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Impact of temperature and freeze-thaw cycling on mechanical properties of polyurethane-modified ground rubber-sand mixture

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Abstract: The constraint of the soil surrounding the pile foundation is significantly larger after freezing seasonally in winter than summer, leading to possible brittle failure during winter earthquakes. Replacing the local soils around the piles at shallow depths with a material that is insensitive to ambient temperature variations and freeze-thaw cycling could be an effective way to improve the seismic performance of bridges in cold regions. This paper explores the feasibility of using polyurethane-modified ground rubber-sand mixture (termed as PloyGRuS) as an alternative local replacement material. The composition of the PloyGRuS material, specimen preparation method, and test plan are described. A series of triaxial tests on the PloyGRuS specimens subject to 0, 25 and 50 freeze-thaw cycles were performed at test temperatures ranging from 20°C to -15°C and confining pressures varying from 25 kPa to 100 kPa to obtain stress-strain curves. Preliminary results including stress-strain curves and Poisson's ratios at various testing conditions are presented. The impact of temperature, confining pressure, and freeze-thaw cycling on the stress-strain curves and Poisson's ratio were analyzed. The PolyGRuS material generally exhibits a strain-hardening behavior and its stiffness tends to increase with a decreasing temperature. However, the stiffness increase is much less than what would be experienced by soils during the same temperature drop. It was found that both the confining pressure and freeze-thaw cycling have little impact on the stress-strain behavior of the PolyGRuS. Poisson's ratio of the PolyGRuS material almost linearly increases from 0.5 at 5% axial strain to 0.6 at 20% axial strain and is generally insensitive to temperature, confining pressure, and freeze-thaw cycling. Preliminary results show that the PloyGRuS material promises to serve as a local replacement material for enhancing the seismic performance of pile foundations in the broad cold regions. Further study should focus on the material's cyclic behavior, damping characteristics, among others.

Key words: *Ground rubber; polyurethane-modified material; temperature; freeze-thaw cycling, Poisson's ratio, triaxial test*

1 Introduction

The stiffness and compressive strength of soil around the bridge foundations in seasonally frozen soils can experience annual changes of up to two orders of magnitude (e.g., Stevens, 1973; Zhu and David, 1984; Fei and Yang, 2019). The horizontal constraint of the soil surrounding the pile foundation after freezing is also significantly enhanced, leading to possible brittle failure during earthquakes, as evidenced by observed damage to bridge foundations during the 1964 Great Alaska Earthquake (Ross et al., 1973). Replacing the local soils around the piles at shallow depths with a material that has similar stiffness and strength of unfrozen soil and is not sensitive to ambient temperature and moisture variations and freeze-thaw cycling could be an effective way to improve the seismic performance of bridges in cold regions. An ideal replacement material would have the following qualities: 1) a density higher than that of water, 2) being elastic with a relatively small stiffness to afford ductility to the soil-bridge foundation system, and 3) durable during the harsh ambient temperature and freeze-thaw cycling in the broad cold regions.

There are over one billion scrap tires generated annually, worldwide. In 2017, the U.S. alone generated almost 250 million scrap tires, about 33% of which were recycled as ground rubber or being used in civil engineering applications (USTMA, 2018). For example, tire shreds have been used as permeable, light-weight backfill in slope stabilization, retaining wall construction, and other projects (e.g., Humphrey, 1996; Gacke et al, 1997; Tsang, 2008; Reddy and Krishna, 2015). Ground rubber is produced by grinding scrap tires into different sized particles with metal and fabric removed and has been used to produce rubber-modified asphalt pavement, resulting in quieter, more durable roads. Ground rubber has attractive engineering properties such as being light-weight, relatively low Young’s modulus and high damping. There is great potential to recycle ground rubber and find other innovative applications in civil engineering.

Many studies have been devoted to the physical and mechanical properties of ground rubber or tired shred derived materials and their application in caviling engineering. Lee et al. (1999) conducted a consolidation triaxial test on a rubber-sand mixture with a rubber mass fraction of 40% and found that its shear characteristics were between pure rubber particles and pure sand. Rao and Dutta (2006) performed compression and triaxial tests on a mixture of tire fragments and sand and found that the tire fragment can be used as a highway embankment filler when the mass fraction of the tire fragments is less than 20%. Li et al. (2013) found that the shear strength and internal friction angle of the tire chip-sand mixture increased with the increase of the tire chip content. Sellaf et al. (2014) performed a direct shear test on a rubber particle-soft soil mixture and found that its internal friction angle first increased and then decreased with the increase of the rubber particle content. Balunaini et al. (2014), through a large-scale shear test, reported that the internal friction angle of tire chip- and tire shred-sand mixtures is between 30°~33°, and found that the longer, the slender rubber particles are, the better the reinforcement effect on the sand. Lee et al. (2014) performed two-dimensional discrete element simulation on rubber sands of same particle size distributions with different volume ratios and found that the friction angle decreases with the increase of the rubber particle volume ratio. Signes et al. (2015) studied the mechanical properties of rubber particles to improve ballast. Perez et al. (2016) investigated the effect of rubber particle size on the macro-mechanical response of rubber-sand mixtures under small strains. Dong et al. (2016, 2017) studied the effect of tire particles on the shear strength of sea sand. Limited studies have described the use of tire shreds as thermal insulation to control frost penetration in cold regions (Yasuhara 2008).

Little studies have focused on the harsh cold regions environment on the engineering properties, such as thermal and mechanical properties, of scrap tire derived materials. This study aims to explore the feasibility of applying such materials for enhancing the seismic performance of bridge foundations in cold regions and present preliminary results on the impact of temperature and freeze-thaw cycling on the mechanical properties of such materials. The composition of the ground rubber-sand mixture, the modifier and specimen preparation method are presented first. Triaxial tests are carried out to obtain the stress-strain curves under various test parameters including confining pressure, test temperature, and the number of freeze-thaw cycles. The influences of confining pressure, test temperature, and freeze-thaw cycles on the mechanical properties are analyzed. Future studies are recommended in the end.

2 Experiment methods

2.1 Experiment materials and sample preparation

Fig. 1 presents the particle size distribution of the ground rubber and coarse quartz sands. The bulk density of ground rubble is 0.62 g/cm^3, and the density of rubber particles is 0.7 g/cm^3. The majority of the ground rubber falls between 1 mm and 5 mm. For the intended usage, it is preferred to use a temperature-insensitive binder to bond the ground rubber-sand mixture. For this purpose, a type of polyurethane adhesive was selected as the binder. For lack of standards, the specimens were prepared in batches according to the standard preparation method for remolded soil samples. Through trial and error, a certain ratio was selected to mix ground rubber, sand and polyurethane adhesive for acceptable consistency. The polyurethane-modified ground rubber-sand (termed as PolyGRuS hereafter) mixture was compacted in a three-lobed mold in three layers to achieve a controlled density of 1.3 g/cm^3. The prepared PolyGRuS specimens were cured in an environmental chamber with a temperature of 20°C and a humidity of 45% for 2½ days. Fig. 2 shows a ground rubber-sand mixture, a three-lobed test mold, and a cured PolyGRuS specimen. The finished specimens had a diameter of 101 mm and a height of 200 mm.

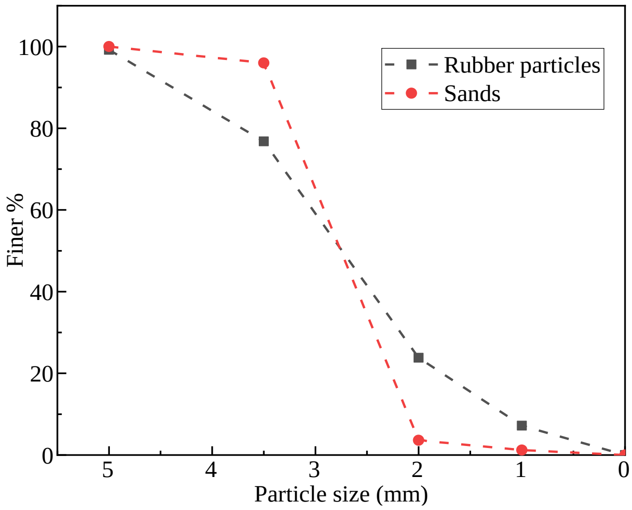

Fig.1 Gradation curves of ground rubber and coarse sand materials.

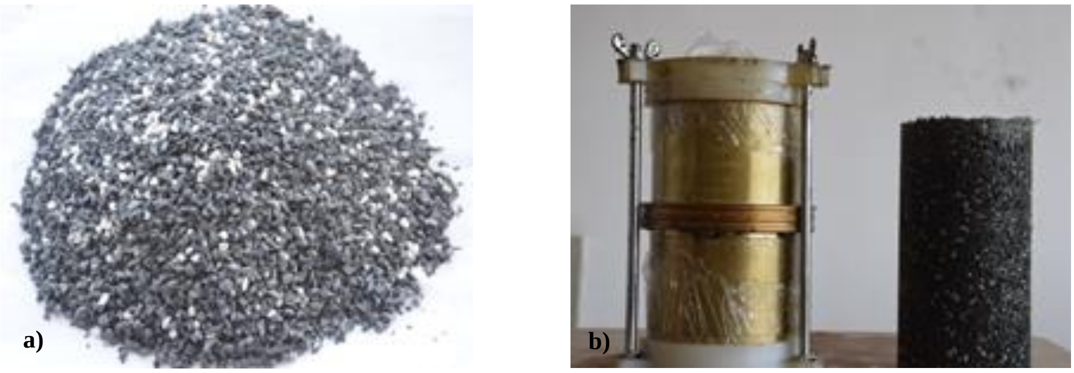

Fig. 2 Preparation of test specimens: a) the mixture of ground rubber and sands and b) a specimen after remolded and curing.

Freeze-thaw cycling was conducted as follows: 1) freeze the specimens from 20°C to -20°C. Experiments show it took about 3.5 hours for the center of specimens to reach -20°C. And keep specimens at -20°C for 5h to allow thermal equilibrium. This is the freezing process; 2) remove the specimens from the environmental chamber and store them in an environmental chamber at 20°C. It took about the same time, i.e. 3.5 hours, for the entire specimens to reach 20°C, and then keep them at 20°C for 5 hours to allow thermal equilibrium. This is the thawing process. It took a total of 17 hours to complete one cycle of freeze-thaw. Fig. 3 depicts the relationship between the temperatures at the specimen center vs. time (hours) during the freeze-thaw cycling.

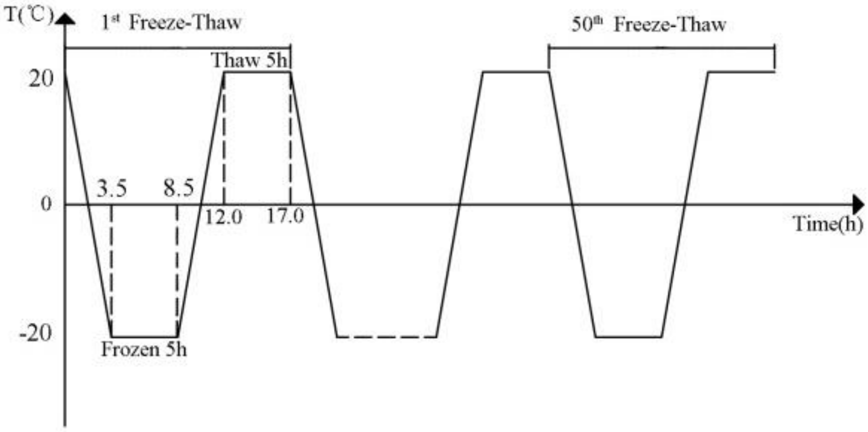

Fig. 3 Diagram of freeze-thaw cycling.

2.2 Test equipment

Fig. 4 illustrates a triaxial test apparatus used in this study. It consists of a loading unit, a data acquisition unit, and a temperature control unit. The maximum applied confining pressure is 70 MPa with an accuracy of 0.01 kPa. Specimen deformation is measured by linear variable differential transformers (LVDT) with a range of ±100mm and an accuracy of 0.1 μm. The temperature control range is -40 °C ~ 65 °C with an accuracy of ±0.01 °C.

Fig. 4 An environmental triaxial apparatus manufactured by GDS.

2.3 Test plan

Specimens were subjected to 0, 25, or 50 freeze-thaw cycles and tested under temperatures including 20°C, -5°C, -10°C, and -15°C at three confining pressures, including 25 kPa, 50 kPa, and 100 kPa. The specimens were almost impermeable. For intended use at very shallow depth and the short duration of earthquake loading, unconsolidated undrained tests were performed. All tests were conducted at a preload of 0.02 kN and a loading rate of 1mm/min under strain-control. The loading was terminated automatically when the axial strain reached 20%. Table 1 summarizes the test conditions.

Table 1 Testing conditions.

Serial number	Temperature T (°C)	Freeze-thaw cycle times N	Confining pressure σ_3 (kPa)
A	20	0, 25, 50	25, 50, 100
B	-5	0, 25, 50	25, 50, 100
C	-10	0, 25, 50	25, 50, 100
D	-15	0, 25, 50	25, 50, 100

3 Test results and analyses

3.1 Stress-strain curves

3.1.1 Influence of temperature

Temperature impact on the stress-strain behavior is of primary concern. Fig. 5a, b, and c compare the stress-strain curves under a confining pressure (σ_3) of 25kPa and various temperatures (T) for PolyGRuS specimens subjected to freeze-thaw cycles N = 0, 25 and 50, respectively.

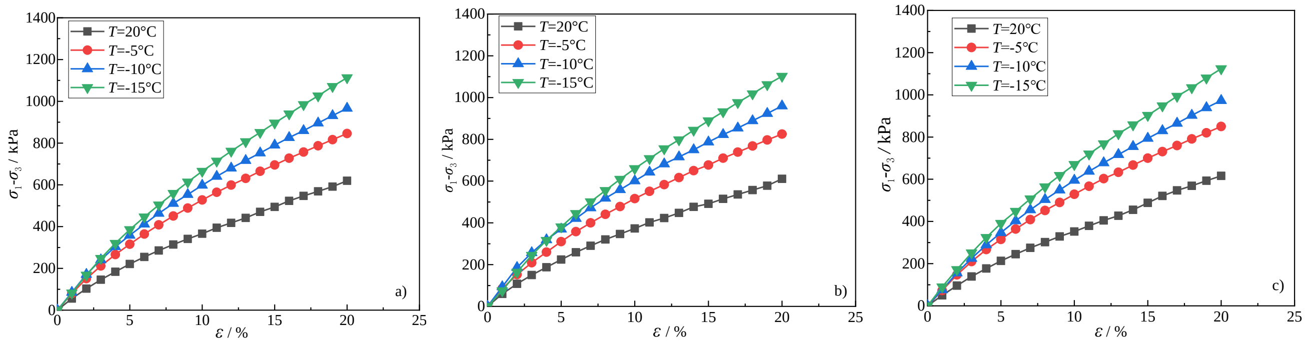

Fig. 5 Temperature impact on stress-strain curves: a) $N = 0$, b) $N = 25$, and c) $N = 50$.

It is seen from Fig. 5 that the PolyGRuS specimens generally exhibit a strain-hardening behavior. No stress peaks were observed on the stress-strain curves when the axial strain reached 20%. The stiffness of the material increases with decreasing temperature. The deviator stress (σ_1-σ_3) at 20% axial strain increases from 610 kPa to 850 kPa, or by 40%, when the temperature dropped from 20°C to -5°C. When the temperature further decreased from -5°C and -15°C, the stress increased from 850 kPa to 1130 kPa, or by 33%. The stress at 20% axial strain increased by a total of 73% when T dropped from 20°C to -20°C, which is much less than what would be experienced by soils during the same temperature drop (often in one or two orders of magnitude). Therefore, the influence of temperature on the PolyGRuS is relatively small.

3.1.2 Influence of confining pressure

Fig. 6 shows the stress-strain curves of the PolyGRuS specimens subjected to 50 freeze-thaw cycles under various confining pressures and temperature of 20°C, -5°C, -10°C and -15°C.

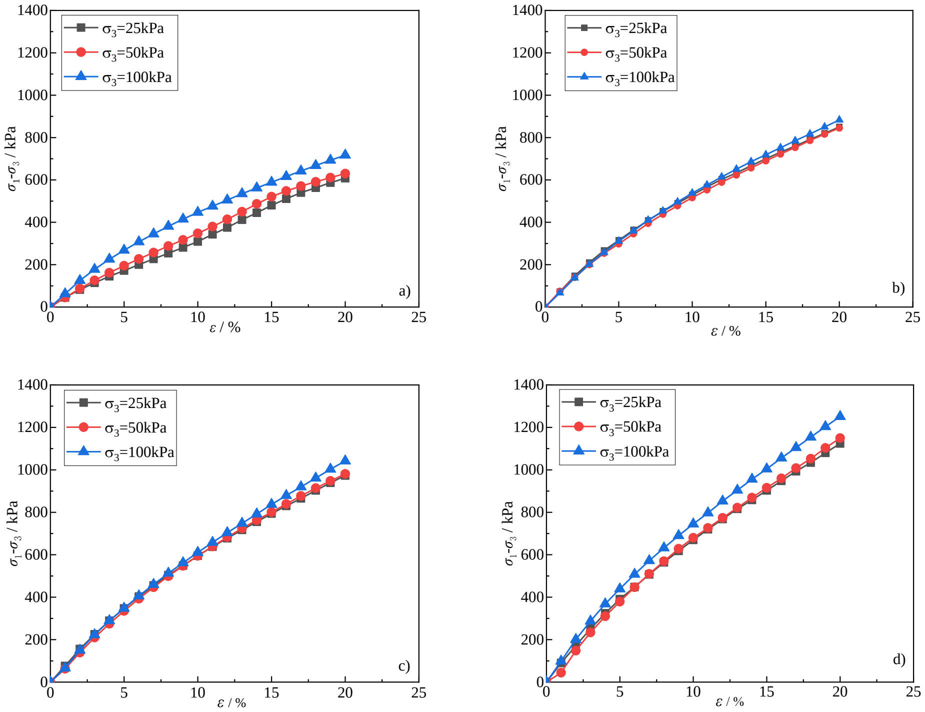

Fig.6 Confining pressure impact on stress-strain curves: a) T = 20 °C, b) T = -5 °C, c) T = -10 °C, and d) T = -15 °C.

It can be seen from Fig. 6 that, at the same temperature, the deviator stress slightly increases when the confining pressure σ_3 increases from 25 kPa to 50 kPa, and further to 100 kPa. For example, as shown in Fig. 6a, the deviator stresses corresponding to the confining pressure σ_3 of 25 kPa, 50 kPa and 100 kPa are 600 kPa, 610 kPa, and 710 kPa, respectively, or an increase less than 20%. In general, the effect of the confining pressure σ_3 on the failure strength is relatively small. A Mohr-circle analysis found that the friction angle was almost zero. This is because the ground rubber-sand mixture is mostly saturated with polyurethane adhesive, lending no effective contacts between soil particles.

3.1.3 Influence of freeze-thaw cycling

Existing studies show that the freeze-thaw cycles often induced significant impact on the material stiffness and strength in cold regions (e.g., Chen, 2006; Orakoglu and Liu, 2017; Cao, 2017; Wen et al., 2017; Ding et al., 2018; Yang and Wang, 2019). Fig. 7a, b, c, and d compare the stress-strain curves of the PolyGRuS specimens subjected to various freeze-thaw cycles under a confining pressure of 50 kPa and temperatures of 20°C, -5°C, -10°C, -15°C, respectively.

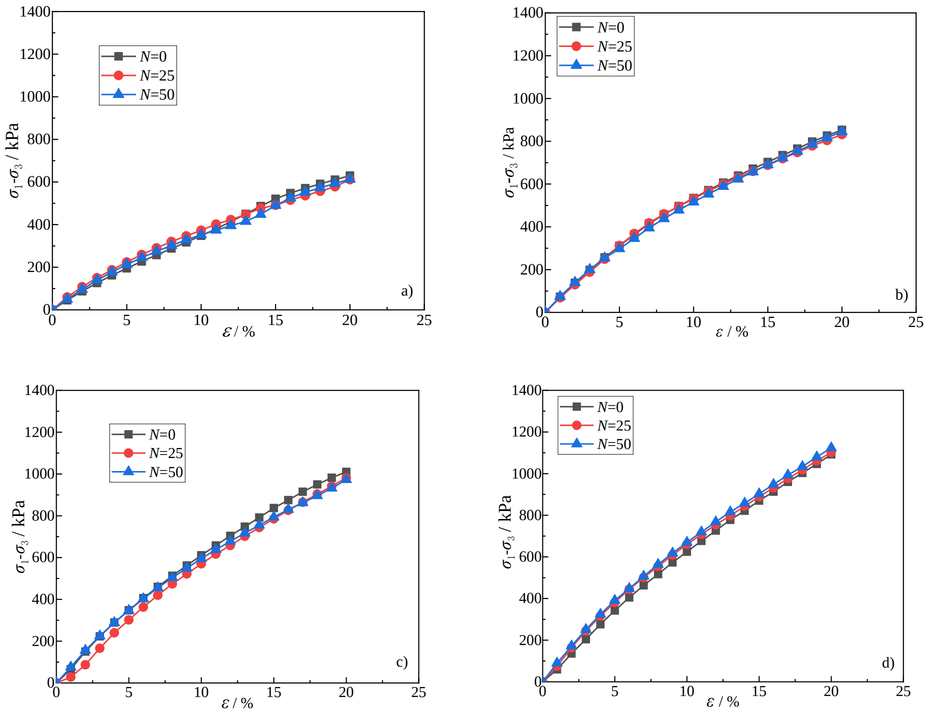

Fig. 7 Influence of freeze-thaw cycling on stress-strain curves at: a) T = 20 °C, b) T = -5 °C, c) T = -10 °C, d) T = -15°C.

One can see from Fig. 7 that the stress-strain curves of the PolyGRuS specimens subjected to 25 and 50 freeze-thaw cycles almost overlap with the ones without freeze-thaw cycling at the same test temperature. For example, as shown in Fig. 7a, the stresses at 20°C for specimens subjected to 0, 25, and 50 freeze-thaw cycles at 20% axial strain are 630 kPa, 616 kPa, and 610 kPa, respectively, or about 3% of change. The maximum change on the deviator stress at 20% axial strain was within 5.0% for all tested temperatures. It is reasonable to conclude that the PolyGRuS material has excellent anti-freeze-thaw characteristics.

3.2 Poisson's ratio

Within the proportion limit of the material, the ratio of the transverse strain caused by a uniformly distributed longitudinal stress to the corresponding axial strain is called Poisson's ratio (v):

$$v = \frac{-\varepsilon_3}{\varepsilon_1} \tag{1}$$

where ε_1 is the axial strain and ε_3 is the lateral strain. Poisson’s ratios were evaluated for all test specimens and Fig. 8a, b, and c compare the relationship between v and ε_1 under various temperatures, confining pressures, and freeze-thaw cycles, respectively.

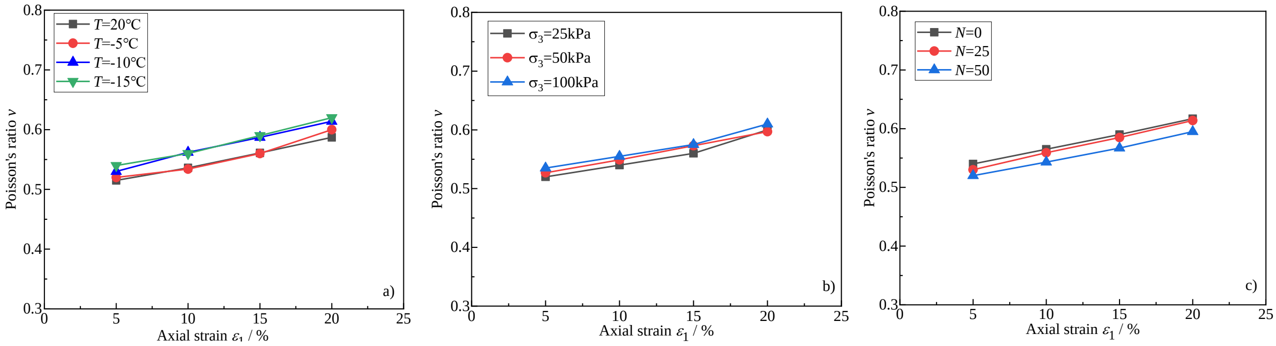

Fig.8 Variation of Poisson's ratio with axial strain: a) N = 25, σ_3 = 25 kPa, b) T = -5°C, N = 25, c) T = -10°C, σ_3 = 25 kPa.

One can see from Fig. 8 that Poisson's ratio almost linearly increases with the increase of the axial strain ε_1 with the values at ε_1=5% slightly greater than 0.5 and increasing to 0.6 at ε_1=20%. The fact that Poisson’s ratio is greater than 0.5 may be due to the inclusion of ground rubber and, more importantly, the polyurethane binder. Literature reported that polyurethane foam can have a Poisson’s ratio greater than 1 (Lee and Lakes, 1997). Fig. 8a shows that Poisson's ratio tends to increases with decreasing temperatures. Poisson's ratios at ε_1=20% and test temperatures of 20°C and -15°C are 0.59 and 0.62, respectively, or 5% increase. Fig. 8b shows confining pressure has little, if any, impact on Poisson's ratio. Fig. 8c shows Poisson's ratios ε_1=20% under T = -10°C and σ_3 = 25 kPa for specimens subjected to freeze-thaw cycles of 0, 25 and 50 are 0.62, 0.61, and 0.60, respectively. Generally, temperature, confining pressure and freeze-thaw cycling have little effect on Poisson's ratio of the PolyGRuS material.

3.3 Observation of tested specimens

The PolyGRuS material appears to be very consistent, even after subject to up to 50 freeze-thaw cycles and 20% axial strain temperatures as low as -15°C. Fig. 9 shows a PolyGRuS specimen subjected to 50 freeze-thaw cycles before and after triaxial loading under a temperature of -15°C and confining pressure of 50 kPa. As shown in Fig. 9, the surface of the specimen before loading was smooth without cracks, and it remained so after loading to 20% axial strain; no particles fell off, or apparent cracks could be observed. The diameter and height remained almost the same (D_1 = 100.98 mm, D_2 = 100.94 mm, H_1 = 200.01 mm, and H_2 = 199.97 mm).

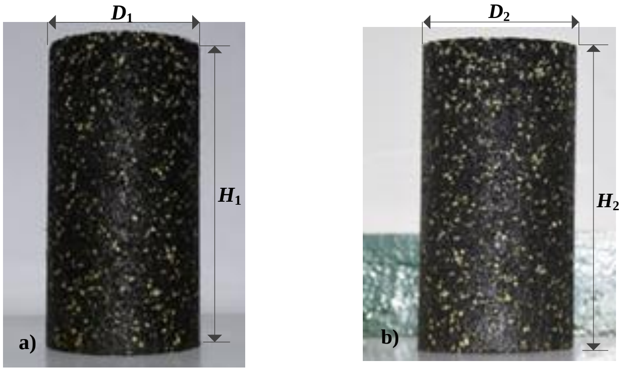

Fig. 9 Comparison of a specimen of before (a) and after (b) loading.

4 Conclusions

This study explores the feasibility of polyurethane-modified ground rubber-sand mixture (PolyGRuS) for use as a local replacement material for enhancing the seismic performance of pile foundations in the broad cold regions. A mix ratio was determined through trial-and-error. A series of triaxial shear tests were performed on PolyGRuS specimens subject to varying number of freeze-thaw cycling under different temperatures, confining pressures. Preliminary results including stress-strain curves and Poisson's ration were presented. The impact of temperature, confining pressure, and freeze-thaw cycling on the stress-strain curves and Poisson's ratio were analyzed. The following conclusions can be drawn：

(1) The PolyGRuS material generally exhibits a strain-hardening behavior and its stiffness tends to increase with decreasing temperature. The stress at 20% axial strain increases by 73% when the test temperature decreases from 20°C to -15°C, which is much less than what would be experienced by soils during the same temperature drop.

(2) The influence of both confining pressure and freeze-thaw cycles on the stress-strain behavior of the PolyGRuS is small and can be neglected for a practical purpose.

(3) Poisson's ratio of the PolyGRuS almost linearly increases from 0.5 at 5% axial strain to 0.6 at 20% axial strain. Temperature, confining pressure, and freeze-thaw cycling have little effect on Poisson's ratio.

These preliminary results show that the polyurethane-modified ground rubber-sand mixture promises to serve as a local replacement material for enhancing the seismic performance of pile foundations in the broad cold regions. Further study should focus on the material's cyclic behavior, damping characteristics, thermal properties, among others.

Acknowledgments

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