Correlation between concrete properties and sonic wavespeed using non-destructive field testing procedures

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ABSTRACT

The correlation between the sonic wave speed in concrete and its compressive strength is one that has caught the interest of many geotechnical professionals dealing with Non-Destructive Testing (NDT) of concrete foundations. The present paper reports the findings from a study carried out by AATech Scientific Inc. (ASI) Engineers. Multiple miniature concrete columns are built with different mixes varying the content of aggregates, sand, and cement materials, along with several molded cylinders of each batch. The compressive strength of the samples was determined following ASTM C39/C39M-17 and sonic wave speed was determined using low strain Pile Integrity Testing (PIT). Similar work has been published by others, however, the present study targets the effects of concrete mix proportions and age. The NDT testing method used in the present study is an industry standard Quality Control (QC) testing method used in the field, as opposed to laboratory ultrasonic testing.

RÉSUMÉ

La corrélation entre la vitesse de l'onde et la capacité compressive du béton a attiré l'attention de nombreux professionnels géotechniques traitant des essais non destructifs (END) sur les fondations profondes. Le présent document rapporte les résultats d'une étude menée par les ingénieurs d'AATech Scientific Inc. (ASI). Plusieurs colonnes miniatures en béton sont construites avec différents mélanges variant le contenu des agrégats, du sable et de ciment, ainsi que plusieurs cylindres moulés de chaque lot. La résistance à la compression des échantillons a été déterminée selon la norme ASTM C39/C39M-17, la vitesse d'onde a été déterminée en utilisant un test à faible contrainte de l'intégrité des pieux (PIT). Des travaux similaires ont été publiés par d'autres, mais la présente étude a pour but de tenir compte de l'effet des variations dans le mélange et l'âge du béton. La méthode de test NDT utilisée dans la présente étude est un test de contrôle de qualité (QC) standard de l'industrie utilisé sur les chantiers, ce qui est différent des tests par ultrason aux laboratoires.

1 INTRODUCTION

Quality assurance of fresh and hydrated concrete is traditionally performed using various established methods: visual inspection, field tests for workability, temperature, air content, etc. (fresh concrete) and sample cylinders are formed on site for laboratory strength testing by mechanical means after hydration milestones, including compression, tension, durability, etc.

In recent years, modern technologies were adapted for testing solid concrete materials, be it on laboratory samples or on full-scale structures in the field. Some of these technologies include methods based on radioactive sources (X-Ray, Gamma-Gamma probes, etc.). Other methods requiring less pronounced safety measures include penetrating high and low frequency radar wave technology, and, of interest to this research, sonic wave propagation and reflection techniques. While sonic waves have been used extensively in scientific advancements for many years, this technology is gaining grounds in the deep foundations industry as more advanced portable devices are being used for non-destructive testing (NDT) of the integrity of deep-buried concrete foundations poured in-place. Among NDT tests using sonic wave techniques, two distinct categories of techniques used on site for integrity testing of pile and caisson foundations can be identified: sonic wave scanning known as cross-hole sonic logging (CSL), and pulse echo testing, of which one variation is most commonly known in North America as low-strain pile integrity testing, hereafter referred to as PIT, based on popular equipment manufactured by Pile Dynamics Inc.

Field sonic testing devices such as CSL and PIT, which will be described in more detail later, are intended for finding potential defects such as voids, or intrusions in concrete foundation members (Davis et al 1998). With the sonic wave speed in the tested concrete being a byproduct of these tests, the interest in correlating it to the physical properties of the concrete, and specifically to the strength of the material fueled extensive research. The attractiveness of such correlation can potentially eliminate the need for intrusive methods such as coring out samples from the structure for lab testing, which can be costly and time consuming.

Earlier research into such correlation was done using Ultrasonic Pulse Velocity (UPV), which is usually performed in the laboratory on cast or cored concrete samples. This technique is similar to sonic wave testing but involves waves in the higher frequency spectrum.

Arioglu, 1998 compiled earlier published UPV-concrete strength correlations by several researchers, as shown in Figure 1. It is important to note that, while each dataset shown in Figure 1 depicts a well-defined curvilinear relationship, the combined data shows significant scatter, which suggests that other factors than strength are in play.

Research by Turget (2004) also suggests that UPV-concrete strength correlation is a well-defined curve. His research was limited to laboratory testing on cores taken from mature structures, varying in age and with unknown concrete mix proportions and additives.

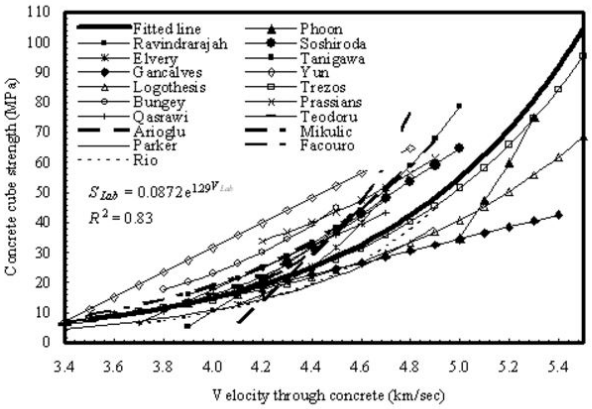

Figure 1. Published correlations between concrete strength and UPV, after Arioglu, 1998

2 RESEARCH DESCRIPTION AND SCOPE

In recent years, there has been significant progress in the development of NDT which lead to published standards by the American Society for Testing and Materials (ASTM), American Concrete Institute (ACI), the International Standards Organization (ISO) and the British Standards Institute (BSI). The scope of this study is to investigate the reliability of correlating the speed of the stress wave in concrete versus the compressive stress of the material. As stated earlier, there has been a tendency in the industry to apply published relationships to determine the strength of concrete, from any source, by determining the sonic wave speed in the material using NDT techniques. While specific curvilinear relationships are suggested by researchers in the literature, the obvious large discrepancies between the suggested relationships (see Figure 1) and the significant scatter of data used to determine these relationships raises a flag with respect to the reliability of such relationships. Obvious questions arise from examining the different publications on this subject: Is the data scatter due to multiple sources of concrete samples used in the study?

If so, does the sonic wave speed in concrete from various sources, with the same compressive stress, vary with other properties of the concrete material such as age, mix proportions, type of materials, additives, etc.?

To answer these questions, engineers from AATech Scientific Inc. (ASI) decided to conduct an in-house study. The scope of the study can be summarized as follows:

1. Mix four different concrete batches with varying mix proportions.
2. Build one sample from each batch with length to diameter ratio 10:1; this sample is intended for NDT application to determine the sonic wave speed in the material.
3. Build several standard size samples from each batch for compressive strength testing.
4. Perform NDT testing on the long samples at specific intervals during the hydration process, coupled with compressive strength testing of standard samples at the same time.
5. Determine the effect of the different controlled variables on the wave speed-strength relationship.

Both age and mix proportions are reflected in this study and the sonic wave speed obtained from PIT testing is used for correlation.

3 SONIC NDT METHODS

As stated earlier, two general categories of sonic NDT are most popular in testing the integrity of deep concrete foundations: cross-hole sonic (CSL) and Low-strain pulse echo PIT.

In CSL, the concrete to be tested is positioned between a sonic wave transmitter and a geophone (receiver). Usually the probes are inserted in water-filled access tubes, embedded in the foundation along the two ends of the section to be tested. A sonic wave is transmitted from one side of the section and received at the other side by the geophone; repeating this test at multiple depth intervals allows for a full scan of the section. The time it takes for the sonic wave to reach the receiver is referred to as First Arrival Time (FAT), and the distance between the probes divided by the arrival time represents the sonic wave speed in the material. The ultrasonic pulse velocity (or UPV) method is a variation of the CSL method in terms of sending an acoustic pulse on one end of the specimen and receiving it at the other end; however, higher frequency sonic waves are used where the probes are applied directly against the concrete, and the method is limited to a small laboratory specimen that may be cast as such or cored from the actual structure. It should be noted that the speed of ultrasonic pulse may be somewhat higher than the speed of lower frequency stress waves; some comparisons based on frequency levels can be found in literature but this is beyond the scope of this study as only low-frequency pulses are used.

The Low-strain pulse echo is the NDT method used in this study. The equipment used is the Pile Integrity Tester (PIT), developed by Pile Dynamics Inc. (PDI). The method utilizes stress wave propagation theory to study velocity waves. Low strain compressive strains are generated by impacting the top surface of the concrete pile or specimen with a special tool or a hand-held hammer, depending on the dimensions of the specimen. As the downward traveling waves encounter changes in cross-section or material characteristics, upward response waves are reflected to the surface. Both downward and upward waves are detected by a sensitive accelerometer, typically placed at the surface of the specimen near the impact location.

The velocity waves are integrated from acceleration measurements and are typically used to investigate potential problems within the pile shaft. An increase in the impedance of pile material is associated with a decrease in measured particle velocity, and vice versa. An increase in velocity (reduction in material impedance) usually implies a reduction in pile cross-section, a reduction in material stiffness (modulus of elasticity), a void or intrusion of softer material in the pile, or a combination of the above. A decrease in velocity is usually an indication of stiffer material or an increase in cross-section. Of particular interest for this study is the reflection of the impact pulse from the pile toe or the end of the specimen, which is easily identifiable and indicates the time it took the stress wave to travel twice the length of the specimen to return to the sensor location. A typical velocity trace is shown in Figure 2 where the impact and toe response are clearly identified.

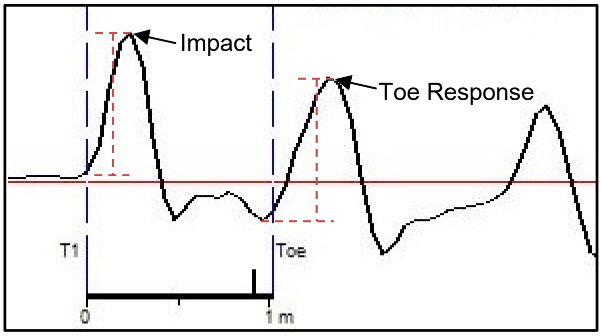

Figure 2. Typical Velocity traces from the Pulse Echo Method (PIT Testing)

The equipment is portable and easy to use in the field which makes such testing highly economical and efficient to determine the speed of the stress wave.

4 CYLINDER BREAK TESTS – COMPRESSIVE STRENGTH

Traditionally, concrete strength in piles and other structures is measured using field-cured cylinders prepared and tested in accordance with ASTM C39/C39M-17 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens). These cylinders are cured under similar conditions, as practical as possible, to those of the pile or structure. While this is the most direct way to measure the concrete strength, it is difficult and often impossible to replicate the identical curing conditions of the actual structure. Take, for example, cast-in-place (CIP) piles built in cold weather conditions; samples cured on site may be subjected only to the curing conditions of the top 300 mm of the pile. Furthermore, it is not practical to cast and test specimens from every concrete batch used in the foundations. Therefore, the need often arises to core through piles and extract specimens for testing when field tests suggest a discrepancy between the strength of the field-cast specimens and the actual pile. In-situ testing using NDT methods, if correlated to concrete strength, can provide significant savings in time and cost.

5 EXPERIMENT SETUP

The concrete batches were prepared in the ASI laboratory using a portable mixer (see Figure 3). In order to limit the number of variables to contend with, no additives or pozzolan materials were used in the mixes. The following basic materials were used in varying proportions between the for different batches:

1. General use (GU-type) Portland cement.
2. Natural crushed limestone, 12.5 mm diameter max.
3. Multi-purpose high quality mortar sand.
4. Potable tap water

All the materials were accurately weighed and mixed following a consistent procedure throughout. Four batches were mixed with varying proportions of the basic materials were prepared. Table 1 shows the concrete mix design proportions for each batch. Four sets of specimens were cast, one set per batch, and each consisting of the following:

- One miniature pile, cast in a piece of schedule-40 PVC pipe, 100 mm in diameter and 1,020 mm in length. This specimen was used to perform multiple PIT tests for determining the speed of the stress wave for the corresponding concrete.
- Twelve cylindrical samples, 100 mm in diameter by 200 mm length (See Figure 4). These samples were prepared for compressive strength testing in a special load press.

Table 1. Mix design proportions (by weight)

Mix Number	Water-Cement Ratio	Aggregate (%)	Sand (%)
1	0.45	45.0	22.5
2	0.45	36.7	36.7
3	0.55	45.8	30.5
4	0.55	36.7	36.7

Figure 3. Concrete batch mixing using a portable mixer

Before casting the specimens, each concrete batch was subjected to a concrete slump test (see Figure 5), air content test, and temperature test. All the mix cylinders and specimens were cured under controlled laboratory setting. Testing, sampling, and curing were done in accordance with CSA A23.02 and CSA A23.03 (C1064/C1064M – Temperature of Freshly Mixed Hydraulic-Cement Concrete, C172/C172M – Sampling Freshly Mixed Concrete, and C31/C31M – Making and Curing Concrete Test Specimens in the Field). Table 2 shows the temperature, air content, and slump measurements for each of the four mixes.

Each cylinder sample was cured for 24 hours in the plastic mold. The cylinders were then demolded, and cured in lime saturated water in containers at constant ambient temperature of 20°C until the time of testing.

Figure 4. Molding of cylinders for strength testing

Table 2. Temperature, Air, and Slump measurements

Mix Number	Temperature (°C)	Air Content (%)	Slump Test (mm)
1	18	1.3	190
2	16	2.2	65
3	18	1.5	135
4	20	1.4	185

Figure 5. Slump Test conducted on mix design 1

6 TESTING PROCEDURE

Starting at three days after casting each mix, and following the schedule shown in Table 3, a pair of cylinder samples were subjected to a compressive strength breaking test (see Figure 6), while the corresponding miniature pile specimen was tested for stress wave speed using the PIT system (see Figure 7). Breaking tests were conducted in the ASI laboratory in a 1000-ton load frame. A calibrated 200-ton ASI hydraulic jack equipped with a constant flow valve was used to apply constant strain/stress, and a calibrated 100-ton GEOKON resistive load cell was used to constantly measure the applied load. A hemispherical bearing plate was used to ensure axial loading. The break was conducted at a stress rate between 0.15-0.35 MPa/s.

Table 3. Concrete break schedule on specimens

Mix Number	Age (days)
1	3, 4, 7, 9, 14, 28
2	3, 4, 7, 9, 14, 28
3	3, 6, 7, 9, 14, 28
4	3, 6, 7, 9, 14, 28

Figure 6. Concrete breaking test in ASI frame

It should be noted that more PIT tests were conducted, in addition to the ones performed at the same time as the breaking tests, including tests at 45 days and 46 days after casting, as shown in Table 4. These tests are performed to check for long-term changes in characteristic stress wave speed

Table 4. PIT testing schedule

Mix Number	Age (days)
1	3, 4, 7, 8, 9, 14, 28, 46
2	3, 4, 7, 8, 9, 14 28, 46
3	2, 3, 6, 7, 8, 9, 14, 28, 45
4	2, 3, 6, 7, 8, 9, 14, 28, 45

Figure 7. PIT testing on miniature pile models

7 RESULTS

The concrete specimens were tested as per the schedule specified in Table 3. Mix 1 was designed with the highest cement content, whereas Mix 2 was designed to have optimized aggregate content and water cement ratio as per industry standards. Mix 3 had the highest ratio of aggregates compared to all other mixes. The water cement ratio was kept within nominal range (0.45-0.55) in all the mixes. Results of the compressive strength tests are shown in Table 5.

Table 5. Concrete strength break results

Mix Number	Age (Days)	Average Compressive Strength (MPa)
1	3	13.78
	4	18.94
	7	22.16
	9	24.30
	14	28.30
	28	34.60
2	3	14.36
	4	15.22
	7	16.92
	9	24.17
	14	25.41
	28	31.70
3	3	14.63
	6	19.39
	7	20.77
	9	25.93
	14	24.37
	28	24.71
4	3	17.41
	6	15.12
	7	19.38
	9	28.58
	14	28.42
	28	31.20

Each reported compressive strength of concrete was averaged from breaking tests of two cylinders performed on the scheduled day. Figure 8 shows graphically the concrete strength versus age for each mix.

The maximum compressive concrete strength measured was 37.72 MPa for Mix 1 at 28-day, whereas the lowest strength was recorded for Mix 3, at about 25 MPa. The compressive strength for Mixes 2 and 4 at 28-day was around 32 MPa.

The PIT testing was conducted on the miniature pile specimens as per the schedule in Table 4. The miniature pile specimens had a known diameter and length: 100 mm and 1,020 mm, respectively. It was therefore simple to determine the sonic wave speed from PIT testing as clear toe reflections were observed in the data, as shown in the typical data in Figure 2. A compilation of the determined wave speed from all PIT tests is provided in Table 6. A plot showing the wave speed versus age of concrete is shown in Figure 9.

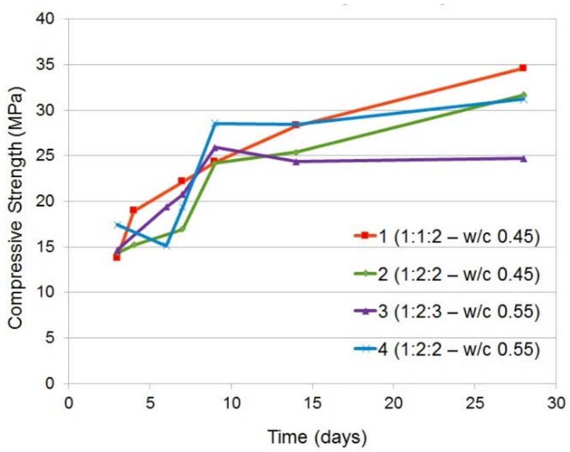

Figure 8. Concrete strength vs. age

The wave speed results showed a surprising trend, as can be seen clearly in Table 6 and Figure 9. The sonic wave speed appears to have peaked at 8 to 9 days after casting, consistently in all four specimens. Specimens from Mixes 2, 3 and 4 peaked at about 4,100 m/s whereas Mix 1 specimen peaked at 4,025 m/s. Subsequently, the sonic wave speed in all specimens started declining after the 9-day peak and continued to decline as of the last measurement, 45 days after casting, albeit at a somewhat lower rate. Furthermore, the sonic wave speed in the specimens at 45 days appears to have declined back to below the 3-day measured speed, and still on the decline.

Selected PIT data from specimens of Mixes 1 through 4 are shown in Figures 10a through 10d, respectively. The selected records are from early testing, peak wave speed, and late testing. The plots show the particle velocity on the x-axis versus distance below the top of the specimen where the reflection is coming from. The time measured between the input pulse and the arrival of the toe reflection is used by the PIT software to compute the wave speed shown on the plot in m/s.

Table 6. PIT testing wavespeed results

Mix Number	Age (Days)	Wavespeed (m/s)
1	3	3850
	4	3900
	7	3975
	8	4000
	9	4025
	14	3925
	28	3750
	46	3700
2	3	3750
	4	3900
	7	4000
	8	4100

	9	4050
	14	3900
	28	3800
	46	3700
3	2	3750
	3	3850
	6	4075
	7	4100
	8	4100
	9	4000
	14	3900
	28	3850
	45	3800
4	2	3700
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	7	4000
	8	4000
	9	4100
	14	4050
	28	4025
	45	3900

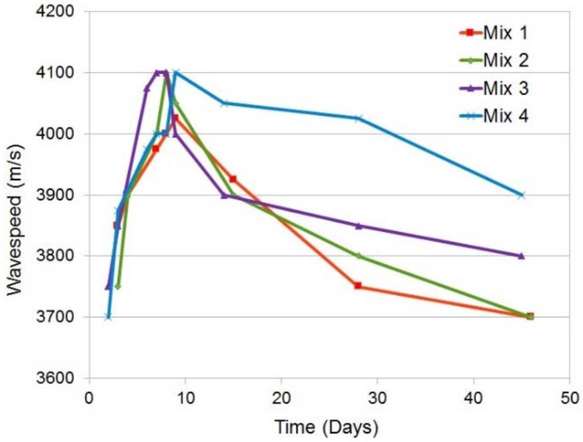

Figure 9. Wavespeed recorded in PIT testing versus Time

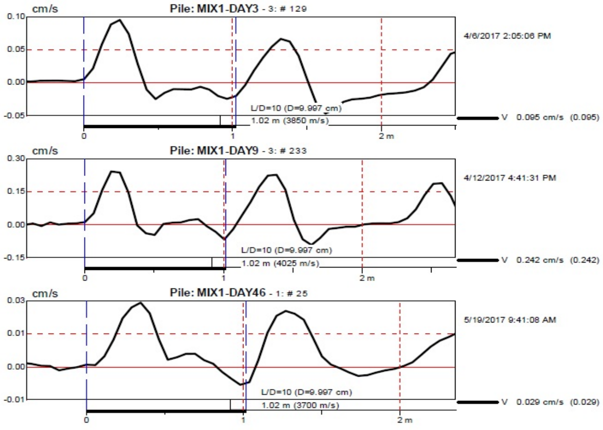

Figure 10a. PIT output – Mix Design 1 Sample testing

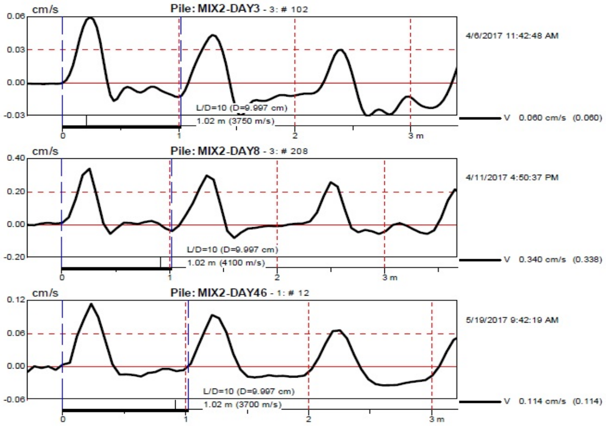

Figure 10b. PIT output – Mix Design 2 Sample testing

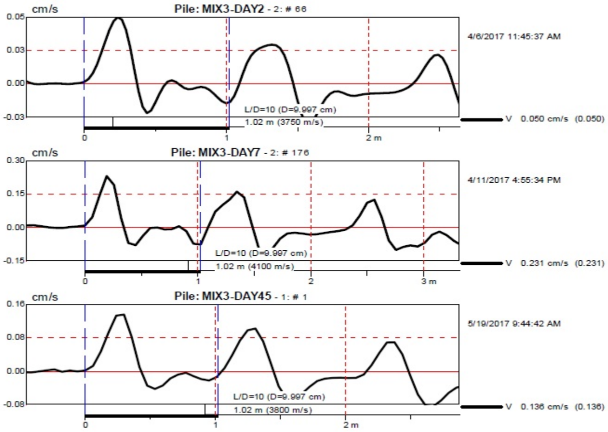

Figure 10c. PIT output – Mix Design 3 Sample testing

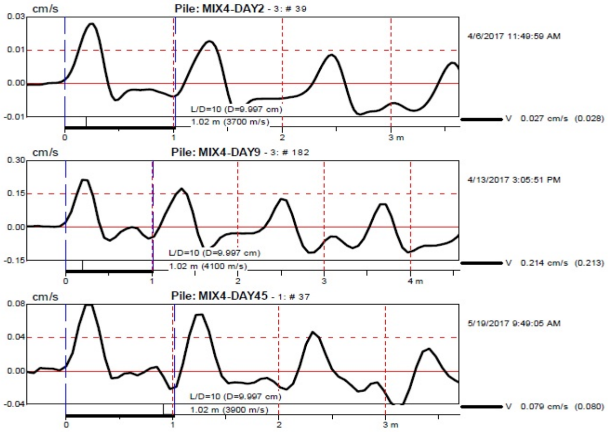

Figure 10d. PIT output – Mix Design 4 Sample testing

8 CORRELATION OF STRESS WAVE SPEED AND CONCRETE STRENGTH

The measured compressive strength of concrete are plotted in Figure 11 against the corresponding stress wave speed obtained from PIT testing. This plot illustrates the findings discussed in the previous section. The wave speed seems to increase with concrete strength during the initial curing stage (up to 9 days). A reverse trend is observed past the ninth day of curing whereby increasing strength is associated with declining wave speed. This parabolic trend is consistent between all four specimens with different mix proportions and is therefore a characteristic behavior of concrete. Another important observation is that Mixes 3 and 4 show the highest wave speed after 45 days while having the lowest measured strengths; based on mix proportions, and by comparing Mixes 2 and 4, the common factor appears to be the higher water/cement (W/C) ratio.

The concrete mix with the highest compressive strength by design (Mix 1) shows the lowest long-term wave speed of all specimens. By comparison with Mix 2, with the same W/C ratio, we conclude that the low aggregate content may explain the low wave speed.

These same conclusions can be made by looking simultaneously at the plots in Figure 8 and Figure 9.

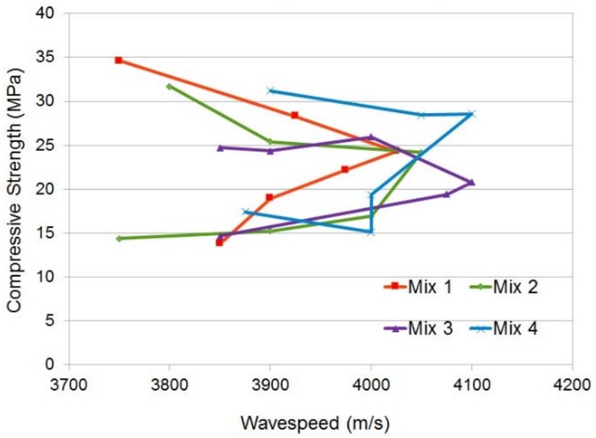

Figure 11. Concrete strength vs. Wavespeed (plotted chronologically over curing period)

9 DISCUSSION AND CONCLUSION

This study shows that concrete age is a crucial factor affecting the stress wave speed in the concrete whereby the wave speed peaks after about 9 days then declines significantly in long term. Furthermore, as shown earlier, the concrete mix with the highest compressive strength (Mix 1) shows the lowest long-term wave speed of all specimens, and the concrete mix with the lowest measured strength, by at least 20% (Mix 3), is not the mix with the lowest wave speed.

The data also showed a solid argument for the wave speed increasing with W/C ratio, and declining with lower aggregate and sand content (higher cement proportion). Both conclusions go against the common assumption that that the stress wave speed should increase with concrete strength

It is the Authors' opinion that the observations reported in this study explain the scatter in the data available in the literature, and that the relationship between strength and stress wave speed in concrete is by no means conclusive. Any such relationship must be treated with caution.

This study is by no means comprehensive. There are many other factors that may also affect the stress wave speed in concrete, such as air entrainment, type of cement, the introduction of pozzolans (slag, fly ash, etc.), water reducers,… to name a few.

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