WAVE VELOCITY AND STRENGTH MEASUREMENTS IN CEMENTED SANDS

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ABSTRACT
The change in wave velocity (low–strain property) and unconfined compressive strength (large-strain property) with the change in cement content, initial water content, void ratio, and curing time for a cemented sand is examined in this paper. The measured pulse velocity is compared with predictions made using empirical and analytical models, which are mostly based on resonant column tests. The wave velocity reaches a maximum at optimum water content, and it is mostly affected by the number of cemented contacts; whereas compressive strength is governed not only by the number of contacts but also by the strength of contacts. Experimental relationships are developed for compressional wave velocity and unconfined compressive strength as functions of cement content and void ratio. Available empirical models under-predict the wave velocity (60% on average). Wave velocity is found to be a good indicator of cement content and unconfined compressive strength for the conditions of this study.

Résumé
Cette épreuve va examiner l'effet de variation du contenu de ciment, contenu initial d'eau, du rapport vide, et du temps requis pour sécher pour la vélocité des ondes (qualité de basse tension) et la force compressive non limitée (qualité de haute tension) sur du sable cimentée. La vélocité d'impulsion mesurée est comparée aux prédictions faites en utilisant les modèles empiriques et analytiques, qui sont la plupart du temps basés sur les résultats publiés des essais résonnants de colonne. La vélocité d'ondes atteint un maximum à un point optimal du contenu d'eau et il est affecté par le nombre de contacts cimentés; considérant que la résistance à la pression est régie non seulement par le nombre de contacts mais également par la force des contacts. Des rapports expérimentaux sont développés pour la vélocité d'ondes de compression et la résistance non limitée à la pression comme des fonctions de contenu de ciment et de rapport vide. Les modèles empiriques disponibles sous prévoient la vélocité d'ondes (60% en moyenne). La vélocité d'ondes est un bon indicateur de contenu de ciment et la résistance non limité à la pression pour les conditions de cette étude.

1. INTRODUCTION

Pulse-velocity test is the most commonly used method for assessing quality of concrete, and for relating wave velocity with strength (Popovics et al. 1990, Popovics and Popovics 1992, Popovics and Rose 1994, Majid et al. 2004). In this method, pulses emitted by a transmitter travel through the material and are detected by a receiver, placed on opposite faces of the test object. The travel time of the first arriving pulse is precisely measured with electronic equipment. Wave velocity is simply computed as distance over time.

The resonant column device has been used extensively to determine the dynamic properties of cemented sands (Chiang and Chae 1972; Acar and El-Tahir 1986; Saxena et. al 1988; Chang and Woods 1992; Baig et. al 1997; Fernandez and Santamarina 2001). Mathematical models have also been developed to predict the wave velocity in cemented sands (Chang et. al, 1990; Fernandez and Santamarina 2001). However, there is a significant variability in the predicted wave velocities depending on the model used. Most of these studies are based on resonant column results; and they focus on the simultaneous evaluation of the effects of confinement and cementation on wave velocity. Confinement has been proven to induce micro-fractures on cemented contacts, which decreases the stiffness and strength of cemented sands (Saxena and Lastrico 1978, Saxena et al. 1988, Asghari et al. 2003). Thus, the effect of cementation on wave velocity decreases as confining pressure increases. This study uses the pulse-velocity method to evaluate the effects of cementation on wave velocity and unconfined compressive strength without a simultaneous variation of confinement.

A total of 156 specimens with different cement and water contents are tested under atmospheric pressure. The specimens are prepared using gypsum cement. The effects of cement content, initial water content, void ratio, cement type, and curing time on wave velocity are studied. The measured wave velocities are compared with the predictions of mathematical and empirical models available in the literature. The relationship between compressional wave velocity and compressive strength is also studied.

Several researchers have studied the low-strain properties of cemented sands (elastic moduli and attenuation), mostly with the resonant column device (Chiang and Chae 1972; Acar and El-Tahir 1986; Saxena et. al 1988; Chang et. al, 1990; Chang and Woods 1992; Fernandez and Santamarina 2001). These studies show that wave velocity of cemented sands is mainly affected by cement content, confining pressure, and void ratio.

For the analysis of wave velocity, it is important to compute the void ratios of the sand matrix (e) and the cemented sand after curing (em). The void ratios e and em are related to the initial mass density of the sand-cement-water mixture (ρI), the mass density of the cemented sand after curing (ρc), and degree of cement saturation (Sc) by the following equations (derived from the phase relationships):

$$\rho_I = \frac{(1+\omega_I)(1+cc)}{(1+e)} G_s \rho_w \quad [1]$$

$$\rho_c = \frac{\left[1 + cc\,(1+\omega_o)\right]\rho_{co}}{(1+e_m)\left[\frac{\rho_{co}}{\rho_{sp}} + cc\,(1+\omega_o)\right]} \quad [2]$$

$$S_c = \frac{cc\ \rho_{sp}\,(1+\omega_o)}{e\,\rho_{co}} \quad [3]$$

$$e = \frac{e_m}{\left[1 - S_c(e_m+1)\right]} \quad [4]$$

where ω_I is the initial water content of the sand-cement mix (cement not cured), ωo is the water content of cured cement (hydration water), and ρw is the mass density of water.

3. EXPERIMENTAL SETUP

The instrumentation used for pulse-velocity measurements is shown in Fig. 1; it consists of a pulse generator (Datel PC-420, 1 kHz up to 10 MHz), two piezoelectric transducers (Physical Acoustics R6I), digital oscilloscope (HP54600A), and a data acquisition system (National instruments, PCI-6110E) interfaced with a desktop computer.
Wave velocity is computed using the travel time of an amplitude-modulated sinusoidal pulse and the distance between transducers (travel time method, ASTM C597). A frequency of 80 kHz is used to ensure at least two wavelengths of separation between transducers, to avoid near field effects (Sanchez-Salinero et al. 1986, Arroyo et al. 2003). For calibration of the system, the travel time in an aluminium cylinder (5×16 cm) is measured. The typical variation of wave velocity of the dry sand with confinement is measured using the resonant column device to assess the relative effect of cementation on low-strain stiffness.
Two groups of samples are prepared, creating 153 specimens in total: 144 specimens (5×5×5cm) prepared with SR-cement and tested under atmospheric pressure to evaluate the effects of cement content, void ratio, and initial water content on wave velocity and compressive strength (Group A); and nine specimens (5×5×5cm) prepared with POP-cement to study the effect of cementing agent on wave velocity and compressive strength (Group B).

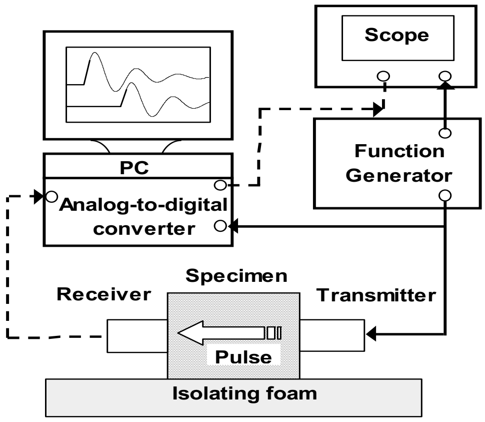

Figure 1: Equipment setup

The mass density and void ratio of the specimens depend on the initial water content. For each cement content, specimens are prepared with different water contents (2.5% to 25%) to obtain the optimum moisture content. Wave velocity is measured daily during curing for 28 days (672 hours). The effect of the type of cementing agent is studied in Group B: nine samples prepared with 10% POP-cement and different water contents (7, 10 and 14%).
To estimate the water content required for complete hydration of the cement, three SR-cement specimens are prepared with three parts dry cement and one part water by volume (manufacturer’s specification). The weight of specimens is monitored daily. The water required for the cement hydration is computed by comparing the initial and final weights of specimens. The final weights are measured after fifteen days when the weights of specimens are constant.
Unconfined compression tests are performed after 28 days on the small specimens (Groups A and B) to investigate the relationship between the unconfined compressive strength (large-strain property) and the wave velocity (low-strain property). Compressive strength of cemented specimens is measured in a universal compression machine (model T57) at a strain rate of 1.44 [mm/mm/hr] in accordance with ASTM C39. The data output from a load cell (Sensotec 41/572-05-06) and a displacement transducer LVDT (Trans-tek 0243-000) are monitored using an analog-to-digital card (National instruments, PCI-6110E) in a desktop computer. To reduce measurement errors, the output from load cell is also logged with a digital multimeter (HP34401A).

4. RESULTS AND DISCUSSIONS

Figure 2 shows small changes in wave velocity for low values of cement content (cc=2.5 and 5%). However, for the higher cement contents (cc=7.5, 10, 12.5, 15, and 20%), there is an optimum water content where the velocity is maximum and the void ratio is minimum (Fig. 3). In all the figures presented, wave velocity refers to longitudinal wave velocity unless otherwise specified. According to the unified soil classification system, if fines are more than 12%, soils behave plastically, which is in agreement with the results of Fig. 2 (clear peaks for cc≥10%). The average optimum water content is 11.7%, whereas the measured average water content required for complete hydration of cement is 9.5%. The additional water is required to improve the workability of the mixture. The degree of cement saturation (Sc) varies from 10.5% to 66.4% for the range of cement contents and initial water contents used.

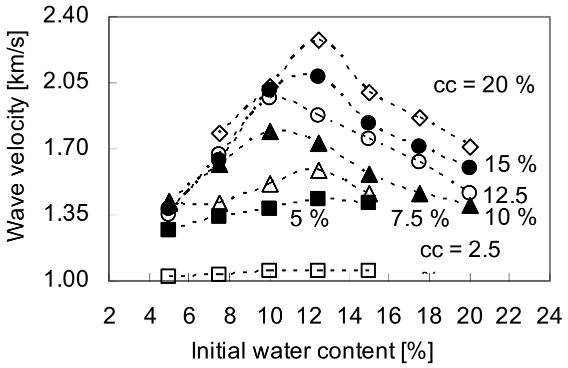

Figure 2: Effect of initial water content.

The maximum change in the mass density (Fig. 4) is approximately 19% which corresponds to a 9% change in velocity. In general, there is more variation in the mass density for water contents below optimum, than for water contents above optimum (void ratios for water contents below optimum tend to be higher than the void ratios for water contents above optimum) likely because of the change in viscosity of the cement paste with water content.

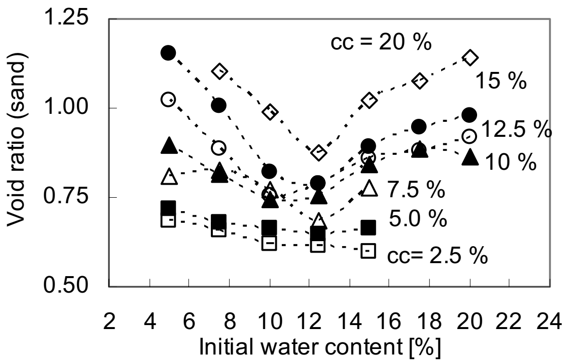

Figure 3: Initial water content and void ratio

The increase in longitudinal wave velocity with increasing isotropic confinement for dry sand (e=0.54) is studied with the resonant column device following the procedures given in Cascante and Santamarina (1997). Longitudinal wave velocity is computed from shear-wave velocity measurements. A Poisson's ratio ν=0.3 is used in the calculations (Das 1997). From the resonant column testing, the predicted wave velocity at σo=25 kPa is 278 m/s.

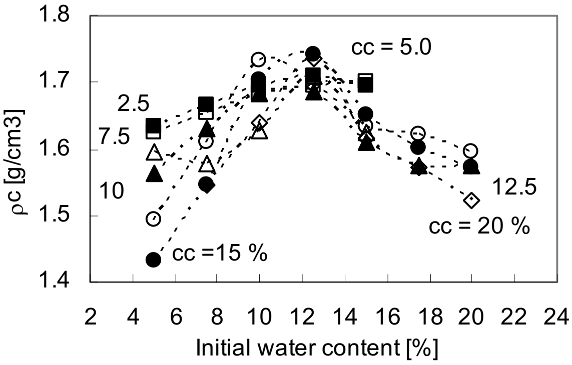

Figure 4: Initial water content and mass density

For specimens with low cement content (cc=2.5%), the velocity is 1050 m/s (Fig. 5), which is almost four times the velocity of dry sand at low confinement (σo=25 kPa), and almost two times the velocity for high confinement test conditions (σo=650 kPa, VL= 648 m/s). Therefore, cementation effects must be properly considered in the interpretation of seismic tests, especially for low-cementation conditions. In this case, the cement bond structure can be easily destroyed during sampling (Acar and El-Tahir 1986); thus in-situ measurements of wave velocity represent an effective technique for the assessment of natural or artificial cementation.
Wave velocity approximately increases with the square root of cement content (Fig. 6). This figure is obtained by interpretation of the data shown in Fig. 5.

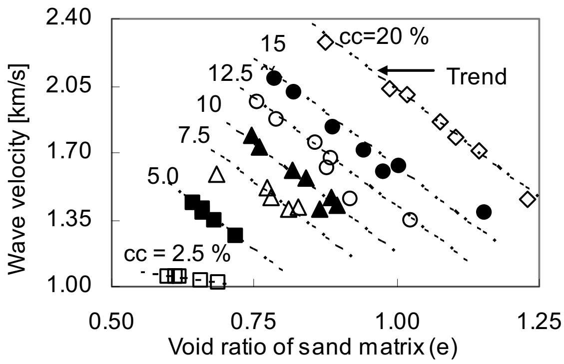

Figure 5: Wave velocity and void ratio of sand matrix for different cement contents.

The pulse velocity of dry sand (compacted in the same manner as the cemented sand) is V_L=283 m/s, e = 0.57. The measured velocity indicates that the compacting procedure induces an equivalent isotropic confinement of 25 kPa; this value is in the range of the average induced stresses reported by Frost and Park (2003) during preparation of Ottawa sand specimens by the moist tamping technique (30 kPa to 150 kPa).

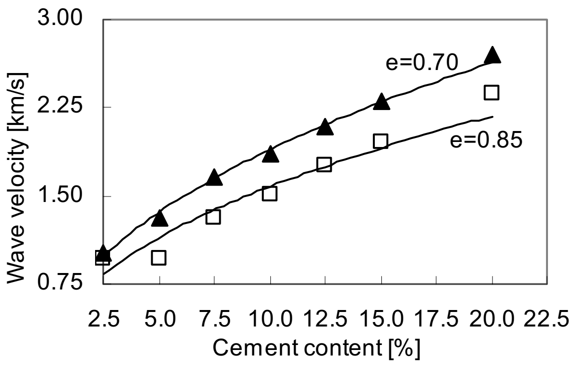

Figure 6: Wave velocity with cement contents for constant void ratio

Failure of cemented sand specimens in uniaxial testing can be ductile or brittle, depending upon the type of cementing agent. Brittle failures mostly occur when the cementing matrix fails, whereas ductile failures are due to progressive breaking of the bonds between soil particles and cementing agent. Brittle failures normally occur in weak cements like gypsum and in cemented soils at low confinement (Ismail et. al 2002, Santamarina et al. 2001). After curing, all of the small specimens are tested under uniaxial stress conditions to measure the unconfined compressive strength. Stress-strain curves display typical brittle and strain-softening behavior for gypsum cement. This failure mode is likely caused by the breaking of the slender gypsum crystals because of strain localization inherent to particulate materials (Schanz 1998, Ismail et. al 2002).

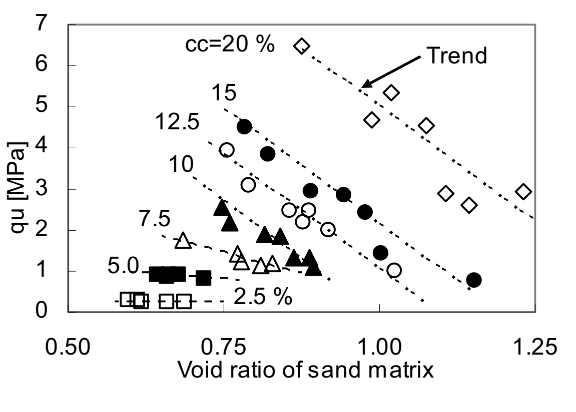

Figure 7: Uniaxial compressive strength and void ratio of sand matrix

As for wave velocity, unconfined compressive strength (qu) increases almost linearly as the void ratio decreases (Fig. 7). The average variation of the measured strength for each group of specimens at a given cement and water content is approximately 14% for all of the tests. For specimens with low cement content (cc=2.5%), the qu=267 kPa, which is almost five times the deviator stress of dry sand at low confinement (σo=25 kPa). For a constant void ratio, strength shows an exponential variation with cement content (Fig. 8, extrapolated from Fig. 7). However, Schnaid et al. (2001) found a linear relationship (qu-cc) for low-cement contents (cc < 2.5 %).

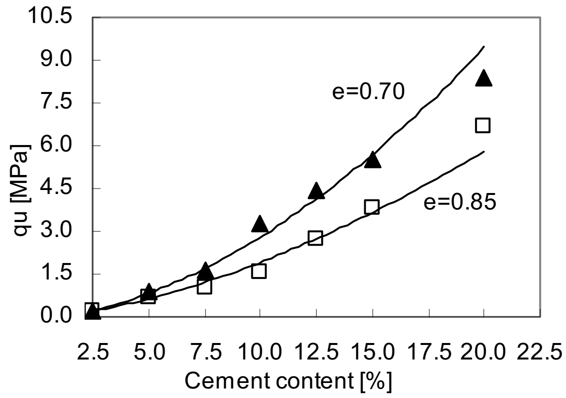

Figure 8: Uniaxial compressive strength for constant void ratio of cemented sand matrix

The unconfined compressive strength (qu) is more sensitive than wave velocity to cement content. Figure 9 shows a power relationship between compressive strength and wave velocity in agreement with previous studies (Nasser and Al-Manasser 1987, Nasser and Lai 1991, and Lopéz 2001). For a given velocity the unconfined compressive strength is higher for e=0.85 because the cement contents for e=0.70 are smaller than for e=0.85.

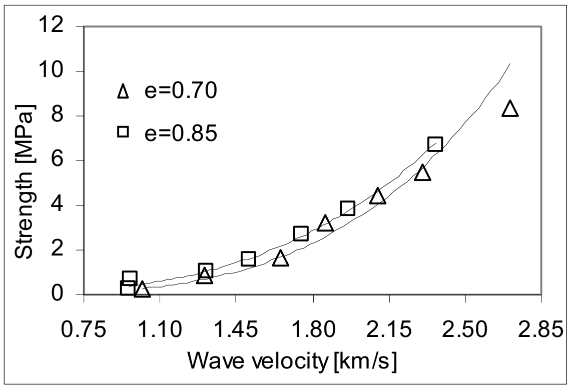

Figure 9: Variation of strength with wave velocity for constant void ratio of sand matrix

Velocity increases exponentially with curing time, and becomes almost constant after 120 hours. Figure 10 shows typical data for the two types of cement used. The effect of cementing agent on wave velocity (contact stiffness) is shown for cc=10% for SR-cement and POP-cement. The measured wave velocities and compressive strengths are higher for SR-specimens than for POP-specimens. The ratio of wave velocities (VSR/VPOP) is 1.42; whereas, the ratio of unconfined compressive strengths is higher (qu)SR/(qu)POP = 4.63.

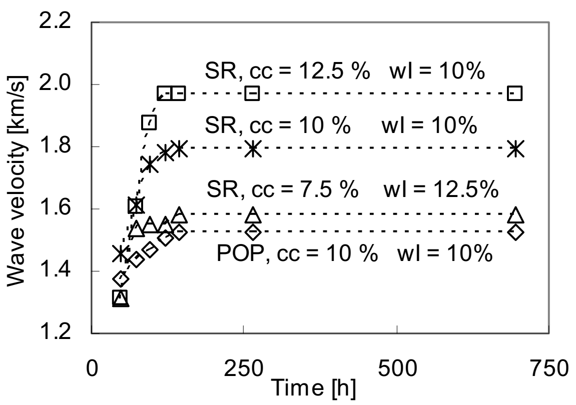

Figure 10: Effect of cementing agent on wave velocity

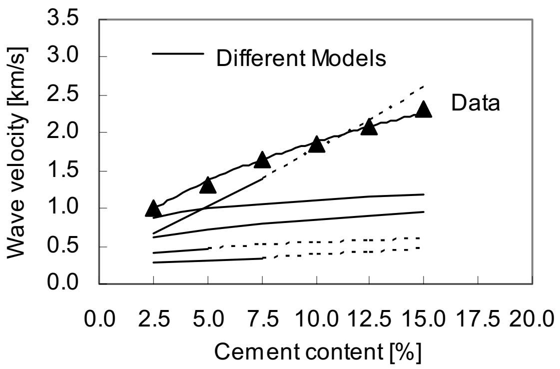

Figure 11.: Comparison of measured data with published models (σo = 25 kPa, e=0.7)

Wave velocity for the empirical and analytical models is computed for ν=0.30, σo = 25 kPa, e= 0.7, and ρ = 1.65 g/cc (Figure 11). In general, published models under-predict the wave velocity by a factor that depends on the cement content. Generally, for cc=2.5% to cc=7.5%, the models under-predict wave velocity by 90%.

5. CONCLUSIONS

The pulse-velocity method has been used to study the effect of cementation on wave velocity and unconfined compressive strength, without changing the confinement. The main conclusions derived from this experimental study are:

The initial water content of sand-cement mixtures affects the final void ratio and wave velocity of cemented sands for cement contents greater than 7.5%. Variations in the void ratio (e) are larger at higher cement content, because the sand-cement mixture behaves as a plastic material; thus there is an optimum water content for which the void ratio of the sand matrix is minimum and the wave velocity maximum. The relationship between coordination number (void ratio) and wave velocity is found to be linear as is assumed in most empirical and analytical models.

Slight cementation (cc=2.5%) increases wave velocity almost four times as compared to the dry sand conditions (σo=25 kPa); and the maximum deviatoric stress at failure increases five times. Therefore, cementation effects must be carefully considered in the analysis of seismic tests. Loss of cementation due to sampling effects can be evaluated by the measurements of wave velocity in the field and the laboratory.

Unconfined compressive strength and wave velocity of cemented sands depend on the coordination number and the cement content (strength of contacts); however, unconfined compressive strength is more sensitive to cement content than wave velocity.

Wave velocities predicted by empirical and analytical models based on laboratory measurements for different confining pressures are smaller (60% on average) than the actual measured values, likely because confining pressure induces micro-fractures at the cemented contacts. Thus, velocities measured in this study at low confinement ($\sigma o \leq$ 25 kPa) provide absolute trends of the effect of cementation on wave velocity and strength without the effects of confinement. The effect of confinement in resonant column tests should be re-evaluated.

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