PREDICTING CURRENT COMPRESSIVE STRENGTH OF CONCRETE BASED ON NON-DESTRUCTIVE TESTING BY WAY OF SOUND

A Senior Honors Thesis

by

EMMIT KEVIN COOTS

Submitted to the office of Honors Programs
& Academic Scholarships
Texas A&M University
In partial fulfillment of the requirements of the

UNIVERSITY UNDERGRADUATE
RESEARCH FELLOWS

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ABSTRACT

Predicting Current Compressive Strength of Concrete Based on Non-Destructive Testing by Way of Sound.

(April 2001)

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There are many ways to test the compressive strength of concrete to include both destructive and non-destructive methods. There are many pros and cons associated with the various methods of testing to include cost, size, and method associated with each piece of equipment. The most common types of testing are the hydraulic compression test, the rebound test, and the maturity test. An alternative method proposed that would give individuals another means to test concrete in a non-destructive manner. The purpose of this research is to determine the current compressive strength of concrete by analyzing the acoustic pattern of a sound made by a hammer striking the surface of a concrete cylinder in a lab environment. Concrete cylinders were made in the traditional fashion and the sound generated when a ball-ping hammer strikes the cylinder was recorded then analyzed. The cylinders were tested on a daily basis and their compressive stress was recorded. Linear regression was used to try and predict the compressive strength of the concrete cylinders. The regression model chosen using the stepwise selection method could only account for 43% of the variation in the compressive strength. The duration of the sound wave was the best predictor of the compressive strength.

Table of Contents

Page

LIST OF FIGURES

LIST OF TABLES

Introduction

Compressive strength is the most commonly tested property of concrete, despite the fact that other characteristics of this widely used construction material may be more important. This is true for three reasons. First, the compressive strength of concrete is the most closely related to the quality of concrete produced from cement, which gives a direct indication of it capacity to resist loads. Second, routine strength tests are relatively easy to make. Third, concrete strength can be related to a number of other important properties that involve more complicated tests. (Klieger, 1994)

Concrete strength tests are used to determine if certain strength specifications have been met for a particular construction project or if the mix proportions are adequate for a particular job. When a batch of concrete is ordered, the required compressive strength is specified. Field-testing is used to verify these given specifications of concrete. Every time concrete is placed on a job site, it is tested. A sample portion of each and every batch is placed in test cylinders, which measure six inches in diameter and twelve inches in height. The samples are cured for twenty-eight days under ideal conditions, and tested for the desired qualities (Popovics, 1998). There are many ways to test a batch of concrete for strength. The three tests that are used in industry today are the hydraulic compression test, the rebound test, and the maturity meter test. The first being destructive and the later being non-destructive.

Current Methods of Testing Compressive Strength of Concrete

Compression Test Method (Destructive)

The primary function of concrete is to resist compressive stresses. Thus, the compressive strength of concrete is a very important property. Even when concrete is used in applications where other stresses are of primary importance, the compressive test is used because it is the easiest property to measure. The results of this test are generally used as a measure for the quality of concrete. Concrete compressive strength testing started about one hundred years ago. Today, this technique is regulated by ASTM standard C39-96 (Goode, 2001). In the United States and Canada, cylindrical samples are used in testing. The standard cylinder size is six inches in diameter and twelve inches in height. The concrete specimens that are to be tested can be made either in the field or in a laboratory. When the concrete is mixed properly, it is then placed in molds, in three layers of equal amount. Each layer compacted with a steel rod that is five-eighths of inch in diameter. Each layer is "rodded" with twenty-five blows so that each layer is compacted equally and that there are no air voids in the specimen. After twenty-four hours, the specimens are taken out of the molds and stored under water to cure at a constant temperature until test time. The moist cured cylinder is tested immediately after removal from the water storage tanks, or humidity room, in a moist condition (Klieger, 1994). Once the specimen is removed from storage both the top face and bottom face are wiped clean. The cylinder is placed in a mechanical testing device so that it is precisely centered on a thruster to obtain the best possible results. Once the test begins, the thruster applies a compressive load to the specimen at a constant rate and with shock. The load is applied at a rate of twenty to fifty pounds per square inch per second, until the concrete fails. Once the specimen fails, the maximum load that was applied is recorded for use in calculating the compressive strength. Most machines in the industry measure the loading results in both ram-pounds and pounds per square inch. ASTM C39-96 allows rounding this number to the nearest 10psi. Currently, this is the most accurate method of testing concrete and is used worldwide. This method was used to attain the most accurate results for our test (Popovics, 1998).

Rebound Testing (Non-Destructive)

Among all the rebound methods, the most popular instrument for measuring the hardness of concrete is the Schmidt Hammer. Ernst Schmidt developed this in Switzerland circa 1948. Rebound testing is regulated by ASTM standard C805-97. The Schmidt rebound hammer is usually less than 10 inches long and only weighs about 1.8kg. It can be used both in a laboratory and in the field. The rebound hammer is most useful for quickly surveying large areas of concrete in the same location (Baker, 1962).

This method of rebound testing is easy to use and inexpensive, which is among the reasons for its popularity rather than its accuracy. The components of the testing device consists of a plunger, steel hammer mass, a main spring, a latching mechanism, and a linear glide scale. The hammer body is pressed against the surface of the concrete that is to be tested and then the spring propels the hammer mass toward the tip of the plunger thus causing it to rebound. When the rebound is at its peak, the slide indicator records numerical data that can be read from the scale (Klieger, 1994). This number represents the magnitude of the rebound, which is a measure of the superficial hardness of the tested material. The higher the rebound numbers the stronger the concrete.

Theoretically, the principal behind this method is that the harder the concrete surface, the higher the rebound will be. This will give the user a higher compressive strength. One test is not enough to determine accurate results, so the test must be repeated to provide a reliable average value. Each test is taken in a different location, yet closely spaced together. Many factors can affect the results of the test. For example, various hammers of the same design may result in different rebound numbers, so the same device should be used for all tests on the same construction project. If numbers are to be compared, the direction of the impact, such as horizontal or downward, must be the same. The test surface can also affect the rebound number. Some factors include the smoothness of the surface, its size and shape, moisture conditions of the concrete, and even its age. The type of cement and coarseness of the aggregates inside the concrete can affect the results. The limitations of the Schmidt hammer should be considered when using it. The hammer cannot be over stressed and should never take the place of a standard compression test. The hammer provides only a rough idea of the quality of concrete, and should always be verified with a second method (Baker, 1962).

Maturity Method (Non-Destructive)

When concrete is correctly cured, its strength increases with time. However, the strength is also controlled by other more important factors, such as temperature and moisture in the curing atmosphere. These combined factors make up the maturity of concrete, and have been studied by many investigators since 1904. There are two maturity functions or mathematical expressions, which aid in computing the strength development in concrete. The first engineering applications of the maturity method for estimating concrete strength was carried out by a gentleman named Swenson, in Canada. A Maturity meter is a device that monitors and records the concrete temperature as a function of time. Its ability to predict the compressive strength is based upon the history of the concrete curing which involves the temperature history and the availability of water to the concrete (Klieger, 1994). Temperature sensors called thermo couples or thermistors, are connected to steel reinforcement within the concrete and are activated prior to concrete placement. These sensors are connected by a cable that runs through the concrete to a maturity meter, strip-chart recorder or digital data-logger. The maturity meter reads the temperature sensor every half-hour displaying the temperature in degrees Celsius, accumulated hours, days and degree-hours. This device is left unattended for up to 45 days as it collects the maturity data. At the end of the recording phase, the wire from the temperature sensor is cut near the surface of the concrete and the maturity meter is disconnected (Klieger, 1994).

A disadvantage of the maturity method is that the concrete must be carefully and appropriately monitored depending on specific mixtures so that it stays properly hydrated. In addition, the method does not accommodate the early testing of concrete by temperature for its ultimate long-term strength. Under the guidelines of ASTM standard C1074-98, the maturity method should not be an independent means of testing. It should always be supplemented with a secondary method. The maturity method is used to estimate the in-place strength of concrete but it does not test the quality of the concrete. The properties of time, temperature and moisture must be supplied correctly in order to determine the true maturity of any concrete (Popovics, 1998).

AIRS System (Acoustical Information Retrieval System)

The AIRS System was designed by Paul Woods, John Bryant, Ken Parker, Kevin Shea, and Hoonsik Seo from Texas A&M University located in College Station, Texas. The system retrieves acoustic information, recognizes acoustical patterns, and then stores resulting data. The system has been tested and is proven to be successful in determining useful information concerning plumbing fixtures. Water flow in each fixture provides a unique acoustic profile that the computer is trained to recognize. This data can be used to monitor fixtures and water usage within a building. Ken Parker developed the microphone utilized in this testing technique during the initial phase of development of the AIRS System. The AIRS System is currently being refined so that it can be utilized for many different types of research.

Intended Use of AIRS System

The AIRS system is used to try and predict the compressive strength of concrete by analyzing certain properties of the acoustic profile of sound that is produced when a hammer strikes the surface of a concrete cylinder. This will be done utilizing a microphone and a computer program called Cool Edit®. The acoustic waveform caused when a ball ping hammer hits a concrete cylinder will be recorded in the Cool Edit® program. Data will then be extracted from the system and analyzed using regression techniques and Pearson's correlation.

Objective

The purpose of this research is to determine the current compressive strength of concrete by analyzing the acoustic pattern of a sound made by a hammer striking the surface of a concrete cylinder in a lab environment. Data obtained in a lab environment more accurately defines and reduces many imperfections of site poured concrete. If the test proves that sound can be used to indicate the compressive strength of concrete, then a new means to test concrete can be devised. This new method may provide important advantages to the common test procedures that are currently used. A sound testing device may be developed that will produce results that are as accurate as a hydraulic compressive tester while eliminating the need for a laboratory or certified technician. This concept may produce an effective means of field-testing concrete. The advantages of being able to verify the compressive strength of concrete in the field, greatly reduces the amount of time spent on testing concrete in a lab plus reduces fees charged by lab technicians. Then the destructive compressive method would only have to be utilized when a second measure of compressive strength is needed or if test results must be very accurate. In addition, it could give field personnel on construction projects an effective way to verify if they were meeting the specifications indicated in the contract documents, and a means of determining if concrete forms could be stripped so that other construction activities could begin. This could be beneficial to the contractor both financially and for reducing the duration of the project. A sound testing device could also prove to be more reliable than the maturity method or the rebound method because neither one of the methods test the quality of concrete and should only be used as a secondary test.

Methodology

The purpose of this research is to determine the current compressive strength of concrete by analyzing the acoustic pattern of a sound made by a hammer striking the surface of a concrete cylinder in a lab environment. During the Fall Semester a small pilot test was conducted. Eight cylinders were made and tested throughout the twenty-eight day cure cycle of the concrete samples. The eight samples gave ample coverage of the twenty-eight days and provided sufficient data. This data showed a good indication that there was enough evidence to continue the experiment with a more extensive test consisting of five cylinders per day for thirty days. The pilot test was used to correct deficiencies in the testing procedure before the larger-scale test was performed. During the test, the data obtained included a large amount of excessive noise, which required adjustments to the apparatus being used. The computer program was also adjusted as a result of the pilot test, to facilitate the collection of more consistent data.

During the Spring Semester 2001, the actual test was carried out to determine if the compressive strength of concrete could be predicted by analysis of the sound made by the strike of a hammer on a concrete cylinder. On February 22, 2001 one hundred and eighty cylinders were made. The cylinders were made at CME Engineering lab in College Station, Texas. The concrete used was 3,500 PSI, mix 351 and was being supplied by the Transit Mix Company located in Bryan, Texas. The three yards that were used contained four hundred pounds of aggregate per cubic yard, twenty-percent ash, and a water reducer to make the concrete more workable. This is the most widely used mix by Transit in the Bryan, College Station area. When the truck arrived, the experiment was treated as if actually on a construction project, and the concrete was tested as a company would normally do.

The first stage in making the cylinders is to perform a slump test. The slump test determines the consistency of unhardened concrete. The test is performed with a cone shaped device that is open on both ends. The base is eight inches in diameter and the top is four inches with a height of twelve inches. The first step is to dampen the cone and place it on a rigid surface that is nonabsorbent. Then, the cone is filled in three equal layers of concrete and each layer compacted with twenty-five strokes of an iron rod. Once the final layer is achieved the excess concrete is leveled off with the top of the cone. Immediately thereafter, the cone is removed with a steady vertical pull and placed next to the concrete. The rod is placed across the top of the cone and the distance from the rod to the peak of the "slumped" specimen is measured. This concludes the slump test, and the measurement will be reported in terms of inches. The slump of the concrete used for the test was five and a half inches. The temperature of the concrete was also taken when it arrived, at approximately 73°F.

The next phase of the testing was making the actual cylinders. Standard molds of six inches in diameter by twelve inches deep were used. The molds used in a field environment are rigid and hold their shape, non-reactive with concrete, and watertight. The molds are placed on a rigid surface that is level and free from any disturbances until the molds are removed, normally after a twenty-four hour period. The cylinders are made by placing three equal layers called "lifts" of concrete into the molds, while rodding them twenty-five times per lift. The first lift is rodded completely through the entire layer while distributing the rodding equally across the cross section of the mold. The second two lifts are rodded through the entire layer to penetrate the previous layer approximately half-inch. After each layer is rodded, the outside of the mold is tapped gently to close any of the rodding holes and release any air bubbles that may be in the concrete. After all three lifts are performed, the excess concrete is leveled with the top of the cylinder and the final layer smoothed using an appropriate finishing tool. Immediately after the finishing procedure is completed, the cylinder is capped to avoid evaporation of water in the specimen. Once the cylinders are cured on site for the initial twenty-four hour period they can then be taken to the lab, stripped of the plastic mold and placed in a moist condition within thirty minutes of being stripped. This may be a curing room that provides one hundred percent humidity, or in tanks filled water, water was used for our test due to availability. The room temperature, or water temperature, depending on what method is used is maintained at 73° ± 3°F.

Approximately twenty-four hours after this process was accomplished, testing began using five cylinders per day for the next thirty days. The cylinders were tested by striking the cylinder with a hammer five times, and recording the resulting sound. The average of the five readings was taken for the independent variables. Extra cylinders were made in case any were lost due to unfortunate accidents involving the testing equipment or the cylinder itself. Each day, five cylinders were tested while retrieving the data using the Cool Edit® system. The Cool Edit® system is a digital audio recorder, editor, and mixer program. It was chosen due to the analysis program that is built directly into the system. Once each cylinder was taken from the curing tank, it was placed in the apparatus that was designed and constructed to hold the cylinder while retrieving the sound data. The apparatus, shown in Figure 1, was a two-foot by two-foot hollow wooden box that was approximately two-foot deep.

Figure 1: Apparatus used for testing cylinders.

The bottom of the box was filled with twelve inches of grout so that the cylinder sat on a solid surface. On top of the grout, a semi-spongy flat mat was placed to reduce the effects of any imperfections in the cylinder or grout itself. This allowed the cylinder to remain upright during the testing phase. On the top of the apparatus was a ball-ping hammer, utilized for creating the sound waves that were recorded. The hammer weighed approximately two and a half pounds. It was attached to the box with two small angle brackets. A pre-drilled hole was placed in the handle of the hammer, and then attached it the brackets with a bolt to allow the hammer to pivot freely. The brackets were oriented so that when the hammer was released from an elevated position, the head would strike the top of the concrete cylinder flush. Between the attachment for the hammer and the center of the cylinder was the mechanism for dropping the hammer. Two eight-inch brackets that had pre-drilled holes in them were used to hold the hammer upright. The brackets were placed strategically so that when the hammer was at rest, in the upright position, it was at a forty-five degree angle to the surface of the cylinder. To hold the hammer at rest a straight sixteen-penny nail was used. The system allowed a smooth release of the hammer to strike the cylinder. As the hammer struck the surface of the concrete cylinder, the resulting sound was recorded. This was done with a microphone system designed by Ken Parker. The microphone system was made with a metal junction box used by electricians for outlets. Inside the box was a stethoscope that was spring loaded so that the flat area of the stethoscope lay directly in contact with the wall of the junction box. Inside the stethoscope tube was the microphone that attached to a computer or tape recorder system that could record the sound being made by any number of sources in direct contact with the junction box. Attaching the junction box to the concrete cylinder as the hammer impacted it, allowed the resulting sounds to be entered directly into the Cool Edit® program. Once the record button on the Cool Edit® system was activated, the nail could be removed to allow the hammer to drop freely and strike the cylinder. This procedure was repeated five times per cylinder to give a large range of data to evaluate. Once the acoustical data was retrieved from the cylinder, it was immediately tested for compressive strength using a hydraulic tester. From this machine, the strength of the cylinder was reported both in ram pounds and pounds per square inch.

The evaluation process began by taking the information correlated to the compressive strength from Cool Edit®, as well as information taken from the footprint of the sound both visually and from various data analysis options within the computer program. First, the waveform or footprint of the sample was used to determine how many times the viewer perceived the hammer to bounce. The number of peaks in the waveform were counted to obtain the number of bounces of the hammer. This is the first of the independent variables that was used to predict the compressive strength of concrete. Figure 2 shows a typical waveform from the Cool Edit® program. This waveform shows approximately five peaks, indicating five bounces of the hammer. Each time the hammer bounced there was a definite peak then a lull in the sample. Only towards the end of the footprint was it difficult to determine exactly how many more times it bounced. Many times this was an estimate, but normally could be determined fairly closely.

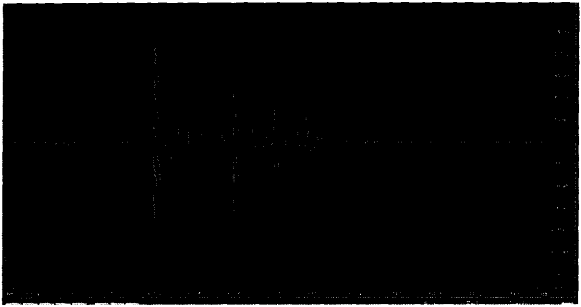

Figure 2: Waveform from Cool Edit®

The footprint of the waveform was outlined as to what the viewer felt was the full duration of the footprint. This initial outline gave the duration of the sound sample as it traveled through the cylinder. The duration lasted from the largest peak until the sound had terminated. The duration of the waveform was another independent variable. Next, the viewer began to record the information that Cool Edit® retrieved from the analyze function. All of these variables are independent variables in the test. The definitions of the statistics recorded were taken directly from the Cool Edit® system to give the most accurate portrayal of the data reported. First, the frequency was recorded. The frequency was measured in Hertz (Hz), and is defined as the rate at which the sound cycles per second. The cycle is when the sound travels from its point of origin (0) through the positive and negative amplitudes then returning to zero. This is the determination of the pitch of the sound. Figure 3 shows the frequency being recorded and the analytical portion of the system that shows the statistics related to the waveform.

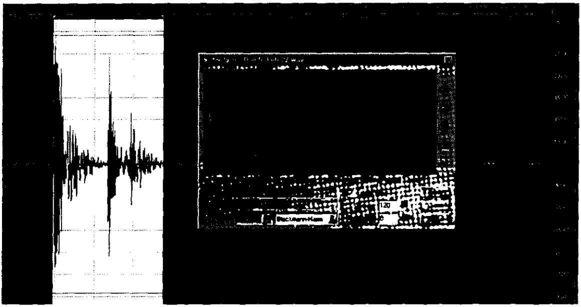

Figure 3: Outlined Waveform in Cool Edit® with Frequency

The sample minimum and maximum value showed the lowest and highest values in the range. The peak amplitude is the absolute maximum sample value given in decibel form. If the amplitude reaches a certain height, the sample is referred to as "clipped". This height is set at –32768 or 32767 for a 16-bit computer. Clipping causes the signal to distort and appears in the display as a "chopping-off" of the top of the waveform. Initially, the current is introduced into the center of the card causing the waveform not to be exactly centered in the waveform display. The DC offset, or direct current, measures the center of the waveform. Positive values are above the center of the line, the center being zero, and negative values are below. The RMS minimum, maximum, and average power was then taken. This is the root mean squared, which takes the sound closer to what the ear actually hears. Also, taken from the footprint was the difference of the RMS maximum power of the first peak from the RMS maximum power of the second peak. Figure 4 shows how the majority of the data was obtained. The Cool Edit® program has this option built in.

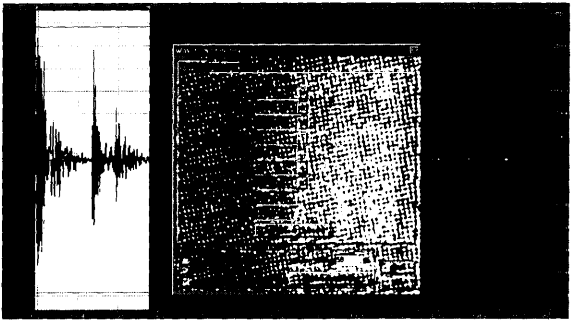

Figure 4: Outlined Waveform in Cool Edit® with Data

Once the data was taken, the waveform was outlined from the first peak to the second peak. This duration of the difference between peaks gave one more independent variable to plot against the dependent variable. The independent variables were taken from the waveform then the dependent variable was found. This procedure was the actual breaking of the cylinder on the hydraulic tester to give the ram pounds and pounds per square inch (PSI).

Statistical Analysis

Table 1 shows the mean, minimum, maximum, and standard deviation for the dependent and independent variables.

Table 1. Descriptive Statistics of the Dependent and Independent Variables.

	Average	**Minimum**	**Maximum**	**Standard Deviation**
Dependent Variable				
Compressive Strength (PSI)	4364	1732	6113	836
Independent Variables				
Number of Bounces	4.11	2.40	5.60	0.68
Estimated Time	0.41	0.24	0.58	0.07
Frequency	255.66	96.79	664.92	105.74
Sample Minimum	-23399	-32146	-13619	3632
Sample Maximum	26560	15019	32767	3580
Peak Amplitude	-1.79	-6.83	-0.02	1.15
Clipped Samples	0.63	0.00	10.40	1.66
DC Offset	0.41	0.27	0.58	0.10
RMS Minimum	-35.32	-40.90	-24.91	2.43
RMS Maximum	-12.12	-17.36	-7.85	1.59
RMS Average	-21.35	-27.27	-11.50	2.28
Peak One Maximum	26560	15019	32767	3580
Peak Two Maximum	20409	9044	30667	4259
Difference Peak 1-Peak 2	6151	929	19067	3354
Duration From Peak 1 - Peak 2	0.17	0.10	0.22	0.02

The first statistical test was Pearson's Correlation. This correlation is used with two variables and determines the degree to which the variables are related. Pearson's Correlation ranges from +1 to −1 in value. A positive one reflects that there is a positive linear relationship between the two variables being tested. A negative one means that there is a negative linear relationship between the two variables being tested. A zero as the result means there is no linear relationship between the two variables being tested. Rarely are the results ever a zero, positive one, or a negative one. The best correlation was between the compressive strength (PSI) and the duration of the sound wave (duration). Table 2 shows the results of the correlation between Duration and the compressive strength (PSI), and Figure 4 shows graphically the relationship between these two variables.

Table 2: SAS Output for Pearsons Correlation between Duration and PSI.

```
                              The CORR Procedure
                          Variables:  PSI    Duration
                               Simple Statistics
Variable      N        Mean      Std Dev      Sum       Minimum    Maximum

  PSI        150       4364       835.74     654541       1732       6113
Duration     150     0.17415     0.02478    26.1232      0.0966     0.2198

                    Pearson Correlation Coefficients, N = 150
                          Prob > |r| under H0: Rho=0

                                   PSI      Duration
                      PSI        1.00000    0.62735
                      PSI                   <0.0001
                    Duration     0.62735    1.00000
                    Duration     <0.0001
```

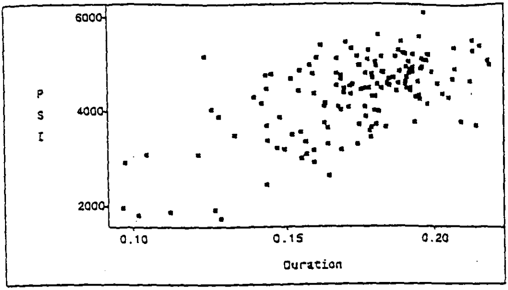

Figure 4: Scatter plot of PSI v. Duration from SAS output.

After the correlation, the SAS system was used to run Stepwise Regression. The data plotted against the dependent variable is called the predictor, explanatory, or independent variables. To do this the data was entered into the SAS computer program for regression. The SAS System was used for testing due to its data, mathematical, and statistical analysis capability

In the process, Stepwise Regression was used, which builds on a simple forward regression. Forward regression begins by finding the variable that produces the optimum one variable model. In the second step, the procedure finds the variable that when added to the already chosen variable, results in the largest reduction in the residual sum of squares or the largest increase in R^2. The third stage finds the variable that when added to the second value already chosen, gives the minimum residual sum of squares or maximum R^2. The process continues until no variables considered for addition to the model provides a reduction in sum of squared considered statistically significant to model provides a reduction in sum of squared considered statistically significant to affect the model. In the Stepwise regression it begins like the forward selection but after a variable has been added to the model the resulting equation is examined to see if any coefficient has a sufficiently larger P value to suggest that a variable should be dropped. This procedure continues until no additions or deletions are indicated according to what will change the model or what the user specifies. (Freund, 1991) In the SAS program the five sound samples averaged together from one cylinder. This data would give a closer interpretation than would five separate samples. When the averages were entered into the SAS system the best model that it picked utilized three independent variables. It also chose not to delete any of the variables in the model. It chose the duration, frequency, and maximum value of our first peak as the model. In the model the duration, estimated time rated at .3936 in the model, which was also the most significant. Then the frequency rated at 0.0323 and the maximum value of the first peak rated at 0.0090. This gave the model a 0.4349 or 43% of the model has been explained. A perfect model would explain 100% of the variability of the compressive strength from cylinder to cylinder. This 100% model means that the user could plug in the numbers received from Cool Edit® and the model would give the compressive strength. Table 3 shows the third procedure in the stepwise model.

The SAS system was also used to run one example to show how far out of the confidence interval the model would actually predict. When the first test was run, one example predicted the PSI to be 3677. The 95% lower confidence interval was set at 3450 and the 95% upper confidence was set at 3903. For this test the actual PSI was

3574. Although the predicted strength did fall within the range, some of the predictions in the model varied from the actual compressive strength by as much 1000psi

Table 3: Stepwise Output in SAS Program.

```
                              The REG Procedure
                               Model: MODEL1
                         Dependent Variable: PSI PSI
                         Stepwise Selection: Step 3
            Variable Peak_1 Entered: R-Square = 0.4349 and C(p) = 4.6159
                            Analysis of Variance
          Source        DF        Sum of        Mean        F        Pr > F
                                  Squares       Square      Value
          Model         3         45260010      15086670    37.45    <0.0001
          Error         146       58810686      402813
     Corrected          149       104070696
     Total

          Variable    Parameter    Standard      Type II SS    F        Pr > F
                      Estimate     Error                       Value
          Intercept   2153.5514    640.16789     4558544       11.32     0.0010
          Freq        -1.54893     0.52714       3477832        8.63     0.0038
          Peak_1      -0.02240     0.01465       941822         2.34     0.1284
          Duration    18380        2267.33229    25470749      65.71    <0.0001
                   Bounds on condition number: 1.1675, 10.002

           All variables left in the model are significant at the 0.1500 level.
      No other variable met the 0.1500 significance level for entry into the model.
                          Summary of Stepwise Selection
No.   Variable       Label       Number    Partial   Model     C(p)      F       Pr > F
      Entered                    Vars In   R²        R²                  Value

1     Duration       Duration          1   0.3936    0.3936    11.3388   96.05   <0.0001
2     Freq           Freq              2   0.0323    0.4258     4.9639    8.26    0.0046
3     Peak_1         Peak_1            3   0.0090    0.4349     4.6159    2.34    0.1284
```

Conclusion

After the analysis was performed on the pilot test and the results were obtained, the independent variables pointed to a possibility that the compressive strength of concrete could be predicted by utilizing the waveform obtained in the Cool Edit® system. After a more extensive test, covering thirty days and testing five cylinders per day, the results obtained did not match those of the initial pilot test. The test proved inconclusive. The compressive strength of concrete could be obtained through the waveform, but only with some changes of the test method and possibilities of using different independent variables. As a result, the 43% could be moved closer to a perfect model. In order to achieve this perfect model, a number of things in the test procedure could be changed to get better results. First, if a magnetic release mechanism could be used instead of a nail, the side-to-side movement of the hammer could be terminated, thus creating a smoother transition and the same magnitude of strike each time a cylinder was tested. Another problem was that nine different individuals were employed to make the one hundred and eighty concrete cylinders. Although instructions were given as to the process of making the cylinders, the actual process is very tiring and each cylinder may not have been made identically. As a result, each cylinder may have had unique properties, when all of them should have been identical. A recommendation that may be considered is for one individual to only make thirty cylinders. This would make the cylinders analogous giving the tester a better representation of the actual curve delineated by the curing cylinder. These cylinders could also be "capped" in the lab environment, which makes the sample perfectly level and the compressive test more accurate.

Finally, close observation of the variables and identifying those that are related, as well as finding other variables that may indicate the compressive strength could be investigated. One possibility is that many of the variables that were analyzed could have resulted in the same results. If a simple correlation was run on the data, then it may determine that some of the independent variables could have been excluded and possible new variables put into their place. With many refinements, this test could give a new means of testing to personnel in the construction industry.

During the experiment it was determined that the best correlation was between the duration of the acoustic sound and the compressive strength of the cylinder. Determining which variables were of no use and replacing them with pertinent variables could improve the experiment. This could be accomplished by utilizing a mechanism to drop the hammer without excessive movement, and better predictions of the variables attained by the user.

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