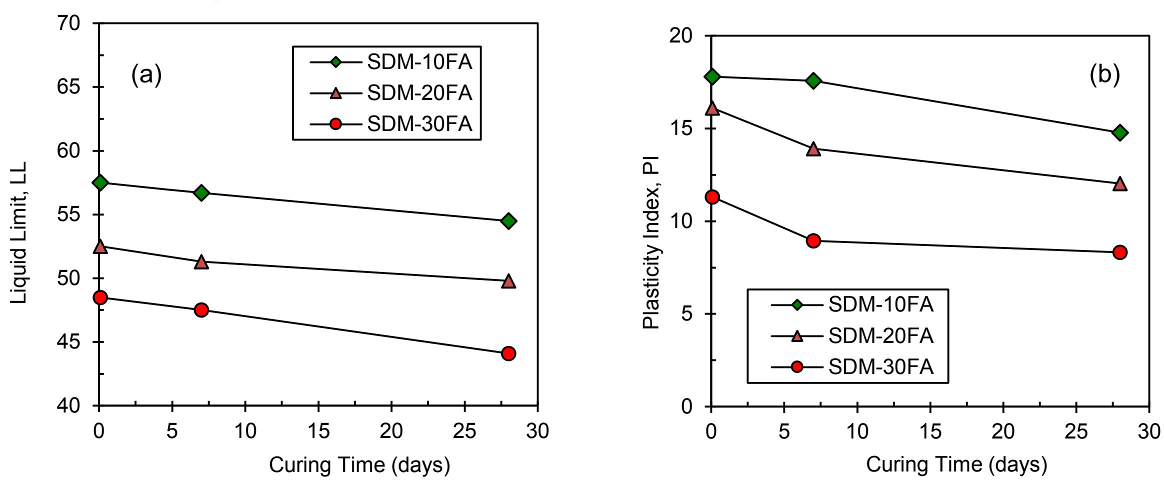


Fig. 2.2. LL and PI versus FA content for RDM and SDM specimens



(a) (b)

Fig. 2.3. LL and PI versus curing time for RDM and SDM specimens

2.5.2 Compaction Characteristics

Typical bell-shaped compaction curves were obtained for all specimens with different FA contents as shown in Fig. 2.4. The zero-air-void curve for RDM is also shown in the figure. Increasing the FA content increased the γ_{dmax} and reduced the w_{opt} (see Fig. 2.5). The γ_{dmax} of RDM-FA mixtures is less than 14 kN/m^3, which is lower than that of typical compacted soils. The low unit weight makes the RDM and SDM a potentially attractive lightweight material for earthwork applications. The SDM-10FA and SDM-20FA samples had approximately the same γ_{dmax} (13.3 kN/m^3-13.4 kN/m^3) and w_{opt} (26.0%-26.5%). Subsequent mechanical tests were conducted using specimens compacted at optimum water content and maximum dry unit weight as obtained from the Proctor tests.

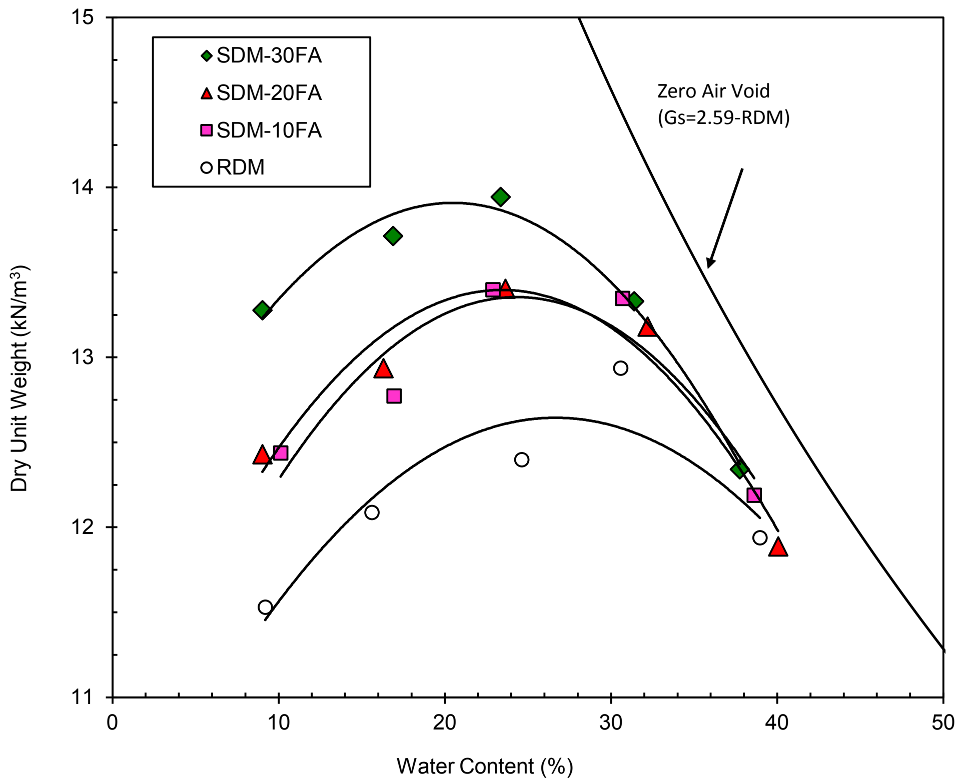


Fig. 2.4. Compaction curves of the RDM and RDM-FA mixtures

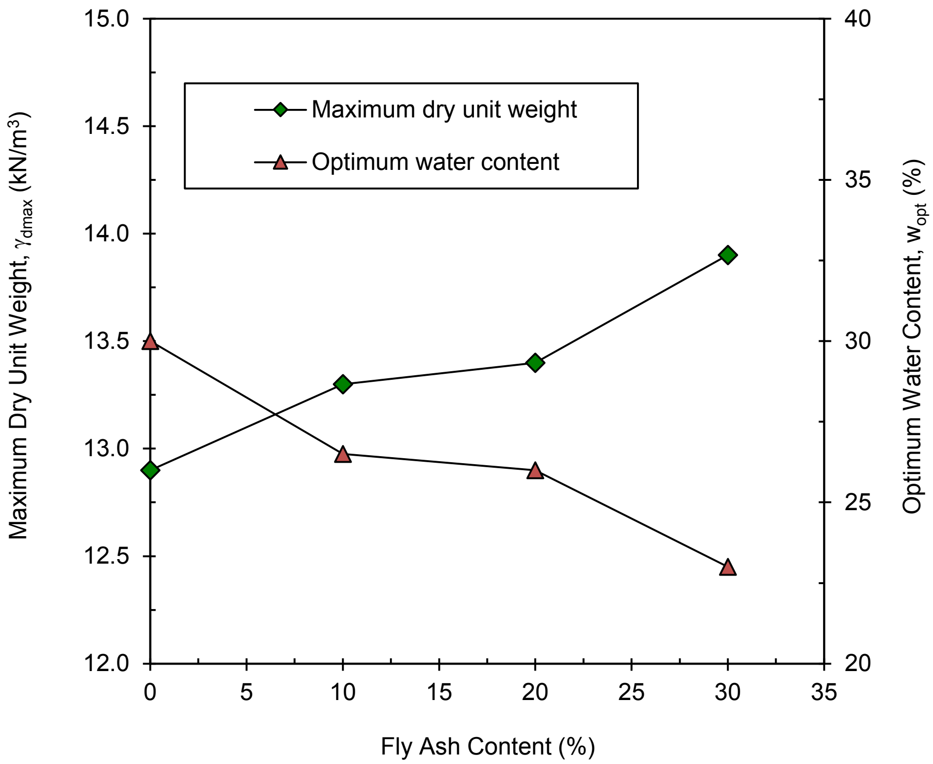


Fig. 2.5. Variation of optimum water content and maximum dry unit weight with FA content

2.5.3 UU Shear Strength

Three replicate UU specimens were tested for undrained shear strength (c_u). Fig. 2.6 reports the average c_u as a function of FA content for three different curing times. The c_u values increased with increasing FA content and curing time. At a given curing time, the c_u-values increased linearly with increasing FA content. For specimens cured for 2 h, however, the effect of FA content is not as significant. By increasing the curing time, the improvement in c_u increases significantly. The percent increase of c_u for the SDM for specimens cured for 7 d ranges from 29% to 108% when FA content increases from 10% to 30%. For the same FA range, the percentage increase for specimens cured for 28 d ranges from 55% to 198%. The effect of curing time on c_u for specimens with high FA content is more significant than for low FA content. For example, for the SDM-10FA specimen, increasing the curing time from 2 h to 28 d increased the c_u by 46%. For the SDM-30FA specimen, the c_u increased by 144% over the same curing time frame. At higher FA content, more pozzolanic reactions occur thus more cementitious bonds between the RDM particles are developed over time. Therefore, higher FA contents affect the c_u values more greatly as the curing time increases (Horpibulsuk et al. 2013).

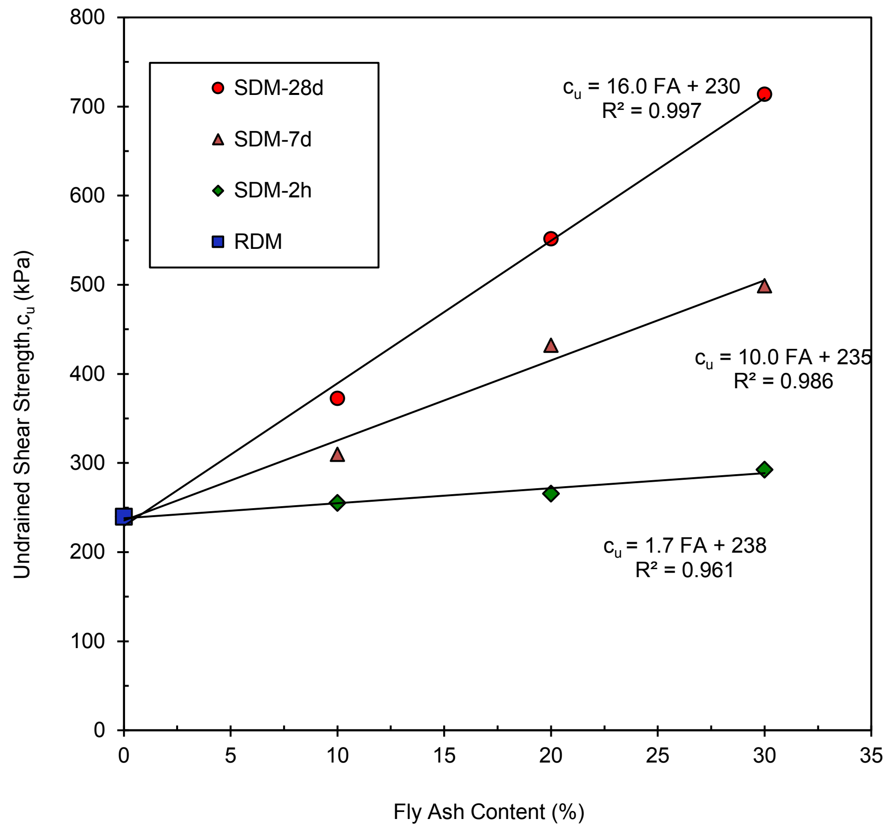


Fig. 2.6. Variation of undrained shear strength with FA content and curing time

2.5.4 Unconfined Compressive Strength and Freeze and Thaw Cycling

Fig. 2.7 shows the variation of unconfined compressive strengths (q_u) of the RDM and SDM specimens with and without F-T cycles as a function of FA content. Whether or not the specimens are subjected to F-T cycles, increasing FA content increases the q_u of the specimens in a similar manner. However, the percent increase in q_u changes at different FA contents. Increase of FA content from 0% to 10%, for example, increases the q_u by 30%. Increasing the FA content from 20% to 30% only slightly increases the q_u for specimens with and without F-T cycles. Unlike for some fine-grained soils, where the benefits accrued by adding FA beyond 20% diminish (Tastan 2011), increase of FA content in SDM to 30% increases the q_u further by 50%.

Fig. 2.7 also includes q_u values of other fine-grained soils stabilized with Class C FA which were cured for 7 days (Senol et al. 2005). Compared to DMs, FA stabilization affects the q_u of CL, ML, or OH more significantly. The greatest improvement was achieved with FA content up to about 10%.

The q_u-values were only slightly decreased after 12 F-T cycles with an average reduction of 4% for different FA contents indicating that SDMs are durable under freeze and thaw cycles. However, the unconfined compressive strength of FA-stabilized soft soils was reduced by 20%. That of FA-stabilized expansive soils was reduced by 40% after 12 F-T cycles (Bin-Shafique et al. 2010). The exact reason of this observation was not investigated; it might be due to freezing of pore water, which exerts pressure to expand the volume of the stabilized soil matrix (Toutanji et al. 2004). This pressure might loosen the cementitious bonding of the particles in the stabilized soils and cause loss of strength.

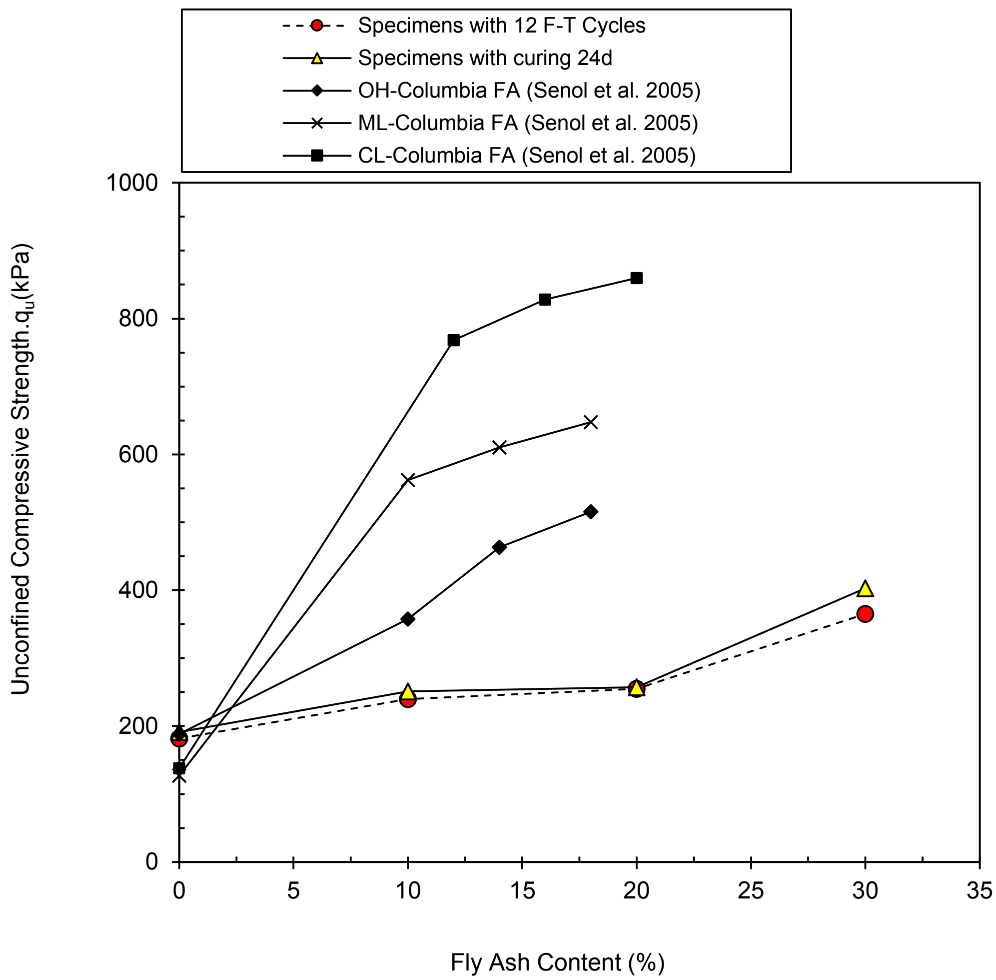


Fig. 2.7. Variation of unconfined compressive strength of SDM specimens with FA content and freeze-thaw (F-T) cycles

2.5.5 California Bearing Ratio

Fig. 2.8 shows that CBR increases with increasing FA content and curing time. CBR increases significantly when the curing time of the SDM specimens increases from 2 h to 7 d (increasing the CBR by 208% on average). However, curing time after 28 d only increases the CBR by 16% on average.

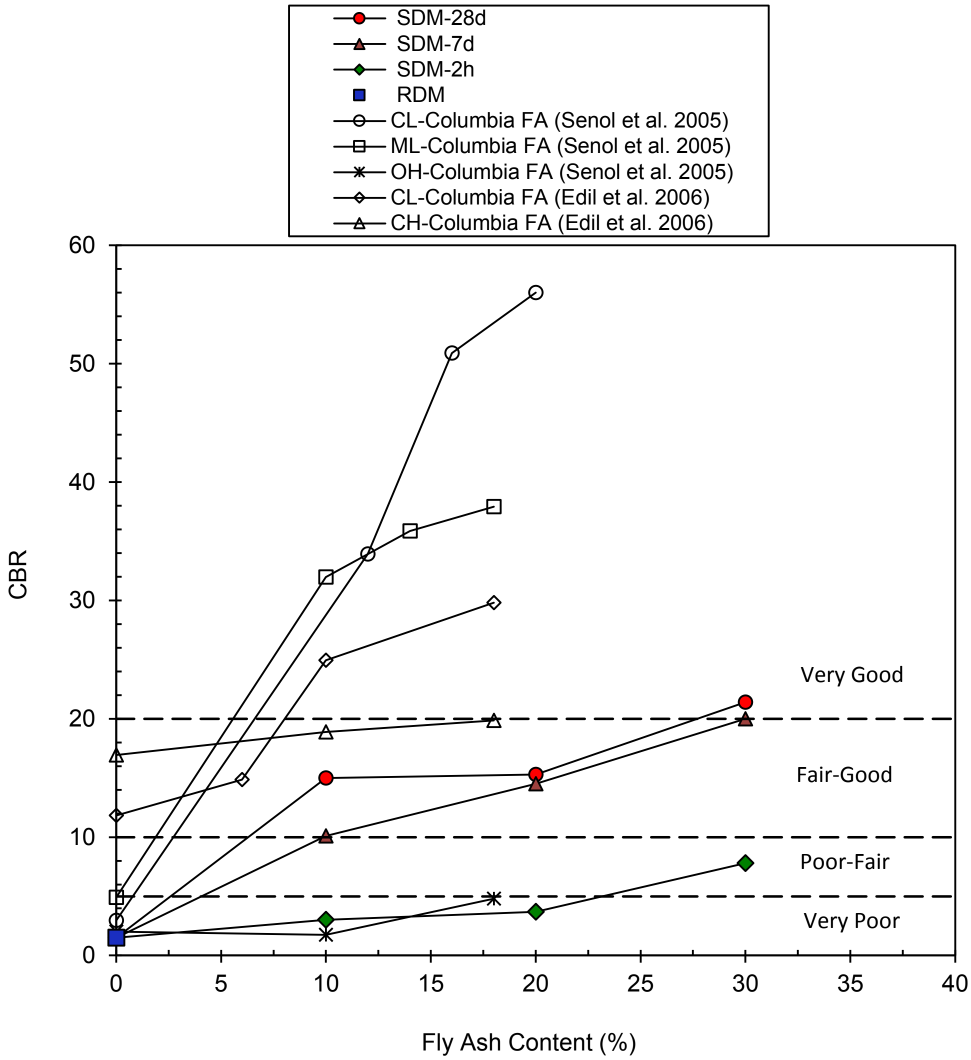


Fig. 2.8. Variation of CBR with FA content

Fig. 2.8 also shows the CBR of other types of fine-grained soils stabilized with Columbia Class C FA. These specimens were cured for 7 d in 100% humidity room before running the CBR tests. All SDM specimens have relatively low CBR values compared to the other fine-grained soils. One possible reason is that RDM has medium organic content (9.8%). Due to various factors including lower solids content, higher water content, lower pH, and chemical interferences that occur in the cementing reactions, soils with high organic content have been more difficult to stabilize than soils with low organic content (Janz and Johansson 2002).

Table 2.3 summarizes the CBR values for RDM, SDM cured for 7 d, and different types of soils. CBR values of SDM specimens vary between 10-20 and are comparable to those of compacted silty sand or sand.

Table 2.3. CBR of RDM, SDM, and Different Soil Types for Subgrade Applications

Material	Soil Type	CBR (%)
RDM	MH	1.5
SDM-10FA (7 d cured)	MH	10.1
SDM-20FA (7 d cured)	MH	14.5
SDM-30FA (7 d cured)	ML	20.0
Soils for subgrade applications*		
Crushed stone	GW, GP and GU	30-80
Gravel	GW, GP and GU	30-80
Silty gravel	GW-GM, GP-GM and GM	20-60
Sand	SW,SP, GP-GM and GM	10-40
Silty sand	SM	5-30
Silt	ML	1-15
Clay	CL	1-15

(From Rollings and Rollings, 1996)

Table 2.4 summarizes the relative ratings of supporting strengths as a function of CBR for subbase and subgrade soils. Based on the CBR range between 10-20, SDMs are classified as fair to good for subgrade application. Fig. 2.8 shows that the SDM should contain at least 10% FA and should be cured for at least 7 d so that the material gains sufficient CBR for subgrade application.

Table 2.4. Relative CBR Ratings for Subbase and Subgrade (Schaefer et al. 2008)

CBR (%)	Application	Rating
> 80	Subbase	Excellent
50 to 80	Subbase	Very Good
30 to 50	Subbase	Good
20 to 30	Subgrade	Very good
10 to 20	Subgrade	Fair-good
5 to 10	Subgrade	Poor-fair
< 5	Subgrade	Very poor

2.5.6 Resilient Modulus

Fig. 2.9 shows the variation of resilient modulus of SDM specimens, normalized with that of RDM specimen (M_R/ $M_{R,\ RDM}$), with curing time and FA content. The M_R of RDM is 22.1 MPa. At a given curing time, M_R tends to increase significantly with increasing FA content. The M_R of the SDM specimen with 10% FA cured for duration between 2 h - 28 d is between 1.2 - 1.7 that of the RDM specimen, while M_R of the SDM specimen with 30% FA cured for the same curing time is between 3.2 - 4.0 times the M_R of the RDM specimen.

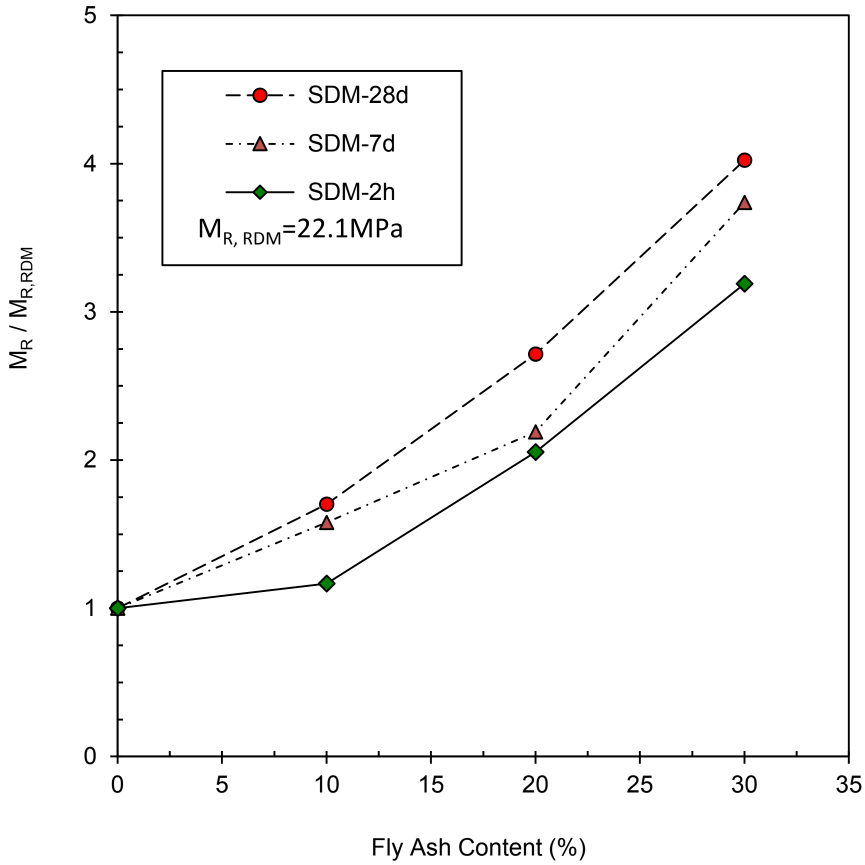


Fig. 2.9. Variation of M_R/ $M_{R,\ RDM}$ with FA content and curing time

The effect of curing time on the resilient modulus of the SDM specimens and CL specimens (Edil et al. 2006) is shown in Fig. 2.10. The CL specimens were prepared with 18% Columbia Class C FA and 18% Dewey FA compacted at optimum water content of 7%. At each curing time, the M_R of the SDM and CL specimens has been respectively normalized by the M_R measured at 2 h and 14 d. A significant increase in resilient modulus was obtained in a relatively short time frame for all specimens (between 2 h - 7 d for SDM specimens and 14 d - 28 d for CL specimens) and little additional increase in resilient moduli was observed after the early short time-frame. The reason is attributed to difference in compaction water content and material characteristics. Khoury and Zaman (2002) also found that curing time beyond 28 d, in which most pozzolanic reactions are completed, has only limited benefits to resilient modulus.

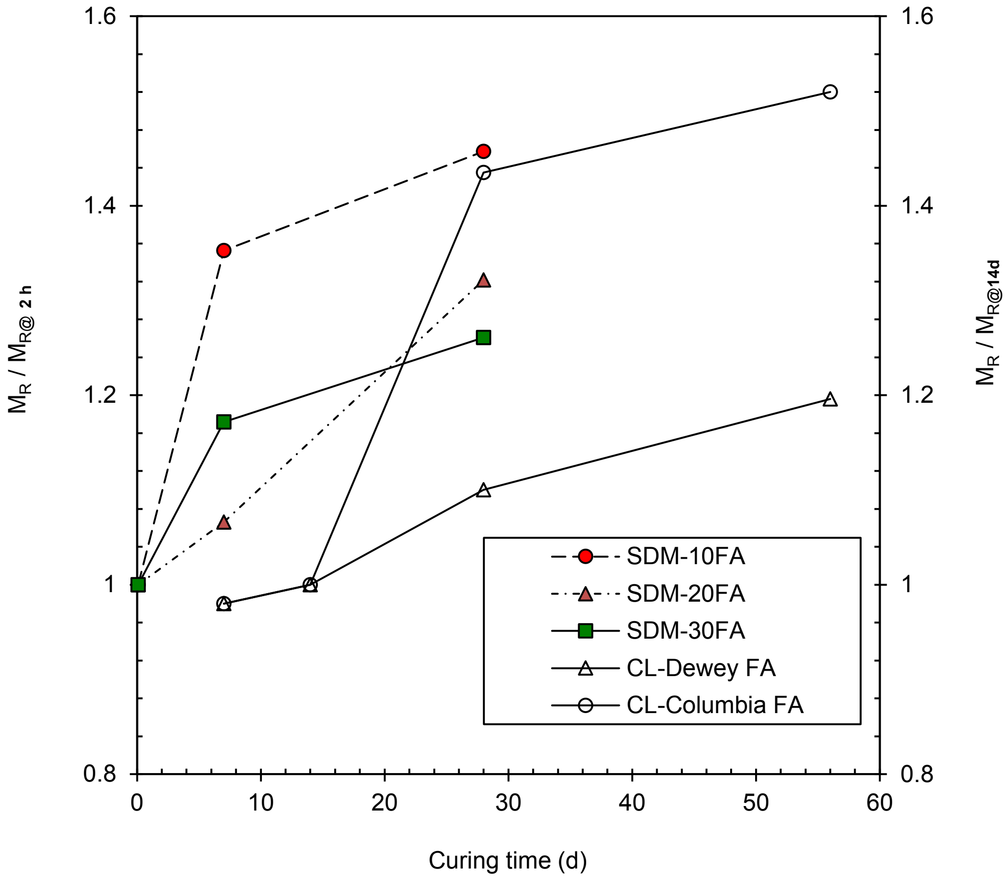


Fig. 2.10. Effect of curing time on M_R

Table 2.5 summarizes the M_R values for RDM, SDM cured for 7 days, and different types of soils. The M_R values of SDM specimens vary between 35-83 MPa. These values are comparable to those of compacted crushed stone or gravel, and indicate that SDMs are rated as "good" to "excellent" for subgrade construction applications. Moreover, M_R values of SDMs in this study are compared with the M_R values of RDMs stabilized with Portland cement (4% PC and 8% PC) for two embankments in New Jersey and subgrade soils that currently underlie roadways (Route 23, Route 295, and Route 206) in New Jersey, as listed in Table 2.6. The M_R for SDM-20FA and SDM-30FA with all curing times is higher than that of the soils taken from Route 206 and Route 295. The M_R for SDM-20FA specimen with 28 d curing time and the M_R for SDM-30FA specimens at all curing times are comparable with M_R for SDMs with 4% PC and 8% PC that were used for roadway embankments.

Table 2.5. M_R of RDM and SDM Specimens along with M_R of Soils for Subgrade Applications

Material	Soil Type	M_R (MPa)*	Rating#
RDM	MH	22.1	
SDM-10FA (7 d cured)	MH	34.9	
SDM-20FA (7 d cured)	MH	48.4	
SDM-30FA (7 d cured)	ML	82.6	
Crushed stone	GW, GP and GU	>39	Excellent
Gravel	GW, GP and GU	31-39	Excellent to Good
Silty gravel	GW-GM, GP-GM and GM	28-39	Good
Sand	SW,SP, GP-GM and GM	28-39	Good
Silty sand	SM	19-28	Good to Fair
Silt	ML	7-19	Fair-Poor
Clay	CL	7-19	Fair-Poor

*From Schaefer et al. (2008), # From Yu and Likos (2014)

Table 2.6. M_R of RDM and SDM Specimens along with M_R of SDMs as Embankment Fill and Subgrade Soils

Material	Soil Type	Curing Time	Compaction	M_R(MPa)
RDM	MH	-	γ_{dmax}	22.1
SDM-10FA	MH	2 h	γ_{dmax}	25.8
SDM-10FA	MH	7 d	γ_{dmax}	34.9
SDM-10FA	MH	28 d	γ_{dmax}	37.6
SDM-20FA	MH	2 h	γ_{dmax}	45.4
SDM-20FA	MH	7 d	γ_{dmax}	48.4
SDM-20FA	ML	28 d	γ_{dmax}	60.0
SDM-30FA	ML	2 h	γ_{dmax}	70.5
SDM-30FA	ML	7 d	γ_{dmax}	82.6
SDM-30FA	ML	28 d	γ_{dmax}	88.9
SDMs as Roadway Embankment Fill in New Jersey*				
SDM(4% PC)	MH	1 m+	90% γ_{dmax}	53.2
SDM (4% PC)	MH	6 m	90% γ_{dmax}	60.3
SDM(8% PC)	MH	1 m	90% γ_{dmax}	85.0
SDM(8% PC)	MH	6 m	90% γ_{dmax}	61.7
Subgrade Soils of Roadways in New Jersey*				
Route 23	SW	-	γ_{dmax}	66.4
Route 295	SM	-	γ_{dmax}	44.2
Route 206	SM	-	□dmax	45.2

*From Sadat Associates Inc. 2001, +m=month

Other parameters, such as CBR may also be used to estimate the M_R based on the empirical correlations. Heukelom and Foster (1960), for example, have reported correlations between CBR value and the in situ modulus of soil, as:

$$M_R = 10\ CBR \quad (1)$$

Through studying the fined-grained soils and mixtures of fine-grained soils and fly ash, Edil et al. (2006) suggested:

$$M_R = 3\ CBR \quad (2)$$

Fig. 2.11 shows the relationship between M_R and CBR values in this study. The data of SDM specimens cured for 2 h fit Eq. (1) well. For the SDM cured for 7 d and 28 d, Eq. (2) is more accurate.

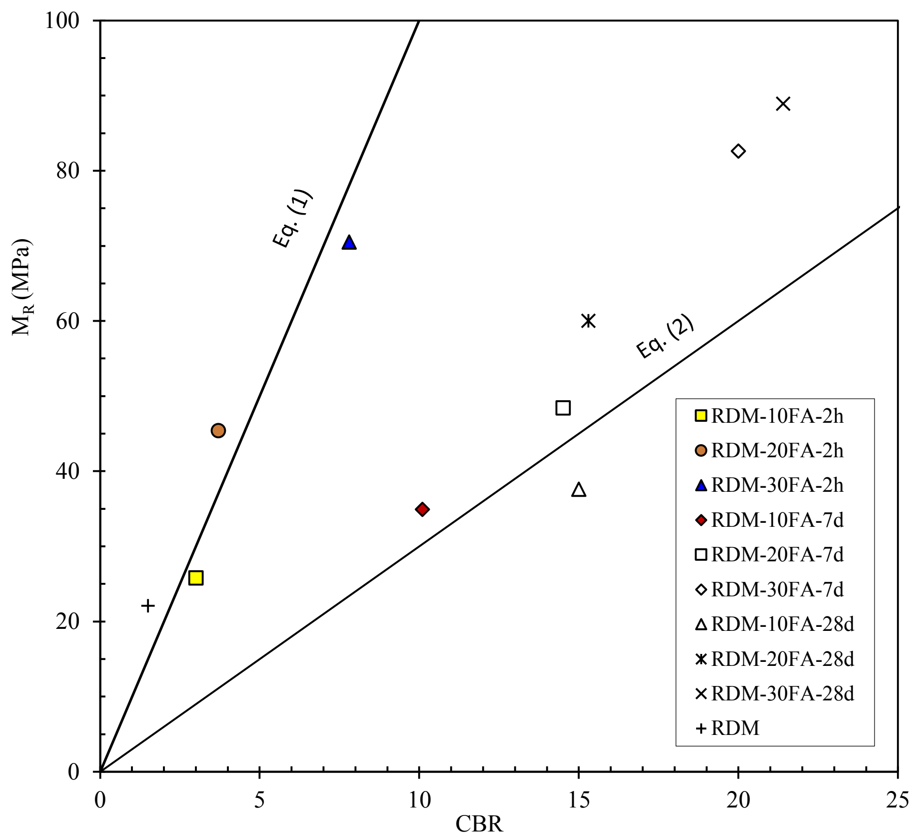


Fig. 2.11. Relations between M_r and CBR

Fig. 2.12 plots a relationship between M_R and q_u. Specimens for these two tests were prepared at the same w_{opt}, FA type and content, and approximately the same length of curing (28 d for M_R and 24 d for q_u tests). Fig. 2.12 indicates a linear relationship ($R^2 = 0.92$) between the M_R and q_u for RDM and SDM specimens. Relationship between M_R and q_u for organic fine-grained soils stabilized with FA from Tastan et al. (2011) is also shown for comparison. Results were obtained from tests on small-size specimens (33 mm in diameter and 72 mm in height) for UC tests and standard size specimens (102 mm in diameter and 203 mm in height) for M_R tests. The conversion factor for q_u to obtain M_R varies from 70-570 with the best fit as 270. The slope value of this study is 305, which is similar to the slope value of 270 obtained by Tastan et al. (2011).

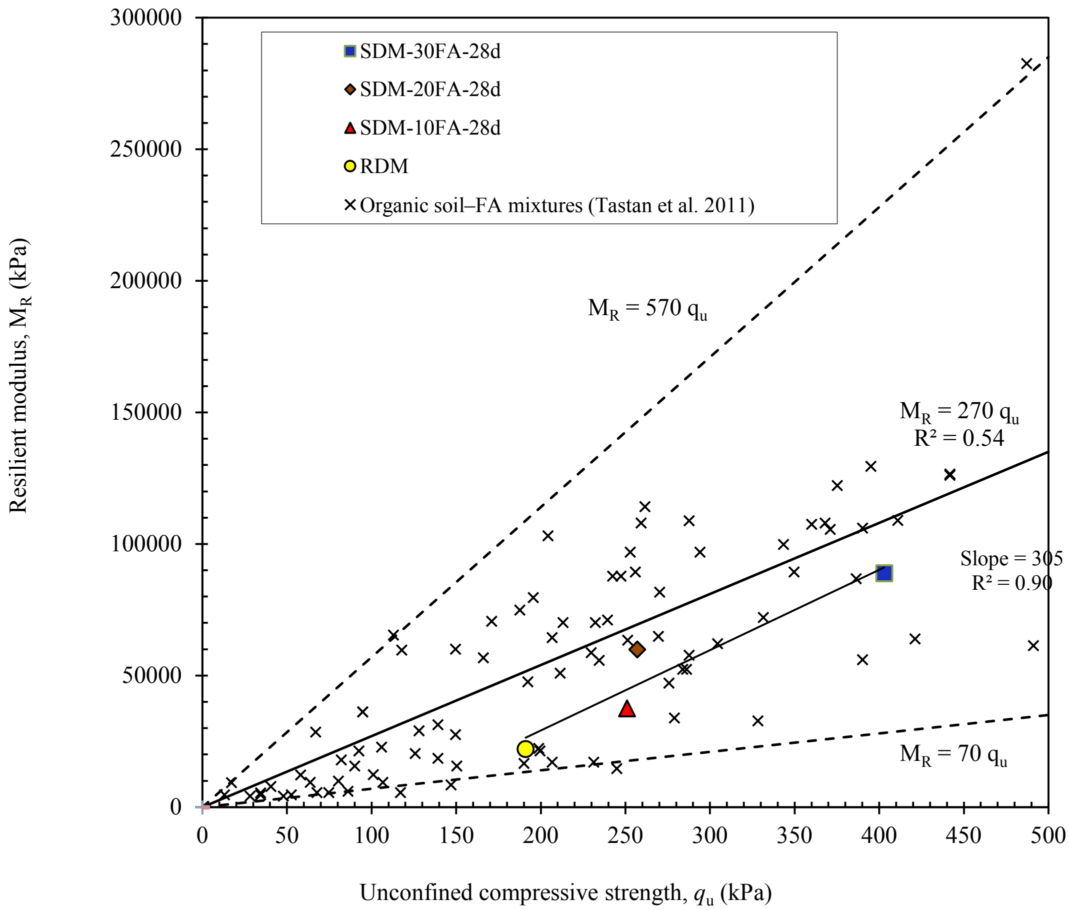


Fig. 2.12. M_r versus q_u for RDM and SDM specimens

2.6 Conclusions

The objective of this study was to identify the stabilization effect of Class C FA on RDMs and to evaluate the effects of curing time and FA content on several index and engineering properties of RDM-FA mixtures that are frequently used for evaluating materials as roadway construction materials. A laboratory study was conducted where RDM–FA mixtures were prepared at different FA contents (10%, 20%, and 30%) and curing times (2 h, 7 d, and 28 d) to evaluate how addition of FA and increment of curing time can improve engineering properties of RDMs. Main findings are summarized in the following:

- All the SDM specimens exhibited lower plasticity compared to RDM. Increase of FA content or curing time will both reduce the PI and LL for SDMs. LL and PI are more susceptible to the FA content than the curing time. Linear relationship was obtained between LL and PI for the entire suite of RDM and SDMs having different FA contents and curing times. Increasing the FA content increased the maximum dry unit weight and reduced the optimum water content of RDM-FA mixtures.

- The undrained shear strength (c_u) increased for all SDMs with increasing FA content and curing time. For a given curing time, c_u increased linearly with increasing the FA content. The improvement in c_u increased significantly as the curing time increased. The effect of curing time on c_u for specimens with higher FA content was more significant than for specimens with lower FA content.

- The unconfined compressive strengths (q_u) of the specimens increases with increasing the FA content. The q_u-values were only slightly decreased after 12 F-T cycles with an average reduction of 4% indicating that SDM in this study is a durable material.

- CBR of SDM specimens increased with increasing FA content and curing time. CBR of SDM specimens cured for 7 days vary between 10-20 which are comparable to CBR of compacted silty sand or sand, and are classified as fair to good for subgrade application.

- The resilient modulus (M_R) values for all SDMs increased significantly with increasing FA content. A significant increase in M_R was obtained in relatively early stage between 2 h and 7 d. The M_R values for SDM cured for 7 d compared well with those of gravel and crushed stone and rated as good to excellent for subgrade applications.

In general, use of Class C fly ash can significantly improve the engineering properties of dredged materials. Use of fly ash to stabilize RDM offers a feasible and effective way for using high volume of dredged materials and reducing the burden of storage and disposal of the fly ash. Economically, coal fly ash stabilization is cheaper than stabilization with the conventional materials such as cement and lime (Mackiewicz and Ferguson 2005). Based on the results of this study, SDMs with fly ash higher than 10% and curing time longer than 7 days can be used as roadway subgrade fill.

Chapter 3: Dissemination and Outreach

Dissemination and outreach components of the project have largely been, or are in the process of being carried out as proposed, with some additional features included. The dissemination/outreach plan for the project consists of three primary product outputs:

1) **A print piece** with the working title of "Converting existing Great Lakes confined disposal facilities (CDFs) into processing and reuse facilities (PRFs)" is being prepared for completion in December 2015. The piece, which will also be posted as a PDF document on line, will draw extensively from data collected from case study CDFs at Wisconsin Great Lakes ports. As proposed, the brochure will document how the detailed material characterization can be compared to various types of re-usable dredged material for a number of potential beneficial uses such as construction, subaquatic, nearshore, and upland habitat restoration or creation, beach nourishment, and brownfield redevelopment. The three case study examples will show how the use of these tools may assist CDF managers with modifications of operations and or placement techniques to allow for the beneficial reuse of the stockpiled clean dredged material. The brochure will be designed as a follow-on to a similar piece prepared for the CFIRE Summit titled "Beneficial Use of Dredged Material in the Great Lakes." Distribution of the piece will include CDF managers, U.S. Army Corps of Engineers (USACE) personnel involved in CDF and PRF operations, port authorities and municipal officials involved in CDF planning and operations.

2) **Website updates** to the existing site "Recycling Dredged Material in the Great Lakes," http://projects.glc.org/rsm/index.html, initially developed in 2008 by the Great Lakes Commission (GLC) for the USACE Regional Sediment Management program. A comprehensive update of the site now underway by the GLC working with USACE will include new information on characteristics of dredged material in CFIRE project case study sites, and a new page dedicated to the metadata and methodologies used for the characterization study conducted as the centerpiece of the project. The update will also re-check, to the extent possible, all individual CDF contact information for accuracy, and will update respective CDF material description information where new data is available.

3) **An informational webinar** will be held for USACE personnel involved in CDF and PRF management, port authority personnel involved in facility maintenance and operations, and other related interests. The webinar will present project findings, including characterizations of dredged material at the case study sites, and suggestions for potential beneficial uses of the material. The webinar will also cover the project's overall objectives, the specific activities carried out, and the above described products/resources that will be available as project outputs.

Produced as an additional outreach component of the project was a six-minute **video documentary, "**Integrated Strategy for Beneficial Use of Dredged Material at Great Lakes Ports," (https://www.youtube.com/watch?v=jDv2YGX5ER8) featuring footage of onsite CDF characterization work conducted at the project case study sites. Dissemination/outreach activities have also included presentations by project PIs at several dredging and dredged material management-related meetings, including the Great Lakes Dredging Team (GLDT) Annual Meeting June 3-4, 2015 in Green Bay, WI (http://greatlakesdredging.net/files/GLDT-Annual-Meeting-CFIRE.pdf). A follow-up presentation will be made at the next GLDT Annual Meeting with full reports on CFIRE products and deliverables resulting from the project.

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