EVALUATION OF SCC FOR DRILLED SHAFT APPLICATIONS

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ABSTRACT

Self-Consolidating Concrete (SCC) has been widely accepted in precast concrete applications. However, in the drilled shaft foundation industry, where it could have a major economic impact, SCC has not yet found widespread use. As a step toward acceptance of SCC technology for drilled shaft applications, a series of test specimens were prepared to compare conventional concrete and SCC mixtures of differing fluidity, strength and workability. Several tests were performed to compare the plastic and hardened properties of the concrete mixtures at different ages. The preferred means of quality assurance testing of drilled shafts are sonic and ultrasonic wave speed measurements. For this reason the concrete samples were subjected to crosshole sonic logging (CSL) and pulse echo testing (PET).

At similar strength levels, SCC mixtures with slump flow values in the range of 460-660 mm (18-26 in.) and conventional concrete mixtures with slump values in the range of 25-200 mm (1-8 in.) were nearly indistinguishable by wave speed or CSL signal strength comparisons. Wave speed and CSL signal developed as the concrete hardened. The trend of the data showed that the wave speed increased with increasing compressive strength and elastic modulus. For conventional concrete mixtures with nominal compressive strengths ranging from 21 to 34 MPa (3000 to 5000 psi) and SCC mixtures with nominal compressive strengths ranging from 34 to 55 MPa (5000 to 8000 psi), wave speeds and elastic moduli obtained from the CSL and PET tests increased as the measured compressive strengths and elastic moduli increased. Hence, the CSL and PET test methods are suitable for evaluating the quality of both conventional concrete and SCC mixtures. This implies that the quality of SCC mixtures can be readily evaluated using these established techniques, enabling the rapid acceptance of SCC in drilled shaft applications.

INTRODUCTION

Since its development in the early 1990’s, Self-Consolidating (or Self-Compacting) Concrete (SCC) has been widely accepted in precast applications, and is now being used on above ground cast-in-place concrete applications around the world. The high fluidity of the mixture and its ability to evenly fill a form without additional energy or vibration have made it a cost-effective and labor saving alternative to traditional concrete mixtures in many applications. Another possible application for SCC is only beginning to be considered: cast-in-place deep foundations. In the drilled shaft industry, where concrete is placed in a deep drilled hole, the opportunity for SCC use seems most promising. Under current construction practice, the concrete is not vibrated after placement because the holes are deep. SCC is also being considered because, in some drilled shaft designs, large amounts of reinforcement are required to resist lateral and seismic loading. Direct, visual inspection of the finished shaft is also not possible, and quality control is performed by one or more non-destructive tests (NDT). Because of its highly fluid properties, SCC may reduce the incidence of certain types of defect, increasing the owner's and design engineer's confidence in the finished foundation.

This paper details a study undertaken to verify SCC's ability to replace traditional concrete mixtures in drilled shaft applications. A number of conventional and SCC mixtures were poured into forms designed to simulate a partial cross section of a drilled shaft. Two different NDT methods were performed on test specimens to measure the ultrasonic and sonic stress wave speeds in the concrete. A variety of tests were also performed on the plastic and hardened concrete to compare to the NDT results.

Drilled Shaft Quality Control Tests

Once a drilled shaft has been poured, a waiting time of two or more days is usually specified before quality assurance activities are performed. Two tests are typically used: crosshole sonic logging (CSL), and low strain integrity or pulse echo testing (PET). CSL requires two or more water filled steel tubes to be attached to the reinforcement cage and cast in the shaft. PET requires only a smooth, clean surface on the shaft top for temporary instrumentation attachment. An overview of these and other technologies used for deep foundation evaluations can be found in Reference 1.

Crosshole sonic logging uses electrical pulses generated by a pulse generator and converted to ultrasonic waves by the transmitter probe. The waves are detected by the receiver probe and converted back to electrical signals. To minimize noise, the receiver probe response is filtered around the receiver's resonant frequency of approximately 100,000 Hz. The test is performed in the field per ASTM D 6760.

Two depth encoders determine the locations of the transmitter and receiver in the test specimen. The transmitter and receiver are dropped to the bottom of the test specimen and pulled up together, such that each probe is at approximately the same depth at the same time. For this project the received signal was recorded every 6 mm.

The concrete's CSL wave speed is generally determined by dividing the distance between the two tubes by the arrival time required for the wave to travel from the transmitter to the receiver. Concrete homogeneity can then be checked for the concrete along the entire length of the two tubes. Major delays in first arrival time (slower wave speeds) or complete loss of signal generally signify weaker or partially cured concrete, voids, soil inclusion or other defects.

TEST PROGRAM

Materials and Test Specimens

The test specimens used in this study were designed to simulate a section through the height of a drilled shaft. Each test specimen, as shown in Fig. 1, was approximately 760 mm long, 203 mm wide and 660 mm high. Two 40-mm inner diameter steel tubes were placed in each mold at approximately 70 mm from each edge prior to casting. With the steel tubes in place, and filled with water, CSL wave speeds could be monitored through the height of the test specimen.

Figure 1. Typical test specimens

The test program was carried out in two phases. Mixes 1-6 were evaluated in Phase I while Mixes 7-12 were evaluated in Phase II. In Phase I, the mixtures were designed to attain similar compressive strengths at different levels of fluidity (i.e., different slumps or slump flows). Phase II mixtures were designed to attain different compressive strengths, with the conventional concrete mixtures at similar slump levels and the SCC mixtures at similar slump flow levels. The mixtures consisted of five conventional concrete mixtures (Mixes 1-3, 7 and 8) and seven SCC mixtures (Mixes 4-6 and 9-12). Type I cement was used for this evaluation at three cement contents of 237, 357 and 476 kg/m^3, and at water-to-cement ratios (*w/c*) of 0.35 for Mixes 1-6 and 12, 0.54 for Mixes 8-11 and 0.75 for Mix 7. Naturally mined gravel and sand of glacial origin were used for the coarse and fine aggregates. A polycarboxylate-based high-range water-reducing (HRWR) admixture was used to achieve the required slump and slump flow of the conventional concrete and SCC mixtures, respectively. A viscosity-modifying admixture (VMA) was used in Mix 6 to stabilize the high slump flow (660-710 mm) mixture. A hydration control admixture (HCA) was used in Mix 10 to purposefully retard the mixture, relative to Mix 9, for approximately two hours. A high dosage of the HRWR admixture was used in Mix 11 to purposefully segregate the mix.

The concrete was poured into the form in one complete freefall motion. This procedure simulated the typical casting of drilled shafts in the field. No special effort was made to push concrete between the tube and walls of the form. In addition to the simulated drilled shaft specimens, thirty cylindrical specimens, 100 x 200-mm size, were also cast from each concrete mixture and moist cured until testing.

Test Procedure

Various standard tests were performed on the plastic concrete to characterize the mixtures. These were slump, air content, unit weight and time of setting. In addition, the SCC mixtures were characterized using the following tests: slump flow, visual stability index, T_{50}, U-box, column segregation and rheology (2-3).

Immediately after the concrete had been poured, an initial CSL test was performed. CSL testing was then performed at 4, 6, 8, 10, 12 and 24 hours after concrete placement. At 24 hours, the forms were removed and both PET and CSL measurements were taken at approximately 2, 3, 5, 7, 14 and 28 days. During the period of testing, the test specimens were covered with plastic and kept in the laboratory environment. Photographs of each specimen were taken after all testing was completed. Three cylindrical specimens each were tested in compression at 1, 3, 7, 14, and 28 days to determine both the compressive strength and modulus of elasticity of each concrete mixture in accordance with ASTM C 39 and ASTM C 469, respectively.

TEST RESULTS

No ultrasonic signal was received, at any probe separation distance, for CSL testing performed immediately after the concrete was placed. Figure 2 shows typical raw CSL results from Mix 5 (SCC with 556-mm slump flow and 55 MPa compressive strength), including the lack of signal in the first few hours. The received signals are indicated by the alternating dark and light bands.

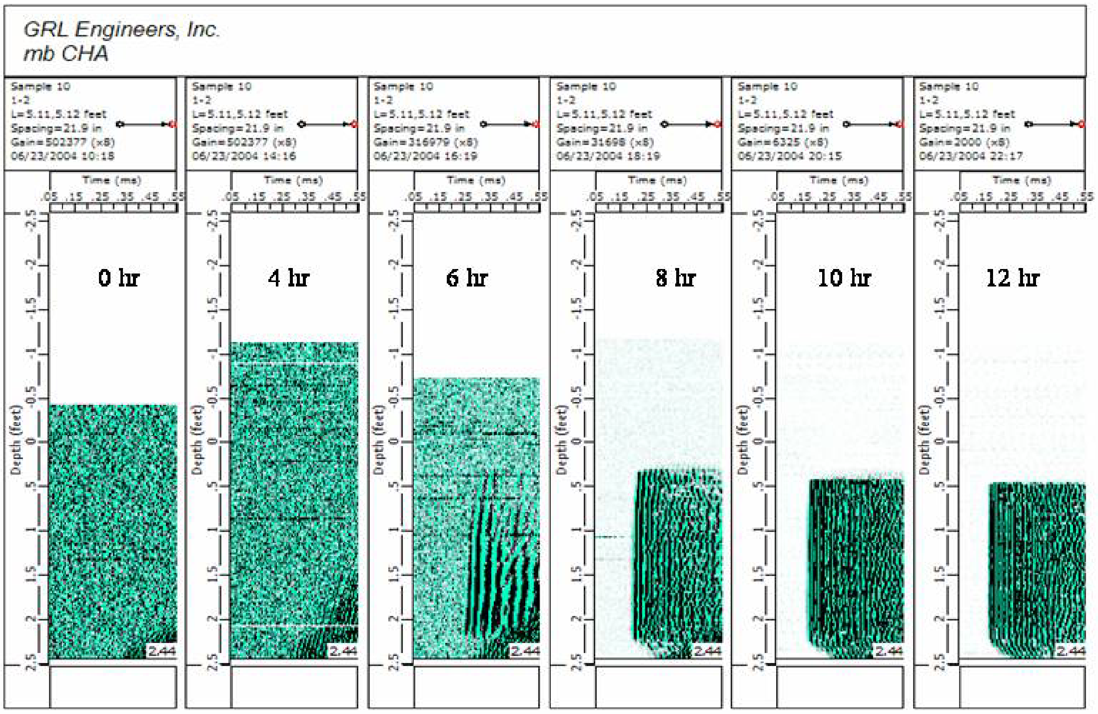

Figure 2. Typical CSL results

The appearance of CSL signal correlates well with the time of final set measured for each concrete mixture. These results support the observations made for conventional concrete in previous studies in which the shear wave velocity was monitored during hardening (4) and ultrasonic pulse velocity was monitored over an extended period of time (5). It appears the SCC and conventional concrete studied here exhibit similar ultrasonic properties to those observed in the previous studies on conventional concrete only.

After final set time is reached, Figure 2 shows decreasing arrival time as time after casting increases. This, in turn, implies an increasing ultrasonic longitudinal wave speed as time progresses. To obtain an average wave speed for a specimen, the arrival times over the height of the specimen were averaged, neglecting the upper and lower 25 mm where boundary conditions could have an effect. The horizontal distance between the tubes was divided by the average arrival time, yielding an average longitudinal wave speed for each specimen at each testing time. These wave speed values are then compared to hardened concrete properties.

Figure 3 shows the CSL wave speed results for Mixes 1-6 which had 28-day compressive strength values of approximately 55 MPa and modulus of elasticity values of approximately 35 GPa. Except for the mixture with a very low slump of 44 mm, the final measured CSL wave speeds were very similar for all the mixtures at different levels of fluidity, averaging 4000 m/s. The measured CSL wave speeds in the 44-mm slump mixture were very erratic, due mostly to the lack of concrete cover over one of the CSL access tubes. This mixture was unable to flow between the tube and the form walls, leaving large portions of the bottom of one tube exposed to the atmosphere. As the concrete cured, the contact between the concrete and the tube worsened, tending to reduce the measured wave speed. In general, the shapes of the wave speed versus time curves for the concrete mixtures are similar to those of the compressive strength and elastic modulus versus time curves.

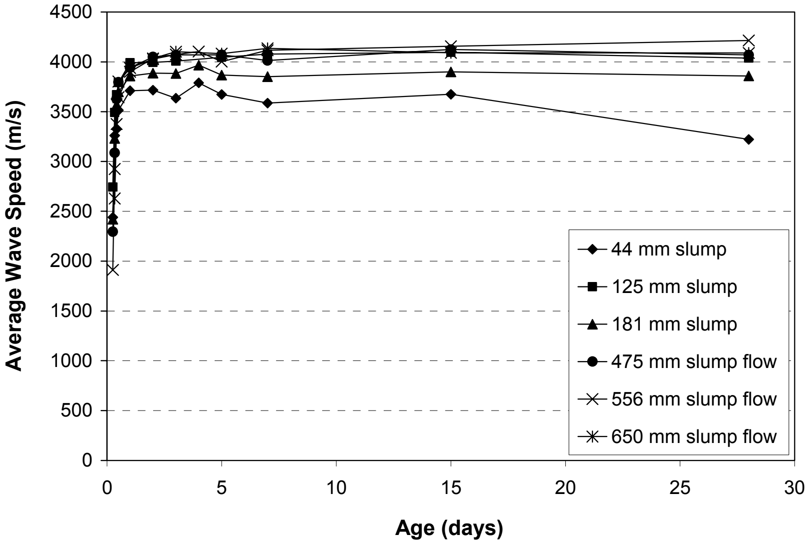

Figure 3. Average wave speed development for concrete mixtures with different levels of fluidity

Figures 4 and 5 are average wave speed results for conventional concrete and SCC mixtures, respectively. The figures show the trend of increasing wave speed with compressive strength. Previous research has shown that, for conventional concrete mixtures that are produced with the same materials (e.g., aggregate size, aggregate type, cement type), a relationship exists between compressive strength and pulse velocity (i.e., wave speed) (6-8). This study shows that such a relationship also exists for SCC. Hence, with adequate calibration, the compressive strength and elastic modulus of SCC could be determined from the CSL wave speed.

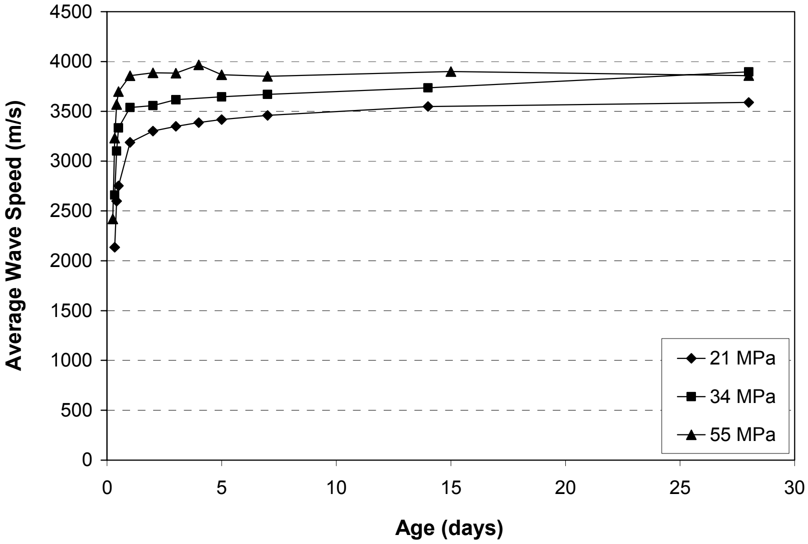

Figure 4. Average wave speed development for conventional concrete mixtures (slump of 181 mm) with different compressive strengths

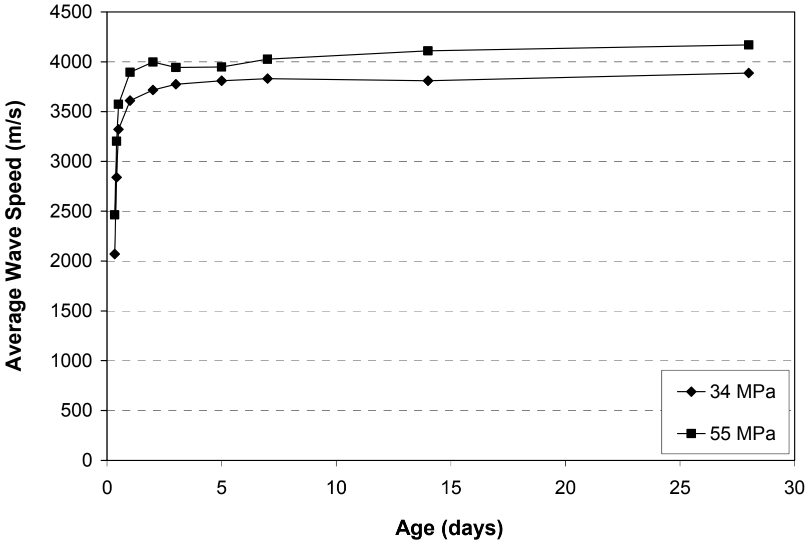

Figure 5. Average wave speed development for SCC mixtures (slump flow of 556 mm) with different compressive strengths

CONCLUSIONS

(1) There is no fundamental difference in CSL wave speed between SCC and conventional concrete at similar strength levels. Therefore, the established CSL and PET test methods for conventional concrete are suitable for evaluating SCC as well.

(2) For concrete mixtures at the same fluidity level but with different compressive strengths, CSL test results showed significant differences in wave speed. Hence, in the absence of soil inclusions, voids or honeycombed concrete typically found as defects in drilled shafts, differences in wave speed are primarily due to differences in compressive strength for both conventional concrete and SCC. If properly calibrated, the CSL method shows promise in estimating compressive strength or elastic modulus in cast drilled shafts.

(3) The appearance of a received signal corresponded well with the time of final set of the concrete mixture. The CSL signal took longer to appear for the retarded and segregated mixtures.

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