Clays and Clay Minerals, Vol. 62, No. 4, 313–323, 2014.

THE DYNAMIC SHEAR MODULUS AND DAMPING RATIO OF CLAY NANOCOMPOSITES

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Abstract—Clay soils are very useful as liners in geotechnical structures such as landfill sites, dams, water channels, *etc*. Swelling is a common problem in clay liners, however. To better understand swelling properties, in the present study clay nanocomposites were produced by means of the sol gel method, using a hydrophobic clay, polymers (locust bean gum, latex, glycerine, vinyl acrylic copolymer), and rubber powder. The study focused on the swelling and dynamic properties (secant shear modulus and damping ratio) of the clay nanocomposites researched experimentally in laboratory conditions. The dynamic tests were conducted on samples compacted using two different compaction energy levels. The test results were compared with those of natural clay and hydrophobic organo-clay. The test results revealed that the damping ratios and secant shear modulus of clay nanocomposites without rubber (CNC) and with rubber (CNCr) that were compacted with both the E1 and E2 energy levels were increased and decreased, respectively. In addition, with increasing percentage of vinyl acrylic in nanoclay composites, the secant shear modulus values were decreased and damping ratio values were increased. Consequently, the test results found that the swelling and dynamic properties of clay nanocomposites can be optimized in order to attenuate the negative effects of dynamic loads on clay liners.

Key Words—Clay nanocomposite, Damping Ratio, Hydrophobic Clay, Secant Shear Modulus, Swelling

INTRODUCTION

Determination of dynamic soil properties is an extremely important aspect of geotechnical earthquake engineering (Kumar *et al*., 2013). The dynamic response of soils is an important engineering property because soils can underlay critical support structures such as highway bridges or levees (Bate, 2010). The dynamic shear modulus and damping ratio of clay soils are important parameters for constructing engineering structures which may be subjected to dynamic loads such as earthquakes, machine vibrations, and waves. Shear modulus is a measure of the shear stiffness of the soil. The secant shear modulus can also be used to approximate dynamic loading over a cycle of loading at any given strain amplitude (Darendeli, 2001). At moderate to high strains, the secant shear modulus is used to represent the average soil stiffness. The material damping ratio is a measure of the amount (or magnitude) of energy dissipated by the soil when undergoing shear or plastic deformation (Zhang *et al*., 2005; Aghaei Araei *et al*., 2010). The most important dynamic parameters of soils are shear modulus and damping ratio (Aghaei Araei *et al*., 2010; Bate and Burns, 2012). Determination of the secant shear modulus and material damping ratio are important for soils, therefore.

Energy-absorbing systems find applications in many situations where excess energy needs to be managed without causing damage to surrounding objects (Chaudhari *et al*., 2005). Energy-absorbing materials are produced from rubber-based elastomers (Moon *et al*., 2002; Kilar and Koren, 2009). In recent years, polymer/layered silicate nanocomposites have been investigated widely because of their excellent properties which are different from either clay or polymer. Polymer/layered silicate nanocomposites are composite materials, obtained from clay which has interacted chemically and physically with polymer (Alexandre and Dubois, 2000; Ray and Okamoto, 2003; Tjong, 2006; Pavlidou and Papaspyrides, 2008). Biopolymers are naturally occurring polymers that are found in all living organisms. Biopolymers are therefore considered to originate from renewable sources; consequently, their use is expected to have a less negative effect on the environment than petroleum-based materials. At present, biopolymers are used in a variety of applications such as therapeutic aids, medicines, coatings, food products, and packaging materials (Petersson and Oksman, 2006).

Surfactants are substances that cause a hydrophilic or a hydrophobic surface which can increase or decrease the surface tension. Clay nanocomposites (polymer/layered silicate nanocomposites) are prepared by incorporating finely dispersed layered silicate materials in a polymer matrix. In recent years polymer/layered silicate nanocomposites have attracted great interest from researchers (LeBaron *et al*., 1999; Paiva *et al*., 2008; Mittal, 2009; Akbulut *et al*., 2010, 2012, 2013). The dynamic properties of organo-clays have also been investigated. The dynamic properties of organo-bentonites using resonant column tests were investigated by Bate and Burns (2012).

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DOI: 10.1346/CCMN.2014.0620405

The fundamental properties and preparation of clay nanocomposites (polymer/layered silicate nanocomposites) were investigated by previous researchers (Lagaly, 1999; Alexandre and Dubois, 2000; Fischer, 2003; Ray and Okamoto, 2003; Liu, 2007; Pavlidou and Papaspyrides, 2008). A number of these studies have focused on the thermal and mechanical properties of polymer/layered silicate nanocomposites (Burmistr *et al.*, 2005; Tjong, 2006; Yasmin *et al.*, 2006; Hbaieb *et al.*, 2007; Zare-Shahabadi *et al.*, 2011). The mechanical properties of silicon rubber consisting of blended silicone gums with varied vinyl contents were improved by Xu *et al.* (2010). Tanniru *et al.* (2006) compared the mechanical response of a clay-reinforced polyethylene nanocomposite with un-reinforced polyethylene under identical processing conditions. Those authors found that the addition of clay to polyethylene led to retention of adequately high-impact strength in the temperature range investigated −40 to +70ºC (Tanniru *et al.*, 2006). Zhu and Wool (2006) synthesized a new bio-based elastomer from soybean oil filled with nanoclay to generate an elastic nanocomposite and observed that the mechanical properties were improved significantly by the addition of organoclays.

Other studies focused on the barrier properties and flame-retardant properties of polymer/layered silicate nanocomposites (Koh *et al.*, 2008; Mohan and Kanny, 2011; Mishra *et al.*, 2012). A series of rubber/clay nanocomposites prepared by the latex-compounding method (He *et al.*, 2010) was shown to have low cost/performance ratios, excellent tensile strength, superior gas-barrier properties, improved flame-retardant properties, and outstanding anti-fatigue properties. The advantages of using nanocomposite materials in civil engineering over those of the more conventional construction materials were listed by Hackman and Hollaway (2006) who noted that the tensile modulus and flexural modulus of nanocomposites were increased.

The damping ratios and secant shear modulus of clay nanocomposites were investigated by a number of researchers. One of these studies focused on improving clay nanocomposites using latex and glycerin. The damping ratios of these clay nanocomposites were investigated (Majedi, 2013) in an attempt to modify clay nanocomposites and to investigate the effects of locust bean gum (biopolymer-LBG), latex (LTX), glycerin (GLC), vinyl acrylic (VA), and rubber powder (RP) on the swelling properties, secant shear modulus, and damping ratio of the natural clay (C) and hydrophobic clay (HOC). The hydrophobic clay was used to eliminate the negative effects caused by the swelling of clayey soils.

To better understand the swelling and dynamic properties (secant shear modulus and damping ratio) swelling of the clay nanocomposites, the present study produced clay nanocomposites by means of the sol gel method, using a hydrophobic clay, polymers (locust bean gum, latex, glycerine, vinyl acrylic copolymer), and rubber powder, and determined swelling and dynamic properties of different combinations and preparations.

MATERIALS

Natural clay

The clayey soil samples came froma clay pit in the Oltu-Narman deposits in Erzurum, Turkey and are classified as high-plasticity clay (CH), according to the Unified Soil Classification System (USCS), and also based on some engineering properties of natural clay (Table 1). Natural clay was used as the template sample.

Hydrophobic organo-clay

In the present study, hydrophobic organo-clay (Table 1) was prepared using the procedure of Kurt (2009). A cationic surfactant, dialkyl ammonium meta

Table 1. Some engineering properties of natural and hydrophobic clays (after Kurt, 2009).

Some properties			Clay	Hydrophobic organo-clay
Clay content	<0.002 mm	(%)	56	–
Specific gravity	G_s		2.62	2.52
Liquid limit	w_L	(%)	72	–
Plasticity index	I_p	(%)	39	–
Contact angle		º	37	88
Cation exchange capacity	(meq/100 g of dry soil)		26.25	21.62
Optimum moisture content*	w_{opt}	(%)	16.5	14
Maximum dry density*	γ_{dmax}	(kN/m^3)	17.55	16.67
Unconfined compression strength*	q_{uu}	(kPa)	1048	998
BET (N_2) surface area		(m^2/g)	10,19	5
Soil classification,	(USCS)		CH	–
Damping ratio*	D	(%)	12.74	16.9
Secant shear modulus*	G_{sec}	MPa	2.843	2.757

* The results were investigated from samples compacted with energy level E1.

Table 2. Properties of LBG, latex, glycerine, vinyl acrylic copolymer, and rubber powder.

Properties	Locust bean gum (LBG)	Latex (LTX)	Glycerine (GLC)	Vinyl acrylic copolymer (VA)	Rubber (RP)
Chemical formula	(1–4) linked beta-D mannose residues and the side chain of (1–6) linked alpha-D galactose.	C_3H_3N	$C_3H_8O_3$	–	–
Chemical composition	Galactomannan (a group of hydrocolloids)	Styrene Butadiene Emulsion	Glycerol	Vinyl acrylic copolymer emulsion	Styrene Butadiene Copolymer
pH	5–7	8–12	7	5 ± 1	–
Viscosity (cps)	2000–3500	–	1200	1000–5000	–
Density (g/cm^3)	–	1.015	1.261	1.03	1.15–1.198

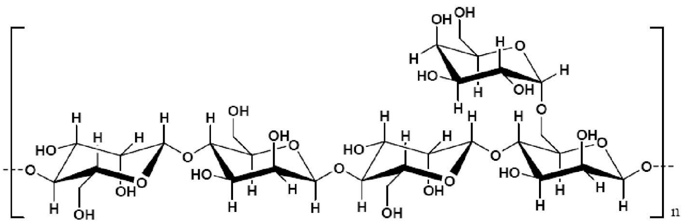
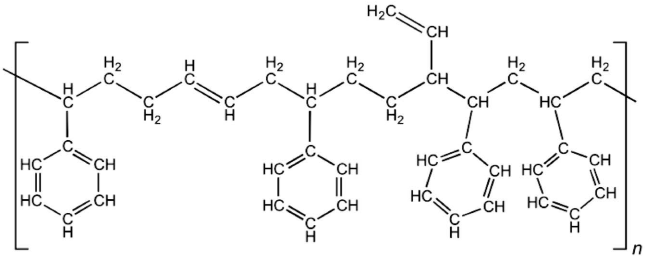
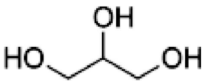
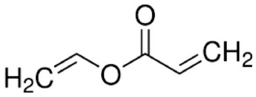
sulfate (DAMS), was used in the preparation of hydrophobic organo-clay. First, 40 g of clay was dispersed in 8 L of deionized water and stirred with a magnetic stirrer at 1000 rpm for 2 h. Previously prepared surfactant solution (DAMS and deionized water) was added slowly to the clay suspension at 30ºC. The modified product (hydrophobic clay) was dried at room temperature. The surfactant included 5% (250 ppm) by weight of clay.

Polymers and other materials

In the present study, locust bean gum, latex, glycerine, vinyl acrylic copolymer, and rubber powder (Tables 2, 3) were used to improve the clay nanocomposites.

Locust-bean gum (LBG). The conventional use of locust-bean gum as an excipient in drug products utilizes its thickening, gel forming, and stabilizing properties (Dey *et al.*, 2012). Locust-bean gum is a virtually neutral

Table 3. Chemical structures of LBG, latex, glycerine, and vinyl acrylic copolymer.

	Chemical structure
Locust bean gum	
Latex	
Glycerine	
Vinyl acrylic copolymer	

galactomannan polymer extracted from the seeds of the carob tree (Lopes da Silva *et al.*, 1994). Locust-bean gum increases the strength of the gel markedly and changes the gel character of the nanocomposite from brittle to elastic (Maier *et al.*, 1993). The LBG was used in the experiments in order to increase the gel strength of the clay nanocomposites.

Latex (LTX). Latex, which was the other polymer used in the experiments, is an elastomer. Natural rubber is produced from the latex of the *Hevea brasiliensis* tree (Hamed, 2001). Latex as an elastomer was used in the experiments in order to improve the elastic properties of the nanocomposites.

Glycerine (GLC). The presence of glycerine is essential for preparing nanocomposites (Lin *et al.*, 1993). In some previous studies for preparing nanocomposites, glycerine was used as the plasticizer (de Carvalho *et al.*, 2001; Tang *et al.*, 2008; Rhim, 2011).

Vinyl acrylic copolymer emulsion (VA). Vinyl acrylic copolymer emulsion is a water-based resin (Barmar *et al.*, 2010). Such resins are often used as the adhesive component of the composition (Murphy *et al.*, 1977). The pigment-binding and film-forming properties of the vinyl acrylic copolymer are significant and its water stability is also notable. Vinyl acrylic copolymer was also used for its adhesive properties.

Rubber powder (RP). The rubber powder used in the present study was purchased from Kahya Rubber, Sakarya, Turkey. Due to its light-weight nature and its capacity for damping energy, the rubber powder can be used to mitigate seismic forces and to absorb earthquake vibrations (Nakhaei *et al.*, 2012). The use of waste fiber materials in geotechnical applications was investigated by Akbulut *et al.* (2007) to evaluate the effects of scrap tire rubber and synthetic fibers on the unconfined compressive strength parameters, and on the dynamic behavior, of clayey soils. Soil samples reinforced with scrap-tire rubber fibers were investigated and the results indicated that increased use of scrap-tire rubber could lead to improved damping ratios and shear moduli of clayey soils.

CHARACTERIZATION OF COMPOSITES

Sample preparation and tests

The clay nanocomposites were obtained by the sol- gel method (Schadler 2003). First, LBG (0.5%) was added to 2 L of water and mixed using a mechanical stirrer at 4000 rpm until dissolved. During stirring, latex (10%) was added and mixed for 20 min. Then, glycerine (10%) was added and the solution was mixed for 10 min. Next, 2500 g of hydrophobic organo-clay and 1 L of water were added and mixed for 1 h. Finally, vinyl acrylic copolymer was added in different proportions (0%, 5%, 10%) and mixed with a mechanical stirrer. (These products were clay nanocomposite samples without rubber powder additive CNC). Rubber powder (5%) was also added and mixed for 10 min to produce clay nanocomposite samples with rubber powder additive (CNCr). The leach products (clay nanocomposites) were dried at room temperature for 48 h. All of the percentages of polymers and additives were used as the percentages of clay weight. The materials used for nanocomposites are listed in Table 4 with the percentage of dry hydrophobic clay weight.

In order to prepare the clay nanocomposite samples for swelling and dynamic simple shear tests, bulk samples of clay nanocomposites were compacted with an automatic compactor. The maximum dry unit weight (γ_{dmax}) and optimum moisture content (w_{omc}) were determined in the clay nanocomposite samples in accordance with standard ASTM D 1557 (2012). To compare the swelling and damping properties of clay nanocomposites with different compactive energy levels and moisture contents, two different energy levels were applied to the samples. The samples were compacted in a 152.4 mm diameter mold with a 44.48 N rammer dropped from a height of 457.2 mm. The samples were added to the mold in five layers and each layer was tamped 25 times. The calculated compactive effort was 2597 kJ/m^3 (energy level E1). In addition, the samples were also added to the mold in five layers in the mold and each layer was tamped 50 times. The calculated compactive effort in this case was 5192 kJ/m^3 (energy level E2). The leach samples with optimum moisture content were then used to prepare samples for swelling tests and dynamic simple shear tests.

Table 4. Clay nanocomposite contents (see Table 2 for abbreviations).

	Content
C	Natural clay
HOC	Hydrophobic clay
CNC0	HO-%0.5LBG-%10LTX-%10GLC
CNC5	HO-%0.5LBG-%10LTX-%10GLC-%5VA
CNC10	HO-%0.5LBG-%10LTX-%10GLC-%10VA
CNCR0	HO-%0.5LBG-%10LTX-%10GLC-%5RP
CNCR5	HO-%0.5LBG-%10LTX-%10GLC-%5VA-%5RP
CNCR10	HO-%0.5LBG-%10LTX-%10GLC-%10VA-%5RP

The swelling tests were carried out in accordance with ASTM D 4546 Method C. The tests were conducted on the compacted samples with optimum moisture contents using a consolidation test apparatus manufactured by ELE (Bedfordshire, UK). The swelling tests were conducted on the natural clay, hydrophobic organoclay and clay nanocomposite (CNC and CNCr) samples.

Dynamic simple shear tests

The dynamic simple shear test apparatus used in this study is a GeocompTM ShearTrac II-DSS system (Geocomp, 2007) (Figure 1). The dynamic simple shear (DSS) tests were carried out in accordance with ASTM D 6528 (2007) on the natural clay, hydrophobic organo-clay, and clay nanocomposite samples compacted with energy levels E1 and E2. The device allows load-controlled constant-volume DSS tests with a load frequency up to 1 Hz on a consolidated soil specimen. A computer controls the micro-stepper motors that apply vertical and horizontal loads to the specimen. A soil specimen of diameter 63.5 mm was confined by a rubber membrane supported by Teflon-covered aluminum rings instead of conventional reinforced membranes.

Natural clay, hydrophobic clay, and clay nanocomposite samples were consolidated under a vertical stress of 100 kPa which was greater than the estimated preconsolidation pressure. In the experiments, the frequency of cyclic load (f) was 1.0 Hz. The cyclic stress ratio (CSR) was 0.40. To compare the effect of VA on the clay nanocomposites, the DSS tests were conducted at a single CSR. The maximum peak to peak strain is ±2.5%.

With the raw data taken from the tests performed on hydrophobic clay and clay nanocomposite, shear strain and shear stress values of the second cycle were determined and the graphs of second cycles were plotted. The hysteresis loop is a stress-strain path. The secant shear modulus (G) and damping ratios (D) were determined from idealized hysteresis loops (Figure 2) produced by cyclic loading. G is defined in equation 1 where τ is the shear stress and γ is the shear strain.

$$G = \tau / \gamma \tag{1}$$

The material damping ratio, D, is the proportion of dissipated energy to the maximum retained strain energy during each cycle at a given strain amplitude (Figure 2). The energy dissipated over a loading cycle is represented by the gray area within the hysteresis loop (A_L), and the maximum retained strain energy is represented by the triangular area (A_T) that is calculated using peak shear stress and peak shearing strain (Kramer, 1996; Darendeli, 2001).

$$D = A_L / (4\pi A_T) \tag{2}$$

The material damping ratio is a result of friction between soil particles, strain rate effects, and non-linearity of the stress-strain relationship in soils

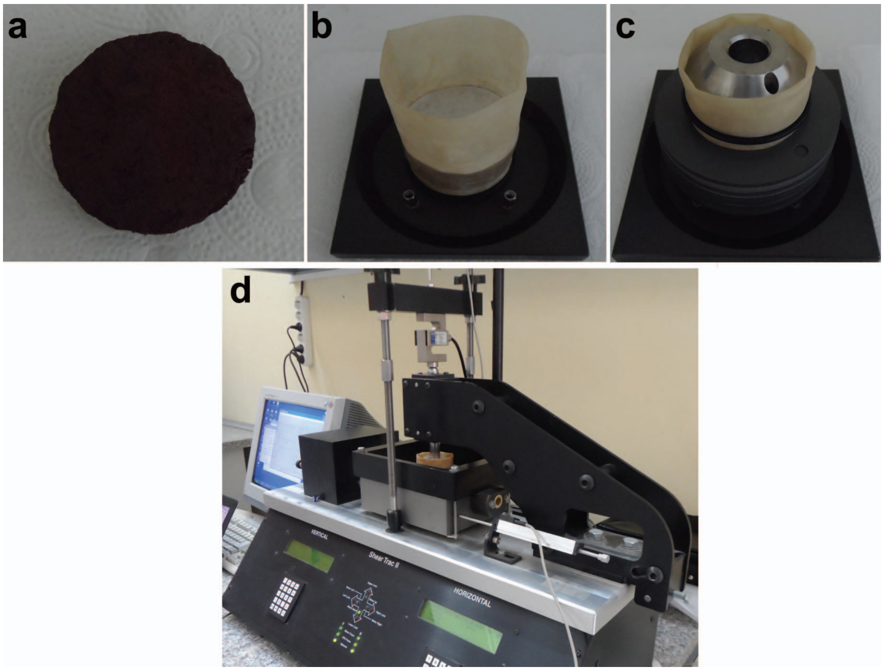


Figure 1. Specimen preparation for DSS tests: (a) the test sample, (b) covering the specimen with a membrane, (c) fixing the membrane to the bottom plate by O-rings and installing Teflon-covered rings around the specimen, (d) the DSS device includes the sample.

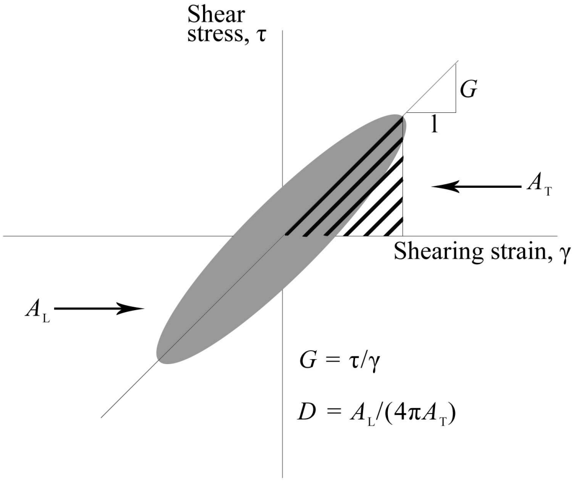


Figure 2. Determination of secant shear modulus, and damping ratios from the idealized hysteresis loop produced by cyclic loading (after Darendeli, 2001).

(Darendeli, 2001). Some of the tests were repeated as many as three times to assure the repeatability of the results.

RESULTS AND DISCUSSION

Swelling tests

The swelling test results (Figure 3) revealed that the swelling pressures of clay nanocomposites (CNC and CNCr) were lower than those of hydrophobic clay. The decrease in the swelling pressures of clay nanocomposite samples are due to the hydrophobic properties of clay nanocomposites (Akbulut *et al.*, 2013). The negative effects of swelling of clayey soils were eliminated by decreasing the swelling pressures of the clay nanocomposites.

Dynamic simple shear test results

Hysteresis loops. The hysteresis loops from second cycles (Figure 4) indicated that the secant shear modulus (determined using equation 1) of clay nanocomposites compacted with energy levels E1 and E2 were decreased when compared with natural clay and hydrophobic clay. The damping ratio values (determined from equation 2) of clay nanocomposites compacted with energy levels E1 and E2 were increased.

Shear modulus. The dynamic simple shear test results (Figure 5) showed that the secant shear modulus of E1- and E2-compacted clay nanocomposites (CNC and CNCr samples) decreased when compared with both C and HOC. Similarly, the secant shear modulus of E1-and E2-compacted clay nanocomposites decreased with increased addition of VA.

The test results (Table 5) showed that the secant shear modulus of hydrophobic organo-clay compacted with the energy level E1 decreased by 3% relative to the natural clay. The secant shear modulus of clay nanocomposite (CNC) samples decreased by 39% and 35%, respectively, relative to natural clay and hydrophobic organo-clay. Similarly, the secant shear modulus of hydrophobic organo-clay compacted with energy level E1 decreased by 17% relative to the natural clay. The secant shear modulus of clay nanocomposites (CNC)

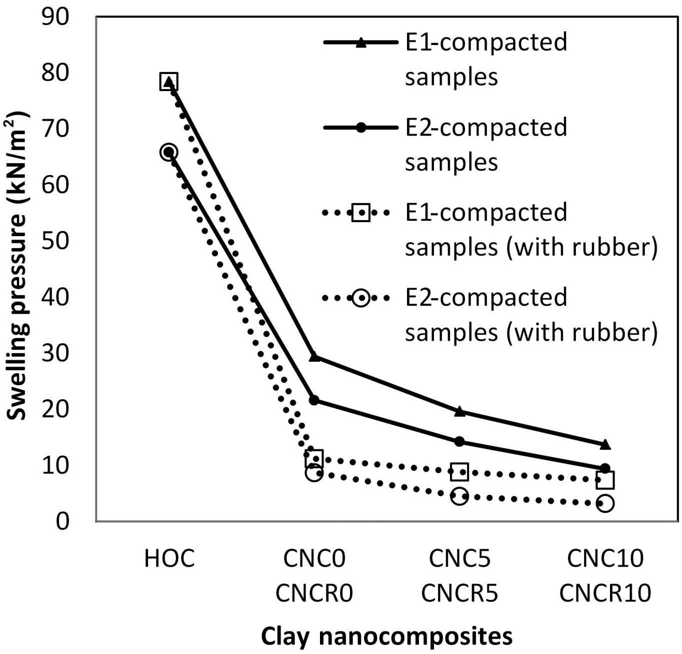


Figure 3. Swelling pressures of clay nanocomposite samples.

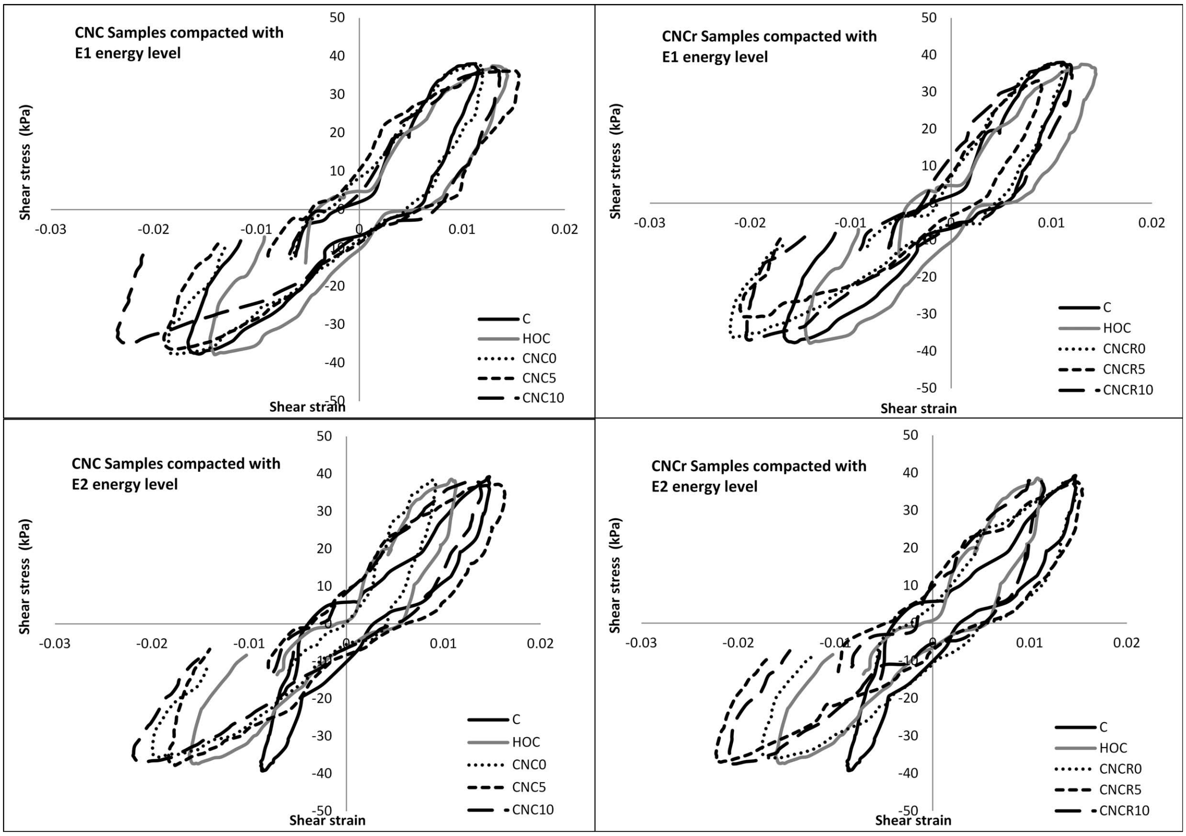


Figure 4. Hysteresis loops at the second cycle of samples.

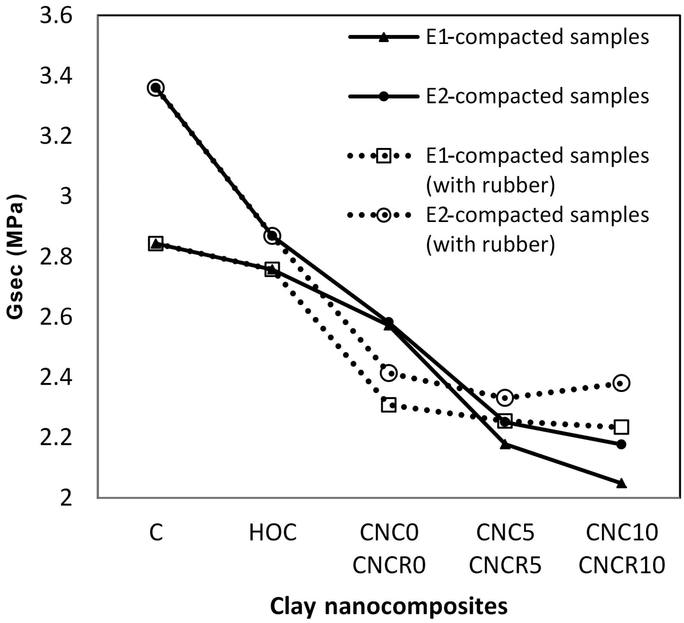


Figure 5. Secant shear modulus values of compacted clay nanocomposite samples.

Table 5. Secant shear modulus values of clay nanocomposite samples compacted with energy levels E1 and E2.

	E1 energy			E2 energy		
	Gsec (MPa)	Decreasing, % (relative to C)	Decreasing, % (relative to HOC)	Gsec (MPa)	Decreasing, % (relative to C)	Decreasing, % (relative to HOC)
C	2,843	–	–	3,360	–	–
HOC	2,757	3	–	2,868	17	–
CNC0	2,572	11	7	2,582	30	11
CNC5	2,178	31	27	2,251	49	27
CNC10	2,048	39	35	2,177	54	32
CNCR0	2,308	23	20	2,414	39	19
CNCR5	2,255	26	22	2,331	44	23
CNCR10	2,234	27	23	2,380	41	21

decreased by 54% and 32%, respectively, relative to natural clay and hydrophobic organo-clay. The secant shear modulus of the CNCr samples compacted with energy level E1 also decreased by 27% and 23%, respectively, relative to natural clay and hydrophobic organo-clay. Similarly, the secant shear modulus of clay nanocomposites (CNCr) compacted with energy level E2 decreased by 41% and 21%, respectively, relative to natural clay and hydrophobic organo-clay.

The test results demonstrated that the secant shear modulus values of E2-compacted natural clay samples were greater than E1-compacted natural clays. The secant shear modulus values of clay nanocomposites increased slightly with increasing energy.

Furthermore, secant shear modulus values in clay nanocomposites decreased when the percentage of VA increased. Large stiffness values may lead to negative dynamic effects, such as reduction of damping; in general, few materials possess both significant damping and rigidity properties (Finegan and Gibson, 1999; Finegan and Gibson, 2000; Ludwigson *et al.*, 2002; Chung, 2003; Rivin, 2007) . This problem was overcome by Finegan and Gibson (2000) who used hybrid composites (with a combination of coated and uncoated fibers) which appear to be a good compromise for obtaining improved damping without much loss of rigidity. The unconfined compressive strengths of clay nanocomposites decreased with the increased VA percentage.

Damping ratios. The dynamic simple shear test results (Figure 6) revealed that the damping ratios of E1- and E2-compacted clay nanocomposites (CNC and CNCr samples) had increased when compared with hydrophobic organo-clay and natural clay. Similarly, the E1- and E2-compacted clay nanocomposites increased when the VA percentage increased.

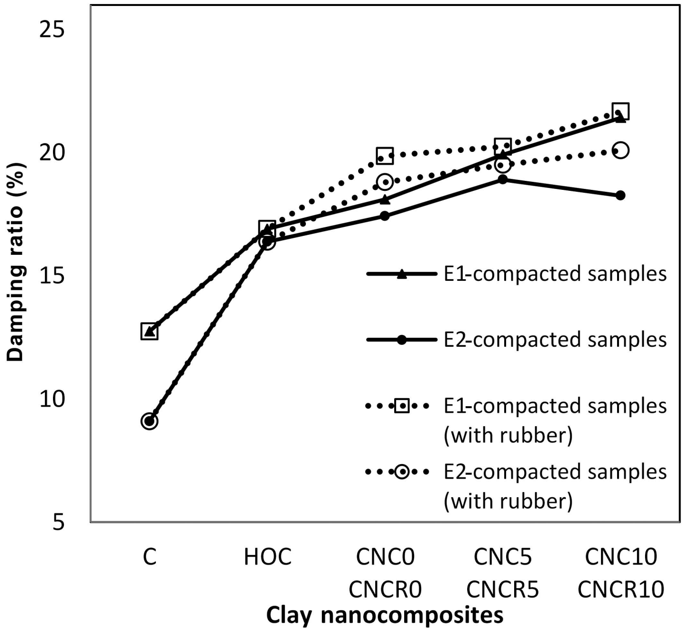


Figure 6. Damping ratios of compacted clay nanocomposite samples.

Previous research indicated that the initial damping ratio decreases when the mean effective stress is increased (D'Onofrio and Penna, 2003). The effective stress increased when the pore-water pressure decreased (Das, 1998). The experimental results revealed that the damping-ratio values of samples compacted at lower moisture contents were less than those of samples compacted at greater moisture contents and these results supported the findings of previous research.

The test results (Table 6) showed that the damping ratio of hydrophobic organo-clay compacted with energy level E1 increased by 33% relative to natural clay. The damping ratio of clay nanocomposites (CNC) increased by 68% and 27%, respectively, relative to natural clay and hydrophobic organo-clay. Similarly, the damping ratio of hydrophobic organo-clay compacted with the energy level E1 increased by 80% relative to natural clay. The damping ratio of clay nanocomposites (CNC) increased by 101% and 11%, respectively, relative to natural clay and hydrophobic organo-clay. The damping ratio of clay nanocomposites (CNCr) increased by 70% and 28%, respectively, relative to natural clay and hydrophobic organo-clay. Similarly, the damping ratio of clay nanocomposites (CNCr) compacted with the energy level E2 increased by 121% and 23%, respectively, relative to natural clay and hydrophobic organo-clay.

The test results also showed that the damping ratio values of E2-compacted natural clay samples were less than E1-compacted natural clays. The damping ratio values of clay nanocomposites decreased slightly with increasing energy, however.

The damping ratios of clay nanocomposites increased when the VA percentage increased. According to Kyminas *et al.* (1989), coating films, which are tough and flexible, which adhere well to various substrates with very low water-vapor permeability, and which have improved weather resistance, contain vinyl acrylic copolymers. The clay nanocomposites could gain these properties from the flexible structure of VA.

In civil engineering, 'base isolation systems' were used in buildings to decrease the negative effects of dynamic loads. 'Base isolation' is a technique in which isolation bearings are installed in structure foundations to reduce the damaging motion transmitted by horizontal earthquakes to those structures (Moon *et al.*, 2002). Seismic base isolation is a valuable earthquake-resistant technique for structures such as buildings and bridges (Ashkezari, 2008). The energy-absorbing ability was increased with increase in the damping ratios of the CNC and CNCr samples. Eventually, the clay nanocomposites may be used as a damper rather like a seismic isolator, under buildings. The clay nanocomposites can also be used as a damper liner between the building and soil because of the decrease in swelling pressures.

CONCLUSIONS

The present study was undertaken to investigate the swelling properties and dynamic properties (secant shear modulus and damping ratio) of some clay nanocomposites and to compare the swelling pressure, damping ratio, and secant shear modulus values with those of natural clay and hydrophobic organo-clay. The swelling pressures of clay nanocomposites that compacted with energy levels E1 and E2 were decreased when compared with hydrophobic organo-clay. The experimental results indicated that the secant shear modulus and damping ratios of clay nanocomposites changed significantly in comparison with those of natural clay and hydrophobic organo-clay. The secant shear modulus values of clay nanocomposite samples without rubber (CNC) and with rubber (CNCr) compacted with energy levels E1 and E2 decreased when compared with natural clay and hydrophobic organo-clay. The secant shear modulus of clay nanocomposites compacted with energy level E1 was less than that for clay nanocomposites compacted with energy level E2.

The damping ratios of clay nanocomposites without rubber (CNC) and with rubber (CNCr) compacted with energy levels E1 and E2 increased when compared with natural clay and hydrophobic organo-clay. The damping ratios of clay nanocomposites compacted with energy level E1 were greater than clay nanocomposites compacted with energy level E2. The secant shear modulus

Table 6. Damping ratios of clay nanocomposite samples compacted with energy levels E1 and E2.

	E1 energy			E2 energy		
	D (%)	Increasing, % (relative to C)	Increasing, % (relative to HOC)	D (%)	Increasing, % (relative to C)	Increasing, % (relative to HOC)
C	12.74	–	–	9.09	–	–
HOC	16.9	36	–	16.38	80	–
CNC0	18.1	42	7	17.42	92	6
CNC5	19.92	57	18	18.9	108	15
CNC10	21.41	68	27	18.25	101	11
CNCR0	19.86	56	18	18.8	107	15
CNCR5	20.24	59	20	19.5	115	19
CNCR10	21.67	70	28	20.09	121	23

and damping ratios of clay nanocomposites decreased and increased, respectively, with increased VA percentage.

The improvement of clay nanocomposites by decreasing swelling pressures and increasing damping ratios could help to solve the dynamic problems of clayey soils, which could then be used as a damper for soils under buildings as a 'base isolation system'.

ACKNOWLEDGMENTS

The present study was conducted under project 2011/122, supported by the Research Development Centre of Ataturk University.

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(*Received 20 March 2013; revised 20 August 2014; Ms. 857; AE: D.P. Jaisi*)