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Effect of Sample Preparation on the Strength of Artificially Frozen Sand

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RÉSUMÉ

Cet article compare la méthode du compactage mouillé à la tige et celle de l'écoulement sur plusieurs tamis, qui sont utilisées pour contrôler la masse spécifique du sable lors de la préparation d'échantillons de sable gelé en vue d'en tester la résistance. La méthode de l'écoulement sur plusieurs tamis permet d'obtenir des échantillons homogènes et reproduisibles pour diverses masses spécifiques à sec. Les essais de compression sans étreinte latérale donnent des valeurs de résistance constantes pour les échantillons préparés par écoulement sur plusieurs tamis, mais des écarts importants pour les échantillons compactés à la tige. Pour les conditions d'essais décrites dans cet article, le comportement des échantillons de sable gelé au plan contrainte-déformation dépendait de la masse spécifique à sec initiale; pour les faibles masses spécifiques, on a observé une résistance dégressive à la déformation et des contraintes de pointe constantes. [illegible], les échantillons [illegible] la déformation [illegible] ment avec la mas [illegible]

Effect of sample preparation on the strength of artificially frozen sand

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ABSTRACT
Wet rodding and multiple-sieve pluviation methods of controlling sand density in the preparation of frozen sand specimens for strength testing are compared. Multiple-sieve pluviation provides homogeneous, reproducible specimens at various dry densities. Unconfined compression tests indicate consistent strength data for specimens prepared by multiple-sieve pluviation, but significant scatter for compacted samples prepared by the wet rodding method. For the testing conditions reported in this paper the stress-strain behaviour of frozen sand specimens was dependent on initial dry density; at low densities, strain softening with constant peak stress was observed. For higher densities, the samples exhibited strain hardening behaviour, peak stress increasing linearly with density.

INTRODUCTION

Information regarding strength and deformation behaviour of frozen soils is required in designing artificially frozen ground structures or assessing their ability to support imposed loads without excessive deformation. The usual practice is to prepare frozen soil specimens and test them in the laboratory to determine their strength and deformation characteristics. So many testing procedures and techniques have been used, however, that there is need for standardization. The International Working Group (IWG) on Testing Methods for Frozen Soils has recently proposed guidelines for the classification and laboratory testing of artificially frozen ground (Baker et al., in press). Applied strain rate, loading conditions for creep tests, test temperatures, specimen end conditions, and test system stiffness were all given considerable attention. Recommendations with respect to specimen preparation, however, relate only to shape and size; density distribution within the sample, i.e., specimen homogeneity, was largely ignored.

For cohesionless soils, the wet rodding (WR) method of compaction has been used for many years, but it is evident that human performance and procedure differences during compaction affect specimen homogeneity and reproducibility. Recently dry pluviation of sand (with multiple-sieve pluviation apparatus) has been used to overcome such problems. The present paper describes the effects of the two methods of sample preparation on the strength properties of artificially frozen Ottawa sand.

TESTING PROCEDURES

Samples of a silica sand (specifications and some properties are listed in Table 1) were moulded by means of the wet rodding and multiple-sieve pluviation methods. A split sample mould was used to produce a sample 76 mm in diameter and 250 mm in height.

Wet Rodding Method

Wet rodding (WR) involves uniform mixing of water with sand to achieve the desired water content. A known weight of sand-water mixture is placed in a sample mould and a rod is used to tamp each layer to the thickness required for the specified density. This method of compaction

TABLE 1 Sand Specification Standard Graded Sand (ASTM Designation C778-80) previously called Ottawa Fine Sand (ASTM Designation C-109):

Sieve Size	GRADING Accumulated % Retained
No. 16 (1.18 μm)	0
No. 30 (600 μm)	2 ± 2
No. 40 (425 μm)	30 ± 5
No. 50 (300 μm)	75 ± 5
No. 100 (150 μm)	98 ± 2

MEASURED PROPERTIES
Uniformity coefficient (D_{60}/D_{10}) = 2
Specific gravity = 2.67
Maximum index density = 1763 kg/m^3
Minimum index density = 1474 kg/m^3
Average grain size = 400 μm

was used to produce 165 samples at an optimum water content of 14% by dry weight and a dry density of 1700 kg/m^3 (optimum conditions were determined by a standard Proctor compaction test). After compaction in the mould, the top cap was assembled and each sample was vacuum saturated with de-aired, distilled water. At a dry density of 1700 kg/m^3 the total water content at 100% saturation would be about 21% by dry weight.

Multiple-Sieve Pluviation Method

Multiple-sieve pluviation (MSP) is a dry-raining technique used to control the placement density of dry sand (Miura and Toki 1982). The technique involves controlling the rate of sand flowing through a hopper (funnel) by changing the opening diameter. The sand is then passed through a series of sieves for dispersal in a uniform "rain" before it enters the sample mould. By maintaining uninterrupted flow it is possible to deposit sand in the mould at a relatively uniform density. Inserts placed in the funnel opening are used to change the flow rate for samples of different density (Figure 1).

For the fine sand used in this study, funnel openings ranging from 8 to 32 mm in diameter were used to place sand in the moulds at dry densities ranging from 1774 to 1543 kg/m^3. Figure 2 shows the variation in dry density with funnel opening size.

After the sand was placed in the mould, the top cap was assembled and de-aired distilled water was percolated slowly up from the bottom to saturate it. A valve was used to control the flow rate. Low-density samples were most susceptible to changes in void ratio during saturation and transport of the mould, especially in the lower part of the sample.

Uniaxial Freezing

All samples were frozen in the same manner. The top cap of the mould was removed for the freezing process and a heated tube was attached to the valve at the bottom. This tube allowed water to be expelled from the sample during uniaxial freezing. The water level in the tube was maintained at the level of the top of the

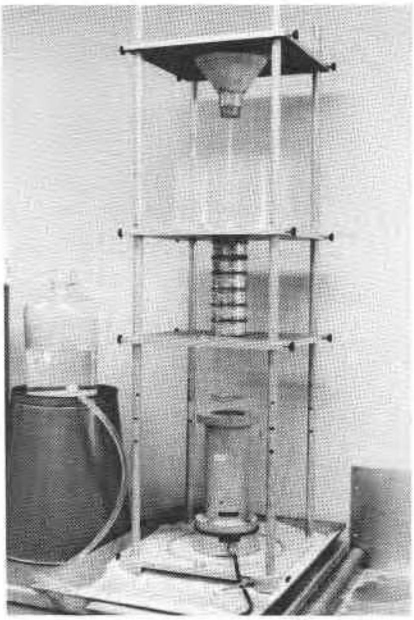

Fig. 1 Multiple-sieve pluviation equipment

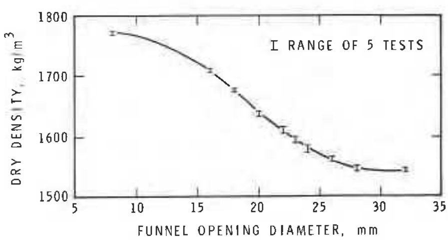

Fig. 2 Control of dry density of sand, MSP method

mould to prevent drainage prior to and during freezing. The mould and attached capillary tube were placed in a cold room in a box of vermiculite to ensure uniaxial freezing of the sand sample.

Samples prepared by the wet rodding method were frozen at -6°C; those prepared by the multiple-sieve pluviation method were frozen at -10°C. These temperatures were dictated by other use of cold room facilities. All samples were completely frozen after 48 h, when they were taken from the mould.

Machining

A band saw and lathe located in the cold room were used to machine the frozen soil samples. Each was cut to a length of about 155 mm, then squared and faced with the lathe to a final test specimen length of 150 mm. Details of the machining process and test specimen storage have been described (Baker 1976a). Final specimen dimensions and weight were recorded for use in determining bulk density.

Strength Tests

Specimens were tested in unconfined compression using both a screw-driven testing machine (Instron Model 1127, 250-kN capacity frame) and a closed-loop servo-hydraulic testing machine (MTS Model 810.15, 1.0-MN capacity frame and 250-kN capacity actuator). Details of testing conditions are presented in Table 2. Displacement transducers were mounted on the test specimens. Displacement measurements from tests performed with the screw-driven testing machine indicated that the strain rate of the specimen increased during the test until it reached the set rate. A control displacement transducer was used to provide a constant strain rate during tests performed on the closed-loop servo-hydraulic testing machine. Other testing procedures followed the guidelines proposed by the International Working Group on Testing Methods for Frozen Soils (Baker et al. in press). After the strength tests were completed, all the specimens were oven dried to determine total water content. Measurements of bulk density and total water content were used in calculating the average dry density of the test specimen.

TABLE 2 Unconfined Compressive Strength Tests

Compaction Method	No. of Spec.	Testing Machine	Strain Rate s^{-1}	Temp. °C
WR	19	Screw-driven	1.17×10^{-5}	- 6
MSP	8	Screw-driven	1.67×10^{-4}	-10
MSP	9	Closed-loop	1.67×10^{-4}	-10

TEST RESULTS

The average dry density, ρ_d, and average water content, WC, for frozen sand specimens prepared by both WR and MSP methods are shown on Figure 3. A linear relation between ρ_d and WC was established for the MSP samples, corresponding to the 87% saturation curve for Ottawa sand. The actual degree of saturation of the MSP samples varied between 82 and 93% (average 87%). Density and water content data for specimens prepared by the WR method exhibited a trend similar to that for MSP data, with an average value corresponding (approximately) to the 87% saturation curve. There was, however, significant scatter, which may be attributed to changes in physical properties of individual compacted soil layers induced by variations in water content and compactive effort.

In order to investigate the inherent homogeneity of samples obtained by both methods the variation in dry density and moisture content with depth was investigated. Specimens prepared by the WR method are characterized by large variations in water content in adjacent sections (Figure 4). A variation of 2% was common and corresponds to one of about 50 kg/m^3 in dry density of individual layers. It must be stressed that the primary intent of the WR method is to produce frozen specimens at a given dry density and water content, i.e., 1700 kg/m^3 and 21%. The dry density varied between 1550 and 1750 kg/m^3, with a concomitant water content variation

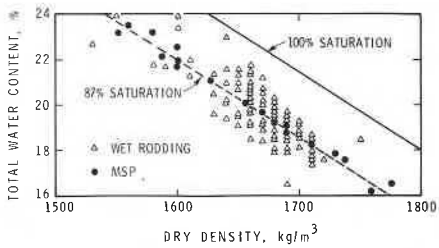

Fig. 3 Dry density and total water content of specimens prepared by WR and MSP methods

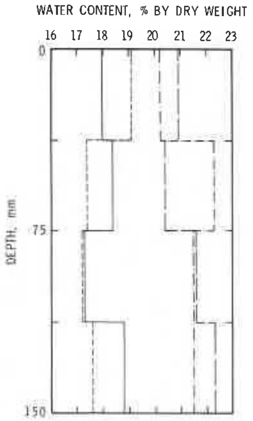

Fig. 4 Typical water content distribution in WR specimens

between 24 and 16%. Most of the data, however, were within ± 50 kg/m^3 of the desired ρ_d and ± 2% of the desired moisture content.

The sand samples obtained by the MSP method showed very little variation in ρ_d and WC with depth (Figure 5). The maximum difference in water content of adjacent sections was approximately 0.3%. For loose sand specimens the dry density distribution in the upper four fifths of the sample was relatively constant, with maximum variation of about 8 kg/m^3 between sections. The bottom part of some specimens showed a slightly higher

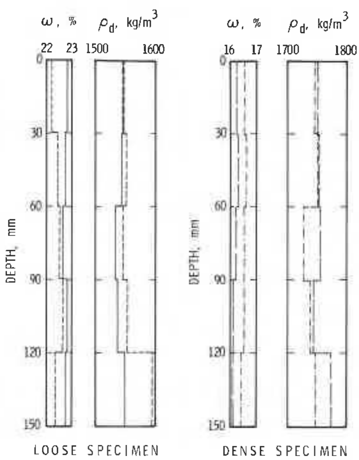

Fig. 5 Typical water content and dry density distribution in MSP specimens

density, probably due to settlement during wetting and handling prior to freezing. For denser sand samples slightly higher variations in ρ_d of successive layers were observed. The average maximum variation within the upper four fifths of the samples was in the order of 15 kg/m^3 and varied between 10 and 30 kg/m^3.

Figures 6 and 7 show typical stress-strain-time curves for loose and dense specimens prepared using the MSP method. Differences in the curves, up to the yield point, are related to strain rate. The servo-hydraulic testing machine maintained a constant strain rate throughout the test; that realized using the screw-driven testing machine gradually increased from a low value to the nominal rate. As the strength of frozen soil is strain rate dependent, yield stress and peak stress determined by each testing machine would be expected to be different. Nevertheless, similar stress-strain behaviour was observed for the uniaxial, unconfined compression tests.

Figure 8 presents the generalized stress-strain behaviour of frozen Ottawa sand as a function of density. For tests at -10°C and low density, i.e., ρ_d = 1550 kg/m^3, the specimens exhibit strain softening, with peak stress and initial yield stress coinciding at a small axial strain of about 0.4%. As density increases slightly, i.e., ρ_d = 1630 kg/m^3, the yield stress and peak stress still coincide, occurring at small axial strain of 0.4%, but there is no strain softening behaviour. Further increase in density results in stress-strain curves characterized by distinct yield and subsequent peak stress. The yield point continues to remain at the same level of stress and axial strain, but peak stress occurs at a higher strain. At higher densities there is a substantial difference between yield and the peak stress, both increasing with increasing density. Peak stresses at high axial strain levels in frozen sand were reported by Goughnour and Andersland (1968) and Baker (1976b). The latter found that peak stress is reached at axial strain of up to 16%.

Several mechanisms for this behaviour have been postulated by Ladanyi (1981), Sayles and Carbee (1981) and Ting et al. (1983). Briefly, it has been proposed that the behaviour at yield is related to the ice matrix and that behaviour beyond yield is related to both the ice and the sand particle structure. Interparticle friction and other dilatancy effects beyond yield would be mainly a function of initial sand density, as shown in Figure 8.

Figure 9 presents strength results, i.e. peak stress, for the WR specimens tested under the conditions reported in Table 2. All 19 samples were characterized by a stress-strain curve with peak stress significantly larger than

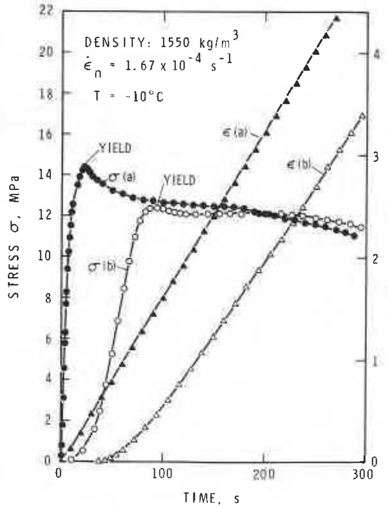

Fig. 6 Stress-strain-time relations for loose specimens tested in (a) servo-hydraulic closed-loop test machine, and (b) screw-driven test machine

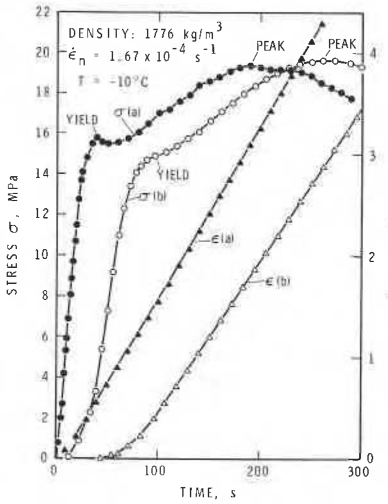

Fig. 7 Stress-strain-time relations for dense specimen tested in (a) servo-hydraulic closed-loop test machine, and (b) screw-driven test machine

yield stress, although the density of the samples varied between 1600 and 1730 kg/m^3. The yield stress was relatively constant over this range in density, but the peak stress exhibited a general increase with increasing dry density of the sample. The significant scatter in the data is thought to be due to significant variations in water content and dry density within and between test specimens (as mentioned earlier).

Figure 10 presents strength results, i.e. peak stress, for MSP samples tested

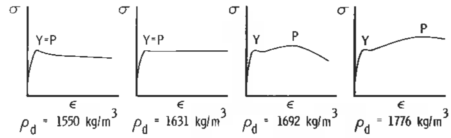

Fig. 8 Typical stress (σ)-strain (ε) curves obtained for the range of dry density (ρ_d) achieved with MSP method. Y = yield point, P = peak stress

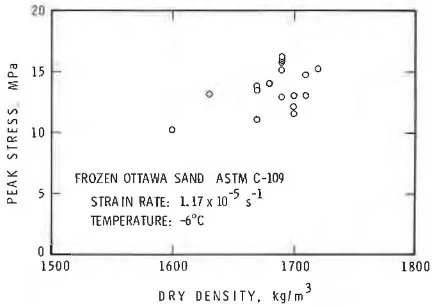

Fig. 9 Strength results for WR specimens

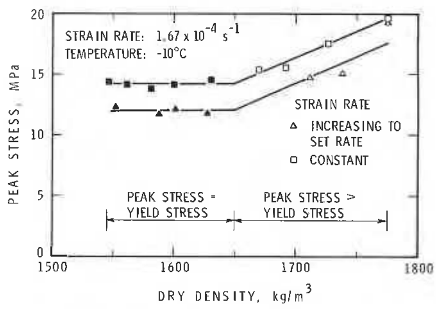

Fig. 10 Strength results for MSP specimens

under the conditions given in Table 2. Owing to better uniformity within samples the scatter is significantly reduced for both types of testing machine. The upper curve corresponds to constant strain rate tests at 1.67×10^{-4} s^{-1}, whereas the lower relation was obtained for conditions where strain rate increased gradually from almost zero to 1.67×10^{-4} s^{-1} at 0.4% strain and then remained constant. The average strain rate during the initial stage, i.e., up to about 0.4% axial strain, was about 0.6×10^{-4} s^{-1}. Solid symbols indicate cases where yield stress and peak stress coincide, and open symbols indicate cases where peak stress is larger than yield stress. The observed yield stress equals peak stress at densities below 1650 kg/m^3. Furthermore, peak stress remained constant at densities from 1550 to 1630 kg/m^3. For densities between 1670 and 1770 kg/m^3 the peak stress was greater than yield stress and increased linearly from 14.2 to 19.5 MPa in the constant strain rate tests.

CONCLUSION

The effect of preparation procedure on the strength of artificially frozen samples of Ottawa sand has been assessed for the wet rodding (WR) and multiple sieve pluviation (MSP) methods. Good reproducibility of dry density can be obtained by means of the MSP method, which gave a relatively homogenous density distribution in the upper four fifths of the sample. The same quality of sample, especially in terms of density distribution within samples, could not be achieved with the WR method. Measurements showed that good control of ρ_d and WC is of paramount importance in obtaining reproducible strength data. Unconfined compression tests indicate that the sand specimens were work softened at low densities and underwent work hardening at higher densities. For a testing temperature of −10°C and a strain rate of 1.67×10^{-4} s^{-1}, the density at transition between strain softening and strain hardening behaviour was about 1650 kg/m^3. At higher densities beyond this transition, the peak stress increased linearly with increasing dry density.

It is recommended that the International Working Group on Testing Methods for Frozen Soils consider the method of sample preparation as an important item in the current guidelines, especially with respect to sample homogeneity.

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