RELIABILITY IN INTERPRETING NON-DESTRUCTIVE TESTING (NDT) RESULTS OF CONCRETE STRUCTURES

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JUDUL : **RELIABILITY IN INTERPRETING NON-DESTRUCTIVE TESTING (NDT) RESULTS OF CONCRETE STRUCTURES**

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RELIABILITY IN INTERPRETING NON-DESTRUCTIVE TESTING (NDT) RESULTS OF CONCRETE STRUCTURES

MOUMOUNI MOUSSA IDRISSOU

A project report submitted in partial fulfilment of the requirements for the award of the degree of Master of Engineering (Civil - Structure)

Faculty of Civil Engineering

Universiti Teknologi Malaysia

APRIL 2006

I declare that this project report entitled "*Reliability in Interpreting Nondestructive Testing (NDT) Results of Concrete Structures*" is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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Date : APRIL 2006

Say, “Indeed, my prayer, my rites of sacrifice, my living and my dying
are for Allah, Lord of the worlds.”

(Al Qur’an 6: 162)

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ABSTRACT

This research was carried out to study the reliability in interpreting non-destructive testing results of concrete structures for assessing concrete strength, concrete uniformity, and concrete cover. An experimental research was carried out, involving both destructives and non-destructive testing methods applied to different concrete mixes ranging from 20 to 55 MPa. The specimens consisting of cubes, slabs, and columns were casted for the correlation purposes and as testing samples. Statistical analysis was used to establish a relationship between destructives and non-destructive readings. Direct and predicted values were made on the testing samples and compared. For the strength estimation, the interpretation by cores calibration is more reliable than calibration by cubes. This interpretation can improve by taking calibration specimens from the same batch and cure them in the same conditions as the structures to be investigated. It also appears that the combined pulse velocity and rebound index method has no effect on the accuracy of the interpretation. The interpretation of covermeter data by calibration is reliable and that of the concrete uniformity also; and the use of more than one test method for the latter will increase the confidence on the interpretation.

ABSTRAK

Projek ini dijalankan untuk mengkaji dalam menggambarkan keboleh percayaan bagi tafsiran yang diperolehi melalui ujian tanpa musnah bagi struktur konkrit dalam penilaian kekuatan konkrit, keseragaman konkrt dan penutup konkrit. Suatu kajian makmal yang melibatkan kaedah ujian musnah dan tanpa musnah telah dijalankan ke atas adunan konkrit yang berlainan kekuatan antara gred 20 ke gred 55. Specimen-specimen yang mengandungi kiub, papak, dan tiang ini dibina bagi tujuan mewujubkan pertalian antara satu sama lain dan juga sebagai specimen ujian. Analisis statistik digunakan untuk menentukan hubungan antara bacaan ujian musnah dan tanpa musnah. Data terus dan data jangkaan dibandingkan seterusnya. Bagi jangkaan kekuatan, penentukuran teras didapati memberikan tafsiran yang lebih tepat daripada penentukuran kiub. Tafsiran ini boleh dimajukan dengan menentukur specimen daripada kumpulan yang sama dan diawetkan dalam keadaan sebagaimana struktur yang akan dikaji. Ketepatan keputusan adalah didapati tidak dapat ditingkatkan melalui ujian gabungan UPV dan "*rebound index method*". Tafsiran yang diperolehi dengan menggunakan "*covermeter*" boleh dipercayai dan sesuai untuk mengkaji keseragaman konkrit. Walau bagaimanapun, adalah didapati bahawa ujian yang berlainan boleh dijalankan untuk meningkatkan keyakinan pada ketepatan tafsiran yang diperolehi.

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LIST OF SYMBOLS AND ABBREVIATIONS

COV - Coefficient of variation

D, D’ - Depth of reinforcement below the concrete surface

$F_{C'}$ - Compressive strength from correlation relationship

F_C - Compressive strength from direct cores

$F_{cu'}$ - In-situ characteristic strength

F_{mean} - Sample mean strength

FKA - Fakulti Kejuruteraan Awam

ICRI - International Concrete Repair Institute

k - Tolerance factor

Khz - Kilohertz

Km - Kilometer

KN - KiloNewton

Ln - Lognormal

Log - Logarithmic

LS - Least square

MPa - MegaPascal

NDT - Nondestructive testing

OPC - Ordinary Portland Cement

P - Covermeter reading

Q - Sum of squared deviation

R - Rebound number

r - Correlation coefficient

R^2 - Coefficient of determination

REHABCON - Strategy for maintenance and rehabilitation in concrete structures

RILEM - International Union of Experts in Construction Materials, Systems and Structures

s’ - Sample standard deviation

sec - Seconde

SISD - Simplified Index of Structural Damage

UTM - Universiti Teknologi Malaysia

V - Pulse velocity

ε - Random error

σ^2 - Variance

LIST OF APPENDICES

Chapter 1

INTRODUCTION

1.1 Background of the problem

Concrete structures as many other engineering structures are subjected to deterioration that affect their integrity, stability and safety. Faced with the importance of the damages noted on the structures, the current choices are directed towards the repair of the existing structures rather than towards the demolition and construction of new ones. But before any repair work being done, it is common practice to determine the causes of the deterioration so that successful repair can be done. Many repair work fail because the exact causes of the deterioration was not adequately identified.

This identification process comprises many methods including non-destructive testing methods. Non-Destructive Testing is usually undertaken as part of the detailed investigation to complement the other methods. Sometimes, the conclusions of the investigation are based essentially on these tests.

First developed for steel, it has not been easy to transfer the NDT technology to the inspection of concrete (Carino, 1994). Because of the characteristics of reinforced concrete the non destructive testing (NDT) of concrete structures is more complex than the NTD of metallic materials (Rhazi, 2001).

Since the spread of their application in civil engineering, one of their main disadvantages lies in the processing and interpretation of the data, which is often not trivial (Colombo and Forde, 2003). In order for the NDT to better achieve its role in structural assessment there must have agreed standards and guidelines on how to do the survey in the field and interpret the data obtained (McCann and Forde, 2001). Unfortunately until now the choice of the best-fitted technique for a specific case is not simple, the relevance of the measurement process not guaranteed, and the question of how to cope with measurement results and how to finally assess the structural properties remains unanswered (Rilem, 2004).

1.2 Statement of the problem

The application of non-destructive testing to concrete structures is sometimes disappointing. There are many NDT techniques, each based on different theoretical principles, and producing as a result different sets of information regarding the physical properties of the structure. Theses properties, such as velocities, electrical resistance and so on, have to be interpreted in terms of the fabric of the structure and its engineering properties.

The interpretation of the data is the most challenging task of the engineer assessing the structure. The recommendations made based on the interpreted result can be very significant. Decision on whether a structure is adequate or not, the standard and specifications are respected or not, and the exact causes of the deterioration, depends on the outcome of the data's interpretation. It is neither desirable that they lead to the condemnation of a structure safe or economically repairable building, nor it is admissible that they provide a false sense of confidence in an otherwise unsafe structure.

Therefore it is vital to study the reliability in interpreting the NDT results of concrete structures. How NDT results are interpreted? What are the factors affecting these interpretations? What is the reliability of the different interpretations methods?

1.3 Objectives of the study

The objectives of the study are to:

- investigate the reliability in interpreting Non-Destructive Testing (NDT) results of concrete structures,
- determine the factors affecting the interpretation of (NDT) results of concrete structures.

1.4 Scope of the study

The present work focuses on the study of the reliability in interpreting non-destructive testing results of concrete structures. It will be conducted on normal hardened concretes ranging from 20 to 55 MPa, and in laboratory.

The study will be restricted to the following properties: compressive strength, uniformity of concrete and covercrete (concrete cover).

1.5 Limitations of the study

This study will investigate neither human being role in the reliability of NDT nor will it focus on how to improve the reliability of the NDT testing equipments.

It will be based on the assumptions that the testing equipments are adequate and the testing operation done with respect to the procedure from the planning of the testing to the recording of the data.

1.6 Importance of the study

The current way of ensuring accuracy in the interpretation of non-destructive testing (NDT) of concrete structures for the assessment of the compressive strength, is to establish a correlation curve relating non-destructive readings to strength, for a particular mix under investigation, (Bungey and Millard, 1996; Naik and Malhotra, 2004). Regression analysis is used in establishing such curve. By consensus, the accuracy of estimation of compressive strength of test specimens cast, cured, and tested under laboratory conditions by a properly calibrated hammer lies between ±15 and ±20%. However, the probable accuracy of estimation of concrete strength in a structure is ±25%. (Naik and Malhotra, 2004). The accuracy of estimation of compressive strength of test specimens cast, cured, and tested under laboratory conditions by the standard calibrated ultrasonic pulse velocity is ±20% (Popovics, 2001).

In order to improve these estimations, a calibration is developed by combining the readings of the pulse velocity and the rebound number and relates them to the compressive strength. However, there is a wide degree of disagreement concerning the increase of the accuracy of the estimation of strength from the combined method. A combined pulse velocity and rebound index method for a specific aggregate type and a specific age of concrete had been developed and this had shown a good behavior (Samarin and Dhir, 1984). But unfortunately, the results obtained were not compared with a calibration from pulse velocity alone or rebound index alone to state the degree of improvement in accuracy. Certain researchers also claimed that accuracy of compressive strength can be improved by the combined method of pulse velocity and rebound index (Tanigawa, Baba, and Mori, 1984). For others, analysis of strength estimated from rebound index made along with pulse velocity contributes little, if any, to the increase of accuracy of the ultrasonic strength estimation (Popovics, 1998; Malhotra and Carette, 1980; cited by Popovics, 2001). It is said that calibration curve obtained from cores taken in the structures under investigation will improve the accuracy of the strength estimation. (Bungey and Millard, 1996).

Chapter 2

LITERATURE REVIEW

2.1 REPAIR PROCESS

2.1.1 Definition of repair

Repair of concrete structure means to replace or correct deteriorated, damaged, faulty materials, components or elements of a structure (ICRI). The others words used to describe the same activity are rehabilitation and renovation.

Repair of reinforced concrete involves treatment, after defects have occurred, to restore the structure to an acceptable condition. Defects cause some compromise in condition or function relative to the original, and this generally means that a process or processes have resulted in movement, loss of material, and/or loss in materials properties. Repairs are therefore mostly reactive, and initiated when evidence of deterioration becomes apparent.

2.1.2 Repair process

The variables involved in repair make it a complex subject. It has been suggested that repair is more complex than design of new structures, and that management of rehabilitation is more complex than of new construction.

Johnson (1965) states that repair involve five basics steps: (1) finding the deterioration, (2) determine the causes, (3) evaluating the strength of the existing structure, (4) evaluating the need for repair, and (5) selecting and implementing a repair procedure. Kamijoh (1990) cited by Baldwin, N.J.R. et al., (2003) presents a detailed procedure for the investigation and repair of a deteriorated bridge structure (Figure 2.1). This involved inspection and testing to quantify the problem followed by repair. A modified form of the procedure is summarized as follows: the information gathered during the investigations is used to provide an understanding of the mechanisms that cause deterioration, the severity and extent of defects, and the implications for repair or other rehabilitation strategy. Mays (1999) cited by Baldwin, N.J.R. et al., (2003) provides a useful summary of the stages involved in the design of an appropriate repair or protection scheme. This involves seven stages, as follows:

(a) Assessment of the condition of the structure
(b) Identification of the causes of deterioration
(c) Deciding the objectives of protection and repair
(d) Selection of the appropriate principles for protection and repair
(e) Selection of methods
(f) Definition of properties of products and systems to be used in works
(g) Specification of maintenance requirements following protection and repair.

It can be said that the process of repair concrete structure involves the following stages:

- Investigation of the structure condition: gathering sufficient information that the problems are understood
- Evaluation of the need of repair: relating the current condition of the structure to the intended use and life (requirements) in order to select the required outcome of the future maintenance strategy
- Selection of the repair option, principles and systems: identification and selection of appropriate methods and materials for repair
- Implementation of the repair
- Inspection and maintenance programme of the structure

Figure 2.2 summarizes the different stages.

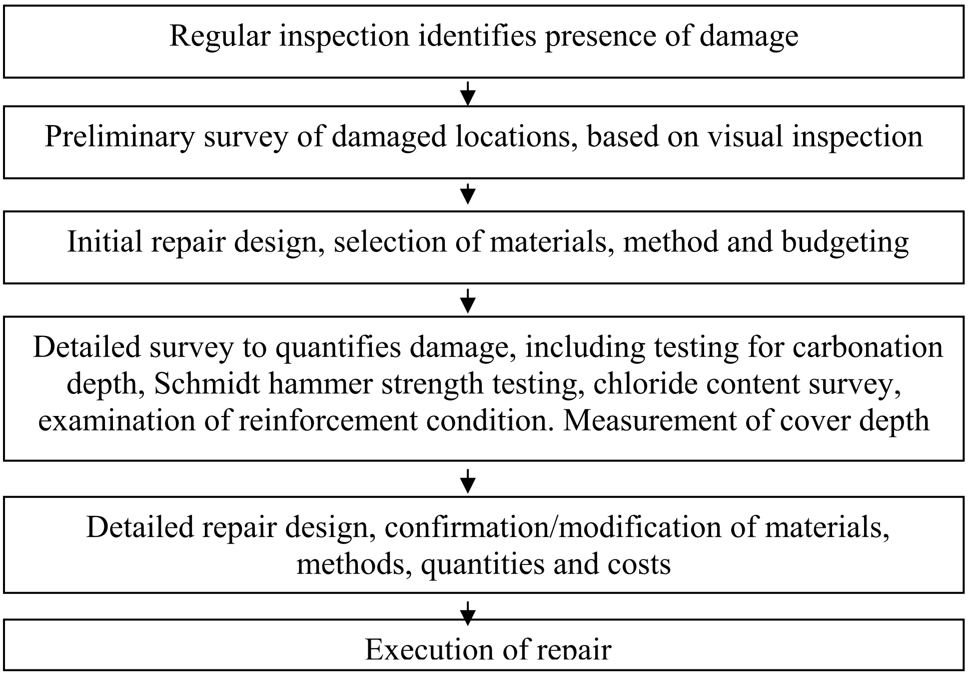


Figure 2.1 Stages in the investigation and repair of a structure (Ref. Kamijoh, 1990; cited by Baldwin, N.J.R. et al., 2003)

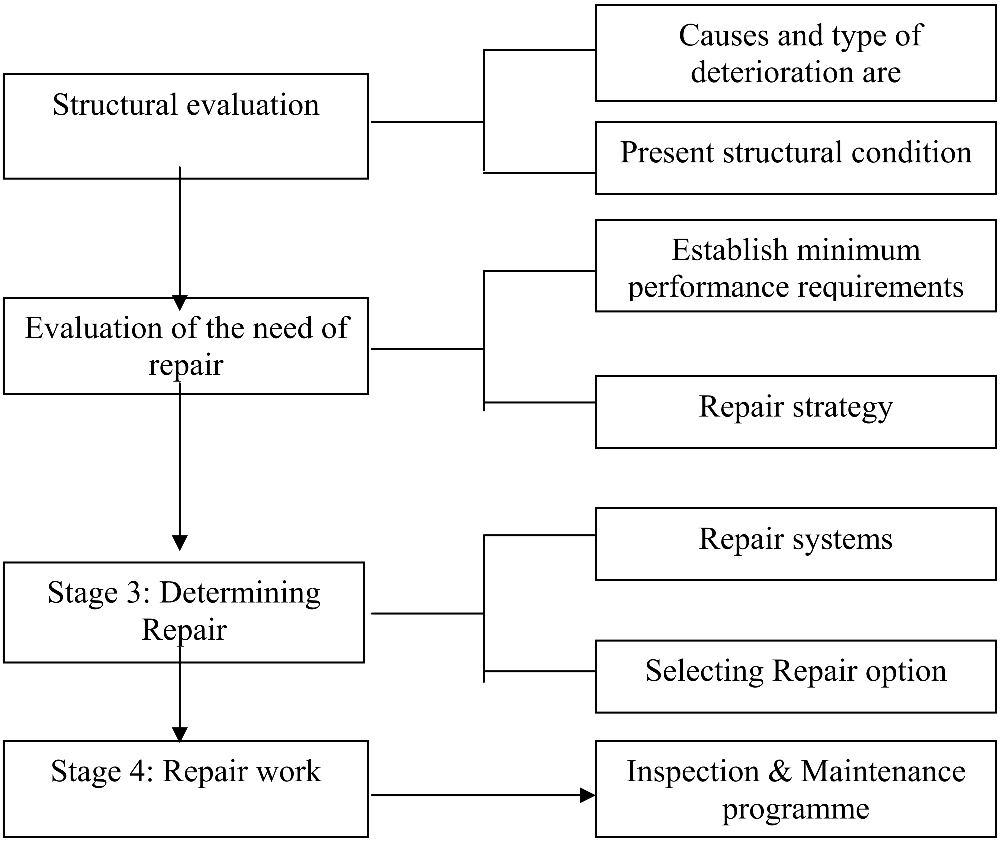


Figure 2.2 Repair process

2.2 STRUCTURAL EVALUATION

A correct assessment of a deteriorated structure is a crucial basis for the success of a repair system. Experienced has shown that in many cases repairs fail much earlier than expected due to improper diagnosis of the actual situation of the structure, either because the cause of the degradation was not properly understood, or the extent of the damage was under-stated. There are numerous references describing methods for investigating the condition of a structure. These include methods presented by the Concrete Society and in British Standards. The investigation process may involve a preliminary visual survey, followed by more detailed inspection and testing to determine the cause and general extent of deterioration. Depending on these findings, further investigation and testing may be required, perhaps to identify specific boundaries of deterioration or potential deterioration.

The more precise steps in a typical evaluation of a concrete structure are given by Peter Emmons (1993):

1. Visual inspection (walk-through)
2. Review of engineering data
    i. Design and construction document
    ii. Operation and maintenance record
    iii. Concrete (including materials used) records
    iv. Periodic inspection report
3. Condition survey
    i. Mapping of the various deficiencies
    ii. Monitoring
    iii. Joints survey
    iv. Sampling and testing
    v. Nondestructive testing
    vi. Structural analysis

4. Final evaluation
5. Condition survey report

The European project CONTECVET (2001) acknowledges the same steps but recommends an overall approach based on the principles of progressive screens (Figure 2.3):

1. Preliminary Assessment
2. Detailed Assessment

The type of input necessary both for Preliminary and Detailed Assessment are indicated in Table 2.1.

Preliminary Assessment is a qualitative approach based on damage classification methods, leading to values for SISD ratings (Simplified Index of Structural Damage) and to decide whether or not a Detailed Assessment is required. Detailed Assessment is a quantitative structural assessment of the impact of deterioration on individual actions effects (bending, shear, bond, ect).

Besides determining the type, extend and cause of the deterioration, the structural assessment includes an establishment of the average rate of deterioration and therefore the present structural capacity, and a prediction of the development of the damage and its structural consequences.

Table 2.1 Schematic outline of progressive assessment procedures (Ref. Fagerlund, 2001)

Assessment Phase	Conclusion			Recommendations
	Based on	Result	Reason	
Preliminary	Records Survey data Site management Cores Crack pattern & widths Simple analyses	Adequate	Sufficient residual service life and load-carrying capacity	Monitor
		Borderline	Insufficient data; or residual service life and load-carrying capacity marginally less than that required	Detailed assessment
		Inadequate	Insufficient residual service life and load-carrying capacity	Modify adequacy criteria, and reassess. Consider alternative remedial actions. Detailed assessment
Detailed	As preliminary plus: Monitoring Laboratory tests More sophisticated analyses (i.e. more Insight)	Adequate	Sufficient residual service life and load-carrying capacity (by calculation or load test)	Monitor
		Borderline	Insufficient data; or residual service life and load-carrying capacity marginally less than that required	Load test to classify as adequate or inadequate. Consider future management and maintenance
		Inadequate	Insufficient residual service life and load-carrying capacity (by calculation or load test)	Options are: Modify adequacy criteria and/or evaluate actual loading, and reassess. Consider possible actions in Table 1

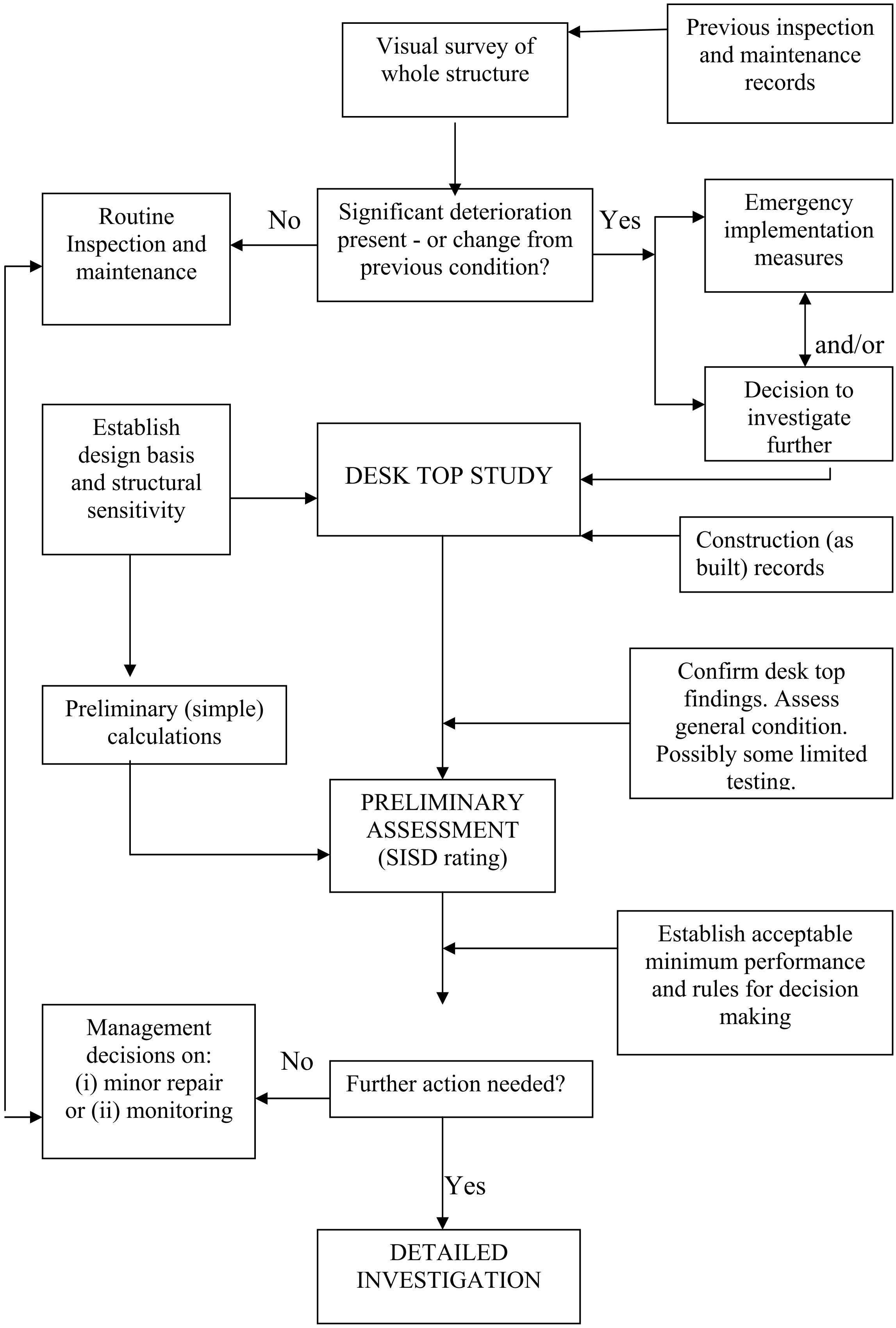


Figure 2.3 Flow diagram of progressive screening (Ref. REHABCON, 2004)

2.3 INTERPRETATION OF NDT RESULTS

Interpretation of NDT results is generally done in three distinct phases: computation, examination of variability, and calibration and/or application. According to testing method, the emphasis varies.

2.3.1 Computation of test results

The amount of computation required to provide the appropriate parameter at a test location will vary according to the test method but will follow well-defined procedures. For example, cores must be corrected for length, orientation and reinforcement to yield equivalent cube strength. Pulse velocities must be calculated making due allowance for reinforcement, and pull-out, penetration resistance and surface hardness tests must be averaged to give a mean value.

2.3.2 Examination of variability

The comparison of the variability of results provides valuable information on the properties being investigating. This is done by graphic method which expresses in the form of "contour' or histograms. Figure 2.4 is an example of such a contour. This contour is compared with well-defined patterns to identify normal zone and zone of concern. Figure 2.5 shows the histogram of an in-situ test results.

It is also done by calculating the coefficient of variation of test results (numerical method) and comparing it with the typical values given in Table 2.2 to have idea of the construction standard employed. The values given are not exact since the coefficient of variation varies but it is valuable for evaluation (Bungey and Millard, 1996).

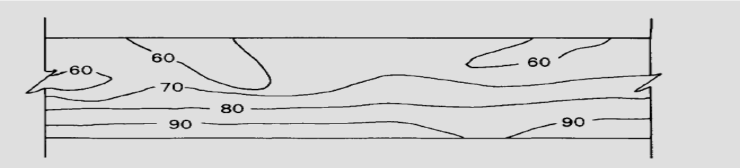


Figure 2.4 Typical relative percentage strength contours for a beam. (Ref. Bungey and Millard, 1996)

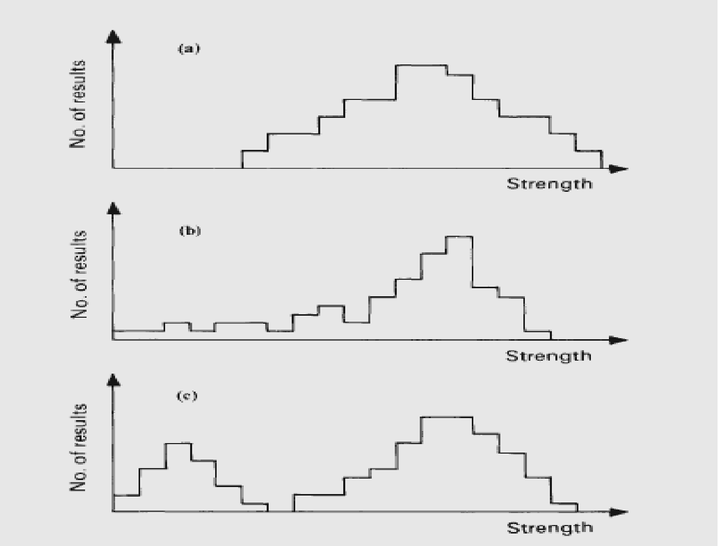


Figure 2.5 Typical histogram plots of in-situ test results: (a) uniform supply; (b) poor construction; (c) two sources. (Ref. Bungey and Millard, 1996)

Table 2.2 Typical coefficients of variation (COV) of test results and maximum accuracies of in-situ strength prediction for principal methods (Ref. Bungey and Millard, 1996)

Test method	Typical COV for individual member of good quality construction	Best 95% confidence limits on strength estimates
Cores – 'standard'	10%	± 10% (3 specimens)
'small'	15%	± 15% (9 specimens)
Pull-out	8%	± 20% (4 tests)
Internal fracture	16%	± 28% (6 tests)
Pull-off	8%	± 15% (6 tests)
Break-off	9%	± 20% (5 tests)
Windsor probe	4%	± 20% (3 tests)
Ultrasonic pulse velocity	2.5%	± 20% (1 tests)
Rebound hammer	4%	± 25% (12 tests)

2.3.3 Calibration

Most of the NDT equipments do not measure directly the properties of concrete. In order to determine these properties, the manufacturer of test equipment provides a calibration chart relating the readings to the desired properties. These charts do not appear to be satisfactory because their development is based on the use of certain types and sizes of aggregates, test specimens, and test conditions. The relationship between strength and non-destructive test readings is not unique, and is affected by many factors such as aggregate size, type, and content; cement type and content; water-cement ratio; and moisture conditions. Users must prepare their own calibration charts that are adapted to their situation (Carino, 1984).

For estimating strength in hardened concrete, a preestablish calibration chart is done by casting specimens (cylinders or cubes) covering the strength range to be encountered on the job site under laboratory conditions similar as much as possible to the site conditions, submit them to the non-destructive test before doing a core testing. The specimens are made for the particular type of concrete under investigation and the curing period must be the same as the specified control age in the field. The least-squares curve fitting is used to establish the correct form of the relation between the test readings and the concrete strength.

In most of the case, the investigation to assess the strength is done when there is no data of the construction, or when the cylinder strength test result fails, or the quality of concrete is doubtful. In these instances, the common method of determining the strength, when a sufficient number of cores cannot be drilled due to lack of money or other problems, is by establishing a correlation between drilled cores and non-destructive test readings. Non-destructive readings are taken in the location of the cores before their extractions and testing. The correlation curve is then fitted by the least-squares method.

The validity of the correlation curve is assessed by the correlation coefficient. The higher is the correlation coefficient the more satisfactory is the correlation curve. Figure 2.6 shows a typical correlation curve between exposed probe length and 28 day compressive strength of concrete.

For the determination of strength, the regression analysis for determining the correlation curve is not sufficient. This is due to the fact that a number of other properties of concrete such as its elastic behaviour and in some extent its service performance can be approximated, directly or indirectly, from its strength characteristics. In addition to the correlation curve, a procedure is needed for analyzing the results so that one can estimate the in-place compression strength with a high degree of accuracy. Both of these steps require statistical analysis of test data (Carino and Stone, 1987). There are many procedures developed but none of them has been consensual and the matter is still under consideration. The current procedure used is based on statistical tolerance factors. (Bungey and Millard, 1996).

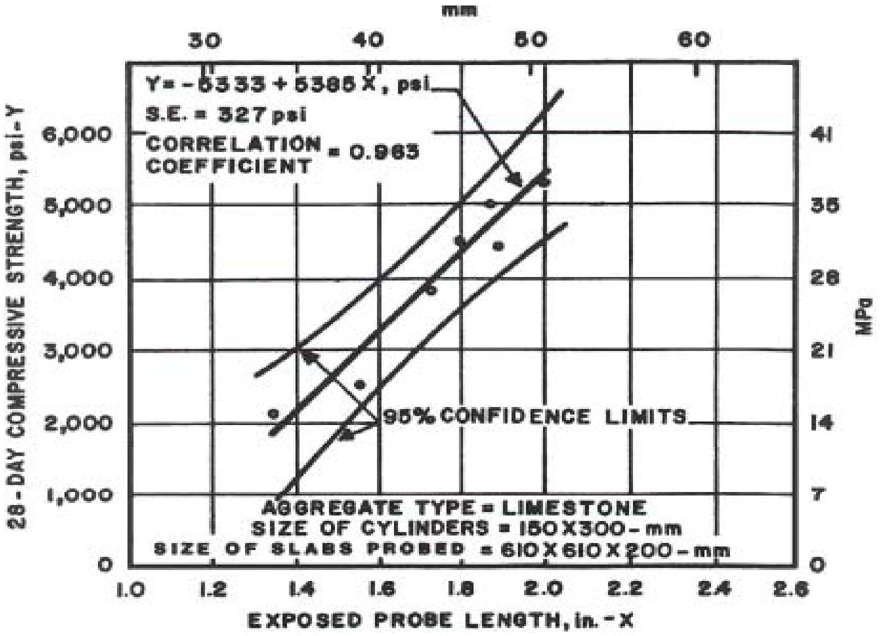


Figure 2.6 Relationship between exposed probe length and 28 day compressive strength of concrete. (Ref. Samarin, 2004)

2.3.3.1 Regression analysis

Regression analysis is a statistical tool for the investigation of relationships between variables. Usually, the investigator seeks to ascertain the causal effect of one variable upon another—the effect of a price increase upon demand, for example, or the effect of changes in the money supply upon the inflation rate. To explore such issues, the investigator assembles data on the underlying variables of interest and employs regression to estimate the quantitative effect of the causal variables upon the variable that they influence. The investigator also typically assesses the “statistical significance” of the estimated relationships, that is, the degree of confidence that the true relationship is close to the estimated relationship.

If a perfect fit existed between the function and the actual data, the actual value of each observation in your data file would exactly equal the predicted value. Typically, however, this is not the case, and the difference between the actual value of the dependent variable and its predicted value for a particular observation is the error of the estimate which is known as the "*deviation*" or "*residual*". The goal of regression analysis is to determine the values of the parameters that minimize the sum of the squared residual values for the set of observations. This is known as a "*least squares*" regression fit.

Once the values of the parameters are determined, you can use the formula to predict the value of a dependent variable based on its independent variable. The predicting value represents the mean response; the exact value is likely to fall above or below this mean.

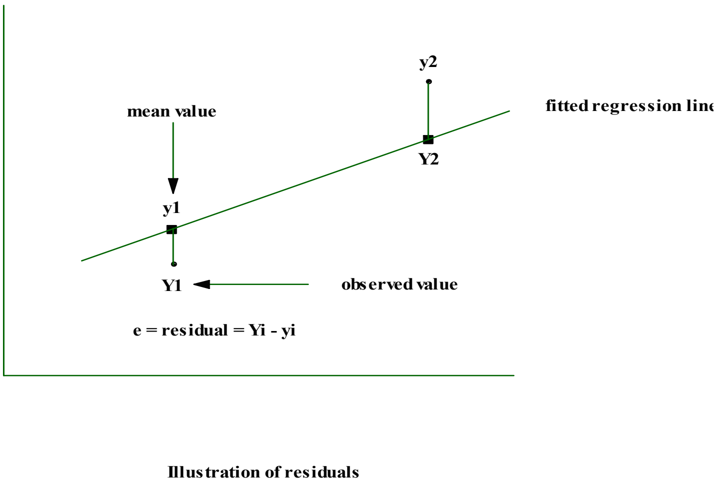


Figure 2.7 Illustration of residuals

a- Simple linear regression analysis

Simple regression analysis is used to establish a relationship between two variables, one is called the dependent and the other is the independent. Let take the example of the relationship between the covermeter readings (P) and the depth of reinforcement below the concrete surface (D). The information for all of the individuals in the sample is plotted using a two-dimensional diagram, conventionally termed a “scatter” diagram.

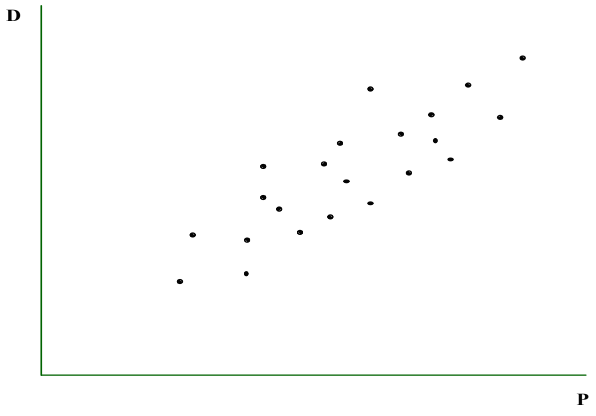


Figure 2.8 Example of scatter plot of reinforcement depth vs. covermeter readings

The diagram indeed suggests that higher values of *P* tend to yield higher values of *D*, but the relationship is not perfect, it seems that knowledge of *P* does not suffice for an entirely accurate prediction about D. The relationship can be linear or nonlinear. Let suppose the linearity.

Then, the hypothesized relationship covermeter readings and depth of reinforcement may be written:

$$D = e + f.P$$

Where e and f are called the regression coefficients

Remember what is observable and what is not. The data set contains observations for *P* and *D*. The parameters e and f are also unobservable. The task of regression analysis is to produce an *estimate* of these two parameters, based upon the information contained in the data set.

Let $x_1, x_2, \ldots\ldots, x_n$ be the value of the covermeter readings and let $y_1, y_2, \ldots..,$ y_n be the corresponding values of the depth. We assume that y_i is the measured value of the random variable Y_i, which depends on x_i according to the following model:

$Y_i = e + fx_i + \varepsilon_i \quad (i= 1, 2, \ldots., n)$

Here ε_i is a random error with $E(\varepsilon_i) = 0$ and $Var(\varepsilon_i) = \sigma^2$. Thus,

$E(Y_i) = \mu_i = e + fx_i$ represents the true but unknown mean of Y_i. This relationship between $E(Y_i)$ and x_i is called the true regression line, with e being its unknown intercept and f being its unknown slope. The ε_i are assumed to be independent and identically distributed. These random errors may arise due to a variety of causes (measurement error, etc.) The assumption $E(\varepsilon_i) = 0$

means that there is no systematic bias due to these causes. Usually the ε_i are assumed to be normally distributed with unknown variance σ^2. Then the Y_i are independent $N(\mu_i = e + fx_{i,}\ \sigma^2)$.

The linear regression model, which is represented graphically in figure, has four basic assumptions:

1. The mean of Y_i is a linear function of x_i
   This means that the errors vary by the same amount when x_i is a low as when x_i is a high value.
2. The Y_i have a common variance σ^2 , which is the same for all values of x_i
3. The errors ε_i (and hence the observations Y_i) are normally distributed.
4. The errors ε_i (and hence the observations Y_i) are independent.

If the data does not satisfy these assumptions, correction for them must be made.

Fitting the simple linear regression models

Before attempting to fit the linear regression model to the data, it is advisable to first make a scatter plot and see if the plot is approximately linear. To do so, the least square method is used.

The task of regression analysis is to produce an *estimate* of these two parameters, based upon the information contained in the data set and, as shall be seen, upon some assumptions about the characteristics of ε. To understand how the parameter estimates are generated, note that if we *ignore* the ε, the equation for the relationship between Y_i and x_i is the equation for a line—a line with an "intercept" of ε on the vertical axis and a "slope" of f. Returning to the scatter diagram, the hypothesized relationship thus implies that somewhere on the diagram may be found a line with the equation $Y_i = e + fx_i$. The task of estimating e and f is equivalent to the task of estimating where this line is located.

What is the best estimate regarding the location of this line?

To estimate it, we look at the deviations between the observed y_i and the corresponding point on the straight line $Y_i = e + fx_i$:

$y_i - (e + fx_i)$ $(i = 1, 2, \ldots\ldots, n)$

For the fit to be good, these deviations should be small. The sum of squared deviations

$Q = \sum (y_i - (e + fx_i))^2$

is used as an overall measure of distance of the data points from the fitted line; the smaller the value of Q, the better the fit. The value of e and f that minimize Q are referred as the **least squares (LS) estimates** and denoted by α and β respectively.

$\beta = S_{xy} / S_{xx}$, $\alpha = \bar{y} - \beta \bar{x}$, where

$S_{xx} = \sum x_i^2 - \{ (\sum x_i)^2 / n\}$, $S_{yy} = \sum y_i^2 - \{ (\sum y_i)^2 / n\}$,

$S_{xy} = \sum x_i y_i - \{ (\sum x_i) (\sum y_i) / n\}$, $\bar{x} = (\sum x_i) / n$, $\bar{y} = (\sum y_i) / n$

Goodness of fit

The goodness of the fit is assessed by the **correlation coefficient r.** It measures how well the straight line fit the point (x_i , y_i) form n paired observations. The correlation coefficient is the square root of the **coefficient of determination r^2**

$$r = S_{xy} / \sqrt{(S_{xx}.\ S_{yy})}$$

b- Simple non-linear regression analysis

When data depart more or less widely from linearity, a curve fitting must be considering other than a straight line. This is the case of a polynomial curve or an exponential curve.

There are two types of nonlinear models: those that are called *intrinsically linear models* and those called *intrinsically non linear models.* Intrinsically linear models are nonlinear models that initially appear to be nonlinear, but can be transformed to a linear form.
The simple linear procedure is applied by transforming the equation of such a curve into that of a line.

Consider the equation of a curve given by: $y = ab^x$.

This equation is transformed into a logarithmic form

$\log y = \log a + x (\log b)$

which is a linear equation in x and log y, where log stands for logarithm to the base 10. the equation becomes $Y = A + Bx$, where we write A for log a, B for log b, and Y for log y.

For finding an exponential curve, the same transformation can be applied.

$y = a + bx + cx^2$ becomes $y = a + bx_1 + cx_2$, where $x_1 = x$ and $x_2 = x^2$

Those that cannot be transformed fall in the second category.

Estimation of regression parameters

Estimation of the regression parameters of a nonlinear regression model is usually carried out by the method of least squares, just as for linear regression models. But unlike linear regression, it is not usually possible to find analytical expressions of these parameters. Instead, numerical search procedures must be used with both of these estimation procedures, requiring intensive computations. Iterative solve method is used, and for this purpose, several algorithms for the estimation are available.

For these estimations, initial starting values must be specified. Good starting initial values are important and may provide a better solution in fewer iterations

c- Multiple regression analysis

When the relationship is to be established between the dependent and more than one independent variable, multiple regression analysis is used. Multiple regression analysis is in fact capable of dealing with an arbitrarily large number of explanatory variables. With *n* explanatory variables, multiple regression analysis will estimate the equation of a “hyperplane” in n-space such that the sum of squared errors has been minimized.

In multiple regression where there are at least two independent variables, the *coefficient of multiple determination* is used.

2.3.3.2 Statistical analysis procedure

For the determination of strength, the regression analysis for determining the correlation curve is not sufficient. This is due to the fact that a number of other properties of concrete such as its elastic behaviour and in some extent its service performance can be approximated, directly or indirectly, from its strength characteristics. In addition to the correlation curve, a procedure is needed for analyzing the results so that one can estimate the in-place compression strength with a high degree of accuracy.

There are many procedures developed but none of them has been consensual and the matter is still under consideration.

The number of in-situ test results is seldom sufficient to permit a full statistical assessment of the British Standard 6089 confidence limit of 95%. Therefore, it is vital to establish a statistical procedure to formulate acceptance/rejection criteria with a greater level of confidence. The one developed by Hindo and Bergstrom (1985), based on statistical tolerance factors, is used.

The procedure is a function of quality control, number of tests (n), and the required confidence limit (p). Three quality control levels are considered: excellent, average, and poor, with the distribution function of strength assumed as normal, mixed normal-lognormal, and lognormal, respectively.
Let f'_1, $f'_{2,}$ ...., f'_n be the in-situ test results, so that f'_i is the i-th test, and n = number of tests.

For a normal distribution function (excellent quality control), the equation for the 95% confidence limit is: $f'_{cu} = f'_{mean} - ks'$

where,

f'_{cu} = in-situ characteristic strength
f'_{mean} = sample mean strength = $\mathbf{(1/\mathit{n})\sum f'_i}$
k = tolerance factor
s' = sample standard deviation = $\sqrt{}\,\mathbf{(\sum f'^{2}_{i} - n\, f'^{2}_{mean})/(n-1)}$

The tolerance factor k, along with the sample mean f'_{mean}, and the standard deviation s', is used to establish a tolerance limit. The tolerance factor is determined for statistical characteristics of the normal probability distribution and depends upon the number of tests *n*, the confidence limit *p*, and the defect percentage.

Bungey and Millard (1996) has suggested the following 95% confidence tolerance factor, according to the number of test results *n*.

Table 2.3: Suggested 95% confidence tolerance factor related to number of test *n* (Ref. Bungey and Millard, 1996)

Number of test *n*	Confidence factor k
3	10.31
4	4.00
5	3.00
6	2.57
8	2.23
10	2.07
12	1.98
15	1.90
20	1.82
oo	1.64

For the lognormal distribution (poor quality control), the confidence limit is calculated using the relationship between the normal and lognormal distribution. f' is a lognormal random variable if, and only if, ln f is a normal random variable. Therefore, if the test results are f'_1, $f'_{2, \ldots\ldots,}$ f'_n, then ln f'_1,ln $f'_{2, \ldots\ldots,}$ln f'_n follow a normal distribution. Hence,

ln f'_{cu} = mean value of (ln f') – k x standard deviation of (ln s')

where

f' is an individual in-situ test result,

mean value of (ln f') = $(1/n)\sum$ ln f'_i

standard deviation of (ln s') = √ (∑(ln $f'_i)^2$ - n (mean value of ln $f')^2$)/(n-1)

f'_{cu} = exp(mean value of (ln f') – k x standard deviation of (ln s'))

These relationships can conveniently be represented in graphical form as in Figure 2.9, which can be used to evaluate the characteristic value as a proportion of the mean for a particular coefficient of variation of results. In this figure 'normal' and 'log-normal' distributions are compared directly for a coefficient of variation of 15% and the less demanding nature of the 'log-normal' distribution is demonstrated. This effect increases with increasing coefficient of variation. The combined effects of variability of results and number of tests can also be clearly seen and the importance of having at least four results is apparent. Coefficient of variation = s' x 100/f'_{mean}

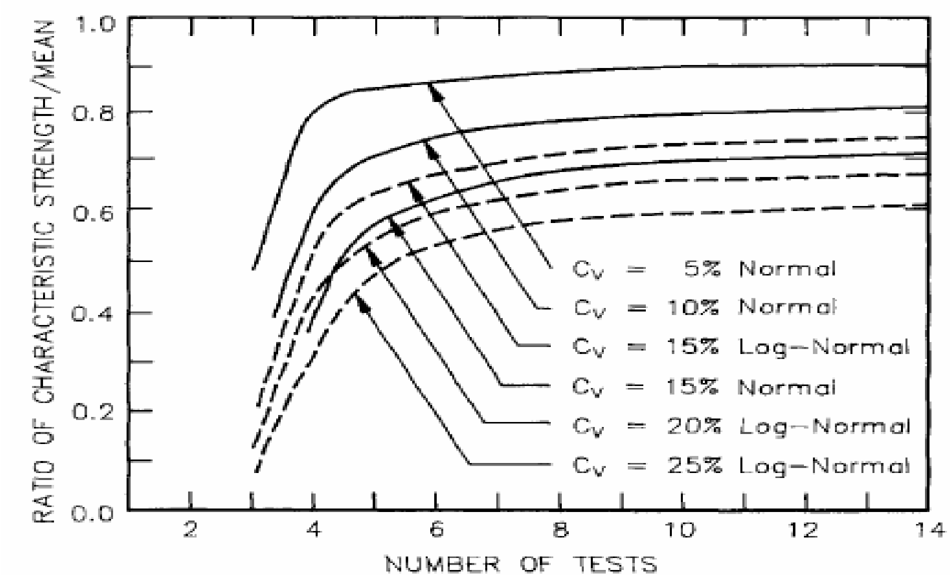


Figure 2.9: Characteristic strength (95% confidence limit) as a function of coefficient of variation and number of tests (Ref. Bungey and Millard, 1996).

The choice of distribution type for use in particular circumstances is a *matter of judgment*

The in-situ characteristic strength estimated can be compared with the specified value if numerous in-situ results are available, but this approach is not recommended. It is more appropriate to use the mean value from a number of test readings and to apply a factor of safety to this to take account for test variation, possible lack of concrete homogeneity and future deterioration. (Bungey and Millard, 1996)

2.3.4 Combination of tests

The interpretation of test results is improved by test combinations. The calibration between non-destructive readings and desired properties is done by combining the readings of two non-destructive tests to relate them to a desired property.

The most successful combination is the use of ultrasonic pulse velocity and rebound hammer to produce a correlation to concrete strength. This is done by developing a multiple regression analysis. Of course, the regression analysis is done for a particular type of aggregate.

The results of this combination compared to the correlations between compression strength and ultrasonic pulse velocity alone, or between compressive strength and rebound hammer readings alone, show an increase in the correlation coefficient and a decrease in the standard error. The improvement of this combination depends on the curve fitting model used. (Samarin, 2004)

There are various linear and nonlinear multiple regression correlations suggested by different researchers for estimating compressive strength of concrete. Table 2.4 resumes them along with their degree of significance.

Table 2.4 Various multiple regression correlations suggested by different researchers to estimate the compressive strength of concrete (Ref. Samarin, 2004)

Researchers	**Equations**	**Significance of the combined Effect**
McLeod	$S = k_o + k_1R + k_2V$	Significance in some case, but not in others
Di Maio, et al		
Tanigawa, et al		
Knaze and Beno	$S = b_o + b_1V + b_2V^2$ $S = a_o + a_1R + a_2R^2$	Use of monogram "Curve of Equal Strength"; effect considered significance
Bellander	$S = k_o + k_1R^3 + k_2V$	Significance to a certain degree
Weibinga	$Log_eS = k_o + k_1R + k_2V$	Significance (within test conditions)
Shah		
Tanigawa, et al		
Schickert	$S = k_oR^nV^m$	Some evidence of significance effect
Samarin, et al	$S = k_o + k_1R + k_2V^4$	Significance
Tanigawa et al	$S = V(a_o + a_1R + a_2R^2 + a_3R^3)$	Significance (but possibly too complex)

2.3.4.1 Combined Pulse Velocity and Rebound Index

Considering the limitations of the Ultrasonic Pulse Velocity and those of the Rebound Hammer, and the need of a more reliable non-destructive method for assessing concrete structures, it is a current practice to associate the two methods. This combination is developed since many years ago and in some countries has gained recognition in the assessment of concrete structures.

Two ways of combining the ultrasonic pulse velocity and the rebound hammer have been developed: the SONREB method and the one developed by Samarin and Smorchevsky.

a- *The SONREB method*

The SONREB method was developed largely due to the efforts of RILEM Technical Committees 7 NDT 43 and CND, and under the chairmanship of Focaoaru. It is the most popular nondestructive method in Romania.

The method is based on the definition of a reference concrete, for which a family of iso-compressive strength curves is developed.(Figure 2.10)

If the concrete to be tested is not the reference one, in order to get the real strength, the result obtained according to Figure 2.10 has to be corrected, by a correction factor.

The accuracy of the estimated strength (Table 2.5), the range comprising 90% of all the results, is considered to be according to Focaoaru:

- 10% to 14% when the correlation relationship is developed with known strength values
of cast specimens or cores and when the composition is known

- 12% to 16% when the correlation relationship is developed with known strength values
of cast specimens or cores

- 15% to 20% when the correlation relationship is developed when only the composition is known.

- above 20% if neither specimens nor the composition of concrete is known.

Table 2.5 Accuracy of the estimated strength in function of the correlation conditions

Accuracy of the estimated strength	Conditions
10% to 14%	known strength values of cast specimens or cores and composition
12% to 16%	known strength values of cast specimens or cores
15% to 20%	only the composition is known.
above 20%	neither specimens nor the composition of concrete is known

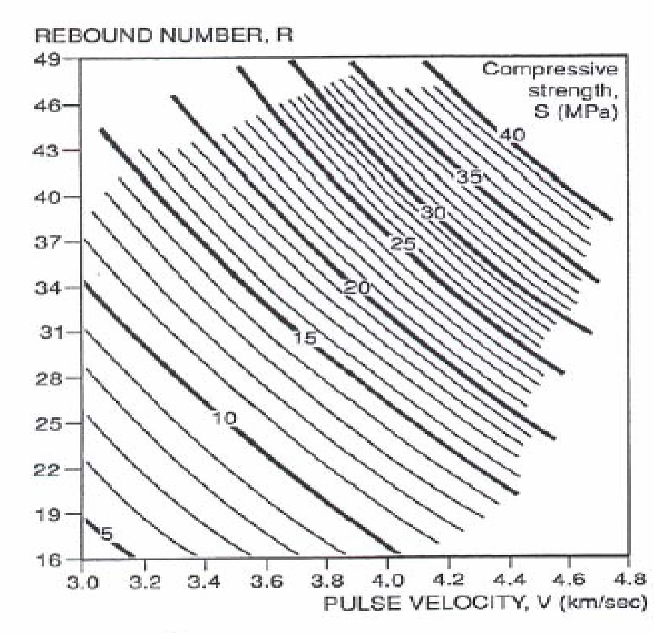


Figure 2.10: ISO-strength curves for reference concrete in SONREB method. (Ref. Samarin, 2004)

b- *Method developed by Samarin and Smorchevsky*

Establishment of a series of specific correlations between the combination of rebound hammer number (R) and ultrasonic pulse velocity (V) and the compressive strength (S) of concretes, each containing a particular aggregate type and being of a particular age group, was completed in the early 1970s by Samarin and Smorchevsky for Australian concrete.

The authors took account of the fact that in an ordinary concrete, between 60% and 70% of the absolute volume is taken up by aggregate and the rest by cement paste. The strength characteristics of a given cement paste, subjected to the influence of a particular environment, can be considered time independent and a function of its petrological type only. Thus, even in concrete of suspect quality and unknown composition, there are two variables which can be identified with a reasonable degree of accuracy, namely, petrological type of the aggregate and approximate age of the concrete. Removing some of the matrix in an out-of-sight part of a structural member can identify the aggregate. Coarse aggregate is particularly easy to identify in this way and, in the majority of commercial grade concrete, coarse aggregate content is significantly higher than the fine aggregate content.

As reported by Elvery and Ibrahim (1976), the sensitivity of ultrasonic pulse velocity to concrete strength is very high in the first few days, but after about 5 to 7 days (depending on curing conditions) the results become considerably less reliable. Also, most of the concrete, which is identified as being suspect, is subsequently tested *in situ* at the age of between 1 and 3 months. The majority of the laboratory test data for which the correlations have been developed also fall into this period.

Therefore, in their work, they have divided concrete into three age groups, namely:

- 7 days and younger
- Over 7 days, but less than 3 months
- 3 months and older.

The method enables to draw a monogram of concrete for a particular aggregate type and age (Figure 2.11). This monogram is then applied for the strength estimation.

Comparing the multiple correlation relationship developed for each aggregate type and each age group to the correlations between compressive strength and ultrasonic pulse velocity alone, or between compressive strength and rebound hammer reading alone, they indicate:

- an increase in the multiple correlation coefficient above the correlation coefficient for rebound number alone or pulse velocity alone
- a decrease in the standard error of estimate for a multiple correlation relationship compared with relationships between rebound number and strength alone and between pulse velocity and strength alone.

The degree of improvement due to the combined technique depends on a number of factors. Of these, the most significant (in the order of importance) appear to be the use of least-squares curve fitting to establish the correct form of the relation between concrete strength and each independent variable separately.

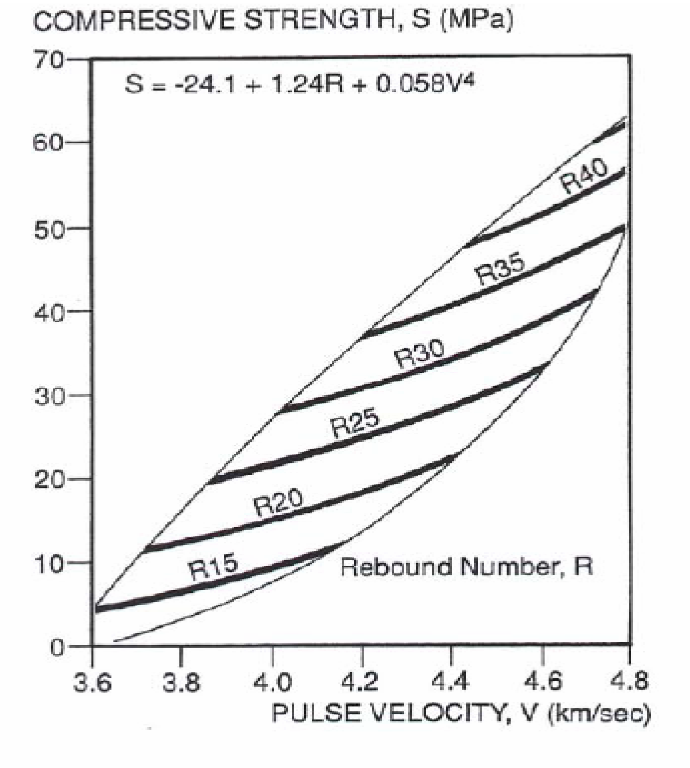


Figure 2.11: Monogram for concrete of a particular aggregate type and age. (Ref. Samarin, 2004)

Chapter 3

Materials and Methods

3.1 Introduction

In this study, the accuracy of the estimation of the compressive strength is investigated by:

1- using a same type of aggregate and a same type of cement
2- using cube and column specimens taken from the same batch as the testing specimens
3- curing the calibration cubes and column specimens and the testing specimens in the same conditions
4- taking cores from the column specimens
5- using regression analysis to define the calibration curves

Calibration curves from cubes and cores were developed both by simple and combined methods. Two columns are used for the comparison of the strength estimated.

The reliability of interpreting covermeter data by regression analysis was investigated by developing first a calibration curve, and then applied it to a testing slab.

The reliability of interpreting ndt results of the uniformity of concrete was also investigated by comparing the results obtained from graphical and numerical methods with the standard ones. The strength calibration and testing data are used for this purpose.

3.2 Testing equipment

The equipment used are those available in the structural laboratory of FKA, UTM.

i. Measurement of pulse velocity

Pulse velocity on specimens are taken with a Pundit 6 Model PC1000 generating a low frequency ultrasound pulses of 54 kHz, and covering two times ranges from 0.1 μs to 999.9 μs in units of 0.1 μs and 1 μs to 9999 μs in units of 1 μs. (Figure 3.1)

ii. Measurement of rebound number

Measurement of rebound numbers were made with a Concrete Test Hammer Type N generating an energy impact of 2.207 Nm , shown in Figure 3.2

iii. Measurement of compressive strength

For cubes and core drilled are tested at various rates of loading with a Tonipact compression machine with a maximum capacity of 3000 KN. (Figure 3.3)

iv. Core drilling machine

The core drilling machine is (figure 3.4)

v. Covermeter

The covermeter used is shown in figure 3.5.

3.3 Materials

The materials used in this investigation and their characteristics are here summarized.

Cement

Locally available Ordinary Portland Cement (OPC)

Supplementary cementitious materials

Silica fume in the form of powder

Fine aggregate

Commercial, locally available sand was used.

Coarse aggregate

Commercial, locally available crushed coarse aggregate with a nominal maximum aggregate size of 20.0 mm was used.

Admixture

Two types of superplasticizer and one retarding admixture were used.

- Rheobuild 1100
- Glenium 51, a new superplastifier based on carboxylic ether polymer
- Pozzolith 322 N

3.4 Concrete Mix Proportions

Three normal concrete mixes with the same cement, size and type of aggregates were casted. The concrete mixes were proportioned to give a 28 day strengths ranging from 20 and 55 MPa. The specimens were cured under laboratory air conditions. The concrete mix proportions are detailed in table 3.1

Table 3.1: Mix proportions

Mix	**1 (30 MPa)**	**2 (40 MPa)**	**3 (50 MPa)**
W/(cement+silica fume)	0.6	0.57	0.4
Water (w), kg/m^3	190	190	188
Cement, kg/m^3	337	334	441
Silica fume, kg/m^3 (powder)	00	00	30
Fine aggregate, kg/m^3	564	539	768
20 mm Coarse aggregate, kg/m^3	1379	1387	1032
Superplasticizer, ml/100 kg of (cement+silica fume)	00	00	700
Retarder, ml/100 kg of (cement + silica fume)	00	00	700

3.5 Specimens

The following specimens (Table 3.2) were casted :

Group A

a. From each of the two mixes, Ten 150 mm x 150 mm x 150 mm cubes, for pulse velocity, rebound hammer and standard compression tests
b. From one of the two mixes, one slab 600 mm x 600 mm x 200 mm containing 10 mm high strength steel bars at different depths, for covermeter.

Group B

c. From each of the two mixes, one column 200 mm x 200 mm x 2100 mm for pulse velocity, rebound hammer and cores drilling and testing

Group C

d. From each of the two mixes, two columns 200 mm x 200 mm x 2100 mm for pulse velocity, rebound hammer and cores drilling and testing
e. From one of the two mixes one slab 600 mm x 600 mm x 200 mm containing same specific steel bars (as in Group A) of same diameter at different depths, for covermeter.

Table 3.2: Specimens

SPECIMENS AND TESTS (Same cement and type of aggregates) (mm)	**NUMBERS OF SPECIMENS**		
	Mix 1 (30 MPa)	**Mix 2 (40 MPa)**	**Mix 3 (50 MPa)**
A) CORRELATION SPECIMENS			
GROUP A			
Slab - 600 x 600 x 200 containing 6 mm high strength steel at different depths ; **Test** : Covermeter	1	1	1
Cube- 150 x 150 **Tests** : UPV, Rebound, Compression Test	15	15	15
GROUP B			
Column - 200 x 200 x 2100 **Tests** : UPV, Rebound, Cores drilling & testing	2	2	-
B) TESTING SAMPLES			
Slab - 600 x 600 x 200 containing 3 x 6 mm high strength steel at 3 different depths ; **Test** : Covermeter	1	-	-
Column - 200 x 200 x 2100 **Tests** : UPV, Rebound, Cores drilling & testing	1	1	-

3.6 Casting details

Each mix was mixed on a concrete mixer of 0.5 m^3. All the specimens (cubes, slabs, and columns) were vibrated with a pocket vibrator in the same conditions. After that they were cured in the laboratory air conditions.

3.7 Testing procedures

3.7.1 Testing details

On the columns, locations free of reinforcement were determined by a covermeter before the measurement of the pulse velocities and the drilling of cores. The cores were drilled avoiding the top 300 mm on each column.

After the pulse velocity reading, the cubes were restrained on the compression machine with a load varying of 8MPA.

The compression strength on the core were determined just after the drilling, and on dry conditions.

3.7.2 Compressive strength tests

The following tests were done after 7 days for the cubes and after 28 days for the others:

Group A

- Four (4) pulse velocities and twenty (20) rebound readings (5 on each side) on each cube specimen
- compression test on cube specimens

Group B

- Four (4) pulse velocities and ten (10) rebound readings at each of the four (4) selected locations on each column
- compression test on cores drilled at the positions where the rebound and ultrasonic testing have been done

Group C

- Rebound and pulse velocity readings on each column
- Compression test on four core drilled on each column

3.7.3 Covermeter test

Group A

With the covermeter, a reinforcement bar was located and its orientation determines, and the careful reading (P) to the nearest whole number recorded. At the location of the reading a hole was drilled to the concrete surface, and the depth (**D**) of the bar below the concrete surface was measured and recorded. This process was repeated at a total of 10 locations.

Group C

With the covermeter, a reinforcement bar was located and its orientation determines, and the careful reading (P) to the nearest whole number recorded. At the location of the reading a hole was drilled to the concrete surface, and the depth (**D’**) of the bar below the concrete surface was measured and recorded. This process was repeated at a total of 10 locations.

Figure 3.1: Pundit 6 Model PC1000

Figure 3.2: Rebound Hammer

Figure 3.3: Tonipact Compression Machine

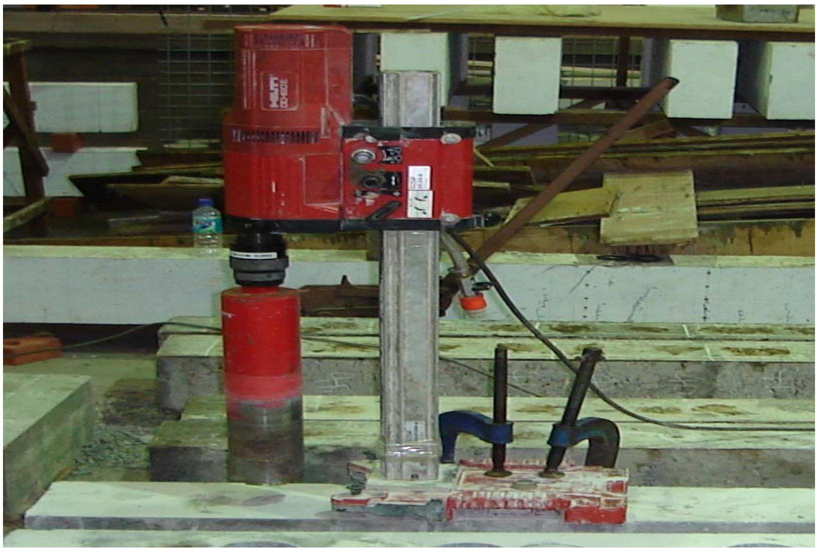


Figure 3.4: Core drilling machine

Figure 3.5: Covermeter

Chapter 4

Results and discussion

For the regression analysis, SPSS 13.0 was used. This regression software uses the least square method.

4.1 Compressive Strength

The following relationships were established between destructive and non-destructive parameters:

- compression strengths ($F_{C'}$) against rebound numbers (R)
- compression strengths ($F_{C'}$) against pulse velocities (V)
- compression strengths ($F_{C'}$) against rebound numbers (R) and pulse velocities (V)

Two types of relationship were established: from cubes and from cores. Eight calibrations curves were developed. The different curves obtained are shown in Figures 4.1 to 4.8

Comparing the different coefficients of correlation R (Table 4.1), we can see that those of the cores are generally higher than those of the cubes. That means that the relationship between the cores non- destructives and destructives are stronger than that of the cubes.

We can also see that the multiple correlation coefficients for the cube correlation (Multiple 1 and Multiple 2) increase above the correlation coefficient for rebound number (Simple 2) alone and pulse velocity alone (Simple 1). Also, the multiple correlation coefficients for the core correlation (Multiple 3 and Multiple 4) increase above the correlation coefficient for rebound number (Simple 4) alone and pulse velocity alone(Simple 3). This confirms what an earlier research has found (Samarin, 2004).

From table 4.2 , we can noted that the predicted values from the cores equations are closer to the exact values from cores testing than the values obtained from cubes relationship, although the casting and curing conditions were the same. The difference between the predicted values from the cores equations and the exact values from cores testing ranges from -4 to +5, while the difference between the predicted values from the cubes equations and the exact values from cores testing ranges from +2 to + 16. We can say as attested by some researchers that the calibration from cores improves the accuracy of the strength estimation (Bungey and Millard, 1996).

The differences between the predicted values and the direct value from cores testing are higher for the second column (12% to 40%) compared to that of the first column (10% to 16%). This can be compared to the difference in strength between the two columns: the second column direct strength (40 MPa) is higher than the first column one (37 MPa).

Although the multiple correlation coefficients increase above the correlation coefficient for rebound number alone and pulse velocity alone, the strengths estimated by the multiple regressions are not closer to the exact one. (See table 4.2) We can say that the combined method have little if not no effect in the increase of the accuracy of the strength estimation (Popovics, 1998; Malhotra and Carette, 1980; cited by Popovics, 2001).

Table 4.1: Regression correlation coefficients

REGRESSION			
NATURE	**TYPE**	**FORMULA**	**R**
By cube	Simple 1	$F_{c'} = 0.198e^{1.098V}$	0.81
	Simple 2	$F_{c'} = 2.455e^{0.088R}$	0.90
	Multiple 1	$F_{c'} = 0.00201R^{2.32}V^{1.20}$	0.91
	Multiple 2	$F_{c'} = -63.76 + 2.85R + 0.03V^{4}$	0.91
By core	Simple 3	$F_{c'} = 0.272e^{1.044V}$	0.91
	Simple 4	$F_{c'} = 4.717e^{0.059R}$	0.86
	Multiple 3	$F_{c'} = 0.00745R^{0.97}V^{3.27}$	0.95
	Multiple 4	$F_{c'} = -28.26 + 1.05R + 0.06V^{4}$	0.96

Table 4.2: Compressive strength results

REGRESSION		**VALUE (MPa)**					
		Column 1 PV = 4.8, RN = 33			**Column 2 PV = 4.9, RN = 36**		
FORMULA		**Predicted Fc’**	**Core Fc**	**Fc’- Fc**	**Predicted Fc’**	**Core Fc**	**Fc’- Fc**
By cube	Simple 1	39	37	+ 2	43	40	+ 3
	Simple 2	45		+ 8	58		+ 18
	Multiple 1	44		+ 7	55		+ 15
	Multiple 2	46		+ 9	56		+ 16
By core	Simple 3	41		+ 4	45		+ 5
	Simple 4	33		- 4	39		- 1
	Multiple 3	37		+ 0	43		+ 3
	Multiple 4	38		+ 1	44		+ 4

4.2 Covermeter

The relationship was established between the Covermeter readings and the measured depths”.

The curve obtained is shown in figure 4.9.

The correlation coefficient is very high (99%) meaning that the regression analysis is good.

From Table 4.3 we note that at low depth the estimation is perfect. As the depth goes deeper the estimation is not equal to the exact one, but is still very good. It can be said that with the reinforcing bars at greater depths, variation in the estimation from the true depth can be expected (Dixon, 1987). This should be expected since, for a given bar size, the sensitivity of the instrument decreases as the bar’s depth (cover) increases.

Table 4.3: Covermeter results

Bar	**REGRESSION LAW** **$D = -0.63 + 1.02P$** **R = 0.99**	
	Predicted	**Exact**
Bar 1 (depth = 75)	76	75
Bar 2 (depth = 54)	54	54
Bar 3 (depth = 40)	40	40

4.3 Uniformity of concrete

The histograms obtained from the columns calibration data and the columns testing data are shown in Figures 4.11 and 4.12 both from pulse velocities and rebound number. Numerical methods are also used to study the uniformity of concrete. These are shown in Table 4.4.

The comparison of the pulse velocity histogram from the calibration data (Figure 4.11 a) and the one from the testing columns data (Figure 4.12 a), shows almost similarity. The same similarity is observed by comparing the rebound number histogram from the calibration data (Figure 4.11 b) and the rebound number histogram from the testing columns data (Figure 4.12 b). The coefficients of variability for the pulse velocity, 3.24% and 2.94% for the calibration data and the testing columns respectively, are almost equal. The coefficients of variability for the rebound number, 8.17% and 6.19% for the calibration data and the testing columns respectively, are also almost equal. We can say that pulse velocity alone and rebound number alone provides a good idea of the concrete quality in a structure. Then, the interpretation by histogram method and by numerical method leads to the same conclusion, both for the pulse velocity and the rebound number.

The comparison of the pulse velocity histograms with the typical ones (Figure 4.10) indicates a supply of concrete of almost same quality. And the comparison of the rebound index histograms with the typical ones (Figure 4.10) indicates a supply of concrete of almost same quality but from different sources.

The coefficients of variation from pulse velocity (3.24% and 2.94%) are closer to the typical one of good quality construction (2.5%), but the ones from rebound index (8.17% and 6.19%) are different to the typical one of good quality construction (4% for individual member). The difference in the coefficients of variability of rebound number is expected to be higher as a number of different members are involved (Bungey and Millard, 1998).

As the results from one pulse velocity is confirmed by those of the rebound hammer, we can say that interpreting concrete uniformity data by comparing them to the typical ones is reliable. We can say that the use of more than one testing method increases the reliability of the interpretation.

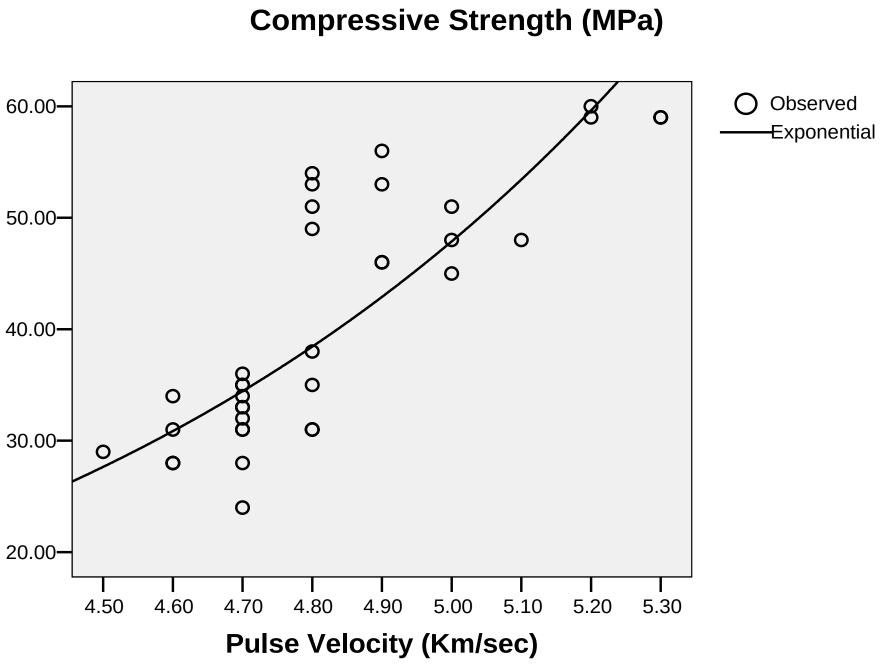


Figure 4.1 : Compressive strength vs pulse velocity (Cube)

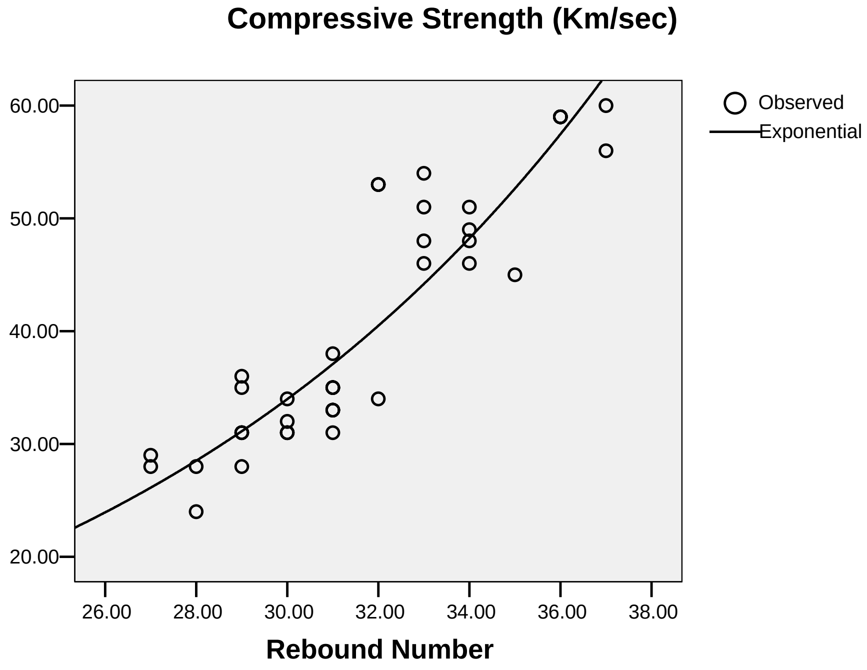


Figure 4.2: Compressive strength vs rebound index (Cube)

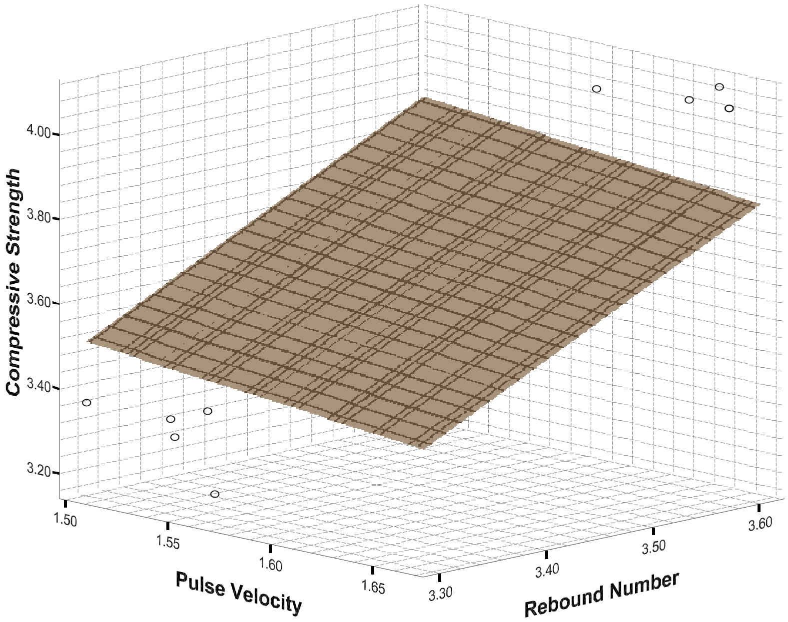


Figure 4.3: Compressive strength vs pulse velocity and rebound index by SonReb law (Cube)

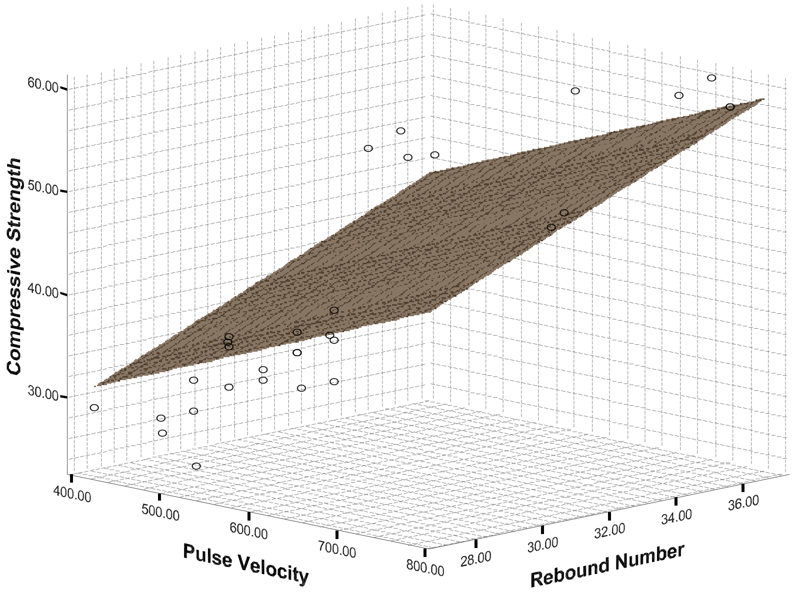


Figure 4.4: Compressive strength vs pulse velocity and rebound index by Samarin law (Cube)

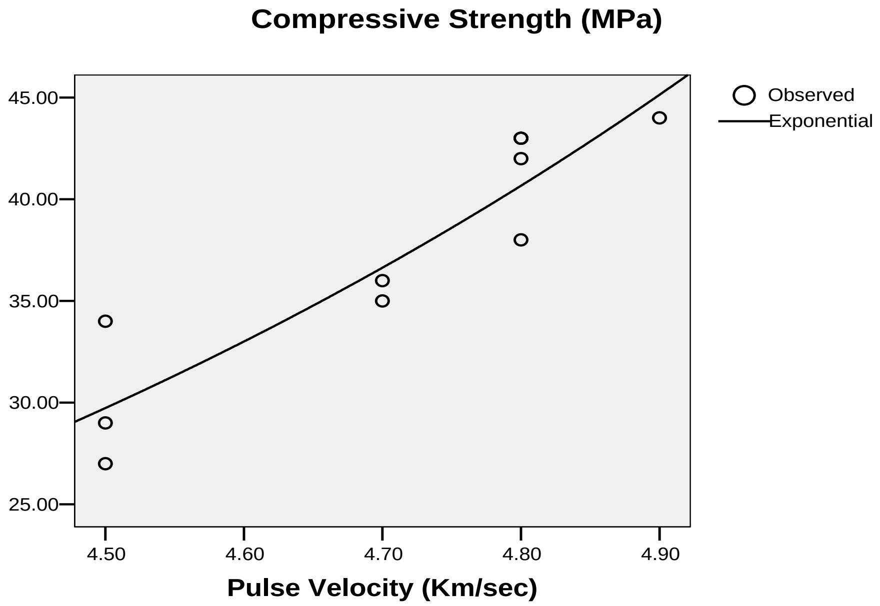


Figure 4.5: Compressive strength vs pulse velocity (Core)

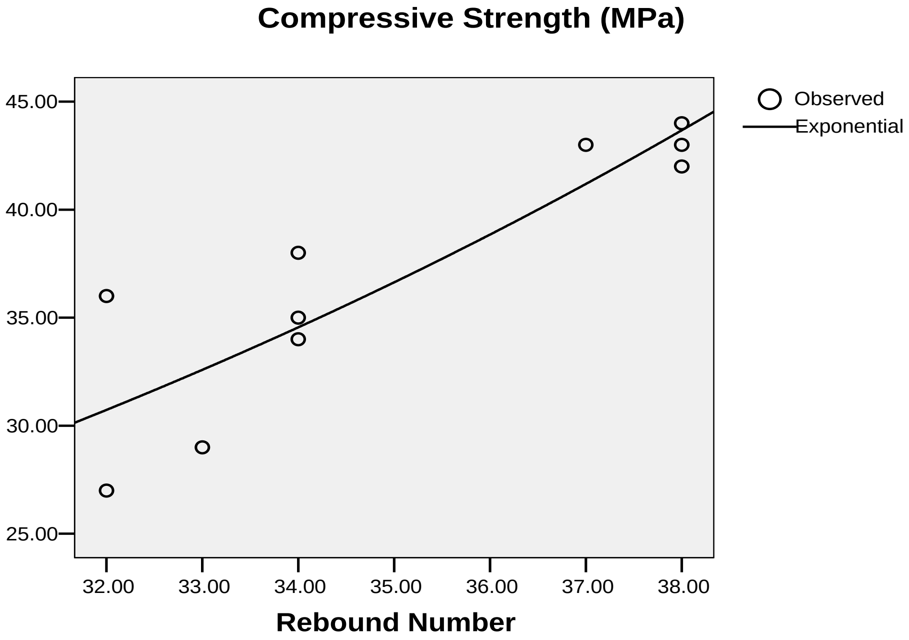


Figure 4.6: Compressive strength vs rebound index (Core)

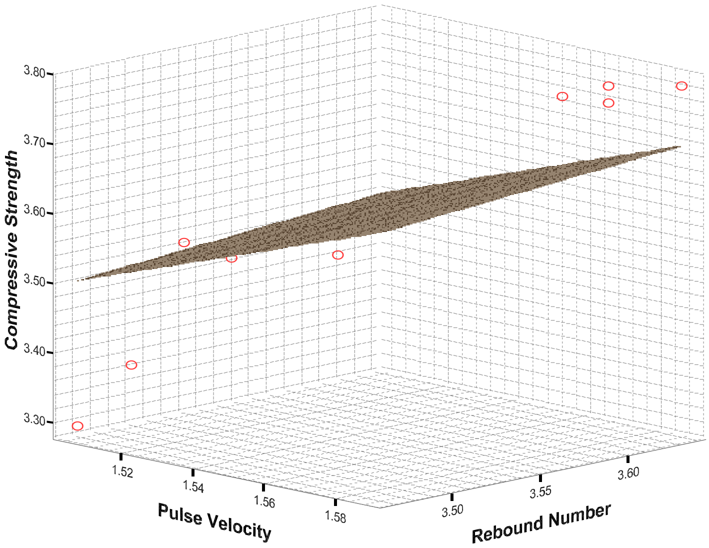


Figure 4.7: Compressive strength vs pulse velocity and rebound index by SonReb law (Core)

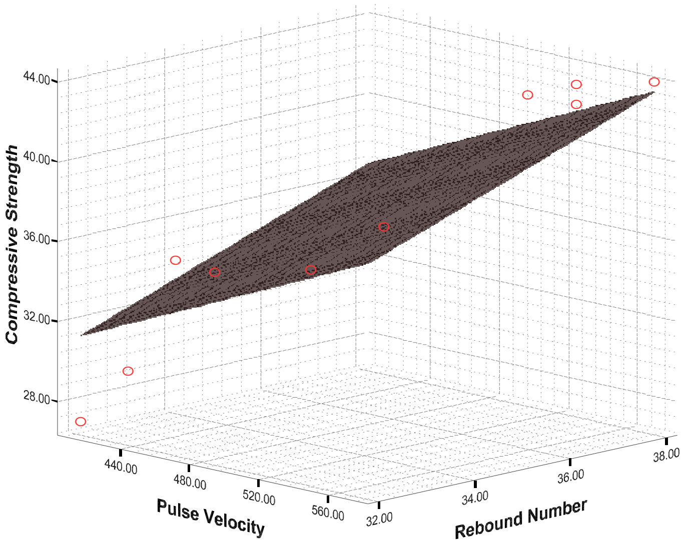


Figure 4.8: Compressive strength vs pulse velocity and rebound index by Samarin law (Core)

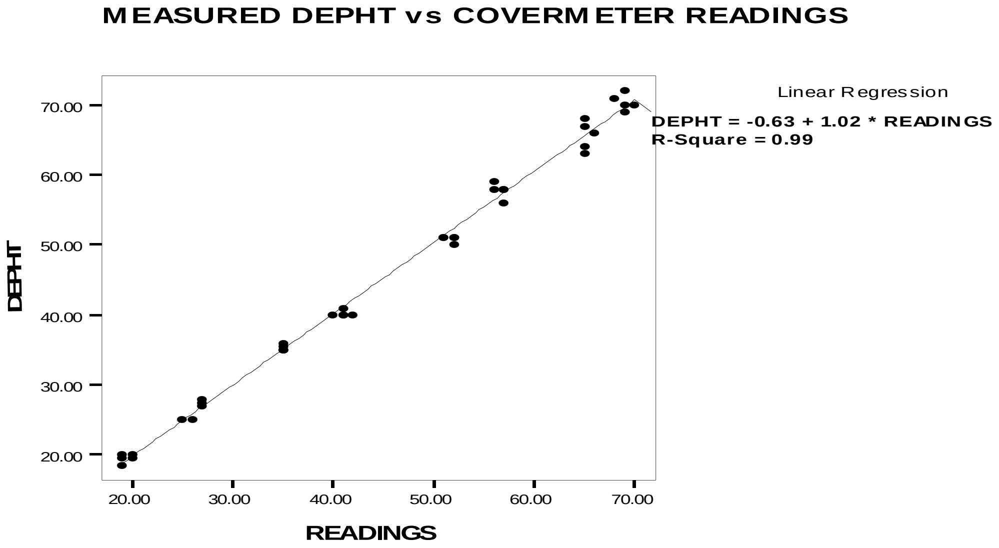


Figure 4.9: Depth vs. covermeter readings

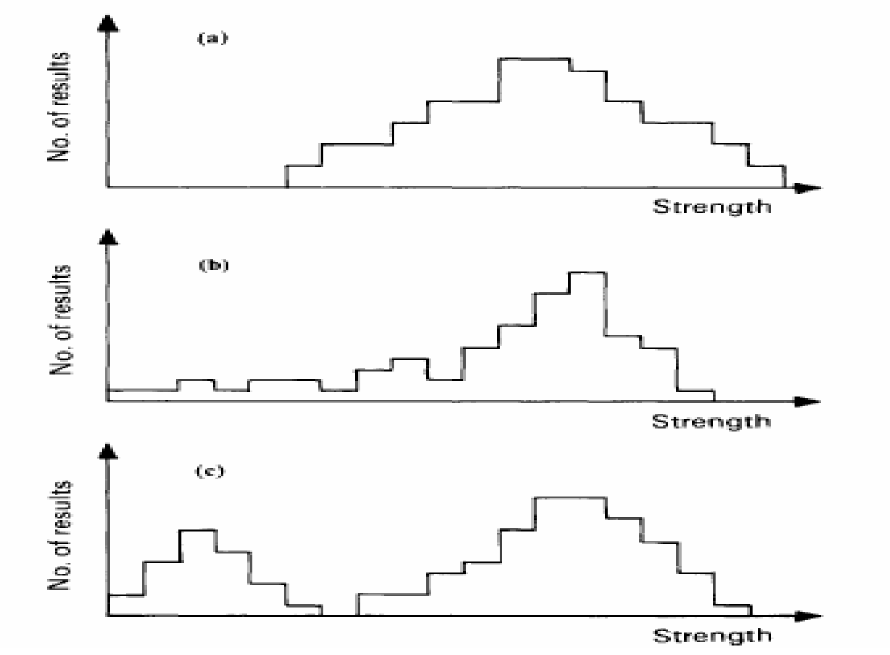


Figure 4.10: Typical histogram plots a) uniform supply; b) poor construction; two sources (From Bungey, 1998)

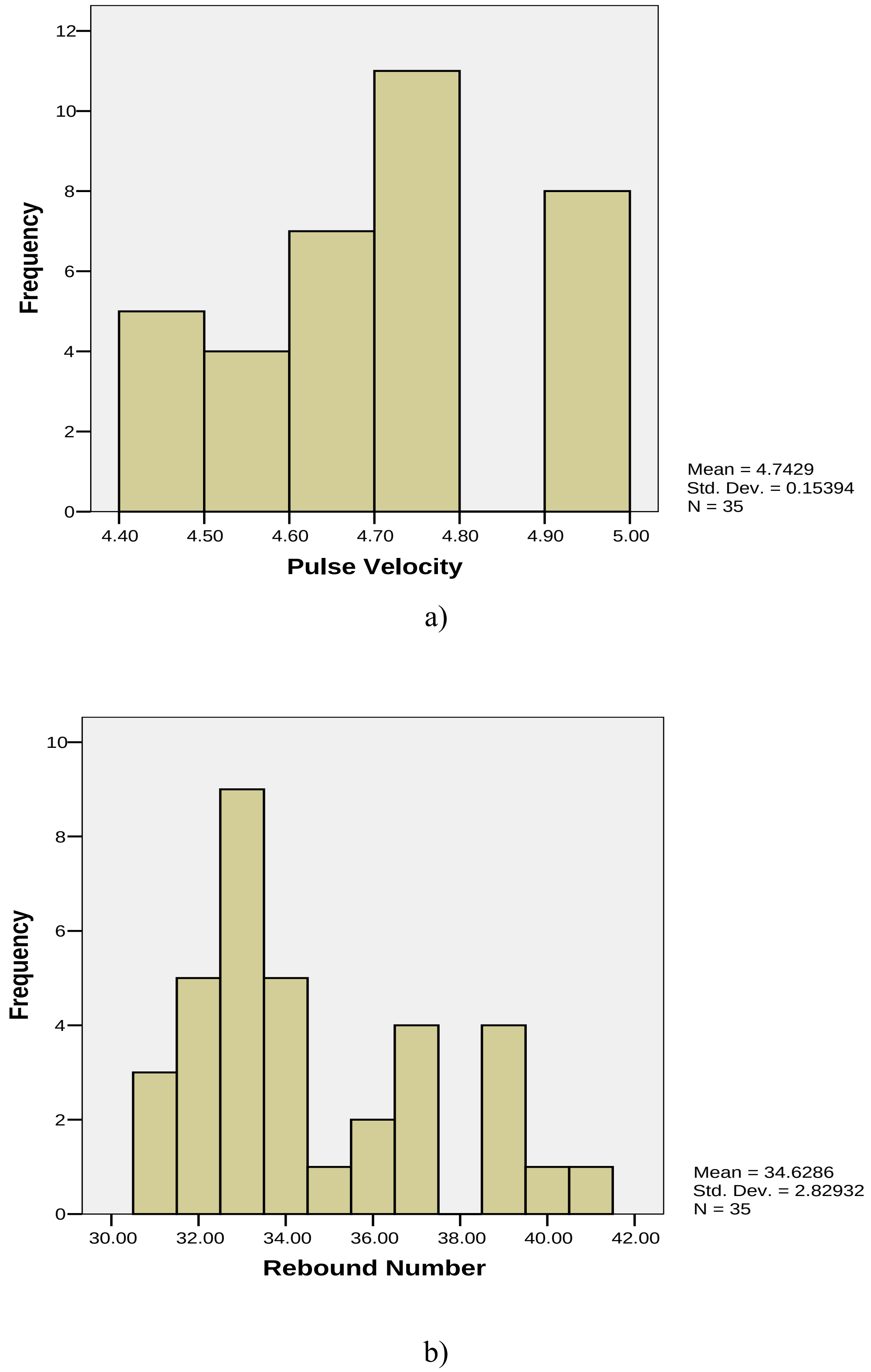
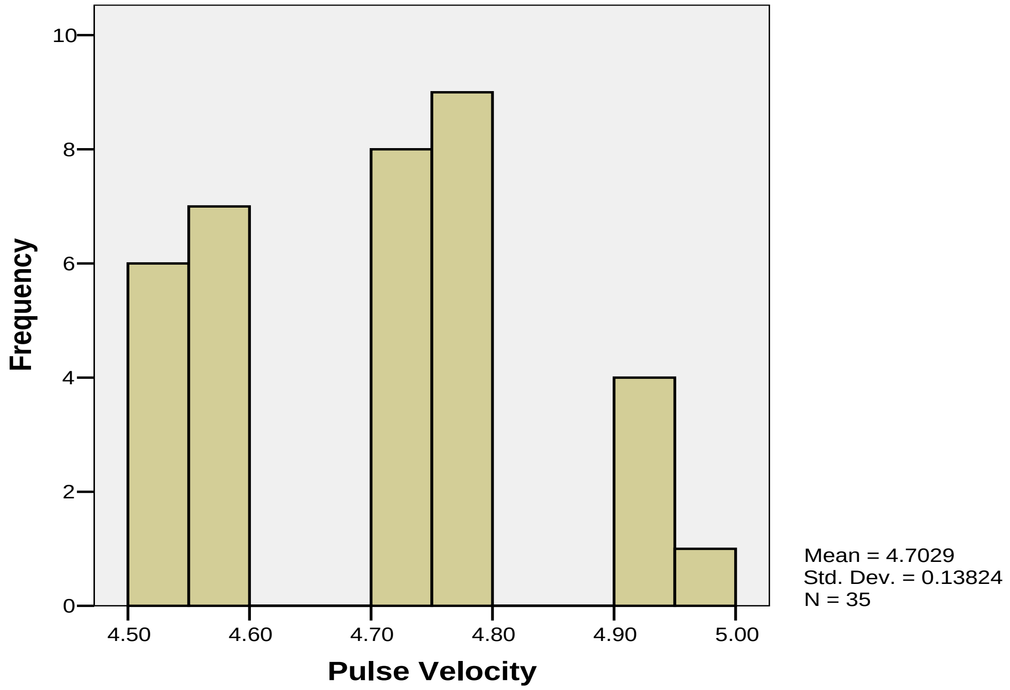
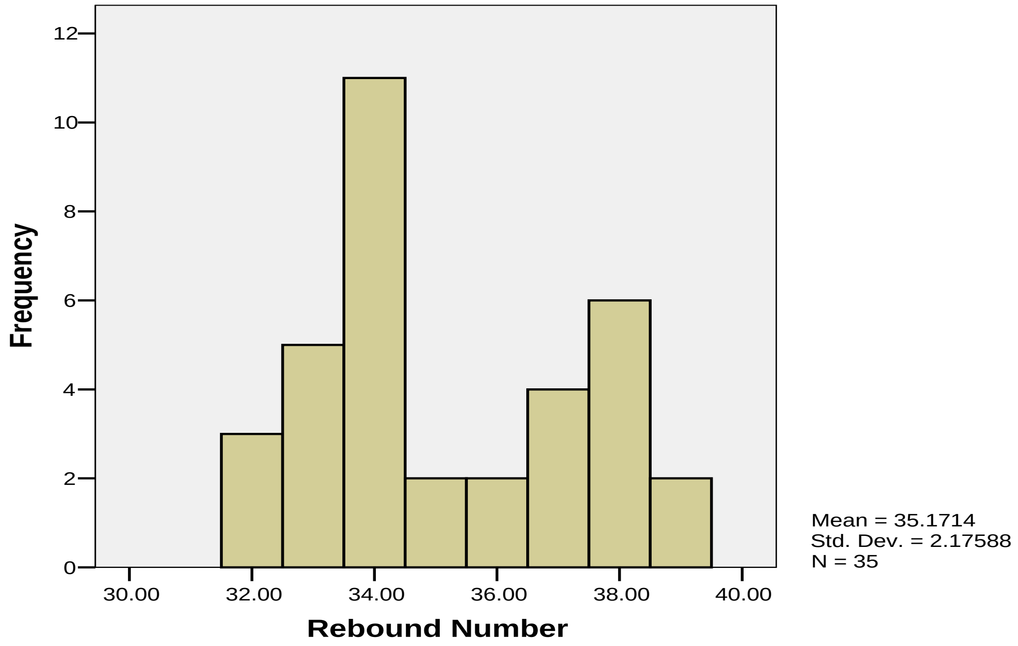


Figure 4.11: Histogram plots of test results from calibration data, a) by pulse velocity, b) by rebound number



a) By pulse velocity



b) By rebound number

Figure 4.12: Histogram plots of test results from testing data, a) by pulse velocity, b) by rebound number

Table 4.4: Numerical evaluation of the uniformity of concrete, a) by Pulse Velocity b) by rebound number

a)

MIX	**NUMERICAL VALUES**		
1, 2		**Calibration columns**	**Testing columns**
	Mean	4.7429	4.7029
	St. deviation	0.15384	0.13824
	N	35	35
	Coefficient of variation	3.24%	2.94%

b)

MIX	**NUMERICAL VALUES**		
1, 2		**Calibration columns**	**Testing columns**
	Mean	34.6286	35.1714
	St. deviation	2.82932	2.17588
	N	35	35
	Coefficient of variation	8.17%	6.19%

Chapter 5

Conclusions and recommendations

5.1 Conclusions

The main results obtained by the present study are summarized as follow:

1- The reliability in interpreting ndt results of concrete for strength estimation

   - depends on the type of specimens used for the calibration. Calibration with cores from structures under investigation gives more accurate estimation.

   - taking calibration specimens from the same batch and cure them in the same conditions as the structure to be investigate can improve the accuracy of the strength estimated

   - combined ultrasonic and rebound method has little effect on the reliability of the interpretation of strength

2- The reliability in interpreting ndt results of concrete for cover depth estimation is quite good.

3- The interpretation of the concrete uniformity graphical and numerical methods is reliable and the reliability is increased when done by more than one testing method.

5.2 Recommandations

Since the advantages of the nondestructive testing are its rapidity and non destructivity, priority should be given to develop correlation relationship by laboratory specimens instead of core taken from structure. For future work, emphasis should be put on establishing correlation relationship on specimens cured and vibrated in different conditions. Different mixes targeting the same strength should also be considered.

As the age of the specimens has a major influence on the nondestructive parameters, relationships should be developed to relate reading on samples of different ages.

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APPENDIX A

Cube calibration data

N^o	**Pulse Velocity (km/sec)**	**Rebound Number**	**Compression Strength (Mpa)**	**MIX (MPa)**
1	4.9	37	56	50
2	4.8	34	49	50
3	4.9	32	53	50
4	4.8	32	53	50
5	4.8	33	54	50
6	5.0	33	48	40
7	4.9	33	46	40
8	4.8	34	51	50
9	4.9	34	46	40
10	5.0	33	51	50
11	5.3	36	59	50
12	5.3	36	59	50
13	5.2	37	60	50
14	5.2	36	59	50
15	5.0	35	45	40
16	5.1	34	48	40
17	4.7	28	24	30
18	4.6	29	28	30
19	4.6	28	28	30
20	4.5	27	29	30
21	4.7	27	28	30
22	4.6	29	31	30
23	4.7	30	32	30
24	4.7	29	31	30
25	4.7	30	31	30
26	4.8	31	31	30
27	4.7	31	33	30
28	4.7	32	34	40
29	4.7	31	33	30
30	4.6	30	34	40
31	4.8	30	31	30
32	4.7	29	36	40
33	4.7	29	35	40
34	4.8	31	35	40
35	4.8	31	38	40
36	4.7	31	35	40

APPENDIX B

Core calibration data

N°	Pulse Velocity (km/sec)	Rebound Number	Compression Strength (Mpa)	MIX (MPa)
1	4.80	34.00	38.00	30.00
2	4.70	32.00	36.00	30.00
3	4.50	32.00	27.00	30.00
4	4.50	34.00	34.00	30.00
5	4.80	38.00	43.00	40.00
6	4.90	38.00	44.00	40.00
7	4.80	37.00	43.00	40.00
8	4.80	38.00	42.00	40.00
9	4.70	34.00	35.00	30.00
10	4.50	33.00	29.00	30.00

APPENDIX C

Covermeter calibration data

N^O	Covermeter reading	Measured depth
1	19	18.5
2	19	19.5
3	20	20.0
4	20	19.5
5	19	20.0
6	42	40.0
7	41	40.0
8	41	41.0
9	41	40.0
10	40	40.0
11	70	70.0
12	69	70.0
13	69	69.0
14	68	71.0
15	69	72.0
16	52	50.0
17	52	51.0
18	51	51.0
9	51	51.0
20	52	51.0
21	66	66.0
22	65	67.0
23	65	68.0
24	65	63.0
25	65	64.0
26	57	58.0
27	57	58.0
28	56	58.0
29	56	59.0
30	57	56.0
31	25	25.0
32	27	27.0
33	27	27.5
34	27	28.0
35	26	25.0
36	35	35.0
37	35	35.5
38	35	36.0
39	35	35.0
40	35	35.0