REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01012007

2. REPORT TYPE
Journal Article

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
The Effects of Microstructure on Shear Properties of Shallow Marine Sediments

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Gil Y. Kim, Hong J. Yoon, Jin W. Kim, Dae C. Kim, Boo K. Khim, Seok Y. Kim

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Seafloor Sciences Branch
Stennis Space Center, MS 39529

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/JA/7430-07-4

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Korea Research Foundation Grant (KRF-2003-050-C00017)
304, Youmgok-dong, Seocho-gu
Seoul 137-170, Korea

10. SPONSOR/MONITOR'S ACRONYM(S)
KRF

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES
Marine Georesources and Geotechnology, 25:37-51, 2007

14. ABSTRACT
This study was undertaken to investigate the implication of geoacoustic behaviors in the shallow marine sediments associated with the changes in geotechnical index properties. Two piston cores (270 cm and 400 cm in core length) used in this study were recovered from stations 1 and 2, the western continental margin, the East Sea. Scanning electron microscopy (SEM) was employed to illustrate the effects of microstructure on shear properties. The direct SEM observation of sediment fabrics is inevitable to understand the correlation of the changes in geoacoustic properties to the sediment structure. The consolidation of sediments by overburden stress resulting in the clay fabric alteration appears to play an important role in changing shear properties. Water contents and porosity of sediments gradually decreases with increasing depth, whereas wet bulk density shows a reverse trend. It is interesting to

15. SUBJECT TERMS
geotechnical and shear properties, microstructure, SEM, the East Sea

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(Include area code)*
Unclassified	Unclassified	Unclassified	SAR	15	Jin-Wook Kim / 228-688-5495

Marine Georesources and Geotechnology, 25:37–51, 2007

ISSN: 1064-119X print/1521-0618 online
DOI: 10.1080/10641190601177564

Taylor & Francis
Taylor & Francis Group

The Effects of Microstructure on Shear Properties of Shallow Marine Sediments

GIL Y. KIM

Petroleum & Marine Resources Division, Korea Institute of Geoscience and Mineral Resources (KIGAM), South Korea

HONG J. YOON

Department of Satellite Information Sciences, Pukyong National University, Busan, South Korea

JIN W. KIM

Seafloor Sciences Branch, Naval Research Laboratory, Stennis Space Center, MS, USA

DAE C. KIM

Department of Environmental Exploration Engineering, Pukyong National University, Busan, South Korea

BOO K. KHIM

Department of Marine Science, Pusan National University, Busan, South Korea

SEOK Y. KIM

Department of Oceanography, Pukyong National University, Busan, South Korea

This study was undertaken to investigate the implication of geoacoustic behaviors in the shallow marine sediments associated with the changes in geotechnical index properties. Two piston cores (270 cm and 400 cm in core length) used in this study were recovered from stations 1 and 2, the western continental margin, the East Sea. Scanning electron microscopy (SEM) was employed to illustrate the effects of microstructure on shear properties. The direct SEM observation of sediment fabrics is inevitable to understand the correlation of the changes in geoacoustic properties to the sediment structure. The consolidation of sediments by overburden stress resulting in the clay fabric alteration appears to play an important role in changing shear properties. Water contents and porosity of sediments gradually decreases with increasing depth, whereas wet bulk density shows a reverse trend. It is interesting to

Address correspondence to Gil Young Kim, Petroleum & Marine Resources Division, Korea Institute of Geoscience and Mineral Resources (KIGAM), Daejeon 305–350, South Korea. E-mail: gykim@kigam.re.kr

note that shear wave velocities increase rapidly from 8 to 20 m/s while compressional wave velocities significantly fluctuate, ranging from 1450 to 1550 m/s with depth. The fabric changes in sediment with increasing depth for example, uniform grain size and well oriented clay fabrics may cause the shear strength increase from 1 to 12 kPa. Shear wave velocity is, therefore, shown to be very sensitive to the changes in undrained strength for unconsolidated marine sediments. This correlation allows an in-situ estimation of shear stress in the subsurface from shear wave velocity data.

Keywords geotechnical and shear properties, microstructure, SEM, the East Sea

For the past three decades geotechnical and geoacoustic properties of marine sediments have been of a great interest to various fields such as geophysics, seafloor engineering, sedimentology, soil mechanics, and underwater acoustics (Hamilton 1971, 1980; Hamilton and Bachman 1982; Richardson et al. 1991, 1997, 2002). The history of sea level changes can be revealed by the information of textural changes and the burial diagenetic deformation obtained by acoustic properties (Hamilton 1980; Hamilton and Bachman 1982). Shear wave velocity, shear modulus, and shear strength are used to predict the stability of sediment slopes, consolidation behavior of sediments, and the strength of marine foundation (Nacci et al. 1974; Theilen and Pecher 1991). This is because the shear wave velocity in unconsolidated marine sediments has been shown to be sensitive to overburden pressure or compaction (Brunson 1993). The stability of seafloor sediments is closely related to the physical state, behavior to the external loading, and the stress history (Davis et al. 1993). The depositional environment and sediment supply initially control the texture, sediment grade and sedimentation rate. These characteristics in turn influence the petrophysical properties such as porosity, water content, and grain packing. The consolidation of sediments has been causing a porosity reduction by mechanical overburden pressure with increasing depth, which is well documented (Kim et al. 1999, 2001; Bryant et al. 1991). The weight of the overlying sediments rearranges the individual sediment particles (fine clays) and domains manipulating the petrophysical properties of sediments (Bennett et al. 1991; Bryant et al. 1991).

Previous studies have given little consideration on the relation between sediment fabric and shear properties, which can be used to develop a model to predict an in-situ estimation of shear stress. Most studies have mainly focused on the change of microstructure related to geotechnical index properties (Bowles et al. 1969; Bohlke and Bennett 1980; Bennett et al. 1981, 1989; Kim et al. 2001), and little is known about the effect of microstructure on shear properties, particularly of shear wave velocity in marine sediments. In this article, the response of shear wave velocity to fabric changes is studied by direct observation of the particle arrangements of seafloor sediments. This suggests that the relationship between shear properties and microstructure is important to understand the geoengineering behavior of marine sediments.

Materials and Methods

Two piston core samples used in this study were recovered from station 1 (Water depth: 2,205 m, Lat.: 36°52' 6248N, Long.: 130°07'547E) and station 2 (Water depth: 1,481 m, Lat.: 36°06'1N, Long.: 130°05'24E), the western continental margin of the

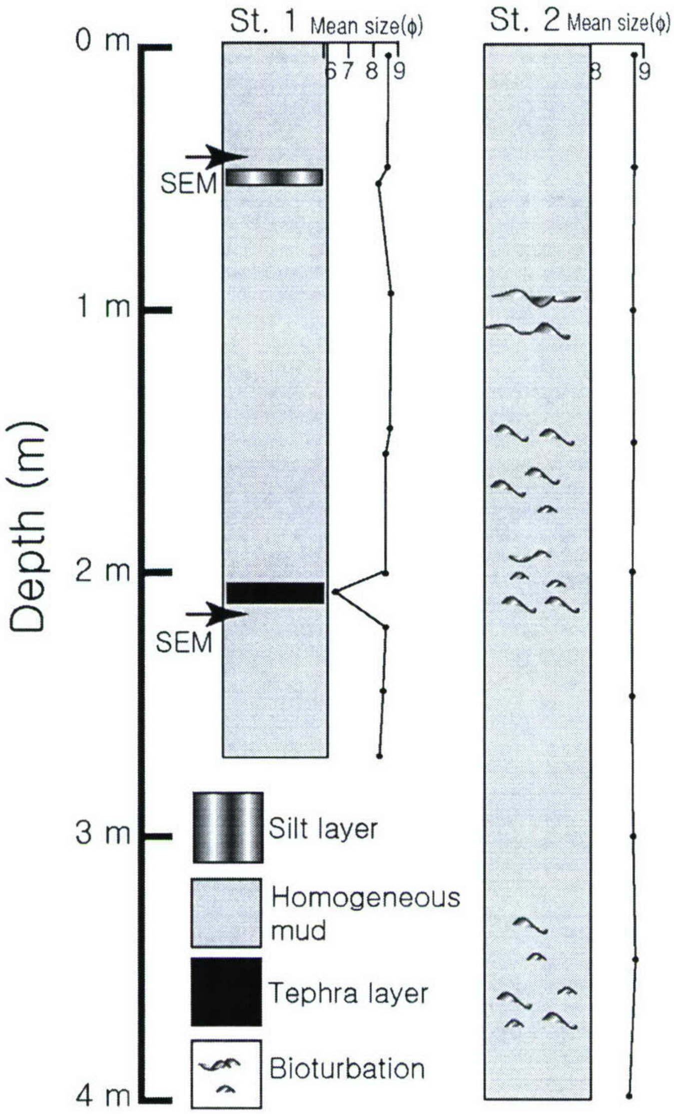

Figure 2. Columnar sections of the cores at station 1 and 2. These cores consist of homogeneous mud with tephra layer (St. 1) and bioturbation (St. 2). Mean grain size is also displayed. Arrow marks of station 1 are the depth selected for SEM micrograph.

The wet mass (g), dry mass (g), wet volume (cm^3) and dry volume (cm^3) of the sample were measured using methods described by Blum (1997). The samples were oven-dried at 105°C for 24 hours and allowed to cool in a desiccator for about 3 hours. Wet and dry volume of samples were determined using a Quantachrome Penta-Pycnometer, helium-displacement pycnometer. Sample volume was determined at least five times, until readings were consistent (i.e., standard deviation less than 0.01%). Sample mass was determined with an error within 0.1% using Scitech electronic balances.

Geoacoustic Properties

Compressional and shear wave velocity was measured on the split cores from top to the bottom at 10-cm interval using a pulse transmission technique (Birch 1960). To improve the coupling between the transducer head and the sample, distilled water was applied to the contact. Driving frequency and voltage were set at 75 kHz and 5 V p-p for P-wave; 500 Hz and 10 V p-p for S-wave, respectively. Pulse generator (Model: Wavetek 178, 50 MHz) and oscilloscope (Model: LeCroy 9400A, Dual 175 MHz) were used to generate signals and detect the signals transmitted through the sample. A bimorph ceramic bender transmitter and receiver, designed and constructed at the Naval Research Laboratory-Stennis Space Center, were utilized to measure shear wave velocity. Shear wave velocity was measured along both the horizontal and the vertical directions to the core-axis.

Scanning Electron Microscopy (SEM)

The initial sample pretreatments were performed following the L.R. White (LRW) resin impregnation method described by Kim and Peacor (1995). This method allows the original fabric of the sample to remain intact. The samples (50 cm and 214 cm in core depth from station 1) were polished by using diamond pastes and then coated with gold. The significant variations in shear strength and shear velocity were observed in these depth ranges of station 1. SEM observations were carried out with a HITACHI S-2400 at 20 kV and a beam current of 80–90 nA in the cooperative laboratory center at Pukyong National University, Busan, Korea.

Results

Grain Size Analysis

The sediment in station 1 shows a coarse-grained layer (about 6.5ϕ), tephra layer originated from the Ulleung-Oki volcanic eruption (9.3 ka ago) at the 210 cm in depth (Figures 2 and 3). Gravel-sized pumices also occurred at this interval, while silt-sized particles are shown around the 62-cm depth (Figures 2 and 3). The sand and silt-sized particles (e.g., pumice, foraminifers) are scattered around the 230-cm depth and the mean grain size slightly increases from 8.5 to 8ϕ with increasing depth. The average contents of sand, silt, and clay are 1.79%, 24.51%, 72.27%, respectively. The sediment in Station 2 is characterized by the uniformed grain size (about 8.8ϕ) and homogeneous mud with bioturbations (Figures 2 and 4). The average contents of sand, silt, and clay are 0.06%, 20.47%, 79.47%, respectively.

Geotechnical Index Properties

Water content and porosity of the sediment in station 1 show an abrupt decrease at 62 cm (from 65 to 50% in water content, from 85 to 75% in porosity) and 230 cm (from 60 to 50% in water content, from 80 to 70% in porosity) in depth (Figure 3), which may be caused by particle size increase (coarse grains), while wet density shows a reverse trend of water content and porosity. Dry density shows the lowest value (about 2.1 g/cm^3) at 210 cm depth (Figure 3) where a tephra layer (e.g., pumice)

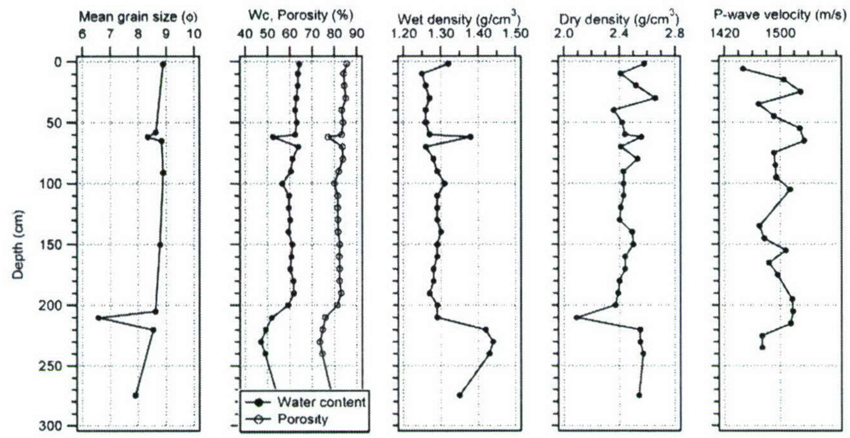

Figure 3. Mean grain size, geotechnical properties, and p-wave velocity for core samples at station 1. The values are markedly changed the intervals below 210 cm depth.

appears and the highest value (2.57 g/cm^3) around the 240-cm depth due to the abundant sand-sized foraminifers.

Water content and porosity of the sediments in station 2 show a similar trend with each showing approximately 60% and 80%, respectively (Figure 4). As shown in Figure 4, the highest values appear at 80 cm depth. Wet density shows a mirror image of water content variation having the lowest value at 80 cm depth corresponding to a higher water content and porosity. The variation of dry density shows from 2.2 to 2.5 g/cm^3 with depth.

Geoacoustic and Shear Properties

Compressional wave velocity measured in sediments of station 1 shows fluctuations from 1450 to 1550 m/s (Figure 3) and shear wave velocity is significantly increased from approximately 5 m/s to 14 m/s at the depth of 100 cm (Figure 5). There is no

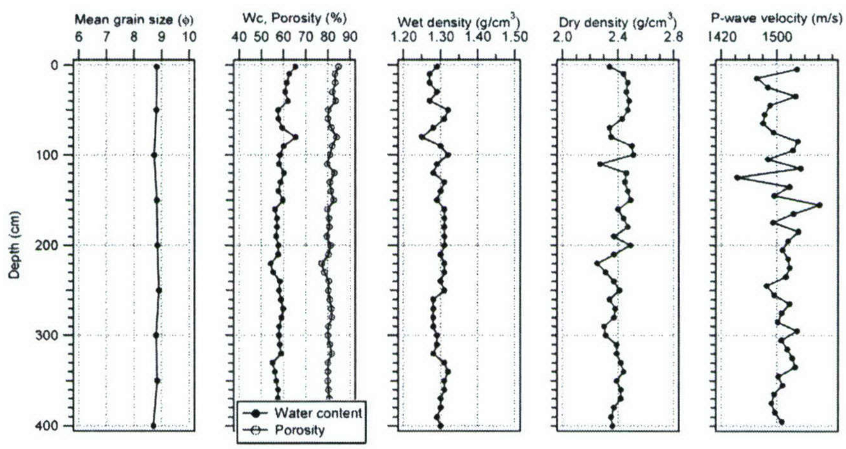

Figure 4. Mean grain size, geotechnical properties, and p-wave velocity for core samples at station 2. The values are characterized by an uniform variation with depth.

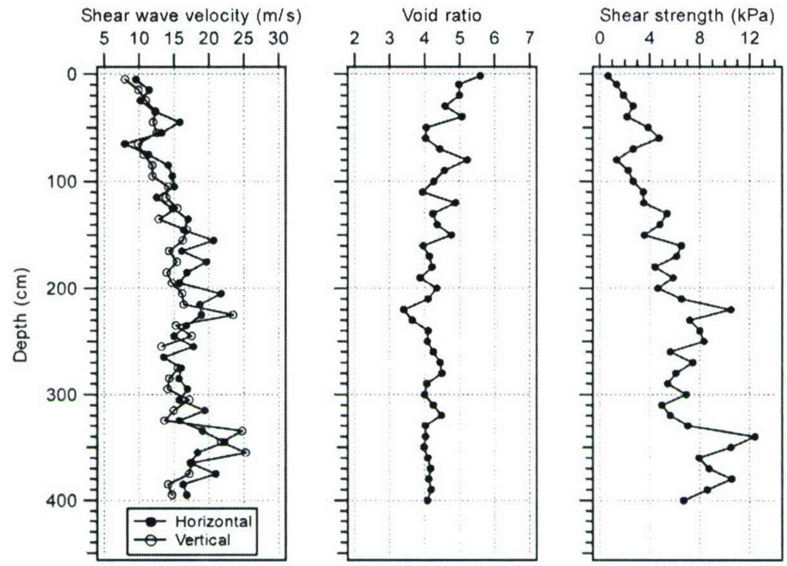

Figure 5. Shear wave velocity, void ratio, and shear strength versus depth at station 1. The values are significantly increased from the boundary of 100 cm depth.

systematic variation of compressional wave velocity for the core from Station 2, and the pattern is also similar to that in Figure 3.

Shear properties (shear wave velocities, shear strength) and void ratio gradient are plotted with depth (Figures 5 and 6). Shear wave velocities in the horizontal and vertical directions show a similar pattern with depth. Shear wave velocity of

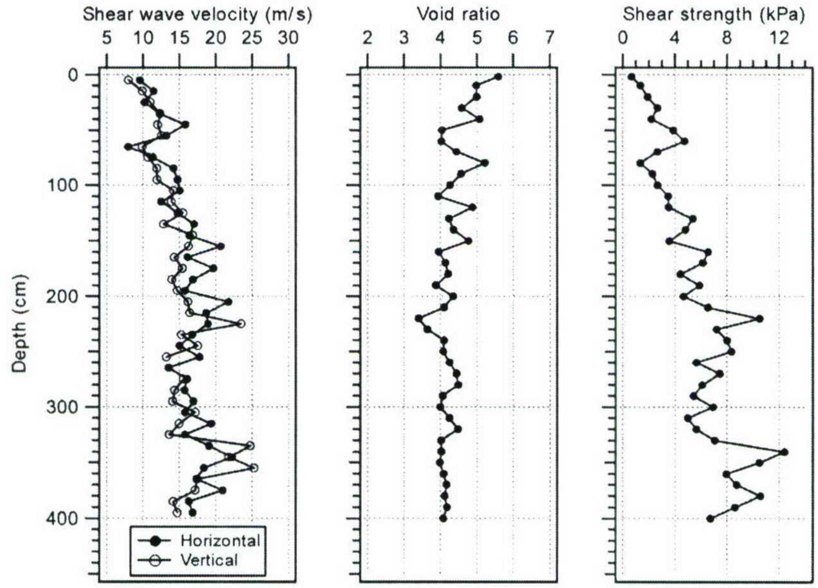

Figure 6. Shear wave velocity, void ratio, and shear strength versus depth at station 2. The values gradually increase with depth.

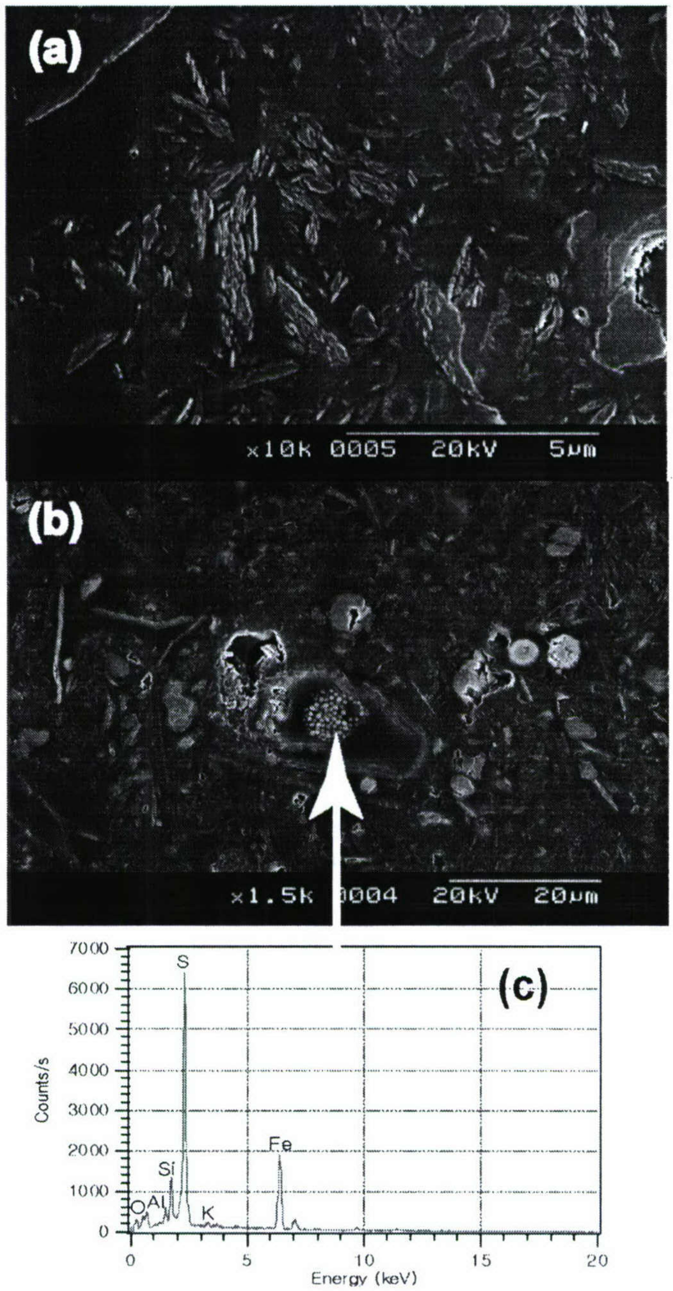

Figure 7. Clay fabric of sample taken at a depth of 50 cm at station 1. Top (a): SEM micrograph showing typical clay domains and clay particles. Middle (b): SEM micrograph showing framboidal pyrite cluster, skeletal grains, and clay particles. Bottom (c): EDS spectrum showing chemical composition (FeS_2) of framboidal pyrite. Note that iron and sulfide are greatly enriched.

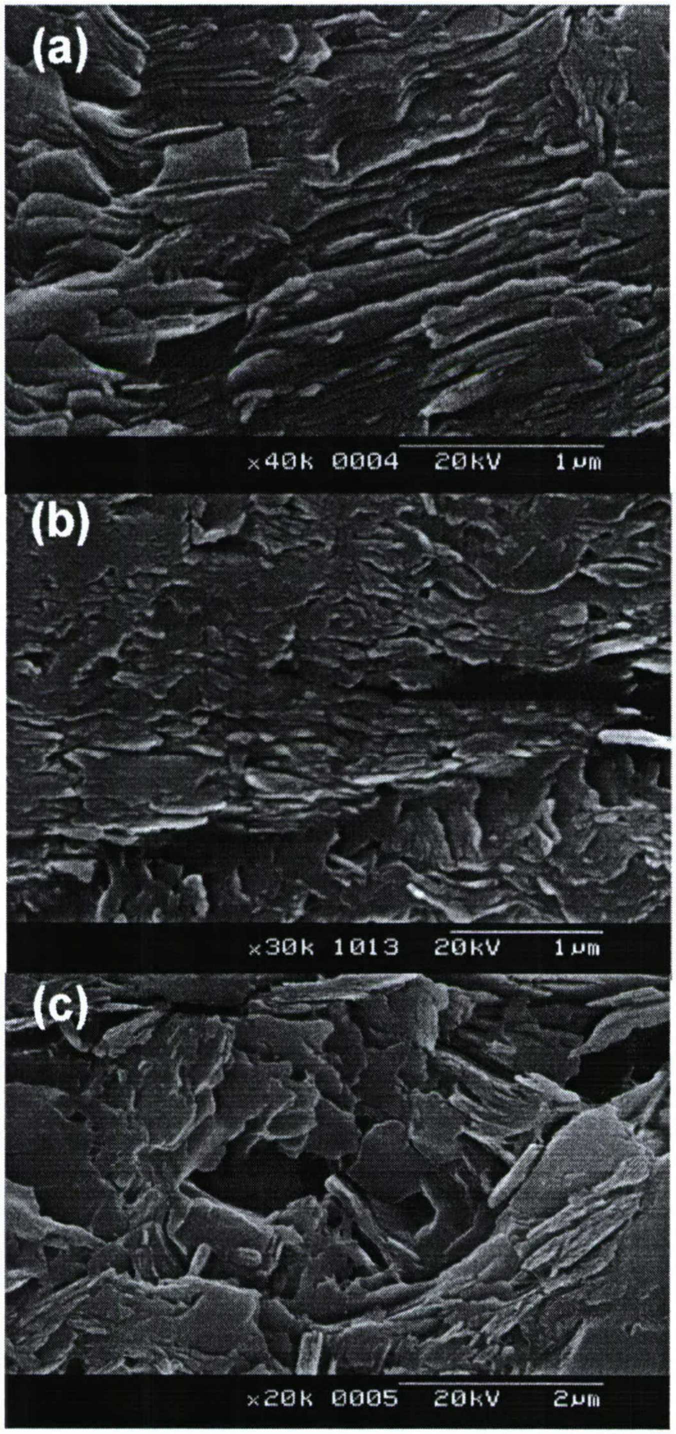

Figure 8. Clay fabric of sample taken at a depth of 215 cm at station 1. Top (a) and middle (b): SEM micrographs showing parallel orientation and well oriented clay fabric. Bottom (c): SEM micrograph showing typical cardhouse clay fabric, the voids appear at the center and upper right.

(approximately 10 m/s) than that of the model (i.e., shear wave velocity gradient with sediment depth) suggested by Richardson et al. (1991). Hamilton's (1987) and Bryan and Stoll's (1988) models have higher values than those of Richardson et al. (1991) for a similar sediment type. This discrepancy may be caused by environmental parameters, such as sedimentary processes and environments, various sediment types, degree of consolidation and compaction, and burial depth (Richardson et al., 1991).

The changes in shear wave velocity caused by increased overburden pressure are noticed in Figures 5 and 6. The value was significantly increased from 8 to approximately 25 m/s (Figure 6), suggesting that shear wave velocity in unconsolidated marine sediments are sensitive to the effects of compaction and the decrease of void ratio (Stoll 1989; Richardson et al. 1991). The shear strength with depth also increases from 1 to 12 kPa (Figures 5 and 6), which corresponds well to shear wave velocity. Decrease in shear strength at a few random depths may be artifacts caused by the sampling disturbance. As shown in Figures 3 and 4, the profiles such as water content, porosity, density, and p-wave velocity do not reveal significant variation with burial depth, compared to the relative variations of shear properties. It is, therefore, suggested that the shear properties might be useful to predict compaction and consolidation of the unconsolidated sediments.

Rigidity modulus shows the ranges between about 100 and 600 $dyn/cm^2 \times 10^6$ (Figure 9). The relationship between rigidity modulus and wet bulk density/porosity is poor (Figures 9a and 9b), whereas rigidity modulus and shear strength/shear wave velocity shows a good correlation (Figure 9c, 9d) because shear wave velocity depend mainly on grain structure and moduli of the sediment frame (Hamilton 1971; Orsi and Dunn 1991).

Clay Fabric by SEM

Clay fabric (or clay microstructure) is defined as the orientation and arrangement or spatial distribution of the solid particles and the particle-to-particle relationships (Bennett et al. 1991). Fabric changes in clay are mainly related to consolidation, mineralogy, and grain size, as well as diagenesis (O'Brien 1970; Bennett et al. 1981; Bryant et al. 1991; Tribble et al. 1991). The microstructure of clay fabric strongly influences and largely controls the physical and mechanical properties of sediments, including its consolidation behavior (Bennett et al. 1991). Clay fabric with preferred orientation provides better sediment integrity and higher shear strength because of greater surface area contacts, and higher bonding force, compared to clay sediment with random microstructure that has lower shear strength. Thus, fabric alteration appears to be an important factor influencing both shear wave velocity and shear strength increase of the core sample. This relationship between shear properties and clay fabric is observed by our results (Figures 5 to 8), indicating that diagenesis may play a significant role in shear properties of sediments within several meters (Bennett et al. 1991). The microfabric of this sediment section is most likely in the initial stages of consolidation, where the microstructure has sufficient strength to resist the stresses of the small overburden load impressed upon it (Winterkorn 1948; Bolt 1956; Lambe 1958; Ingles 1968; Bryant et al. 1991). Accordingly, the corresponding pattern in the variation of shear properties is not significantly recognized from the geotechnical properties index profiles (Figures 3 and 4).

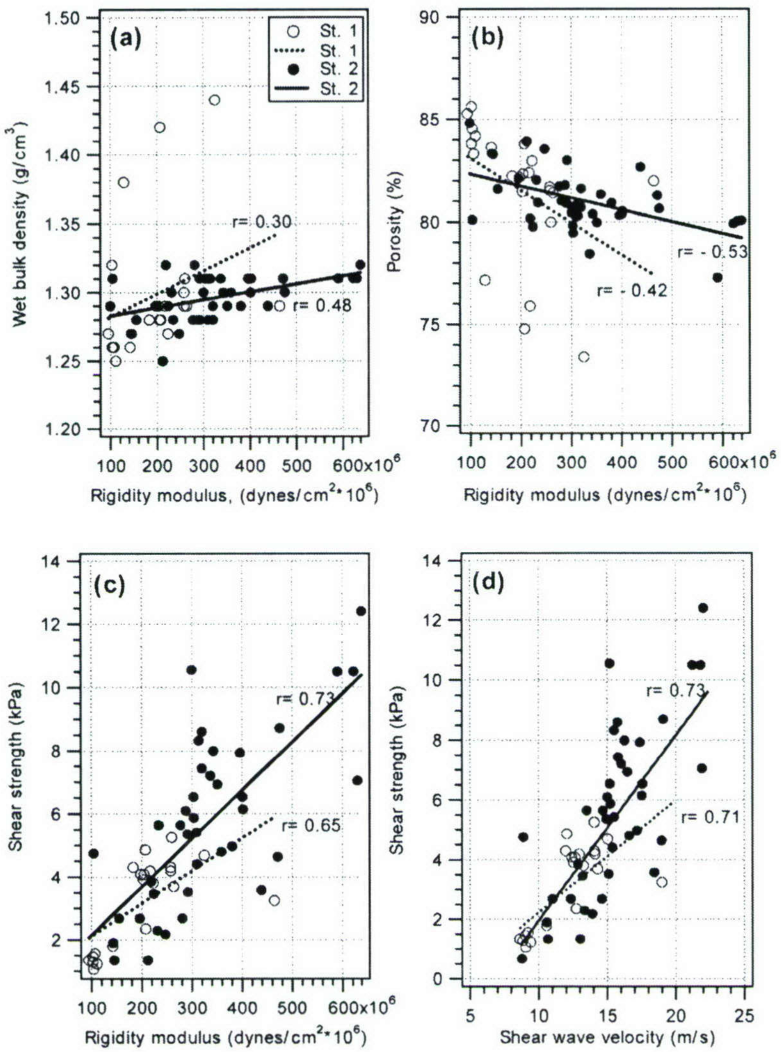

Figure 9. Relationships between geotechnical properties and acoustic properties. Linear regression is displayed. Note that shear properties show a good correlation.

The framboids found in sediments show a spheroidal shape (Figure 7b). The spheroidicity (spheroidal morphology of framboids) is attributed to pseudomorphism of preexisting spherical bodies (e.g., immiscible organic globules or infilling of gaseous vacuoles) caused by bacteria or microflora (Rickard 1970). During the early diagenesis, iron diffusion from the organic-rich anoxic sediment into the bacterial cavity resulted in iron sulfide precipitation (Bennett et al. 1991). The authigenic pyrite changes the clay fabrics, disturbing the particle orientation in the sediments. The typical framboid found commonly in organic-rich sediments displays platy flakes wrapped around the sphere and is associated with a doming of adjacent particles, as shown in Figure 7b.

The samples from the depths of 50 cm and 215 cm with different values of shear properties were characterized by SEM, as shown in Figures 7 and 8. For example, the fabrics of the samples with low shear strength and shear wave velocity were characterized by a random arrangement of clay, while the clay particles of sediments showing high shear strength and shear wave velocity were well oriented caused by increased overburden stress. Therefore, the clay fabric study can be a major tool in understanding the mechanisms of the consolidation process resulting from porosity reduction and its relations to the geotechnical index properties of the sediments.

Conclusions

Geotechnical index properties (water content, porosity, and density) with the exception of upper 50 cm and below 200 cm in depth, do not appear to decrease with depth. Compressional wave velocity fluctuates significantly with depth, while the shear wave velocity (in mean value of horizontal and vertical direction) increased rapidly from 8 to 20 m/s in upper 100 cm. The shear strength also increased from about 1 to 12 kPa, corresponding to the shear wave velocity. SEM micrographs of clay at 215 cm depth show the preferred particle reorientation compared to the depth of 50 cm, which may indicate the possible processes of consolidation affecting the sediments. Therefore, the consolidation of sediments by overburden stress causing the clay fabric alteration appears to play an important role in changing shear properties, which can provide important information to predict the geotechnical properties of the shallow marine sediments.

Acknowledgements

We thank three anonymous reviewers for their critical comments. This work was supported by Korea Research Foundation Grant (KRF-2003-050-C00017). This work was partly funded by the Korea Institute of Geoscience and Mineral Resources (KIGAM). Samples for this study were provided by Dr. Joan M. Gardner at Naval Research Laboratory, Washington D.C. USA. This research was also supported by grant (No. R01-2002-000-00369-0) from the Basic Research Program of the Korea Science & Engineering Foundation. BKK appreciates the support from the second stage of BK 21 in 2006.

References

Bennett, R. H., W. R. Bryant, and G. H. Keller. 1981. Clay fabric of selected submarine sediment: Fundamental properties and models. *Journal of Sedimentary Petrology* 51: 127–152.

Bennett, R. H., K. M. Fischer, D. L. Lavoie, W. R. Bryant, and R. Rezak. 1989. Porometry and fabric of marine clay and carbonate sediments: Determinants of permeability. *Marine Geology* 89: 127–152.

Bennett, R. H., N. R. O'Brien, and M. H. Hulbert. 1991. Determinants of clay and shale microfabric signatures: Processes and Mechanism. Pp. 5–32 in R. H. Bennett, R. H., W. R. Bryant, and M. H. Hulbert (eds.), *Microstructure of Fine-grained Sediments from Mud to Shale*. New York: Springer-Verlag.

Birch, F. 1960. The velocity of compressional waves in rocks up to 10 kilobars. *Journal of Geophysical Research* 65: 1083–1102.

Blum, P. 1997. Physical Properties Handbook-A Guide to the Shipboard Measurement of Physical Properties of Deep-sea Cores by the Ocean Drilling Program, Ocean Drilling Program Technical Note, 26.

Bohlke, B. M. and R. H. Bennett. 1980. Mississippi prodelta crust: A clay fabric and geotechnical analysis. *Marine Geotechnology* 4: 55–82.

Bolt, G. H. 1956. Physico-chemical analysis of the compressibility of pure clays. *Geotechnique* 6: 86–93.

Bowles, R. A., W. R. Bryant, C. Wallin. 1969. Microstructure of unconsolidated and consolidated marine sediments. *Journal of Sedimentary Petrology* 39: 1546–1551.

Boyce, R. E. 1976. Definition and laboratory techniques of compressional sound velocity parameter and wet-water, wet bulk density, and porosity parameter by gravimetric gamma ray attenuation techniques. Pp. 931–958 in S. O. Schlanger, E. D. Jackson, et al. (eds.), *Init. Repts. DSDP, 33*. Washington, D.C: U.S. Govt. Printing Office.

Bryan, G. M. and R. D. Stoll. 1988. The dynamic shear modulus of marine sediments. *Journal of the Acoustical Society of America* 83: 2159–2164.

Bryant, W. R., R. H. Bennett, P. J. Burkett, and F. R. Rack. 1991. Microfabric and physical properties characteristics of a consolidated clay section: ODP site 697. Weddell Sea. Pp. 73–92 in R. H. Bennett, W. R. Bryant, and M. H. Hulbert (eds.), *Microstrucutre of Fine-Grained Sediments from Mud to Shale*. New York: Springer-Verlag.

Brunson, B. A. 1993. Shear wave attenuation in unconsolidated laboratory sediments. *NORDA Technical Note* 159, 242pp.

Davis, A. M., H. Christian, D. G. Huws, R. Parrot, and V. Barrie. 1993. Seabed stability evaluation studies using shear wave propagation phenomena. Pp. 25–32 in N. G. Pace, and D. N. Langhorne (eds.), *Proceedings of the Institute of Acoustics, Vol. 15, Acoustic Classification and Mapping of the Seabed*. Bath University Press, Bath.

Folk, R. L. 1974. *Petrology of Sedimentary Rocks*. Austin, TX: Hemphills, 170 pp.

Hamilton, E. L. 1971. Elastic properties of marine sediments. *Journal of Geophysical Research* 76: 579–604.

Hamilton, E. L. 1980. Geoacoustic modeling of the seafloor. J. *Acoust. Soc. Am.* 68: 1313–1340.

Hamilton, E. L. 1987. Acoustic properties of sediments. Pp. 3–58 in A. Lara-Saenz, C. Ranz-Guerra, C. Carbo-Fite, C. (eds.), *Acoustic and Ocean Bottom*. Instituto de Acustica Madrid.

Hamilton, E. L. and R. T. Bachman. 1982. Sound velocity and related properties of marine sediments. *Journal of the Acoustical Society of America* 68: 1891–1904.

Ingles, O. G. 1968. Soil chemistry relevant to the engineering behavior of soils. Pp. 1–57 in I. K. Lee (ed.), *Soil Mechanics*, selected topics. London: Butterworths.

Kim, G. Y., D. C. Kim, S. C. Park, and G. H. Lee. 1999. Chirp (2-7 kHz) echo characters and geotechnical properties of surface sediments in the Ulleung Basin, the East Sea. *Geosciences Journal* 3(4): 213–224.

Kim, G. Y. and D. C. Kim. 2001. Comparison and correlation of physical properties from the plain and slope sediments in the Ulleung Basin, the East Sea (the Sea of Japan). *Journal of Asian Earth Sciences* 19(5): 669–681.

Kim, J. W., Y. E. Lee, T. T. Tieh, and W. R. Bryant. 2001. Effects of laboratory consolidation on petrophysical properties of fine-grained marine sediments: Electron microscopic observations. *Marine Georesources and Geotechnology* 18: 347–360.

Kim, J. W. and D. R. Peacor. 1995. A technique for maintaining texture and permanent expansion of smectite interlayers for TEM observations. *Clays and Clay Minerals* 43: 51–57.

Lambe, T. W. 1958. The structure of compacted clay. *Journal Soil Mechanics Foundation Division*, Proceedings American Society Civil Engineering 84: 1–35.

Nacci, V. A., M. C. Wang, J. Gallagher. 1974. Influence of anisotropy and soil structure on elastic properties of sediments. Pp. 63–87 in L. Hampton (ed.), *Physics of Sound in Marine Sediments*. New York and London: Plenum Press.

O'Brien, N. R. 1970. The fabric of shale: An electron microscope study. *Sedimentology* 15: 229–246.

Orsi, T. H. and D. A. Dunn. 1991. Correlations between sound velocity and related properties of glacio-marine sediments: Barrents Sea. *Geo-Marine Letters* 11: 79–83.

Richardson, M. D., E. Muzi, B. Miaschi, and F. Turgutcan. 1991. Shear wave velocity gradient in near-surface marine sediment. Pp. 295–304 in Hovem et al. (eds.), *Shear Wave in Marine Sediments*. Netherlands: Kluwer Academic Pub.

Richardson, M. D., D. L. Lavoie, K. B. Briggs. 1997. Geoacoustic and physical properties of carbonate sediments of the lower florida keys. *Geo-Marine Letters* 17: 316–324.

Richardson, M. D., K. B. Briggs, S. J. Bentley, D. J. Walter, and T. H. Orsi. 2002. The effects of biological and hydrodynamic processes on physical and acoustic properties of sediments off the Eel River, California. *Marine Geology* 182: 121–139.

Rickard, D. T. 1970. The origin of framboids. *Lithos* 3: 269–293.

Stoll, R. D. 1989. *Sediment Acoustics, Lecture Notes in Earth Sciences*. New York: Springer-Verlag, 153 pp.

Theilen, F. R. and I. A. Pecher. 1991. Assessment of shear strength of the sea bottom from shear wave velocity measurements on box cores and in-situ. Pp. 67–74 in Hovem et al. (eds.), *Shear Wave in Marine Sediments*. Netherlands: Kluwr Academic Pub.

Tribble, J. S., E. T. Mackenzie, and J. Urmos. 1991. Physical property changes accompanying deep burial of clay-rich sediments. Pp. 93–108 in R. H. Bennett, W. R. Bryant, M. H. Hulbert (eds.), *Microstrucutre of Fine-grained Sediments from Mud to Shale*. New York: Springer-Verlag.

Winterkorn, H. F. 1948. Physico-chemical properties of soils. *Preceedings 2nd International Conference Soil Mechanics Foundation Engineering*, Rotterdam, pp. 23–29.