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Development of a Quality Control Index of Cement Stabilized Road Structures Using Shear Wave Velocity

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Abstract - The Department of Highways of Thailand has used cement stabilized materials as road base and subbase for more than 30 years. However, the quality control index of the construction is only undertaken by measuring Unconfined Compressive Strength (UCS) of materials after 7 days of curing. As the UCS test is a destructive and time-consuming method, this study sought to evaluate the use of using seismic waves to inspect material quality as a nondestructive and less time-consuming method which may serve as a basis for the establishment of a new quality control index using shear wave velocity (V_S) measured from Free-Free Resonance (FFR) tests. Four types (360 samples) of cement stabilized materials including soil cement subbase, soil cement base, cement modified crushed rock base, and pavement recycling with cement ratios of 1, 3 and 5% by weight were tested. The results indicated that V_S increased nonlinearly with increasing UCS and also increased with increasing cement ratio for all materials. Moreover, at the same cement ratio, the V_S and the UCS of cemented crushed rock base and pavement recycling were higher than soil cement materials because the first two materials had lower amounts of fine content. Quality controlled shear wave velocities were also calculated by doing a back analysis of developed V_S-UCS empirical equations, and were 536, 970, 1033 and 1095 m/sec for constructions of soil cement subbase, soil cement base, cement modified crushed rock base, and pavement recycling, respectively.

Keywords: quality control, shear wave velocity, resonance, soil cement, unconfined compressive strength

1. Introduction

The Department of Highways of Thailand (DOH) has used Portland cement to improve soil quality in road base and subbase constructions for more than 30 years. However, the only quality control index of the construction is a measurement of Unconfined Compressive Strength (UCS) of cement stabilized materials after 7 days of curing. Because the UCS test is a destructive (coring is required) and time consuming method, the use of using seismic waves to inspect the material quality is valuable as it is a nondestructive and less time-consuming method. In order to obtain a high confidence of using low strain dynamic property (shear wave velocity) as a quality control index, the relationship between shear wave velocity and UCS of cement stabilized materials has to be developed.

In this study, shear wave velocity was measured by the Free-Free Resonance (FFR) test because of it's simplicity. At first, this technique was only used to test the stiffness of Portland cement [1] but over time the test has additionally been adapted for cement stabilized materials such as soil cement column [2]. This method is also a very reliable technique according to [10].

2. Objectives

There are 3 main objectives of this study. The first is to study the effect of the amount of cement on shear wave velocity and UCS of cement stabilized materials. The second is to develop empirical relationships between shear wave velocity and UCS of cement stabilized materials, and the third is to attain required shear wave velocity which will be used as a quality control index of constructions of cement stabilized materials.

3. Methodology

3.1. Basic Properties of Materials

There were 4 materials used in this study including soil cement subbase, soil cement base, cement modified crushed rock base and pavement recycling .These materials were collected from 40 different material resources, 10 for each type . Their basic properties, without any addition of cement, comprising Liquid Limit, Plastic Limit, Plasticity Index, Sieve Analysis, Modified Proctor Compaction, Los Angeles Abrasion)for base materials(, California Bearing Ratio and Soundness)for crushed rocks (were tested to verify that their properties met DOH standards of cement stabilized materials [5] - [8] .Tested results of all materials are shown in Table 1 while grain size distributions of soil cement subbase, soil cement base, cement modified crushed rock base and pavement recycling are shown in Figure 1, Figure 2, Figure 3 and Figure 4, respectively.

3.2. Sample Preparation

Materials used in this study were all sieved through a number 4 sieve, mixed with cement at 1, 3, and 5 %by weight, and compacted at optimum water content using developed mold and compaction hammer which were able to provide efficient energy equivalent to the Modified Proctor test .The size of the compacted samples was 0.05 m)2 inches(in diameter and 0.1 m)4 inches (in height .Three samples were tested at one cement ratio so there were a total of 360 tested samples in this analysis.

After compacting, the samples were put into plastic bags for curing for 7 days .The samples then were soaked in water for a couple hours before performing Free-Free Resonance)FFR (tests.

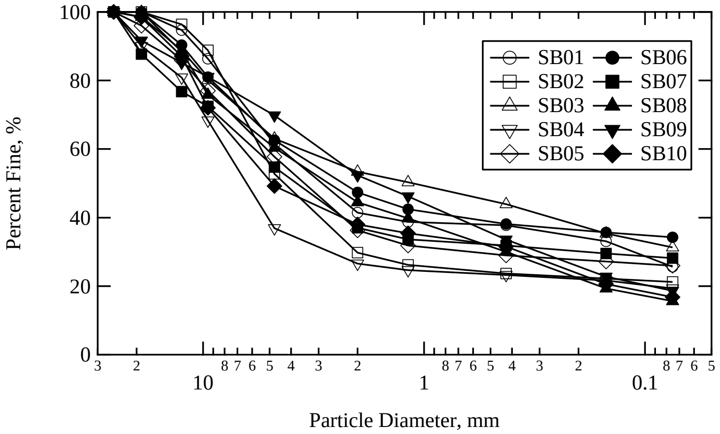

Fig. 1: Grain Size Distribution of Soil Cement Subbase.

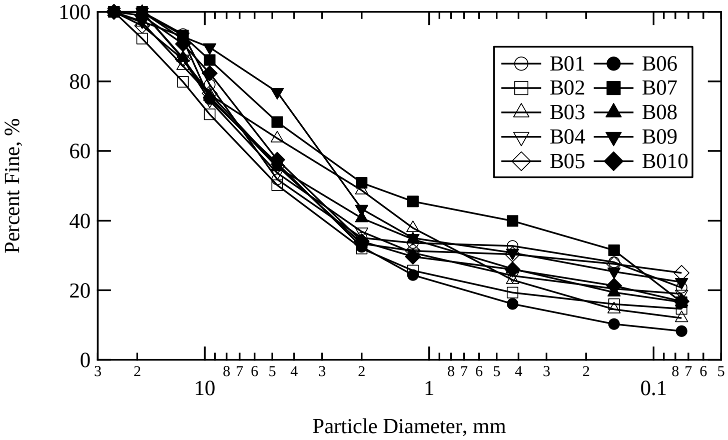

Fig. 2: Grain Size Distribution of Soil Cement Base.

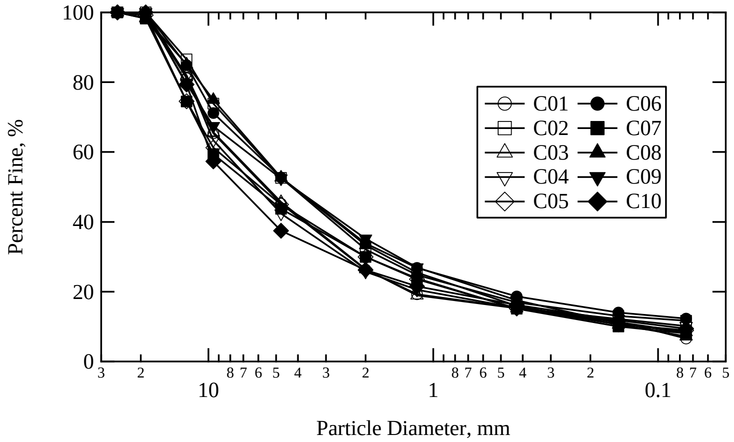

Fig. 3: Grain Size Distribution of Cement Modified Crushed Rock Base.

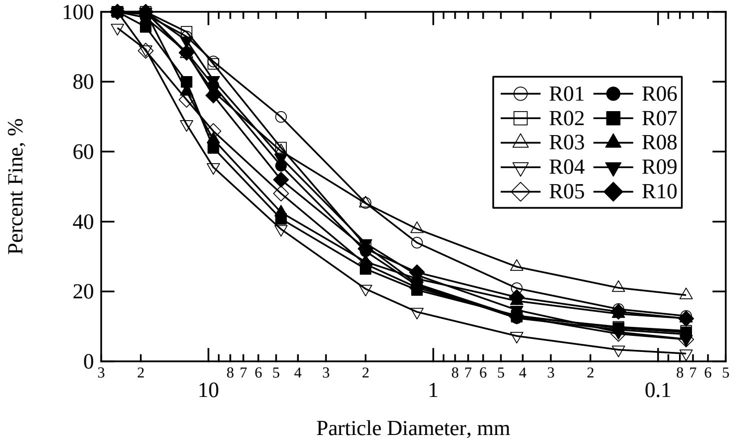

Fig. 4: Grain Size Distribution of Pavement Recycling.

Table 1: Basic Properties of Materials.

No	Material Resource	Compaction		CBR	CBR	Swell	LL	PI	LAA (%)	Soundness (%)
				Unsoaked	Soaked					
		OMC (%)	$\gamma_{d,max}$ (t/m^3)	(%)	(%)	(%)				
SB01	Nalao	10.50	2.12	-	-	-	29.00	16.40	-	-
SB02	Kittiwadee	16.10	2.02	-	-	-	37.50	12.37	-	-
SB03	Highway 1013 Sanpathong - Bankard	14.22	1.89	-	-	-	37.00	18.55	-	-
SB04	Phathai	15.20	1.93	-	-	-	35.00	13.49	-	-
SB05	Phonepheng	14.00	2.01	-	-	-	34.10	14.94	-	-
SB06	Highway 1280	12.80	1.91	-	-	-	39.00	18.62	-	-
SB07	Banguay	14.80	1.95	-	-	-	34.00	16.54	-	-
SB08	Ban Charng Tang Kajard	7.70	2.12	-	-	-	NP	NP	-	-
SB09	Sattaheeb	8.50	2.05	-	-	-	NP	NP	-	-
SB10	Na Ngua	9.79	2.08	-	-	-	NP	NP	-	-
B01	Dontue	9.17	2.17	-	-	-	27.00	13.00	43.13	-
B02	Highway 11 Lumpang - Denchai	7.00	2.16	-	-	-	28.30	13.50	35.55	-
B03	Bansaew	10.00	1.99	-	-	-	NP	NP	59.69	-
B04	Pha Singh	8.85	2.08	-	-	-	30.00	11.92	34.82	-
B05	Nongmeg	9.50	2.19	-	-	-	24.50	13.23	41.63	-
B06	Klongsai	9.80	2.07	-	-	-	NP	NP	40.74	-
B07	Highway 4 Krabi - Klongthom	7.00	2.22	-	-	-	29.00	8.08	33.32	-
B08	Kraburi	7.00	2.21	-	-	-	21.00	12.08	45.36	-
B09	Bansamut	10.80	2.18	-	-	-	31.00	12.17	48.69	-
B10	Bohphuphan	8.00	2.16	-	-	-	NP	NP	53.83	-
C01	Silaphran	6.60	2.36	149.5	130.7	0.010	NP	NP	30.82	3.40
C02	Highway 1280	7.58	2.12	100	89.3	0.170	NP	NP	29.30	4.97
C03	Burirum Ratchada	10.80	2.14	98.7	84	0.260	NP	NP	18.61	4.80
C04	Kittiwadee	10.00	2.20	124	90	0.108	NP	NP	19.69	7.36
C05	Sahasilaloei	5.50	2.28	105.3	81.3	0.108	NP	NP	34.74	8.89
C06	Asian	5.80	2.28	118.7	100	0.195	NP	NP	34.23	3.94
C07	Banmueng Wangphai	7.80	2.11	158.7	120	0.043	NP	NP	33.61	2.53
C08	Silathong	6.90	2.26	99.3	80.7	0.010	NP	NP	31.78	2.83
C09	Ananta Sila	7.30	2.27	140	94.7	0.032	NP	NP	38.21	2.52
C10	Amornphan	8.30	2.23	84	80	0.130	NP	NP	31.78	4.82
R01	Higway 41 Sta.183+700	5.80	2.21	-	-	-	NP	NP	-	-
R02	Highway 112 Khamphangphet Bypass Route	6.90	2.15	-	-	-	NP	NP	-	-
R03	Highway 1109 Wangjao - Lokoh	7.90	2.14	-	-	-	NP	NP	-	-
R04	Highway 43 Janan - Padae	11.00	1.92	-	-	-	NP	NP	-	-
R05	Highway 43 Padae - Porkoh	9.30	2.04	-	-	-	NP	NP	-	-
R06	Highway 323	7.42	2.20	-	-	-	NP	NP	-	-
R07	Recycling Sahakhonsong Authai	10.00	2.06	-	-	-	NP	NP	-	-
R08	Highway 12 Sta 168	8.60	2.11	-	-	-	NP	NP	-	-
R09	Highway 12 Sta 619	14.25	1.91	-	-	-	NP	NP	-	-
R10	Highway 12 Sta 211+500	8.70	2.11	-	-	-	NP	NP	-	-

3.3. Free-Free Resonance (FFR) Test

FFR tests were performed in this study to assess low-strain resonant frequency and hence shear wave velocity of the samples using Equation 1 where vs = shear wave velocity, f = resonant frequency, λ = wavelength, and L = sample length .The low-strain shear waves were generated by tapping perpendicularly at the end of the hanged sample using a developed small hammer, as shown in Figure 5 .The hammer was built from a wooden stick with a weight attached at one end to minimize loss of seismic energy due to resonance in the hammer itself .The waves were recorded in time domain by an accelerometer which was attached horizontally at the other end of the sample .The response was subsequently Fourier transformed into frequency domain using a spectrum analyzer to locate the resonant frequency)the frequency of the maximum peak amplitude in Fourier spectra (of the sample .An example of a resonant frequency obtained from this study is demonstrated in Figure 6.

$$v_s = f\lambda = 2fL \tag{1}$$

Fig. 5: Generating of Shear Waves in FFR Test.

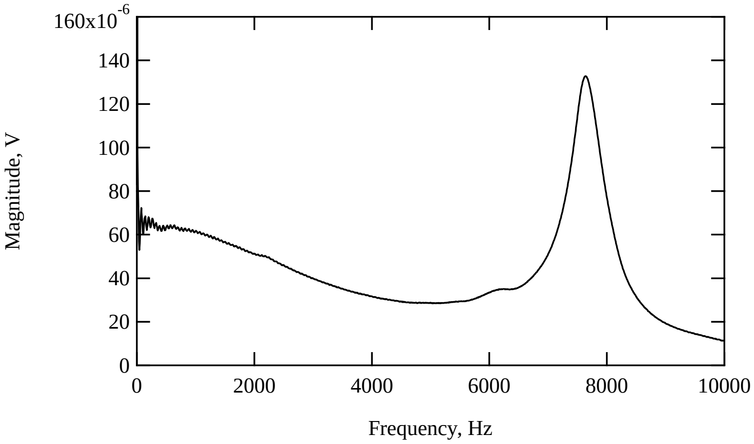

Fig. 6: An Example of Resonant Frequency of a Pavement Recycling Material with 3% Cement Ratio.

3.4. Unconfined Compressive Strength (UCS) Test

UCS tests were performed right after completion of the FFR tests. The test was conducted accordingly to [4] which is equivalent to the AASHTO T208 standard. A photograph and an example of the result of UCS test are shown in Figure 7 and Figure 8, respectively.

Fig. 7: A Photograph of UCS Test of a Pavement Recycling Material with 3% Cement Ratio.

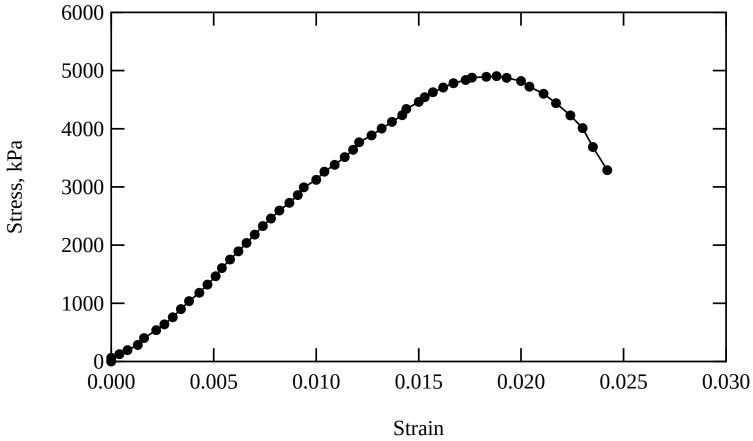

Fig. 8: An Example of UCS of a Pavement Recycling Material with 3% Cement Ratio.

4. Data Analysis

4.1. Effect of Cement Ratio and Fine Particle Content to Shear Wave Velocity and Unconfined Compressive Strength

The effect of cement ratio to shear wave velocity and unconfined compressive strength)UCS(of the 4 mentioned materials was studied .The results indicated that shear wave velocity increased nonlinearly with increasing cement ratio as shown in Figure 9 while UCS increased more linearly with increasing cement ratio as shown in Figure 10 for all materials . The results also showed that at the same cement ratio, soil cement subbase and soil cement base)both were originally lateritic soils (provided the lowest and second lowest shear wave velocity, respectively .On the other hand, cement modified crushed rock base and pavement recycling provided much higher shear wave velocity than those soil cement materials .These results certainly suggest that the higher the fine particle content in the sample, the lower the shear wave velocity and thus the lower the stiffness of the sample .Similar trends were also noticed for UCS of the same materials which coincided with [9].

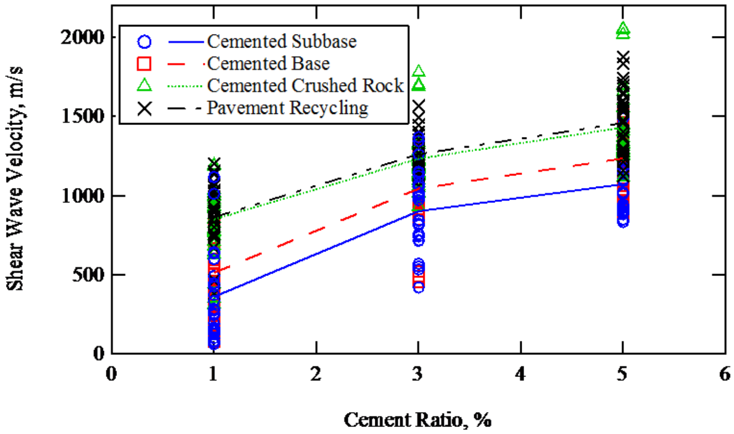

Fig. 9: Comparison of Effect of Cement Ratio to Shear Wave Velocity of Different Cement Stabilized Materials.

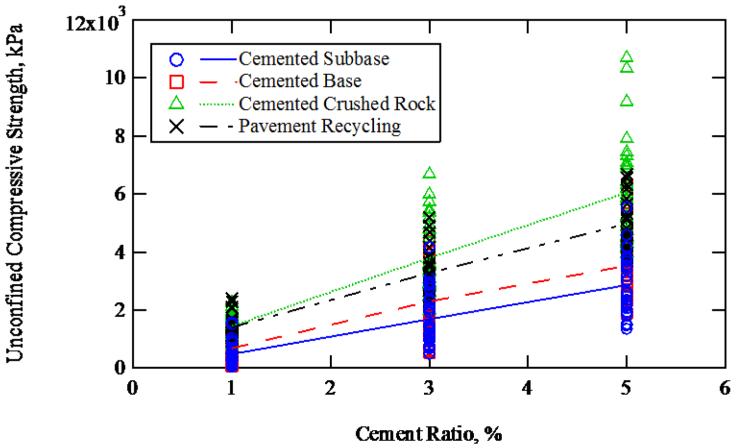

Fig. 10: Comparison of Effect of Cement Ratio to UCS of Different Cement Stabilized Materials.

4.2. Relationship between Shear wave velocity and Unconfined Compressive Strength

Empirical relationships between shear wave velocity and UCS were created to develop quality control index of the materials .The results showed that shear wave velocity increased nonlinearly with UCS, with percent errors ranged in between 20 –30%, as shown in Figure 11, Figure 12, Figure 13, and Figure 14 for soil cement subbase, soil cement base, cement modified crushed rock base, and pavement recycling, respectively .Comparing to other studies, the results demonstrated good agreement, at the same range of UCS, with deep mixing soil cement [2] and cement stabilized Kaolin and PALF)PALF –Pineapple Leaf Fibers([3] as presented in Figure 15.

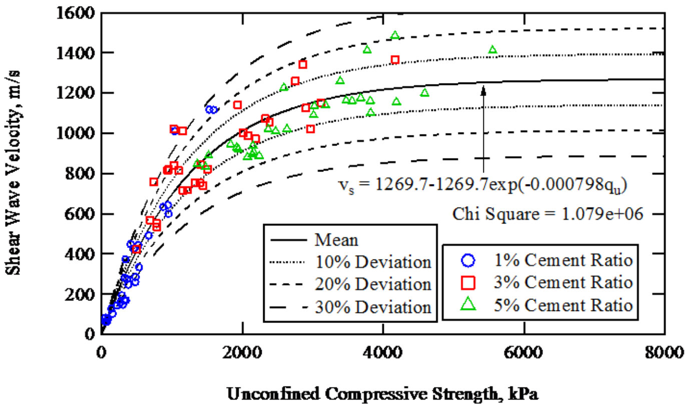

Fig. 11: Relationship between Shear Wave Velocity and UCS of Soil Cement Subbase.

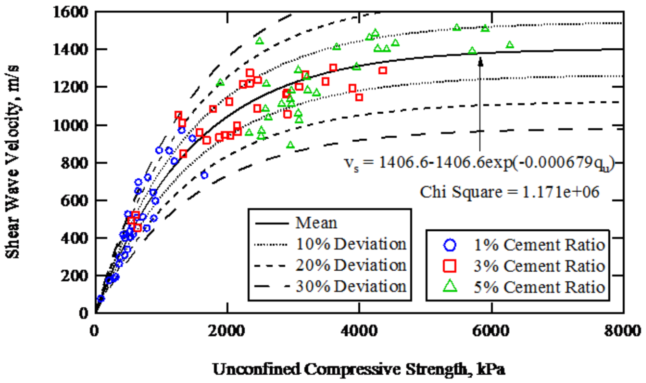

Fig. 12: Relationship between Shear Wave Velocity and UCS of Soil Cement Base.

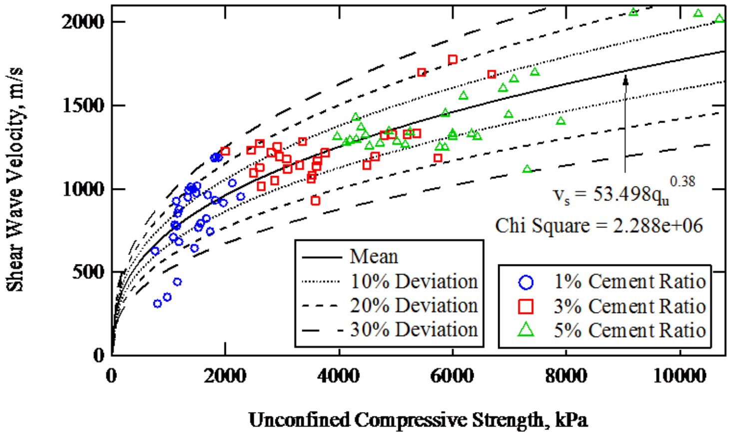

Fig. 13: Relationship between Shear Wave Velocity and UCS of Cement Modified Crushed Rock Base.

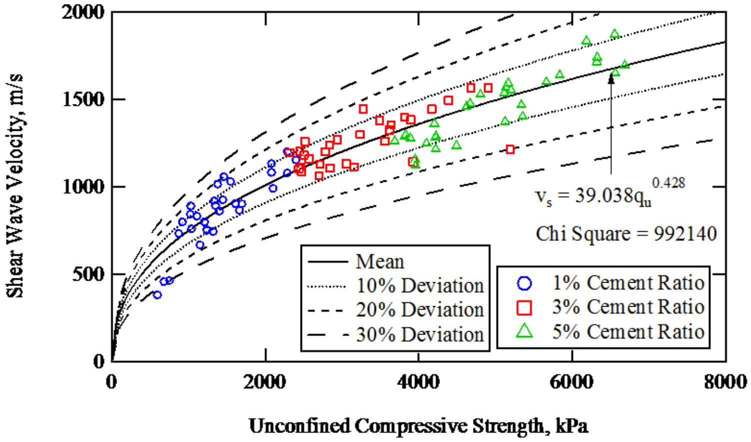

Fig. 14: Relationship between Shear Wave Velocity and UCS of Pavement Recycling.

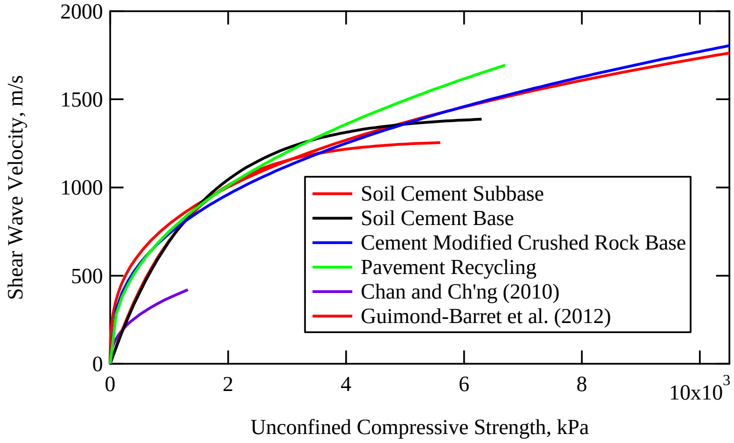

Fig. 15: Comparison of Shear Wave Velocity - UCS Relationships of Different Cement Stabilized Materials.

4.3. Using Shear Wave Velocity as Quality Control Index for Cement Stabilized Road Structures

In previous studies, shear wave velocity was used to investigate stiffness of subbase and subgrade materials, and was correlated with California Bearing Ratio or Dynamic Cone Penetration [11] – [12]. However, according to DOH standards, to ensure that cement stabilized materials have good construction quality their UCS have to be higher than the minimum requirement, 689 kPa (100 psi) for soil cement subbase, 1724 kPa (200 psi) for soil cement base, and 2413 kPa (350 psi) for both cement modified crushed rock base and pavement recycling. However, as doing UCS test at construction sites requires coring and borehole repairing, it is considered as a destructive, inconvenient and time-consuming method. To facilitate nondestructive, more convenient, and less time-consuming quality control methods, shear wave velocity, which can be measured using many low-strain seismic tests, is introduced as a quality control index. According to the results of this study, to ensure that cement stabilized materials have good construction quality their shear wave velocities, back calculated using empirical equations of previous section, have to be higher than the numbers presented in Table 2.

Table 2: Quality Control Index of Cement Stabilized Materials.

Material	Unconfined Compressive Strength		Shear Wave Velocity (m/sec)
	kPa	Psi	
Soil Cement Subbase	689	100	536
Soil Cement Base	1724	200	971
Cement Modified Crushed Rock Base	2413	350	1033
Pavement Recycling	2413	350	1095

5. Conclusions and Recommendations

This study presented the effect of the amount of cement and amount of fine content on shear wave velocity and UCS of 4 types of cement stabilized materials including soil cement subbase, soil cement base, cement modified crushed rock base, and pavement recycling. The results showed that the increase of cement ratio increased both shear wave velocity and UCS while the increase of fine particles in the material decreased both shear wave velocity and UCS of all materials. The study also introduced the possibility of using shear wave velocity, as an alternative to conventional, unconfined compressive strength, as a quality control index. The minimum required shear wave velocity of constructions of soil cement subbase, soil cement base, cement modified crushed rock base, and pavement recycling should be 536, 970, 1033 and 1095 m/sec, respectively. These numbers are very useful for the quality control of any site constructions using cement stabilized materials because shear wave velocity can be measured quicker and more conveniently than the UCS test.

Nonetheless, this study was only performed under laboratory conditions so many factors in the field such as overburden pressure, changing moisture content and temperature, or even the curing method used during construction were not included. These factors could also affect shear wave velocity and the strength of cement stabilized materials. Therefore, further in-situ tests are required to be conducted to obtain detailed information of possible modifying factors.

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