A Regression Model Predicting the Compressive Strength of Concrete by Means of Non-Destructive, Acoustic Measures

Paul Woods, Zeena Pinto, and Richard Burt
Texas A&M University / Clark Construction / Texas A&M University

INTRODUCTION

Concrete differs from other construction materials in that it can be made from an infinite combination of suitable materials and that its final properties are dependent on the treatment after it arrives at the job site. The efficiency of consolidation and effectiveness of curing procedures are critical for attaining the full potential of a concrete mixture[1]. While concrete is noted for its durability, it is susceptible to a range of environmental degradation factors, which can limit its service life. There has always been a need for test methods to measure the in-situ properties of concrete for quality assurance and for evaluation for existing conditions. Ideally, these methods should be non-destructive so that they do not impair the function of the structure and permit re-testing at the same locations to evaluate changes in properties with time.

The standard method of evaluating the quality of concrete in buildings or structures is to test specimens cast simultaneously for compressive, flexural and tensile strengths. The main disadvantages are that results are not obtained immediately; that concrete in specimens may differ from that in the actual structure as a result of different curing and compaction conditions; and that strength properties of a concrete specimen depend on its size and shape.

Although there can be no direct measurement of the strength properties of structural concrete for a reason that strength determination involves destructive stresses, several non- destructive methods of assessment have been developed. These depend on the fact that certain physical properties of concrete can be related to strength and can be measured by non-destructive methods. Such properties include hardness, resistance to penetration by projectiles, rebound capacity and ability to transmit ultrasonic pulses and X- and Y-rays. These non-destructive methods may be categorized as penetration tests, rebound tests, pull-out techniques, dynamic tests, radioactive tests, and maturity concept.

According to Mehta[1], the development of nondestructive test (NDT) methods for concrete has progressed at a slower pace compared to the development of NDT for steel structures because concrete is inherently more difficult material to test than steel. Concrete is highly heterogeneous on a macroscopic scale. It is electrically non conductive but usually contains significant amount of steel reinforcement. Thus it has not been an easy task to transfer the NDT technology developed for steel to the inspection of concrete.

THE REVIEW OF THE RELATED LITERATURE

Nondestructive Testing

Nondestructive testing is used to estimate the strength and to evaluate integrity, which usually involves in superficial local damage to the structure. Prior to World War II, methods to evaluate in-situ strength of concrete were adaptations of Brinell hardness for metals, which involves in pushing a high strength steel ball into a test piece under a given force and measuring the area of the indentation[2]. In metals test, the load was applied by a hydraulic loading system and so this had to be modified to be able to test concrete structure. In 1934 Prof. K. Gaede (Hanover, Germany) reported the use of a spring driven impactor to supply the force to drive a steel ball into the concrete[2]. The spring was compressed by turning a screw, a trigger released the compressed string, and the plunger was propelled toward the concrete. The diameter of the indentation was measured through a magnifying glass. D.G. Skramtajev[3] of the Central Institute for Industrial Building Research, Moscow summarized 14 different techniques, 10 of which were developed in the Soviet Union for measuring the in-situ strength of concrete. He divided the test into 2 groups, those that required installation of test hardware prior to the placement of concrete and those that did not require any pre-installation of hardware.

Methods described included the following: Molds placed in the structure to form in-place test specimens, pullout tests of embedded bars, an in-place punching shear test, an in-place fracture test using a pincer device, penetration of chisel by hammer blows, guns that fired indentors into concrete, and penetration of ball by spring driven apparatus. In many of the modern in-place testing are variations of methods suggested over one-half a century ago[2].

The post world war era brought in a great surge to develop the nondestructive test methods for concrete. It mainly focused on four methods: Ultrasonic pulse velocity, rebound hammer, maturity method, and radioisotopes. Of these the Ultrasonic pulse velocity is similar in some ways to the acoustic methods used in this study.

Ultrasonic Pulse Velocity

The Ultrasonic pulse velocity method is a stress wave propagation method that involves measuring the travel time, over a known path length, of a pulse of ultrasonic waves. According to Parker[4] the pulses are induced in the concrete by a piezoelectric transducer, and a similar transducer acts as a receiver to monitor the surface vibration caused by the arrival of the pulse. It is in turn connected to a timing circuit, which is used to measure the time it takes for the pulse to travel from the transmitting to the receiving transducers. The presence of low density or cracked concrete increases the travel speed and the lowers the pulse velocity. By conducting these tests at different points on the structure, locations with lower quality concrete can be identified by their lower pulse velocity.

In 1946 and 1947, engineers at the Hydro-Electric Power Commission of Ontario (Ontario Hydro) worked on the development of a device to investigate the extent of cracking in dams[5]. The device that was developed was called the Soniscope. It consisted of a 20-kHz transmitting transducer, which was capable of penetrating up to 15 meters of concrete and could measure the travel time with an accuracy of 3%. The stated purpose of a Soniscope was to identify the presence of internal cracking, determine the depth of surface opening cracks, and to determine the dynamic modulus of concrete.

During 1970's considerable attention was given to gaining further knowledge in this field. Researchers continued to explore the relationship between compressive strength and pulse velocity. However, there was no such valid relationship found. Studies showed that type and the quantity of aggregate had major effects on the pulse velocity but not on the combined strength of concrete.

All the above-mentioned methods formed the basis for new-age tools for nondestructive testing of concrete. The fields of smart structures and optic fibers are considered to be the latest in concrete construction. The term smart structure refers to a structure that can sense its environment and take appropriate remedial actions. At present there have only been conceptual ideas of how this technology might be applied to concrete. For example, according to Mehta[1] it has been suggested that capsules could be embedded into concrete, which would provide a substance to heal cracks that, might develop during its service life.

Impact-Echo Method

The impact echo is a nondestructive technique to evaluate concrete using acoustic signals. It was invented at the U.S. National Bureau of Standards in the mid-1980's and developed at Cornell University, in Ithaca, from 1987-1997. In 1997, the American Society of Testing Materials (ASTM) approved this new standard named "Standard Test Method for Measuring the P-Wave Speed and the Thickness of Concrete Plates Using the Impact-Echo Method." This method is based on the laws of elastic stress wave propagation through material. A stress wave is introduced into the test object by a mechanical impact. The stress wave consists of compression, shear, and surface waves. The reflections of the compression wave are analyzed to detect the internal flaws in a concrete member.

The most important advantage of the impact echo method is that access is required to only one side of the member. It can be used to detect voids and honeycombs in walls and slabs, delaminations and internal cracks, thickness measurement and depths of drilled piers and precast piles among many other uses. Our measurement technique also uses impact energy to propagate a sound wave through concrete.

THE DATA, TREATMENT, AND INTERPRETATION

The Data

Observational unit is a 4" diameter by 8" tall concrete test cylinder. Dependent variable is compressive strength of concrete measured in PSI

Independent variables are: Plant Location of Sample collection, Elapsed Time, Frequency, Minimum Sample Value, Maximum Sample Value, Peak Amplitude, DC Offset, Minimum RMS Power, Maximum RMS Power and Average RMS Power. Each of these independent variables will be expressed in three different forms. Impact One to Impact Two Values, Impact Two to Impact Three and the difference between the two.

The Criteria Governing the Admissibility of the Data

All of the independent variables were plotted against the dependent variable. These plots were then visually inspected for any obvious and extreme values. Additionally, each of the variables were sorted from maximum to minimum and inspected for any obvious out of range conditions.

Any record with two or more suspect fields was deleted. A cylinder was deleted if it did not contain at least three good records. There were a total of 422 observations over the original 85 cylinders in the study. Four complete cylinders were deleted and nine individual observations were deleted.

The Research Methodology

Concrete test cylinders were obtained from ready-mix plants located in three cities, Houston, San Antonio and Victoria. The samples were stored in temperature and humidity controlled environment. Cylinders were then tested at 7, 28 and 56-day maturities.

After removal from storage these cylinders were cleaned and placed in the AIRS test stand. Using Cool Edit and Laptop computer digital recordings were made of five impact events. See Figure 1 for the experimental setup. An Impact event was created by dropping a steel ball from a constant height on to the top of the test cylinder. The cylinders were then tested using a hydraulic ram where they were crushed to determine their compressive strength.

The digital recording was loaded into Cool Edit 2000. The acoustic waveform of an impact event was highlighted. All the acoustic measurements were then calculated within Cool Edit for the selected waveform. These values were then entered into an Excel spreadsheet and all second order interactions were calculated.

Correlations were run all first and second order independent variables and the dependent variable. The absolute values of all Co-efficient of Determination (R^2) were computed. All were sorted by these co-efficient from high to low. This produced a rank order list of candidate independent variables for multiple liner regression.

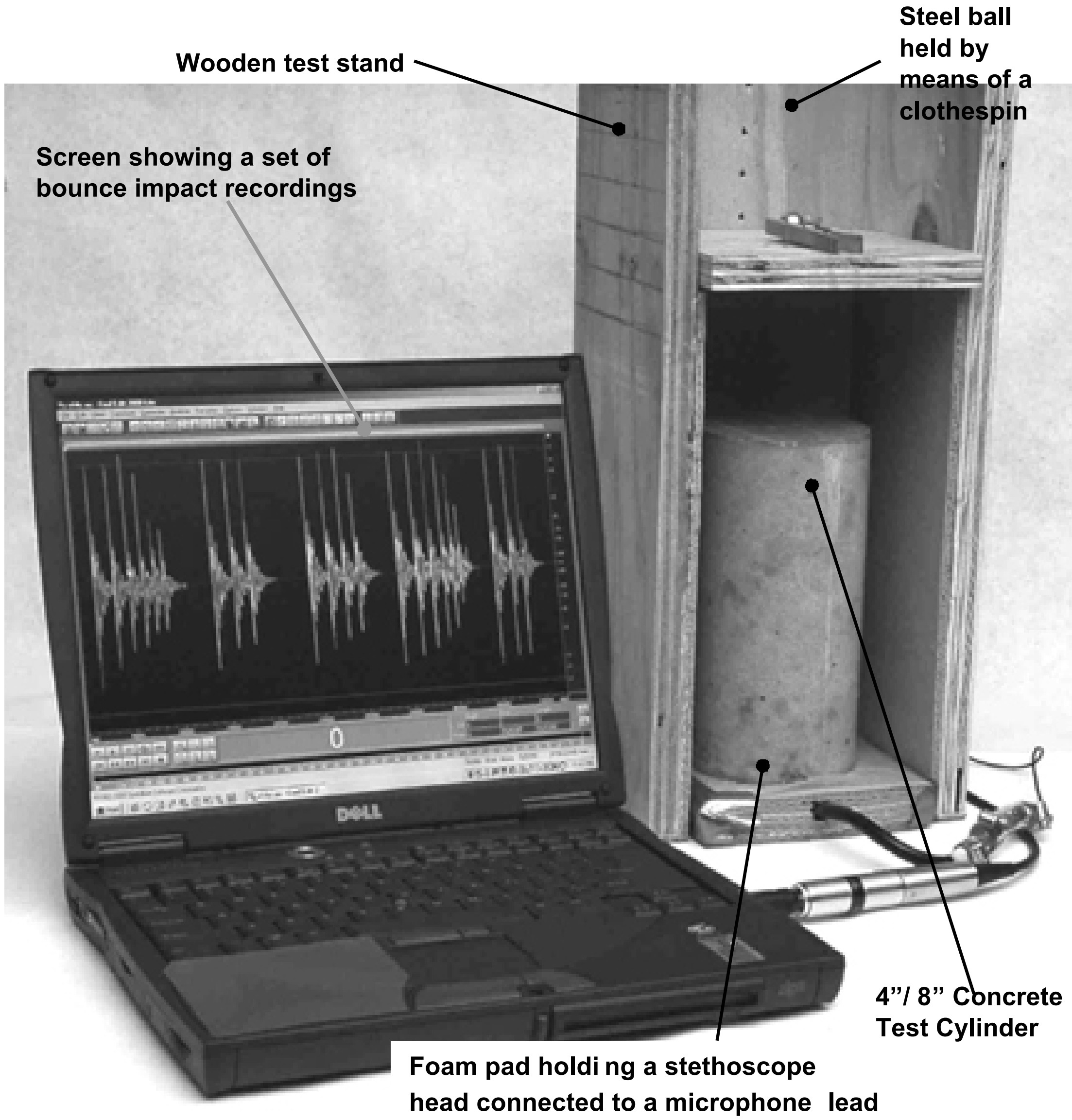

Figure 1. The Experimental Setup

Variable selection started at the top of the rank-order list. An independent variable was chosen for inclusion in the initial regression model if it had an R^2 of over 0.15 with dependent variable and had R^2 of less than 0.40 with any other independent variable. The purpose of this process was to select most likely candidate independent variables while limiting potential multicollinearity.

A multiple regression analysis was performed on these candidates to determine if there was any significant treatment effect on the dependent variable, compressive strength, due to any of the independent variables.

A model was then constructed a model which predicted the compressive strength of a concrete sample based upon a significant set of independent variables. An independent variable was deemed appropriate to be included in the final regression equation if it was significant at p-value<0.05

Experimental Setup

A test stand was constructed with ¾” plywood that holds a 4”x8” concrete test cylinder. Provisions were made in the test stand such that a steel ball could be dropped from a consistent height each time. This cylinder rested on the Acoustic Information Retrieval System (AIRS) sensor, which consisted of a microphone connected to a stethoscope head. The microphone was connected to the sound port of a laptop computer and sound impact was digitally recorded using software called Cool Edit 2000. See Figure 2 and 3.

Cool Edit 2000 is a software package which is easy to use digital audio recorder, editor, and mixer.

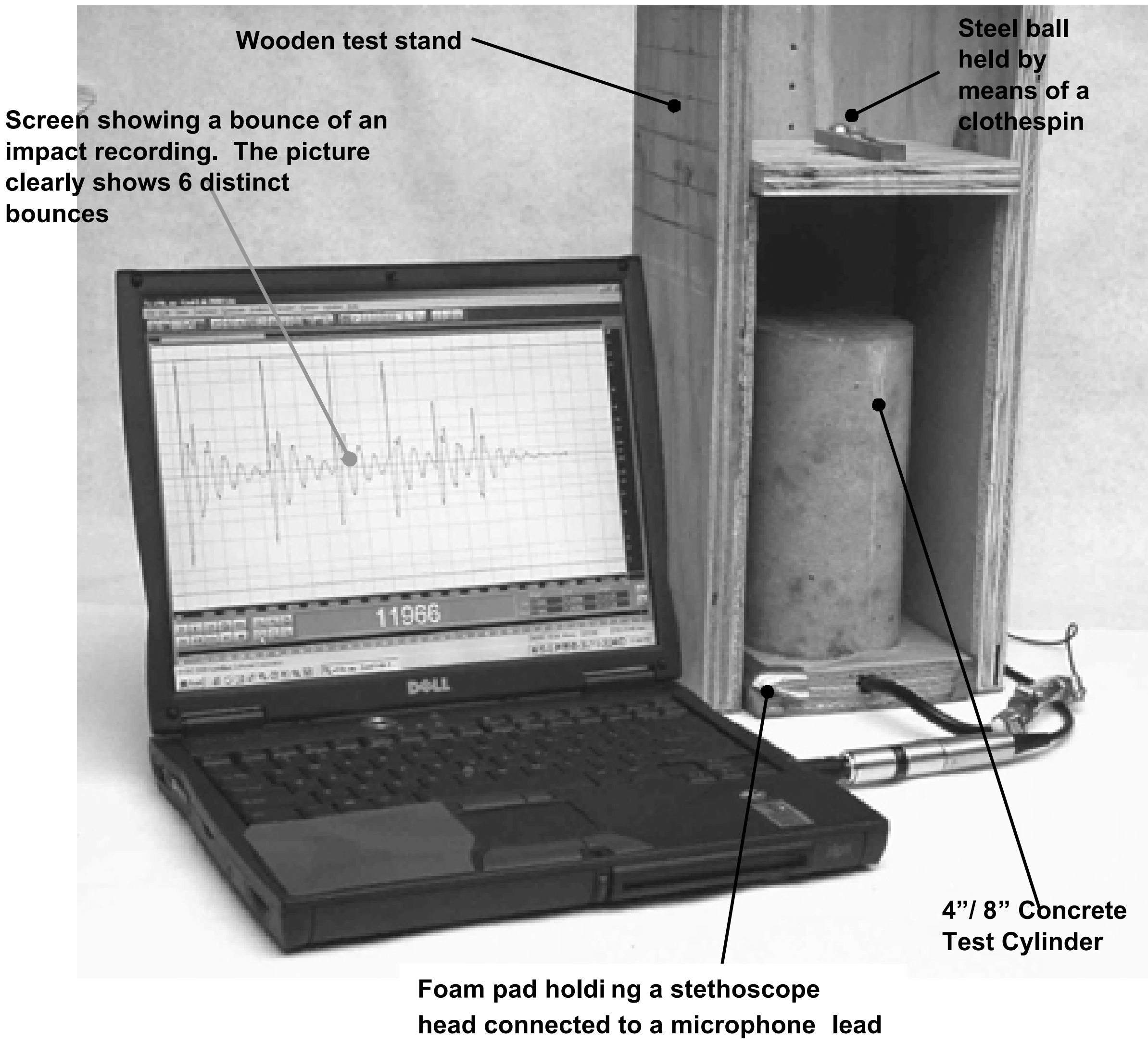

Figure 2. Experimental Setup Showing a Selected Impact

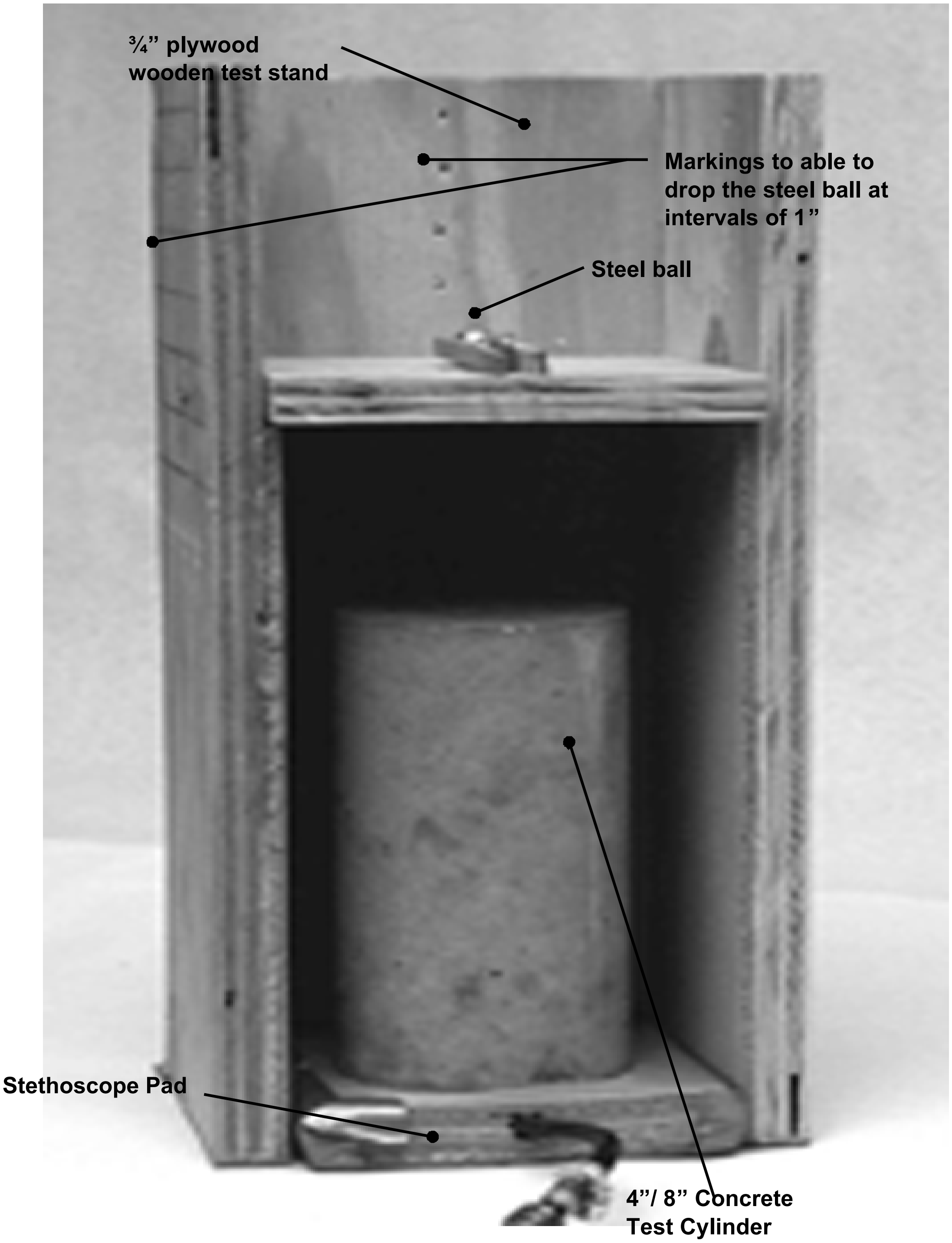

Figure 3. ¾ " Plywood Test Stand Showing Concrete Test Cylinder on Stethoscope Pad.

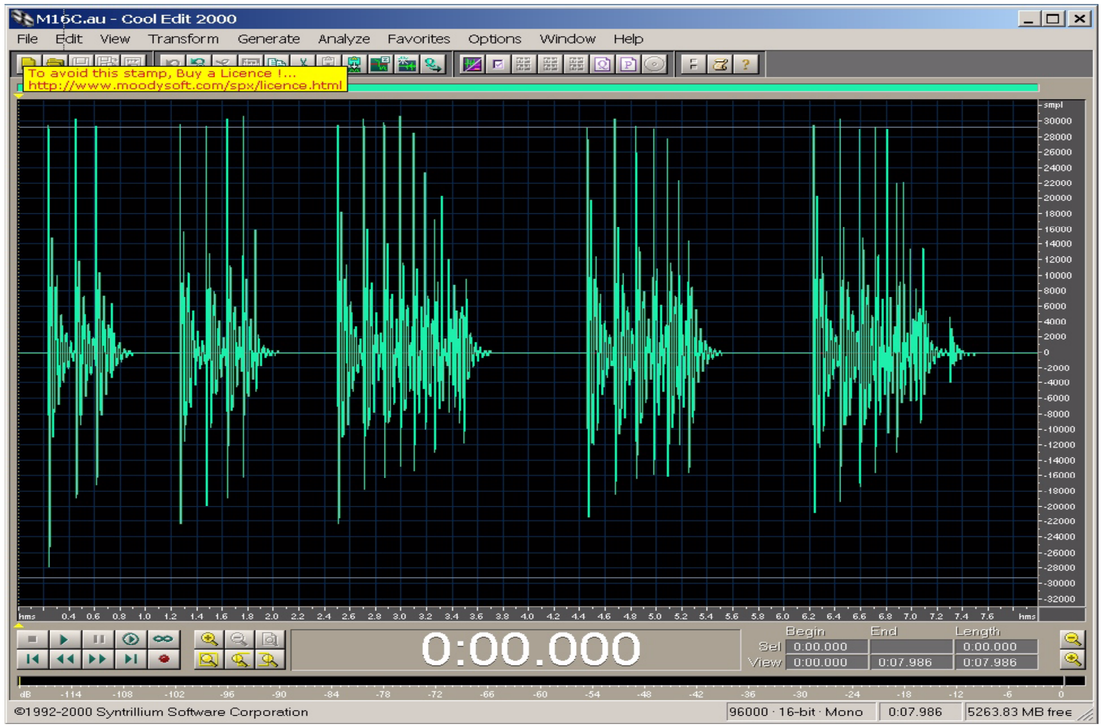

Figure 4. A Typical Acoustic Observation Showing Distinct Bounces on Five Different Concrete Test Cylinders Using Cool Edit 2000

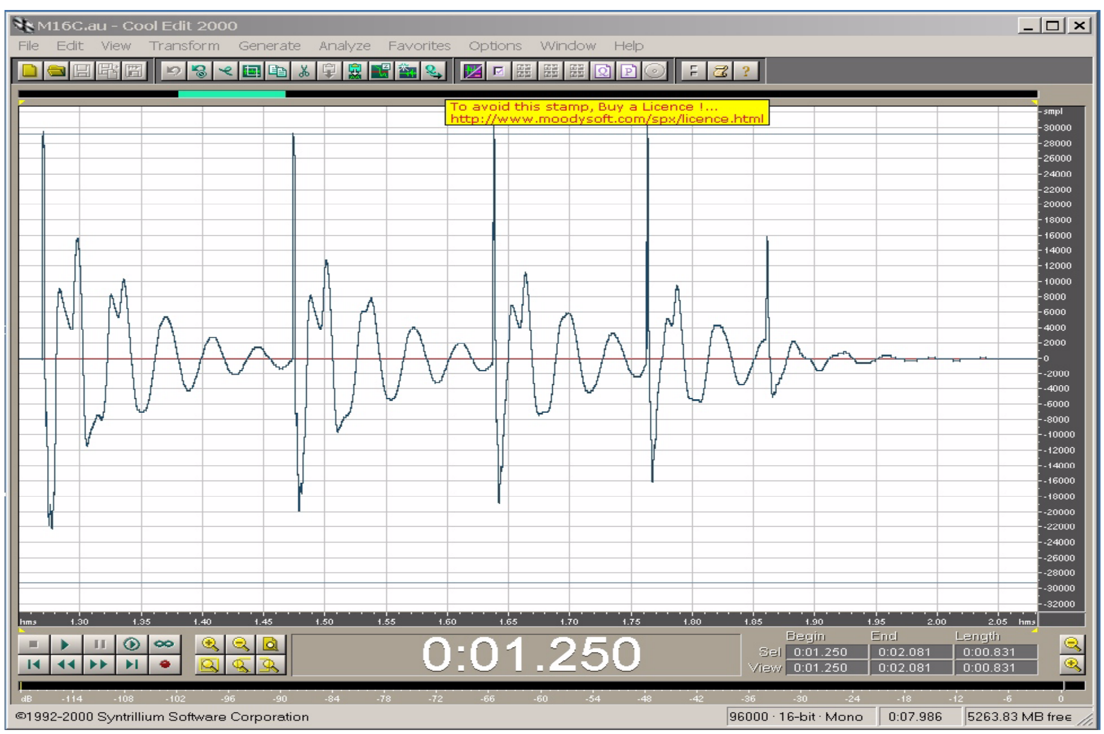

Figure 5. A Typical Acoustic Observation Showing 6 Distinct Bounces on Cool Edit 2000

THE STUDY FINDINGS

The Tests of the Hypotheses

The following independent variables were found significant and included in at least one of the three regression models: Location (H and M), Elapsed time from peak-two-to-peak-three (ET2), Frequency 1 minus Frequency 2 (Freq1-Freq2). Each of these were significant at p-value<0.05. See ANOVA tables 1 and 2 for the summary output.

Hypothesis 1

The proposed regression model for First-peak-to-Second-peak and Second-peak-to-Third-peak First order variables is:

Compressive Strength = $B_0 + B_1$ Minimum RMS Power + B_2 Frequency + B_3 Minimum Sample + B_4 Peak Amplitude + B_5 Location +E.

Although the above model was not accepted as proposed, a model of this form was found to be highly significant. The independent variables were found significant at p<0.05: Location (H and M), Elapsed time from peak-two-to-peak-three (ET2). See Table 1 for the ANOVA output.

The final model accepted for this hypothesis is:

Compressive Strength = $B_0 + B_1 H + B_2 M + B_3 ET2$ +E. This model had a p-value<0.0001and had an Adjusted R^2 of 0.8457.

Table 1

Analysis of Variance of Compressive Strength Using Location H, Location M and Elapsed Time from Peak-Two-To-Peak-Three.

Regression Statistics	
Multiple R	0.92276935
R Square	0.851503
Adjusted R Square	0.8457177
Standard Error	454.58899
Observations	81

ANOVA	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	3	91242686	304142	147.1767	8.44357E-32
Residual	77	15912139	206651.2		
Total	80	107154826			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	6447.2027	1416.8666	4.55032	1.97E-05	3625.857479	9268.547
H	-1378.5882	125.95021	-10.9455	2.35E-17	-1629.387437	-1127.789
M	-2602.6217	142.28643	-18.2914	9.43E-30	-2885.95054	-2319.292
ET2	33177.547	8648.3106	3.8363	0.000254	15956.5401	50398.554

Based on the results of the analysis, the regression equation can be written as:

Compressive Strength = 6447.202709 – 1378.58823* *H* – 2602.62171* *M* + 33177.54748* *ET2*

Hypothesis 2

The proposed regression model for First-peak-to-Second-peak minus Second-peak-to-Third-peak First-order variables is:

Compressive Strength = $B_0 + B_1$ Minimum RMS Power + B_2 Frequency + B_3 Minimum Sample + B_4 Peak Amplitude + B_5 Location +E.

Although the above model was not accepted as proposed, a model of this form was found to be highly significant. The independent variables were found significant at $p<0.05$: Location (H and M), Elapsed time from peak-two-to-peak-three (ET2) and Frequency 1 minus Frequency 2 (Freq1-Freq2). See Table 2 for the ANOVA output.

Table 2

Analysis of Variance of Compressive Strength using Location H, Location M and Elapsed Time from Peak-Two-To-Peak-Three.

Regression Statistics	
Multiple R	0.92846386
R Square	0.86204514
Adjusted R Square	0.85478435
Standard Error	441.029432
Observations	81

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	92372296.6	2309307	118.7262	6.89254E-32
Residual	76	14782528.95	194507		
Total	80	107154825.6			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	6981.74742	1392.38548	5.014235	3.39E-06	4208.567847	9754.92
H	-1365.83652	122.3078564	-11.1672	1.08E-17	-1609.434047	-1122.2390
M	-2617.52212	138.1806907	-18.9427	1.64E-30	-2892.73317	-2342.3110
ET2	30362.6705	8471.261725	3.584197	0.000595	13490.669	47234.672
Freq1-2	110.485195	45.84662527	2.409887	0.018377	19.17361038	201.79678

The final model accepted for this hypothesis is:

Compressive Strength = $B_0 + B_1$ *H* + B_2 *M* + B_3 *ET2* +B_4 *Freq1-Freq2* +E. This model had a p-value<0.0001and had an Adjusted R^2 of 0.8548.

Based on the results of the analysis, the regression equation can be written as:

COMPRESSIVE STRENGTH = 6981.74742 -1365.836528* *H* -2617.5221* *M* + 30362.67057* *ET2* + 110.4851952 *Freq1-Freq2*

Summary of Results

Although the proposed form of both hypotheses were not accepted as originally proposed, a highly significant version of each was found. Each of these Models were significant at a p-value<0.0001 with an Adjusted R2 near 0.85. Each of the independent variables included in the model had a p-value<0.05. In fact most were significant at p-value<0.01.

CONCLUSIONS

This study provides evidence supporting the claim that the compressive strength of concrete test cylinders can be predicted by a combination of acoustic measures and mix characteristics as indicated by the location of the sample source. Three models were developed and each was highly effective as indicated by an adjusted R-square of near 0.85.

RECOMMENDATIONS FOR FUTURE STUDIES

Our test stand could use some improvement. It may be that releasing the ball by means of a switched electromagnet would provide a bit less variability. It would also be nice to have a means of leveling the cylinders so that the surface is exactly parallel to the ground plane. It may also be worthwhile to carry out the same measurements over different frequency bands.

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