

Shear wave velocity of fiber reinforced cemented Toyoura silty sand

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Abstract. Several additives are used to enhance the geotechnical properties (e.g., shear wave velocity, shear modulus) of soils to provide sustainable, economical and eco-friendly solutions in geotechnical and geo-environmental engineering. In this study, piezoelectric ring actuators are used to measure the shear wave velocity of unreinforced, fiber, cemented, and fiber reinforced cemented Toyoura sand. One dimensional oedometer tests are performed on medium dense specimens of Toyoura sand-cement-fiber-silica flour mixtures with different percentages of silica flour (0-42%), fiber and cement (e.g., 0-3%) additives. The experimental results indicate that behavior of the mixtures is significantly affected by the concentration of silica flour, fiber and cement additives. Results show that with the addition of 1-3% of PVA fibers, the shear wave velocity increases by only 1-3%. However, the addition of 1-4% of cement increases the shear wave velocity by 8-35%. 10.5-21% increase of silica flour reduces the shear wave velocity by 2-5% but adding 28-42% silica flour significantly reduces the shear wave velocity by 12-31%. In addition, the combined effect of cement and fibers was also found and with only 2% cement and 1% fiber, the shear wave velocity increase was found to be approximately 24% and with only 3% cement and 3% fibers this increased to 35%. The results from this study for the normalized shear modulus and normalized mean effective stress agree well with previous findings on pure Toyoura sand, Toyoura silty sand, fiber reinforced, fiber reinforced cemented Toyoura sand. Any variations are likely due to the difference in stress history (i.e., isotropic versus anisotropic consolidation) and the measurement method. In addition, these small discrepancies could be attributed to several other factors. The potential factors include the difference in specimen sizes, test devices, methods of analysis for the measurement of arrival time, the use of an appropriate K_0 to convert the vertical stresses into mean effective stress, and sample preparation techniques. Lastly, it was investigated that there is a robust inverse relationship between α factor and β_0 exponent. It was found that less compressible soils exhibit higher α factors and lower β_0 exponents.

Keywords: shear wave velocity; piezoelectric ring actuators; ground improvement; ground remediation; sustainability; oedometer tests

1. Introduction

Laboratory investigations such as resonant column, cyclic triaxial, and torsional shear tests are usually conducted on undisturbed and reconstituted sand samples in order to determine their shear modulus, which can be used to compute shear wave velocity. However, these methods are extremely cumbersome and indirect, they employ cost-intensive instrumentation, and they require trained manpower (Bartake and Singh 2006). Bender element (BE) testing has become increasingly common place in soil laboratories since its introduction in the late 1970s by

Shirley and Hampton (1978). The test allows straight forward small strain stiffness measurements to be made in soil specimens, and can be performed in a wide variety of test systems. Teachavorasinskun and Pongvithayapanu (2016) measured the shear wave velocity of sands subjected to large strains in triaxial loading condition. In addition, a relationship between small-strain shear modulus (G_{max}) and overconsolidation ratio (OCR) based on shear wave velocity (V_s) measurement was established to identify the stress history of centrifuge model ground (Cho *et al.* 2018). However, as the method was implemented by both research and commercial laboratories around the world, it gradually became apparent that there were various issues to be resolved regarding the hardware used, the testing procedures, and the interpretation of the results. With regard to the BEs, the issues that have been discussed include the optimum thickness of the elements, how the layers of the element should be wired (parallel or series), and the details of the insulation, mounting, protrusion distance, shielding, and grounding (Fonseca *et al.* 2009). The bender element necessitates penetration into the soil specimen to transfer its bending deformation to the surrounding soil as a shear

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deformation. The process is invasive and it causes disturbance to undisturbed and cemented specimens. Excavating holes into specimens involves more work to refill the holes with a coupling material, (typically gypsum or epoxy). More disturbances to the specimens are possible during such handling (Ahmad 2016). Hence, it has been proven that the bender elements method, which is widely used to measure shear wave velocity of soil in laboratory setups, suffers from fundamental and interpretative problems. Consequently, its results are controversial and might give highly erroneous values (Gamal El-Dean 2007). The piezoelectric ring actuators (PRA) device is non-invasive, reduces the overall sample disturbance and it is deemed suitable for all soil types including very stiff and cemented soils (Naji *et al.* 2017) that cannot be readily tested with BE. Therefore, it does not require penetration of the test specimen, and hence eliminates the need for coupling material as filler (Ahmad 2016). Few other recent studies related to shear wave velocity measurements using PRA device can also be found in the literature (Karray *et al.* 2015, Mneina *et al.* 2018, Elbeggo *et al.* 2019, Hussien and Karray 2020). The current knowledge on the shear wave velocity (V_s) is mainly based on the results of extensive laboratory studies on clean sands. Often natural sands are not clean, but contain a certain amount of fines. The role of fines in altering the stiffness of sands is a matter of great concern, yet remains poorly understood (Yang and Liu 2016). In addition, limited studies have been reported on the shear wave velocity measurements on fiber, cemented, and fiber reinforced cemented sand (Schmidt 2015, Safdar 2018). Due to the shortcomings of other devices and obvious advantages of PRA device developed by Ahmad (2016), PRA device is used to measure the shear wave velocity of unreinforced, fiber, cemented, and fiber reinforced cemented Toyoura sand specimens.

2. Tested materials

To replicate the in-situ soil conditions of the Tokyo Bay region and provide soil amendments, four different types of material (e.g., Toyoura sand, polyvinyl alcohol (PVA) fibers, ordinary Portland cement (OPC), and silica flour) have been employed in this study. Toyoura sand has been previously used as a benchmark material in previous experimental research projects conducted at Western University, Canada and Fukuoka University, Japan (Schmidt 2015, Safdar 2018, Safdar *et al.* 2020).

2.1 Toyoura sand

Toyouira sand is a Japanese benchmark sand, which is a well-known laboratory test sand. Based on previous investigations of Toyoura sand, it is composed of 75% quartz, 22% feldspar, and 3% magnetite and can be found primarily on the coastal regions of the Pacific Ocean in Japan (Lam and Tatsuoka 1988, De and Basudhar 2008, Schmidt 2015). The particles have a uniformity coefficient (C_u) of 1.24, a minimum void ratio (e_{min}) of 0.62, a maximum void ratio (e_{max}) of 0.95, and a specific gravity of 2.65. The grain size distribution of pure Toyoura sand is presented in Fig. 1. The physical properties of Toyoura sand

Table 1 Physical properties of Toyoura sand

Properties	Values
Specific Gravity (G_s)	2.65
D_{10} (mm)	0.17
D_{30} (mm)	0.18
D_{60} (mm)	0.21
Maximum Void Ratio (e_{max})	0.95
Minimum Void Ratio (e_{min})	0.62
Coefficient of Curvature (C_c)	0.91
Uniformity Coefficient (C_u)	1.24
Constrained Modulus (MPa)	60
Permeability (m/s)	8.7×10^{-6}

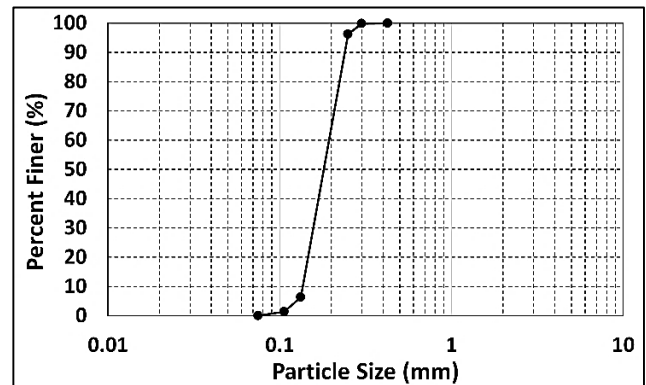


Fig. 1 Grain size distribution curve for Toyoura sand

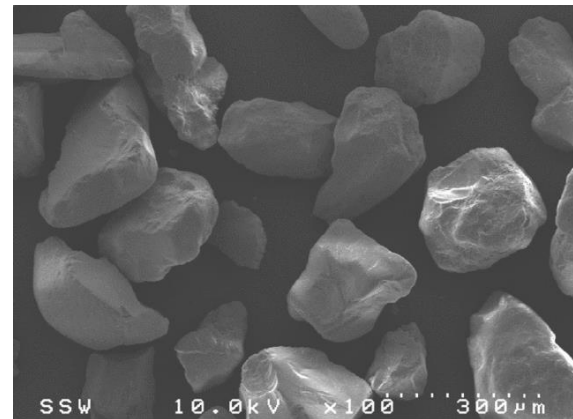


Fig. 2 Toyoura sand 100x optical zoom (Schmidt 2015)

have been listed in Table 1. Toyoura sand has been described as an angular to sub-angular, fine grained and poorly graded sand, which is confirmed by a low coefficient of uniformity and coefficient of curvature, according to the classification of SP by the Unified Soil Classification System (USCS) (Oda 1977, Hyodo *et al.* 1994, Bellotti *et al.* 1997, Whitlow 2001, Wang *et al.* 2002, Schmidt 2015). The peak internal friction angle (ϕ') ranges from 33.5° in a very loose state, to 43.7° in a dense state. The peak dilation angle (ψ_p) ranges from 5° - 10° for normal stresses of 25-300 kPa. Fig. 2 shows SEM scan of pure Toyoura sand to provide an indication of the size, shape and texture of the particles. Microscopically, Toyoura sand can be clearly seen



Fig. 3 Polyvinyl alcohol (PVA) fibers

Table 2 Properties of PVA fibers (Kuraray Co. Ltd, Japan)

Properties	Values
Specific Gravity (G_s)	1.30
Length (mm)	12
Diameter (mm)	0.11
Young's Modulus (GPa)	28
Tensile Strength (MPa)	1200

to be angular to sub-angular and fairly uniform in size (Schmidt 2015, Safdar 2018, Safdar *et al.* 2020).

Oedometer tests were performed (Schmidt 2015) on pure Toyoura sand with silt content ranging from 0-100% by mass, and stress increments from 10-1600 kPa were applied and settlement was measured to determine the sample compressibility, constrained modulus, and permeability. Although tests were run for 24 hours per stress increment, more than 90% of the consolidation of the Toyoura sand samples were obtained in well under 2 hours (Terzaghi and Peck 1948, Schmidt 2015). The initial void ratio at 60% relative density decreased from 0.741 for Toyoura sand, to 0.695 for 50% silica flour, after which it increased again to 1.190 for 100% silica flour based on the relative density. The constrained modulus reduced from nearly 60 MPa for the Toyoura sand to 6.4 MPa for 50% silica flour, then back up to 13.4 MPa for 100% silica flour at $\sigma'_v=1,600$ kPa. In addition, the permeability of the Toyoura sand at 1,600 kPa effective stress linearly dropped with the addition of the silica flour, from 8.7×10^{-6} m/s for the Toyoura sand, to 2.89×10^{-8} m/s for 100% silica flour (Schmidt 2015, Safdar 2018, Safdar *et al.* 2020).

2.2 Polyvinyl alcohol (PVA) fibers

Synthetic monofilament polyvinyl alcohol (PVA) fibers as shown in Fig. 3 have been used as fiber inclusions and reinforcing material in this research study. PVA fibers have been found to have superior chemical resistance, weather resistance, and tensile strength synthetic than propylene fibers. Therefore, the inclusion of PVA fiber produces more effective reinforcement in terms of strength and ductility, when compared to other fibers under the same cementation volumes (Park 2009). Polyvinyl alcohol (PVA) fibers have a specific gravity of 1.3. Nominal dimensions of the individual fibers are 12 mm long and a diameter of 0.11

mm. The fibers have a Young's Modulus of 28 GPa and a tensile strength of 1200 MPa (Kuraray Cooperation Limited, Japan). The properties of the tested fibers in this research program are given in the Table 2.

2.3 Ordinary Portland Cement Type-I (OPC-I)

Ordinary Portland Cement Type-I (OPC-I) shipped from Ube-Mitsubishi Cement Corporation in Japan has been used as a cementing material and added as a percent by mass in each specimen. OPC-I has a specific gravity of 3.15 and a composition consisting of approximately 63% tricalcium silicate, 12% di-calcium silicate, 5% tri-calcium aluminate, 11% tetra-calcium alumino-ferrite (ASTM C150/C150M-12). These cement and fiber additives have been previously used to model the in situ recycled properties of gypsum and bamboo fibers (Schmidt 2015).

2.4 Silica flour

Sub-angular silica flour (Bell and McKenzie, Sil-Co-Sil #106) has been used in this research program. Silt employed here consists of 100% ground quartz and is fine grained and well-graded, based on the high coefficient of uniformity and coefficient of curvature. Fig. 4 shows particle size distribution for pure Toyoura sand and varying percentage of silt contents (Schmidt 2015, Safdar 2018, Safdar *et al.* 2020).

It is classified as low plasticity silt (ML) according to the Unified Soil Classification System (USCS) and has a peak internal friction angle of 41° at 90% relative density, and a peak dilatancy angle that ranges from 6° - 14° at normal stresses of 25-300 kPa. The choice of using silica flour compared to natural silt was to provide experimental repeatability and consistency in the particle size distribution and shape (Schmidt 2015). The engineering properties of silica flour are shown in Table 3 below. Silica flour displayed angular to sub-angular grains with a plate-like structure, as seen in Fig. 5, the plate-like structure is a by-product of the manufacturing process of the silica flour, rather than natural weathering processes (Schmidt 2015, Safdar 2018, Safdar *et al.* 2020).

Table 3 Physical properties of silica flour

Properties	Values
Specific Gravity (G_s)	2.64
D_{10} (mm)	0.0009
D_{30} (mm)	0.18
D_{60} (mm)	0.025
Maximum Void Ratio (e_{max})	1.58
Minimum Void Ratio (e_{min})	0.82
Coefficient of Curvature (C_c)	2.79
Uniformity Coefficient (C_u)	27.50
Constrained Modulus (MPa)	13.4
Permeability (m/s)	2.89×10^{-8}

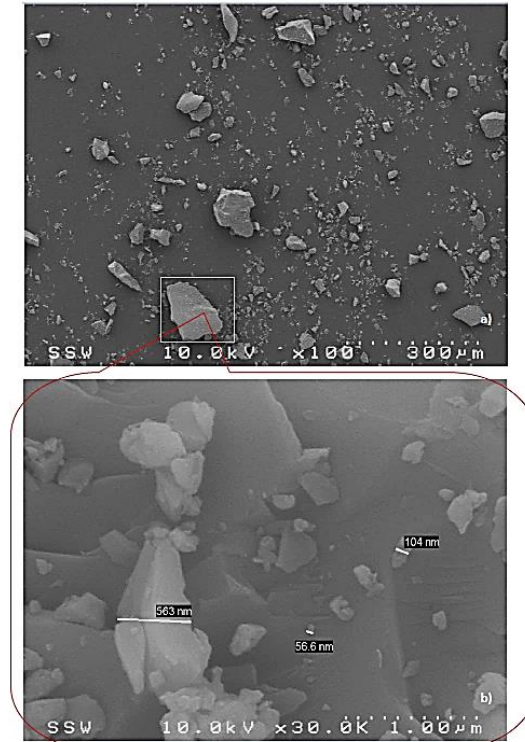


Fig. 5 Silica flour (a) 100x optimal zoom and (b) 30,000x optimal zoom of particle in 1(a) (Schmidt 2015)

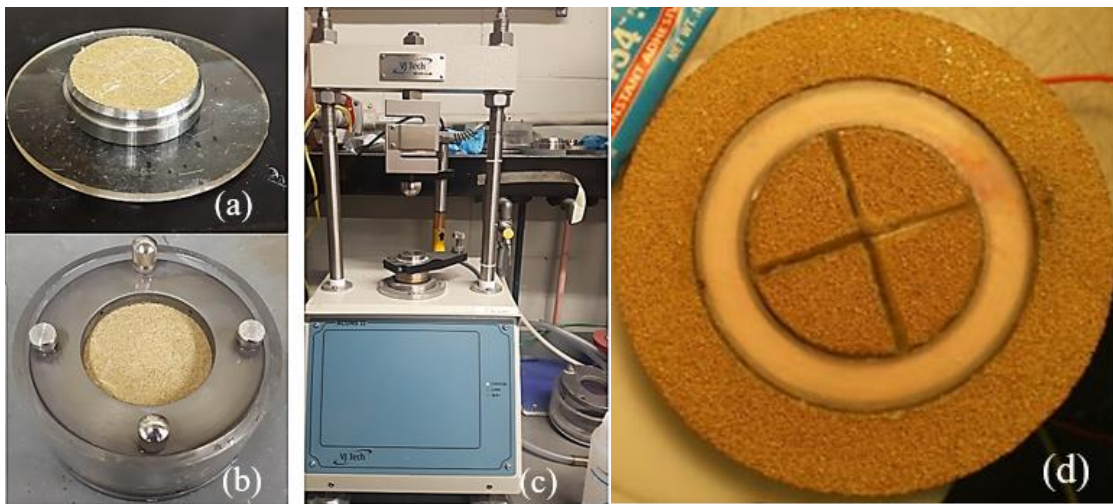


Fig. 6 (a) Fiber reinforced specimen in Oedometer ring, (b) Specimen in oedometer chamber, (c) VJ Tech oedometer apparatus and (d) Piezoelectric device used for measuring shear wave velocity.

3. Sample preparation, testing apparatus, program, and procedure

A series of shear wave velocity measurements were made on unreinforced, fiber, cement and fiber reinforced cemented Toyoura sand specimens using a piezoelectric ring actuators (PRA) device embedded in an oedometer. Tables 4-5 summarize the testing program used to evaluate the effect of silt, fibers and cement content on the shear wave velocity of unreinforced, fiber, cemented, and fiber reinforced cemented Toyoura sand. Samples in dimensions of 70 mm in diameter and height of 20 mm were prepared to a target dry density value (e.g., $\rho_d = 1.489 \text{ g/cm}^3$) of

Toyourea sand in a oedometer ring in 1 layer (see Fig. 6). Unreinforced, fiber, cemented, and fiber reinforced cemented Toyoura sand samples were prepared and mixed to 10 percent of water content by dry mass of soil. 10% initial moisture content was designed to mimic the work (Nakamichi and Sato 2013, Schmidt 2015, Safdar, 2018, Safdar *et al.* 2020) from Fukuoka and Western University. Cemented samples were cured for 3 days.

Recently, a brief study (Schmidt 2015) on shear wave velocity measurements using bender elements on silty, fiber, cemented, and fiber reinforced cemented Toyoura sand was conducted to investigate the effect of these additives on the Vs of pure Toyoura sand. In this study, the zero-crossing

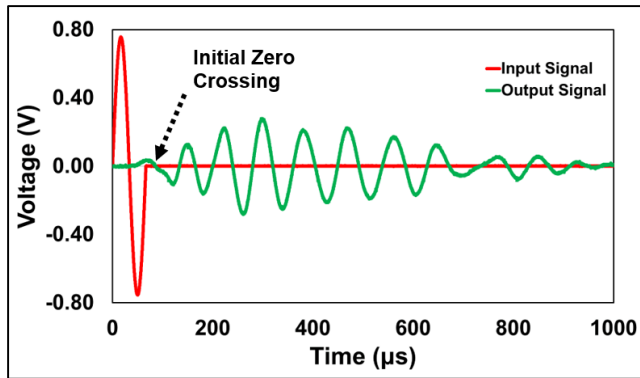


Fig. 7 Typical shear wave velocity input and output signal showing the point of initial-zero crossing used for the calculation of shear wave velocity

Table 4 Previous Western University testing program for bender element (BE) tests

Test No.	Test ID	Mean effective stress (kPa)	Cement Content (%)	Fibers Content (%)	Silt Content (%)
Pure Sand					
1	BE-C0F0M0	0-600	0	0	0
Pure Silt					
2	BE-C0F0M100	0-600	0	0	100
Fiber Only					
3	BE-C0F1M0	0-600	0	1	0
Cement Only					
4	BE-C1F0M0	0-600	1	0	0
5	BE-C2F0M0	0-600	2	0	0
6	BE-C3F0M0	0-600	3	0	0
7	BE-C4F0M0	0-600	4	0	0
Silt Only					
8	BE-C0F0M10.5	0-600	0	0	10.5
9	BE-C0F0M21	0-600	0	0	21
10	BE-C0F0M28	0-600	0	0	28
11	BE-C0F0M35	0-600	0	0	35
12	BE-C0F0M42	0-600	0	0	42
13	BE-C0F0M75	0-600	0	0	75
Cement, Fiber, and Silt					
14	BE-C2F1M0	0-600	2	1	0
15	BE-C2F1M10.5	0-600	2	1	10.5
16	BE-C2F1M21	0-600	2	1	21
17	BE-C2F1M28	0-600	2	1	28
18	BE-C2F1M35	0-600	2	1	35
19	BE-C2F1M42	0-600	2	1	42

Table 5 Testing program for shear wave velocity measurements (V_s) tests for PRA device

Test No.	Test ID	Mean effective stress (kPa)	Cement Content (%)	Fibers Content (%)	Silt Content (%)
Pure Sand					
1.	PRA-C0F0M0	0-1000	0	0	0
Fiber Only					
2.	PRA-C0F1M0	0-1000	0	1	0
3.	BE-C0F3M0	0-1000	0	3	0
Cement Only					
4.	PRA-C1F0M0	0-1000	1	0	0
5.	PRA-C2F0M0	0-1000	2	0	0
6.	PRA-C3F0M0	0-1000	3	0	0
7.	BE-C4F0M0	0-1000	4	0	0
Silt Only					
8.	PRA-C0F0M10.5	0-1000	0	0	10.5
9.	PRA-C0F0M21	0-1000	0	0	21
10.	PRA-C0F0M28	0-1000	0	0	28
11.	PRA-C0F0M35	0-1000	0	0	35
12.	PRA-C0F0M42	0-1000	0	0	42
Cement, Fiber, and Silt					
13.	PRA-C2F1M0	0-1000	2	1	0
14.	PRA-C3F3M0	0-1000	3	3	0

method was used to determine the shear wave velocity. A typical example of this method is shown in Fig. 7. The literature shows that shear wave velocity was measured mainly in pure sands and/or silty sands using bender elements. However, in this study, a piezoelectric ring actuator (PRA) developed recently by Ahmad (2016) was used to measure the shear wave velocity of the fiber reinforced cemented Toyoura silty sand. The details of this device can be found in Ahmad (2016) and this device has been chosen primarily to eliminate sample disturbance due to its non-invasive nature in cemented specimens.

4. Results and discussion

The test results on pure Toyoura sand specimens show that the shear wave velocity increases with higher mean effective MIT stress, s' .

$$s' = \frac{\sigma'_v + \sigma'_h}{2} \quad (1)$$

where, σ'_v = vertical effective stress, and σ'_h = horizontal effective stress ($K_0 \sigma'_v$). Coefficient of earth pressure at rest (K_0) is estimated by relation to frictional angle ($K_0 = 1 - \sin \phi'$). However, the mean effective stress ($p' =$

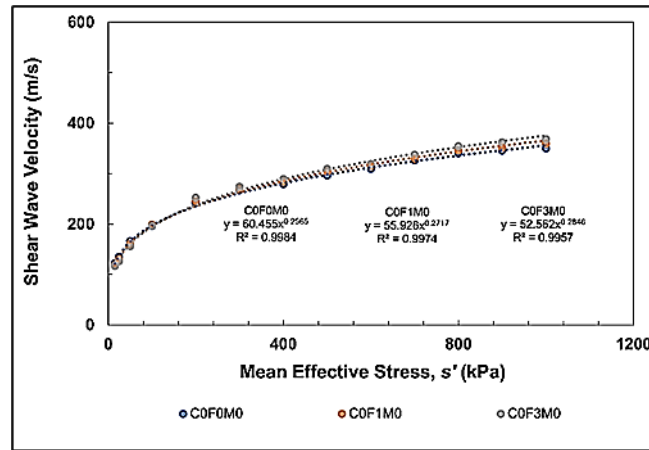
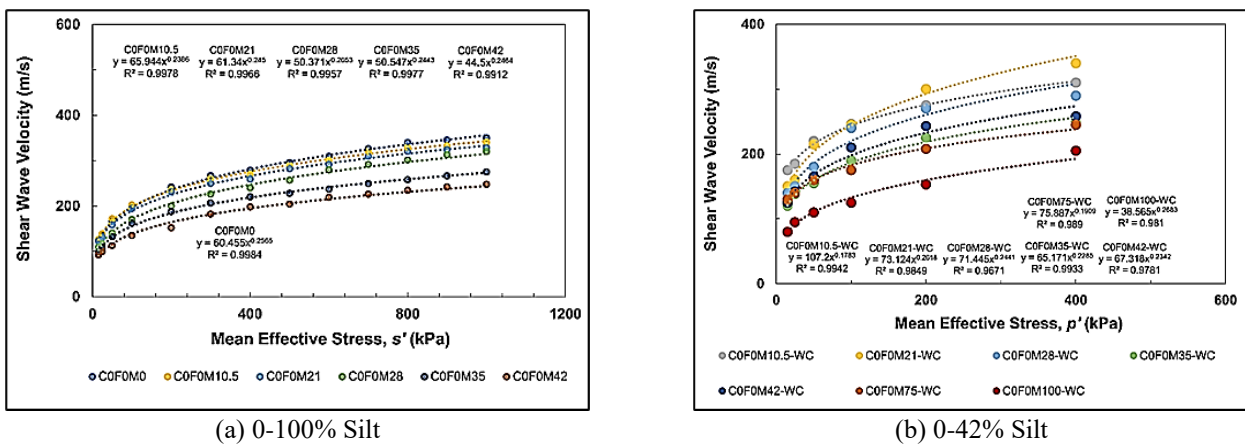


Fig. 8 Shear wave velocity measurements vs mean effective stress for pure Toyoura sand, 1% and 3% fiber reinforced Toyoura sand



(a) 0-100% Silt

(b) 0-42% Silt

Fig. 9 Shear wave velocity measurements vs mean effective stress for pure Toyoura sand, and 0-42% Toyoura silty sand.

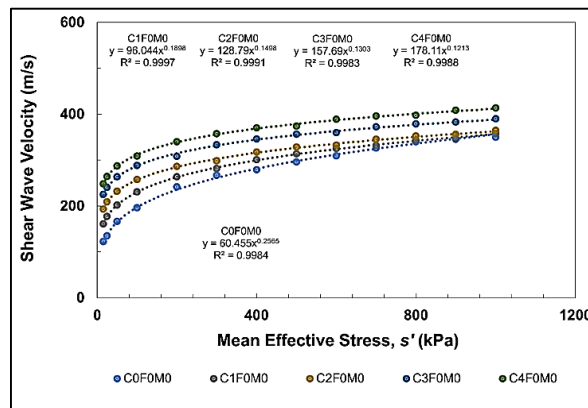


Fig. 10 Shear wave velocity measurements vs mean effective stress for pure Toyoura sand, 1-4% cemented Toyoura sand.

$\frac{\sigma'_1 + \sigma'_2 + \sigma'_3}{3}$) is used by Oztoprak and Bolton (2013) and Schmidt (2015). It can be seen in the Fig. 8 that with the addition of 1-3% of PVA fibers, the shear wave velocity increases by only 1-3%. It is shown that 10.5-21% increase of fines reduces the shear wave velocity by 2-5% but adding 28-42% fines significantly reduce the shear wave velocity by 12-31% (see Fig. 9). However, the addition of 1-4% of cement increases the shear wave velocity by 8-35% (see Fig. 10). Furthermore, the combined effect of cement and

fibers was also found and with only 2% cement and 1% fiber, the shear wave velocity increase was found to be approximately 24% and with only 3% cement and 3% fibers this increased to 35% (see Fig. 11). Initially, when only fiber additives are used, the shear wave velocity reduces slightly and then after applying mean effective stress of approximately 200 kPa and higher, a slight increase of 1-3% was observed. Similar behavior was also reported by previous researchers (Heineck *et al.* 2005, Consoli *et al.*

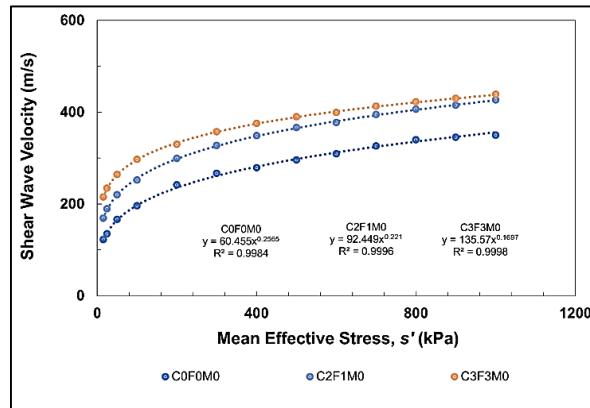


Fig. 11 Shear wave velocity measurements vs mean effective stress for pure Toyoura sand, 1% fiber + 2% cement, 3% fiber and 3% cement reinforced Toyoura sand

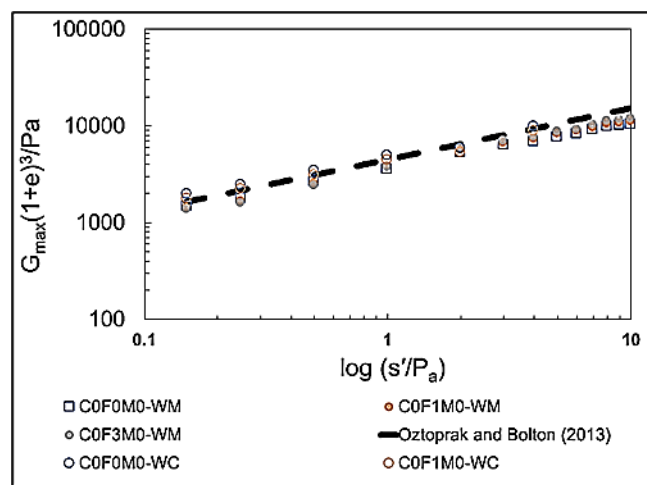
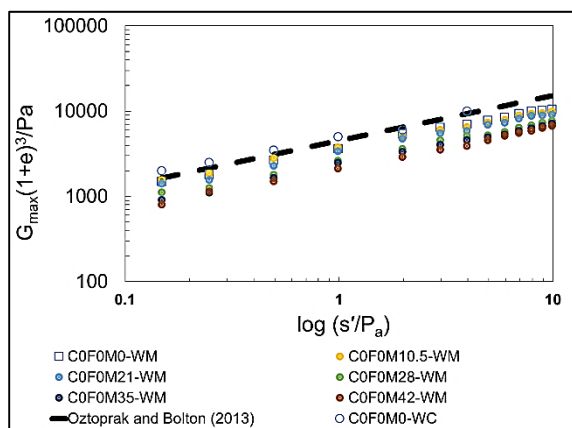
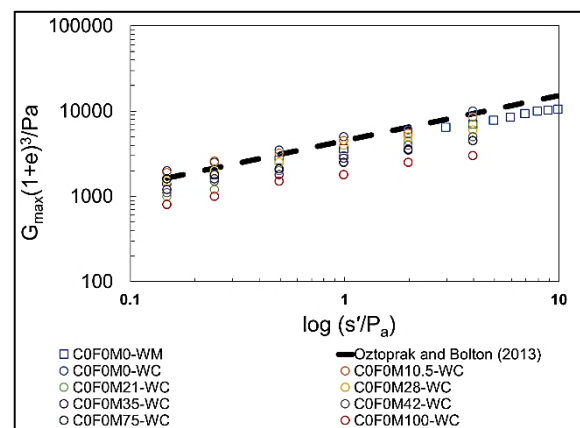


Fig. 12 Normalized shear modulus vs normalized mean effective stress for pure Toyoura sand, 1% and 3% fiber reinforced Toyoura sand



(a) 0-42% Silt



(b) 0-100% Silt

Fig. 13 Normalized shear modulus vs normalized mean effective stress for pure Toyoura sand, 0-100% silty sand

2010, Schmidt 2015). The cemented sand form interlocked clusters (Salah-ud-din 2012), which lead to an improvement of the shear wave velocity. It can be seen in Fig. 10 that for only 1% cement addition, the shear wave velocity increased by approximately 8%. However, this increase was more prominent for 4% cement reaching a 35% increase. The

effect of cementation on small-strain stiffness prevails at low stress. At high stress, the particulate nature of the medium takes over, rendering stress-dependent strength and stiffness (Fernandez and Santamarina 2001). For Toyoura sand with 2-3% cement and 1-3% fiber content, the fibers no longer control the skeletal stiffness. Instead, the

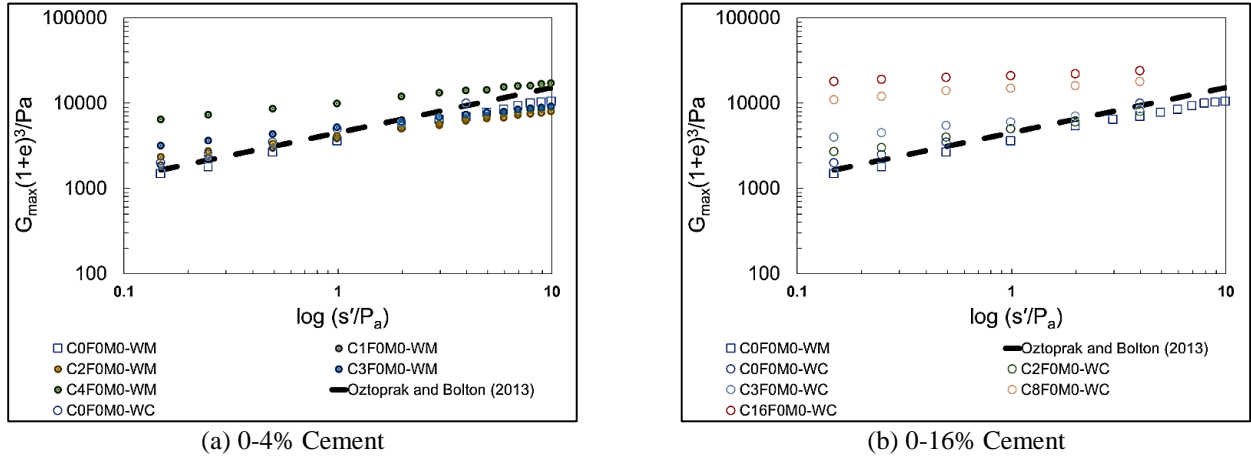


Fig. 14 Normalized shear modulus vs normalized mean effective stress for pure Toyoura sand, 0-4% cemented Toyoura sand

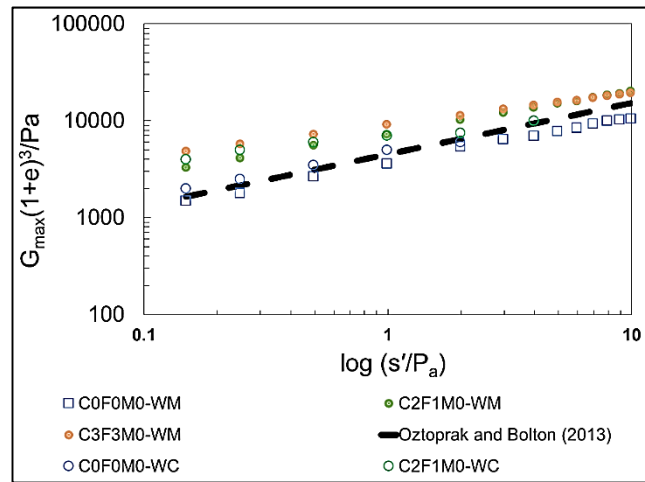


Fig. 15 Normalized shear modulus vs normalized mean effective stress for pure Toyoura sand, 1% fiber + 2% cement, 3% fiber and 3% cement reinforced Toyoura sand

cementitious bonding dominates by interlocking the fibers and the sand grains and creating a less compressible specimen (Salah-ud-din 2012) and it is clear that the addition of OPC both strengthened and stiffened the Toyoura sand (Schmidt 2015). Hence, the interlocking and bonding between the fibers and cement play an important role in determining the shear wave velocity or small-strain shear modulus.

Oztoprak and Bolton (2013) proposed a method to normalize shear modulus using the void ratio function $G_{\max}(1+e)^3/Pa$ and plotted the results as $\log(G_{\max}(1+e)^3/Pa)$ vs $\log(p'/Pa)$. The results from this study for the normalized shear modulus and normalized mean effective stress agree well with previous findings on pure Toyoura sand (Oztoprak and Bolton 2013), Toyoura silty sand, and fiber reinforced, fiber reinforced cemented Toyoura sand (Schmidt 2015). Any variations (see Figs. 12-15) are likely due to the difference in stress history (i.e., isotropic versus anisotropic consolidation) and the measurement method. In addition, these small discrepancies could be attributed to several other factors. The potential factors include the difference in sample preparation techniques, the different test devices (BE vs. Ring piezoelectric actuators), different methods of analysis for the measurement of arrival time, the

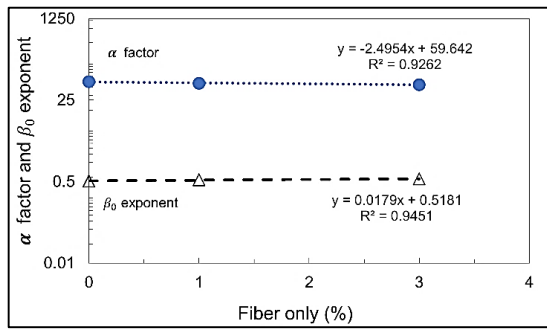
use of an appropriate K_0 to convert the vertical stresses into mean stress, and different specimen sizes etc. (Ahmad 2016).

The small-strain shear modulus is typically dependent on stress in uncemented soils. In effect, the shear wave velocity, which is often used to calculate shear stiffness, follows a power equation with the mean effective stress in polarization plane (Cha *et al.* 2014);

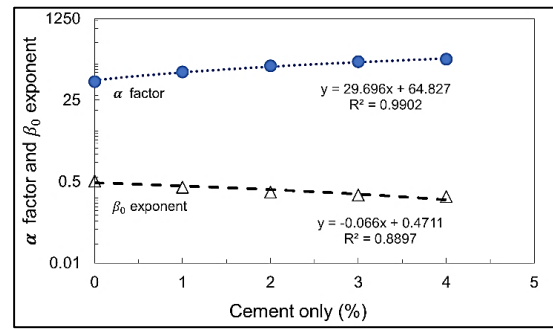
$$V_s = \alpha (s'/1 \text{ kPa})^{\beta_0} \quad (2)$$

where the α factor is the velocity at 1 kPa, and β_0 exponent captures the velocity sensitivity to the state of stress. The small-strain shear stiffness, or velocity, is a constant-fabric measurement at a given state of stress. Table 6 lists and Figs. 16(a)-16(g) show the variation of α factor and β_0 exponent with addition of differing silt, fiber, and cement contents.

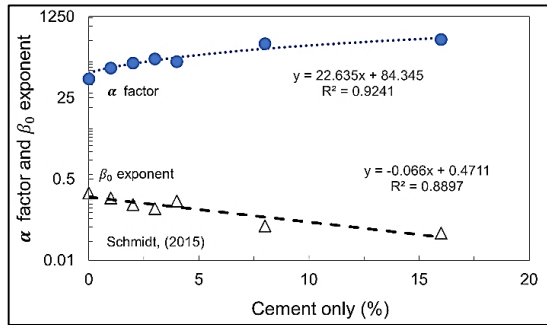
However, parameters α and β_0 are determined by fitting the power equation to velocity measurements conducted at different effective stress levels. So, changes in contact stiffness and soil fabric are inherently involved (Cha *et al.* 2014). It was concluded that less compressible soils exhibit higher α factors and lower β_0 exponents. In



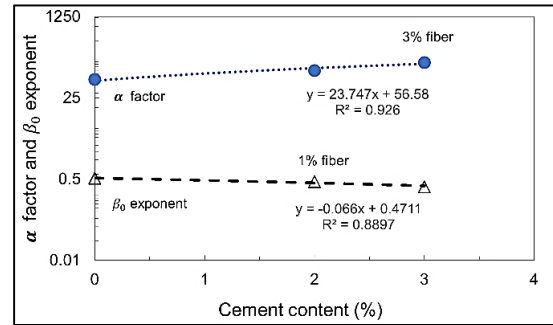
(a) Pure Sand, and 1-3% Fibers



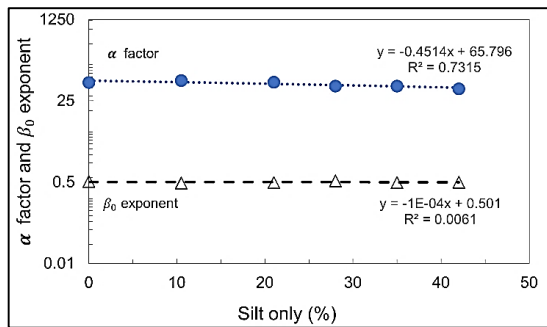
(b) Pure Sand, and 1-3% Cement



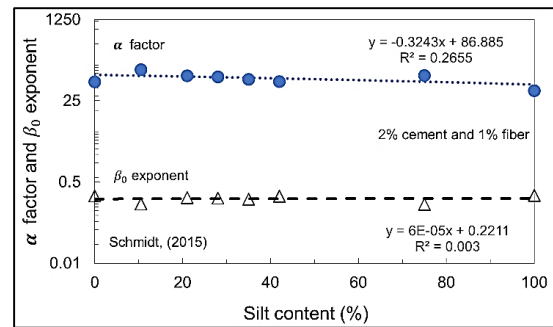
(c) Pure Sand, and 1-16% Cement



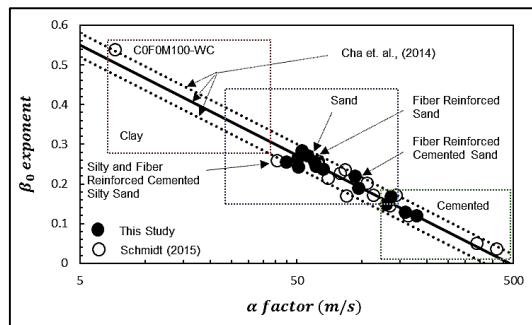
(d) Pure Sand, 1-3% Fiber, and 2-3% Cement



(e) Pure Sand, and 10.5-42% Silt



(f) Pure Sand, 2% Cement and 1% Fiber, and 10.5-100% Silt



(g) Experimental Results of α factor and β_0 exponent and comparison with central trend, and standard deviation (SD) of ± 1 (Cha *et al.* 2014)

Fig. 16 α factor and β_0 exponent from curve fitting of shear wave velocity for unreinforced, fiber, cement, fiber reinforced cemented, silty, and fiber reinforced cemented silty sand

addition, it was further stated that there is a robust inverse relationship between α factors and β_0 exponents. Table 7 lists various shear wave velocity (V_s) and small-strain shear modulus (G_0) correlations using piezoelectric ring actuators (PRA) and bender elements (BE).

For fiber reinforced specimens, α factor decreases approximately 13%, and β_0 exponent increases up to 11% (see Fig. 16). For cemented specimens, α factor

increases by approximately 194%, and β_0 exponent decreases up to 53%. For silty sand specimens, α factor decreases by approximately 26%, and β_0 exponent initially slightly increases up to 28% silt content and then reaches 0.2565 (same as pure sand) at 42% silt content. For fiber reinforced cemented specimens, α factor increases by approximately 124%, and β_0 exponent decreases up to 34%. A similar trend in decrease in α factor and increase

Table 6 α factor and β_0 exponent from curve fitting of shear wave velocity using piezoelectric ring actuators (PRA) and bender elements (BE)

Test No.	Test ID	α	β_0	WM/WC
Pure Sand				
1.	PRA-C0F0M0	60.455	0.2565	WM
Fiber Only				
2.	PRA-C0F1M0	55.926	0.2717	WM
3.	PRA-C0F3M0	52.562	0.2846	WM
Cement Only				
4.	PRA-C1F0M0	96.044	0.1898	WM
5.	PRA-C2F0M0	128.79	0.1498	WM
6.	PRA-C3F0M0	157.69	0.1303	WM
7.	PRA-C4F0M0	178.11	0.1213	WM
Silt Only				
8.	PRA-C0F0M10.5	65.944	0.2386	WM
9.	PRA-C0F0M21	61.34	0.245	WM
10.	PRA-C0F0M28	50.371	0.2653	WM
11.	PRA-C0F0M35	50.547	0.2443	WM
12.	PRA-C0F0M42	44.50	0.2565	WM
Sand + Cement + Fiber				
13.	PRA-C2F1M0	92.449	0.221	WM
14.	PRA-C3F3M0	135.57	0.1697	WM
Previous Western University Research				
Pure Sand				
15.	BE-C0F0M0	62.06	0.254	WC
Pure Silt				
16.	BE-C0F0M100	7.23	0.539	WC
Fiber Only				
17.	BE-C0F1M0	62.78	0.258	WC
Cement Only				
18.	BE-C1F0M0	104.96	0.202	WC
19.	BE-C2F0M0	133.94	0.146	WC
20.	BE-C3F0M0	162.25	0.121	WC
21.	BE-C4F0M0	143.07	0.173	WC
22.	BE-C8F0M0	337.69	0.052	WC
Sand + Cement + Fiber				
23.	BE-C2F1M0	91.66	0.217	WC
Sand + Cement + Fiber + Silt				
24.	BE-C2F1M10.5	112.29	0.172	WC
25.	BE-C2F1M21	83.36	0.236	WC
26.	BE-C2F1M28	79.24	0.228	WC
27.	BE-C2F1M35	69.66	0.216	WC
28.	BE-C2F1M42	62.56	0.250	WC
29.	BE-C2F1M75	84.33	0.171	WC
30.	BE-C2F1M100	40.57	0.260	WC

*WM represents tests conducted using PRA in current study

*WC represents BE tests conducted by Schmidt (2015)

Table 7 Shear wave velocity (V_s) and small-strain shear modulus (G_{max}) correlations using piezoelectric ring actuators (PRA) and bender elements (BE)

Test No.	Test ID	V_s Correlations	R Values	G_{max} Correlations	R Values	WM/WC
Pure Sand						
1.	PRA-C0F0M0	$60.455s^{0.2565}$	0.9984	$5.442s^{0.5131}$	0.9984	WM
Fiber Only						
2.	PRA-C0F1M0	$55.926s^{0.2717}$	0.9974	$4.6572s^{0.5434}$	0.9974	WM
3.	PRA-C0F3M0	$52.562s^{0.2846}$	0.9957	$4.1137s^{0.5692}$	0.9957	WM
Cement Only						
4.	PRA-C1F0M0	$96.044s^{0.1898}$	0.9997	$13.735s^{0.3797}$	0.9997	WM
5.	PRA-C2F0M0	$128.79s^{0.1498}$	0.9991	$24.699s^{0.2995}$	0.9991	WM
6.	PRA-C3F0M0	$157.69s^{0.1303}$	0.9983	$37.026s^{0.2607}$	0.9983	WM
7.	PRA-C4F0M0	$178.11s^{0.1213}$	0.9988	$47.235s^{0.2427}$	0.9988	WM
Silt Only						
8.	PRA-C0F0M10.5	$65.944s^{0.2386}$	0.9978	$6.475s^{0.4773}$	0.9978	WM
9.	PRA-C0F0M21	$61.34s^{0.245}$	0.9966	$5.6025s^{0.4900}$	0.9966	WM
10.	PRA-C0F0M28	$50.371s^{0.2653}$	0.9957	$3.778s^{0.5306}$	0.9957	WM
11.	PRA-C0F0M35	$50.547s^{0.2443}$	0.9977	$3.8044s^{0.4887}$	0.9977	WM
12.	PRA-C0F0M42	$44.50s^{0.2565}$	0.9912	$2.9486s^{0.4928}$	0.9912	WM
Sand + Cement + Fiber						
13.	PRA-C2F1M0	$92.449s^{0.221}$	0.9996	$12.726s^{0.4420}$	0.9996	WM
14.	PRA-C3F3M0	$135.57s^{0.1697}$	0.9998	$27.368s^{0.3393}$	0.9998	WM
Previous Western University Research						
Pure Sand						
15.	BE-C0F0M0	$62.06p^{0.254}$	NG	NG	NG	WC
Pure Silt						
16.	BE-C0F0M100	$7.23p^{0.539}$	NG	NG	NG	WC
Fiber Only						
17.	BE-C0F1M0	$62.78p^{0.258}$	NG	NG	NG	WC
Cement Only						
18.	BE-C1F0M0	$104.96p^{0.202}$	NG	NG	NG	WC
19.	BE-C2F0M0	$133.94p^{0.146}$	NG	NG	NG	WC
20.	BE-C3F0M0	$162.25p^{0.121}$	NG	NG	NG	WC
21.	BE-C4F0M0	$143.07p^{0.173}$	NG	NG	NG	WC
22.	BE-C8F0M0	$337.69p^{0.052}$	NG	NG	NG	WC
Sand + Cement + Fiber						
23.	BE-C2F1M0	$91.66p^{0.217}$	NG	NG	NG	WC
Sand + Cement + Fiber + Silt						
24.	BE-C2F1M10.5	$112.29p^{0.172}$	NG	NG	NG	WC
25.	BE-C2F1M21	$83.36p^{0.236}$	NG	NG	NG	WC
26.	BE-C2F1M28	$79.24p^{0.228}$	NG	NG	NG	WC
27.	BE-C2F1M35	$69.66p^{0.216}$	NG	NG	NG	WC
28.	BE-C2F1M42	$62.56p^{0.250}$	NG	NG	NG	WC
29.	BE-C2F1M75	$84.33p^{0.171}$	NG	NG	NG	WC
30.	BE-C2F1M100	$40.57p^{0.260}$	NG	NG	NG	WC

*WM represents tests conducted using PRA in current study;

*WC represents BE tests conducted by Schmidt, (2015); *NG represents not given values

in β_0 exponent for fiber reinforced, and silty sand specimens, and increase in α factor, and decrease in β_0 exponent for cemented, and fiber reinforced cemented specimens, can also be seen in Schmidt (2015) results. For bender element tests, the fiber reinforced cemented silty sand specimens show an initial increase in α factor by approximately 81% and then decreases up to 31%. β_0 exponent shows an initial decrease by approximately 33% and then increases up to the value of pure sand (0.258).

When Toyoura sand was stabilized with the PVA fibers, the shear wave velocity of the Toyoura sand was virtually unaffected. A very minimal increase over un-stabilized sand was seen at higher effective stress values. This confirms that the addition of fibers alone does not dramatically change a soil's behavior during very small strain loading conditions (Consoli *et al.* 2010). The shear modulus was consequently minimally affected by the PVA fibers, decreasing slightly at lower confining pressures, consistent with the findings of (Heineck *et al.* 2005). There was also no significant change in the α or β values for the Toyoura sand with 1-3% fiber, suggesting that 1-3% fiber concentration does not improve or lessen the stiffness of Toyoura sand. In contrast, higher percentages of cement additive clearly affected the Toyoura sand regardless of the curing time, stiffening the sample and significantly raising the shear wave velocity. The hydrated cement bonds markedly improved the ability of the soil to withstand high confining stresses and dynamic small strains, reducing volumetric strain even at higher confining stresses. In contrast to the Toyoura sand, un-stabilized silica flour is a weak, collapsible soil with a low shear wave velocity and shear modulus, and a high compressibility similar to the values associated with a soft clay. Addition of both stabilizers (e.g., OPC and PVA fibers) is clearly the most effective, and increasing the stiffness behavior of Toyoura sand.

5. Conclusions

In this study, a series of shear wave velocity measurements were made on unreinforced, fiber, cement and fiber reinforced cemented Toyoura sand specimens using a piezoelectric ring actuators (PRA) device embedded in an oedometer. The test results on pure Toyoura sand specimens show that the shear wave velocity increases with increasing mean effective stress. It is shown that with the addition of 1-3% of PVA fibers, the shear wave velocity increases moderately. However, the addition of 1-4% of cement causes more significant increases in shear wave velocity. It is also shown that increase of fines generally reduces the shear wave velocity but adding 28-42% fines significantly reduce the shear wave velocity. The combined effect of cement and fibers was also found to provide quite significant shear wave velocity increases. For Toyoura sand with cement and fiber, the fibers no longer control the skeletal stiffness. Instead, the cementitious bonding dominates by interlocking the fibers and the sand grains and creating a less compressible specimen and it is clear that the addition of cement both strengthened and stiffened the Toyoura sand. In addition, the results from this study for the

normalized shear modulus and normalized mean effective stress agree well with previous findings on pure Toyoura sand (Oztoprak and Bolton 2013), Toyoura silty sand, and fiber reinforced, fiber reinforced cemented Toyoura sand (Schmidt 2015). Any variations in results of bender elements and PRA device are likely due to the difference in stress history (i.e., isotropic versus anisotropic consolidation) and the measurement method. In addition, these small discrepancies could be attributed to several other factors (Ahmad 2016). The potential factors include the difference in sample preparation techniques, the different test devices (BE vs. Ring piezoelectric actuators), the use of an appropriate K_0 to convert the vertical stresses into mean stress, and different specimen sizes etc. Finally, it was found that there is a robust inverse relationship between α factors and β_0 exponents proposed by Cha *et al.* (2014). Hence, it was concluded that less compressible soils (e.g., cemented sand) exhibit higher α factors and lower β_0 exponents and vice versa.

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