Sudan University of Science and Technology
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Statistical Analysis for Concrete Compressive Strength for Dam Complex of Upper Atbara – Setit Project

تحليل إحصائي لمقاومة إنضغاط الخرسانة في مشروع مجمع سـدي أعالي عطبرة و ستيت

A thesis Submitted in partial fulfillment of the requirements for the degree of M.Sc in Civil Engineering [Construction Engineering]

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Date: November, 2017

May 2018

الاية

بسم الله الرحمن الرحيم

قال تعالى:

{وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلًا}

صدق الله العظيم

ســـورة الاســـراء الاية (٨٥)

Dedication

To my father’s soul.

To my mother.

To my sisters.

To all the people out there who believe that tomorrow will be better.

Acknowledgments

Before all, thanks to Allah.

I would like to express my genuine gratitude to Prof .Dr. Salih Elhadi Mohammed Ahmed, Sudan University of Science and Technology, for his help and guidance in the preparation and development of this work. The constant encouragement, support and inspiration offered were fundamental to the completion of this research.

Special thanks to Dam Implementation Unit for their logistic facilitations and their continuous support. I would like to express my deep thanks for my friends for their assistance during the period of this research. Finally, I would like to thank everyone who gave advice or assistance that contributed to complete this research.

My special appreciation goes to my family, whose love and care have brought me to this level. Their substantial encouragements and support have helped me to succeed in finishing my M.Sc program.

Abstract

Concrete is considered as the single most widely used material on this era of construction development, therefore, evaluation of its quality is thought to be one of the most important topic that been studied these days.

This study aimed towards evaluation of concrete quality in Dam Complex of Upper Atbara - Setit Project in Gdareef State - Sudan using concrete compressive strength as a parameter.

More than 4000 concrete compressive strength test sample from different strength classes (C12/15, C20/25, C25/30, C35/45, and C70/85), where two types of Cement Ordinary Portland and Slag cement were used, was taken at DCUAP site, each sample was tested for compressive strength at age of 7 and 28 days according to EN 12390 from the year 2012 to 2016. In this research, statistical analysis for DCUAP concrete compressive strength test was conducted for each class independently to determine compliance with acceptance criteria of (ACI 214.3R-88) and (EN 206-1) codes and then the level of quality control for each concrete class separately was obtained. Then shewhart chart analysis was used to determine whether the process of concrete production was controlled or not.

The statistical analysis conducted on this research resulted in conclusion that the degree of quality for the different concrete classes, when the Ordinary Portland Cement was used, varies through the entire period of the project between fair and good with the exception of poor quality level for concrete compressive strength for class C20/25 which was tested at age 28 day. And the degree of quality for the different concrete classes, when the Slag cement was used, varies between fair, good and very good with the exception of excellent quality level for concrete compressive strength for class C12/15 which was tested at age 7day.

As when subjected the data for shewhart chart analysis, it shows that the process of concrete production for most of the concrete classes was out of control through the earlier stage of the project, where the Ordinary Portland Cement was used with some exceptions, and went down to be controlled for the rest of the period, where the Slag Cement was used, with some exceptions.

At the end it was recommended that, to increase the quality awareness in order to improve it, and also further investigations are required to reveal the deficiencies locations in the process of concrete production at Dam Complex of Upper Atbara to increase the level of quality in the upcoming projects.

المستخلص

تعتبر الخرسانة اكثر المواد استخداماً في هذه الحقبة من التطور العمراني، ولذلك فإن تقييم جودتها يعتبر واحداً من اهم المواضيع التي تتم دراستها اليوم.
هدفت هذه الدراسة الي تقييم جودة الخرسانة في مشروع مجمع سدي اعالي عطبرة وستيت في ولاية القضارف-السودان، مستخدمتاً مقاومة انضغاط الخرسانة كمعيار للتقييم.

اكثر من ٤٠٠٠ عينة اختبار مقاومة انضغاط خرسانة، من فئات مختلفة (C12/15, C20/25, C25/30, C35/45 and C70/85) تم فيها استخدام نوعين من الاسمنت بورتلاندي عادي واسمنت خبث الافران، تم اخذها في مشروع مجمع سدي اعالي عطبرة وستيت كل منها تم اختبار مقاومة الانضغاط لها في عمري ٧ايام و ٢٨يوم طبقاً للمواصفات الاوربية EN 12390في الفترة منذ ٢٠١٢ وحتي ٢٠١٦.

في هذه الدراسة، تحليل احصائي لنتائج اختبارات مقاومة انضغاط الخرسانة بمشروع مجمع سدي اعالي عطبرة وستيت تم عملها لكل فئة من فئات الخرسانة علي حده لتحديد درجة الامتثال لمعايير القبول في المواصفات الامريكية (ACI 214.3R-88) والاوربية (EN 206-1) ومن ثم تم تحديد درجة الجودة لكل فئة علي حده. وبعدها تم استخدام مخططات شيوارت لمراقبة الجودة لتحديد ما اذا كانت عملية انتاج الخرسانة تحت السيطرة ام لا.

التحليل الإحصائي الذي تم عمله لهذه النتائج افضي الي ان مستوي الجودة لفئات الخرسانة المختلفة، عندما تم استخدام اسمنت بورتلاندي عادي، يتفاوت خلال فترة المشروع بين جيد و مقبول باستثناء مستوي جودة ضعيف لمقاومة انضغاط الخرسانة من فئة C20/25 التي تم اختبارها بعد ٢٨ يوم. ومستوي الجودة لفئات الخرسانة المختلفة، عندما تم استخدام اسمنت خبث الافران، يتفاوت خلال فترة المشروع بين مقبول، جيد و جيد جداً باستثناء مستوي جودة ممتاز لمقاومة انضغاط الخرسانة من فئة C12/15 التي تم اختبارها بعد ٧ايام.
وعندما تم تحليل النتائج باستخدام مخططات شيوارت لمراقبة الجودة، وجد ان عملية انتاج الخرسانة لمعظم الفئات كانت خارج السيطرة في الفترات الاولى من عمر المشروع والتي تم فيها استخدام الاسمنت البورتلاندي العادي مع وجود بعض الاستثنآت. وتمت السيطرة علي العملية لاحقاً في الفترة المتبقية من المشروع والتي استخدم فيها اسمنت خبث الافران مع وجود بعض الاستثنآت.

في الختام، تمت التوصية بزيادة الوعي لمفهوم الجودة حتى يتم تحسينها، وايضاً ضرورة عمل استقصاءت اخري للكشف عن اماكن القصور في عملية انتاج الخرسانة في مشروع مجمع سدي اعالي عطبرة وستيت حتي يتم زيادة مستوى الجودة في المشاريع المقبلة.

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List of Abbreviations

Abbreviations	Meaning
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BS	British Standard
EN	European Standard
DIN	German Institute for Standardization
ISO	International Organization for Standardization
σ	Population Standard deviation
X	Mean
S	Sample Standard deviation
V	Coefficient of variation
R	Range
f_{cr}	The required average strength
p	probability factor
fc'	Concrete specified strength
d_2	Factors for computing within-test standard deviation
UCL	Upper Control Limit
LCL	Lower Control Limit
UWL	Upper Warning Limit
LWL	Lower Warning Limit
BRRI	Building and Road Research Institute
DCUAP	Dam Complex of the Upper Atbara Project
OPC	Ordinary Portland Cement

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Chapter One
Introduction

1.1 General

Nowadays, there are two commonly used structural materials: concrete and steel. They sometimes complement one another, and sometimes compete with one another, so that many structures of a similar type and function can be built in either of these materials. And yet, universities, polytechnics and colleges teach much less about concrete than about steel. This in itself would not matter were it not for the fact that, in actual practice, the man on the job needs to know more about concrete than about steel. This assertion will now be demonstrated.

Steel is manufactured under carefully controlled conditions, always in a highly sophisticated plant; the properties of every type of steel are determined in a laboratory and described in a manufacturer's certificate.
Thus the designer of a steel structure need only specify the steel complying with a relevant standard, and the constructor need only ensure that correct steel is used and that connections between the individual steel members are properly executed.

On a concrete building site, the situation is totally different. It is true that the quality of cement is guaranteed by the manufacturer in a manner similar to that of steel, and, provided suitable cement is chosen, its quality is hardly ever a cause of faults in a concrete structure. But cement is not the building material: concrete is. Cement is to concrete what flour is to a fruit cake, and the quality of the cake depends on the cook.

It is possible to obtain concrete of specified quality from a ready-mix supplier but, even in this case, it is only the raw material that is bought. Transporting, placing and, above all, compacting greatly influence the final product. Moreover, unlike the case of steel, the choice of mixes is virtually infinite and therefore the selection cannot be made without a sound knowledge of the properties and behavior of concrete. It is thus the competence of the designer and of the specifier that determines the potential qualities of concrete, and the competence of the contractor and the supplier that controls the actual quality of concrete in the finished structure.

It follows that they must be thoroughly conversant with the properties of concrete and with concrete making and placing.

Concrete, in the broadest sense, is any product or mass made by the use of a cementing medium. Generally, this medium is the product of reaction between hydraulic cement and water. But, these days, even such a definition would cover a wide range of products: concrete is made with several types of cement and also containing pozzolan, fly ash, blast-furnace slag, microsilica, additives, recycled concrete aggregate, admixtures, polymers, fibres, and so on; and these concretes can be heated, steam-cured, autoclaved, vacuum-treated, hydraulically pressured, shock-vibrated, extruded, and sprayed.(Neville, 2010)

Good-quality concrete is a very durable material and should remain maintenance free for many years when it has been properly designed for the service conditions and properly placed. Through choice of aggregates, or control of paste chemistry and microstructure, concrete can be made inherently resistant to physical attack, such as from cycles of freezing and thawing or from abrasion, and from chemical attack, such as from dissolved sulfates or acids attacking the paste matrix or from highly alkaline pore solutions attacking certain aggregates. Judicious use of mineral admixtures greatly enhances the durability of concrete. Unlike structural steel, it does not require protective coatings except in very corrosive environments. It is also an excellent material for fire resistance. Although it can be severely damaged by exposure to high temperatures, it can maintain its structural integrity for a considerable period-long after steel buildings would have suffered irreparable damage. (Mindless, 1981)

1.2 Research Problem

Techniques and methods for checking the quality of materials been used over the centuries. For example, the ancient Egyptians had to make and use precise measurements and adopt very high standards of work in order to build the Pyramids.

The past few years had witnessed a significant development in the construction industry, especially in the concrete field. Worldwide and also in Sudan, major projects that uses concrete as building material were constructed.

In Sudan this extensive use of concrete in construction was not accompanied by strong quality control. This lack of quality control had led to several problems in the construction industry such as over cost of the projects and the consumption of large amount of money in repairing and rehabilitation for the projects constructed in a poorly quality control circumstances. Investigating the aforementioned and other incidents showed that most of the construction failures were due to poor concrete quality. Therefore the quality of the concrete is one of the most important things in the field of construction.

1.3 Research Objective

- In this research compressive strength will be taken as a quality parameter of concretes in Dam complex of upper Atbara project.
- This research's main objective is to apply the acceptance criteria of the ACI and EN codes to evaluate the level of quality control in Dam complex of upper Atbara project (DCUAP) using its concrete strength data.
- Additionally, finding out indications or general conclusions regarding the quality control level in this project.
- The reason behind these evaluations is to identify divergences from desired target values or quality levels, and also these evaluations will help us to identify the concrete quality flaws in this project in order to avoid them in the upcoming ones.

1.4 Research Hypotheses

- Using different types of cement in concrete production to achieve a specific characteristic such as compressive strength, will not only results in reaching the acquired characteristic but will also improve the quality of the concrete production.
- The quality control of the concrete will be low at the beginning of the process and then it will improve gradually with the production process.
- Most of the concrete compressive strength test results irregularities occur at the upper limit of the quality level, this may not affect the safety of the structure however, it has economical repercussions.

1.5 Research Methodology

An over view of the Dam complex of upper Atbara project (DCUAP) will be mentioned and literature review was consulted and studies were different methods of quality evaluation was identified and outlined. And also, previous applications of this method in Sudan and other countries were reviewed.

The compressive strength data available from the Dam complex of upper Atbara project (DCUAP) was arranged and put into tables for the different classes of concrete.

The selected methods of quality evaluation and control was studied and applied to the collected data.

Data analysis using Computer software's were conducted and the results will be presented in graphical forms and discussed.

Different conclusions regarding the existing concrete quality level was obtained from the analysis and also recommendations regarding the improvement of quality level in the upcoming projects will be stated.

1.6 Outline of Research

This research will be organized as followed:

- Chapter one is the preliminary chapter that presents general objective of this research, problem definition, research methodology and layout of the research.
- Chapter two contains an overview of the project, a brief description of concrete, variation in strength, analysis of strength, conformity rules of compressive strength and review of researches on evaluation of quality of concrete.
- Chapter three explains the component material of concrete mix, testing of concrete and technique used to evaluate the quality of concrete.
- Chapter four covers the analysis and discussion of the results.
- Some Conclusions and recommendations were presented in chapter five.

Chapter Two
Literature Review

2.1 General

There are many factors that involved in the production of high-quality concrete: materials, proportioning, handling and placing, curing, and testing. It should, therefore, come as no surprise that concrete, in common with other engineering materials, is inherently a variable material. That is, tests on nominally identical samples of concrete will show some variation in mechanical properties between samples. Clearly, this variability in properties must be considered when writing concrete specifications.

In general, the factors that contribute to this variability may be grouped as follows:

1- Materials: This includes variability in the cement itself; in the grading, moisture content, mineral composition, physical properties, and particle shape of the aggregates; and in the admixtures used.

2- Production: This involves the type of batching plant and equipment, the method of transporting the concrete to the site, and the procedures and workmanship used to produce and place the concrete.

3- Testing: This in dudes the sampling procedures, the making and curing of test specimens, and the test procedures used.

It is, of course, very difficult to assess the relative importance of these three groups of factors; in any event, their importance will vary for different regions and different construction projects. Since the variability in concrete quality is some function of the variabilities of each of these three factors, no one of these can be ignored in concrete production. (Mindless, 1981)

2.2 Concrete Constituent Materials

2.2.1 Cement

Cement is a material which hardens under water. This property and the related property of not undergoing chemical change by water in later life are most important and have contributed to the widespread use of concrete as a building material. Four components which considered the main constituent of cement are listed in Table (2.1) bellow

Table (2.1) Main compounds in Portland cement

Name of compound	Oxide composition	Abbreviation
Tricalcium silicate	$3CaO.SiO_2$	C_3S
Dicalcium silicate	$2CaO.SiO_2$	C_2S
Tricalcium aluminate	$3CaO.AI_2O_3$	C_3A
Tetracalcium alumino ferrite	$4CaO.AIO_3.FeO_3$	C_4AF

2.2.1.1 Portland cement Types

Portland cement is considered as a generic material. However, when hydrated, cements differing in chemical composition may exhibit different properties. It should thus be possible to select mixtures of raw materials for the production of cements with various desired properties. In fact, several types of Portland cement are available commercially, and additional special cements can be produced for special uses. Table (2.2) lists the main types of Portland cement as classified by BS, ASTM and new BS EN Standards. (Neville, 2008)

Table (2.2) Main Types of Portland Cement

Traditional classification		**European classification IBS 8500-1: 2006)**	
British	**American**		
Ordinary Portland [BS 12]	Type I [ASTM C 150]	Type (CEM) I	Portland
Rapid-hardening Portland [BS 12]	Type III [ASTM C 150]	Type IIA	Portland with 6 to 20% fly ash, ggbs, limestone or 6 to 10% silica fume
Low-heat Portland [BS 1370]			
Modified cement	Type IV [ASTM C 150]	Type IIB-S	Portland with 21 to 35% ggbs
Sulfate resisting Portland (SRPC) [BS 4027]	Type II [ASTM C 150]		

Portland blast-furnace (Slag cement) [BS 146]	Type V [ASTM C 150]	Type IIB-V	Portland with 21 to 35% fly ash
High slag blast-furnace [BS 4246]	Type IS Type S Type I(SM) [ASTM C 595]	Type IIB+SR	Portland with 25 to 35% fly ash with enhanced sulfate resistance
White Portland [BS 12]		Type IIA	Portland with 36 to 65% ggbs
Portland-pozzolan [BS 6588; BS 3892]	-	Type IIA+SR	Portland with 36 to 65% ggbs with enhanced sulfate resistance
	-	Type IIIB	Portland with 66 to 80% ggbs
	Type IP Type P Type I(PM) [ASTM C 595]	Type IIIB+SR	Portland with 66 to 80ult, ggbs with enhanced sulfate resistance
		Type IIIC	Portland with 81 to 95% ggbs
		Type IVB-V	Portland with 36 to 55% fly ash
*ggbs is ground granulated blast furnace slag			

2.2.2 Aggregate

Since approximately three-quarters of the volume of concrete are occupied by aggregate, it is not surprising that its quality is of considerable importance.

Aggregate was originally viewed as an inert, inexpensive material dispersed throughout the cement paste so as to produce a large volume of concrete. Natural aggregates are formed by the process of weathering and abrasion, or by artificially crushing a larger parent mass.

Thus, many properties of the aggregate depend on the properties of the parent rock, it should be remembered that 4 to 5 mm (3/16 in., No.4 ASTM) is the dividing line between the fine and coarse aggregate. (Neville, 2008)

2.2.3 Mixing Water

Almost any natural water that is drinkable (potable) and has no pronounced taste or odor is satisfactory as mixing water for making concrete. (ACI 318 M-05, 2004)

2.2.4 Admixtures

An admixture is defined as “a material other than water, aggregates, hydraulic cement, and fiber reinforcement used as an ingredient of concrete or mortar, and added to the batch immediately before or during its mixing” (American Concrete Institute 2010; ASTM C125). Chemical admixtures are primarily water-soluble substances used to enhance the properties of concrete or mortar in the plastic and hardened state. These benefits include increased compressive and flexural strength at all ages, decreased permeability and improved durability, corrosion reduction, shrinkage reduction, initial set adjustments, increased slump and workability, improved pumpability, finish and finishability, rheology modification, improved cement efficiency, alkali-silica reaction (ASR) reduction, and concrete mixture economy. (ACI 214.3R-88, 1997)

2.2.5 Fly Ash and Silica Fume

Fly ash is the finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gasses. (ASTM C618-05, 2005)

Generally, fly ash benefits fresh concrete by reducing the mixing water requirement and improving the paste flow behavior, also replacing cement with the same amount of fly ash can reduce the heat of hydration of concrete. This reduction in the heat of hydration does not sacrifice long-term strength gain or durability. The reduced heat of hydration lessens heat rise problems in mass concrete placements. One of the primary benefits of fly ash is its reaction with available lime and alkali in concrete, producing additional cementations compounds. (Fly Ash Facts for Highway Engineers by American Coal Ash Association)

Silica fume is a very fine pozzolanic material, composed mostly of amorphous silica produced by electric arc furnaces as a byproduct of the production of elemental silicon or ferrosilicon alloys (also known as condensed silica fume and microsilica).(ASTM C1240-03a)

High compressive strength is generally the first property associated with silica fume concrete. Many reports are available (Loland, 1983; Loland and Hustad, 1981; Sellevold and Radjy, 1983) showing that the addition of silica fume to a concrete mix will increase the strength of that mix by between 30 per cent and 100 per cent dependent on the type of mix, type of cement, amount of silica fume, use of plasticizers, aggregate types and curing regimes. (Newman, 2003)

2.3 Concrete Properties

For a given set of raw materials, strength is governed to a large extent by the water-cementitious materials ratio (w/cm). The first criterion for producing concrete of consistent strength, therefore, is to keep tight control over the w/cm. Because the quantity of cementitious material can be measured reasonably accurately, maintaining a constant w/cm primarily requires strict control of the total quantity of water used.

The water requirement of concrete is strongly influenced by the source and characteristics of the aggregates, cement, and mineral and chemical admixtures used in the concrete, as well as the desired consistency, in the sense of workability and placeability. Water demand also varies with air content and can increase with temperature. Variations in water content can be caused by variations in constituent materials and variations in batching. A common source of variation is from water added on the job site to adjust the slump.

Water can be introduced into concrete in many ways— some of which may be intentional. The amount of water added at the batch plant and job site is relatively easy to record. Water from other sources, such as free moisture on aggregates, water left in the truck, or added but not recorded, can be difficult to determine. For a similar concrete mixture at the same temperature and air content, differences in slump from batch to batch can be attributed to changes in the total mixing water content among other factors.

The AASHTO Standard Test Method for Water Content of Freshly Mixed Concrete Using Microwave Oven Drying (TP 23) is one method of determining water content of fresh concrete. The accuracy of the test method is still under study. The test may be useful in detecting deviations in water content in fresh concrete at the construction site. Variations in strength are also influenced by air content. The entrained air content influences both water requirement and strength. There is an inverse relationship between strength and air content. The air content of a specific concrete mixture varies depending on variations in constituent materials, extent of mixing, and ambient site conditions. For good concrete control, the entrained air content should be monitored closely at the construction site.

The temperature of fresh concrete affects both the amount of water needed to achieve the proper consistency and the entrained air content. In addition, the concrete temperature during the first 24 hours of curing can have a significant effect on the later-age strengths of the concrete. Concrete cylinders that are not protected from temperatures outside the range specified in ASTM C 31 may not accurately reflect the potential strength of the concrete.

Admixtures can contribute to variability, because each admixture introduces another variable and source of variation. Batching and mixing of admixtures should be carefully controlled. Changes in water demand are also associated with variations in aggregate grading.

Construction practices will cause variations of the in-place strength due to inadequate mixing, improper consolidation, delays in placement, improper curing, and insufficient protection at early ages. These differences will not be reflected in specimens fabricated and stored under standard laboratory conditions.

The strength test is widely used in specifying, controlling, and evaluating concrete quality. Quality concrete must be able to:

1- Carry loads imposed upon it;
2- Resist deterioration; and
3- Be dimensionally stable.

There are several tests that can be made with plastic hardened concrete, but the strength test is generally accepted as a measure of the quality of concrete placed on a project.

Although the strength test is not a direct measure of concrete durability or dimensional stability, it provides an indication of the water-cement ratio of the concrete. The water-cement ratio, in turn, directly influences the strength; durability; wear resistance; dimensional stability; and other desirable properties of concrete. The strength test is also used to measure the variability of concrete. By using statistical methods based on the strength test, realistic specifications can also be prepared. (ACI 214R-02, 1995)

2.4 Concrete testing

The basic method of verifying that concrete complies with the specifications to test its strength using cubes or cylinders made from samples of fresh concrete. Ideally, it would be preferable to devise conformity tests for the mix proportions of fresh concrete even before it has been placed but, unfortunately, such tests are rather complex and not suitable for site work. Consequently, the strength of hardened concrete has to be determined, by which time a considerable amount of suspect concrete may have been placed. To offset this disadvantage, accelerated strength tests are sometimes used as a basis for conformity. (Neville, 2008)

2.4.1 Concrete compressive strength

The most common concrete property measured by testing is strength. There are three main reasons for this. First, the strength of concrete gives a direct indication of its capacity to resist loads in structural applications, whether they are tensile, compressive, shear, or combinations of these. Second, strength tests are relatively easy to conduct. Finally, correlations can be developed relating concrete strength to other concrete properties that are measured by more complicated tests. (Lamond, et al)

Compressive strength or compression strength can be defined as the capacity of a material or structure to withstand loads tending to reduce size.

2.4.1.1 Compressive strength test

According to BS EN 12390-1: 2000, the test cube is cast in steel or cast iron moulds of prescribed dimensions and planeness, with the upper part of the mentioned mould clamped to the base. BS EN 12390-2: 2000 prescribes filling the mould in about 50 mm (2 in.) layers. Compaction of each layer is achieved by at least 35 strokes (150 mm cubes), or 25 strokes

(100 mm cubes), of a 25 mm (2 in.) square steel punner; alternatively, vibration may be used. The test cubes are then cured until the testing age as prescribed by BS EN 12390-2: 2000. After the top surface has been finished by a trowel, the cube should be stored at a temperature of 20 ± 5 °C (68 ± 9 OF) when the cubes are to be tested at, or more than, 7 days or 20 ± 2 °C (68 ± 3.6 OF) when the test age is less than 7 days; the preferred relative humidity is not less than 90 per cent, but storage under damp material covered with an impervious cover is permitted. The cube is de-moulded just before testing at 24 hours. For greater ages at test, demoulding takes place between 16 and 28 hours after adding water to the mix, and the specimens are stored in a curing tank at 20 ± 2 °C (68 ± 3.6 OF) until the prescribed age. The most common age at test is 28 days, but additional tests can be made at 3 and 7 days, and less commonly, at 1, 2, and 14 days, 13 and 26 weeks and 1 year.

The foregoing curing procedure applies to standard test cubes but, as in the case of cylinders, service cubes may also be used to determine the actual quality of the concrete in the structure by curing the cubes under the same conditions as apply to the concrete in the structure. BS EN 12390-3: 2002 specifies that the cube is placed with the cast faces in contact with the platens of the testing machine, i.e. the position of the cubes as tested is at right angles to the position as cast. The load is applied at a constant rate of stress within the range of 0.2 to 1.0 MPa/sec (29 to 145 psi/sec), and the crushing strength is reported to the nearest 0.5 MPa (50 psi). (Neville, 2008)

2.4.1.2 Definitions

- Concrete sample

  A portion of concrete taken at one time from a single batch or single truckload of concrete.
- Single cylinder (cube) strength or individual strength

  The strength of a single cylinder; a single cylinder strength does not constitute a test result.
- Companion cylinders (cube)

  Cylinders (cube) made from the same sample of concrete.
- Strength test or strength test result

The average of two or more single-cylinder strengths of specimens made from the same concrete sample (companion cylinders) and tested at the same age.

- Range or within-test range

  The difference between the maximum and minimum strengths of individual concrete specimens comprising one strength test result.
- Test record

  A collection of strength test results of a single concrete mixture.

2.5 Variation in Strength

Strength of concrete is commonly considered to be its most valuable property, although in many practical cases other characteristics, such as durability, impermeability and volume stability, may in fact be more important. Nevertheless, strength usually gives an overall picture of the quality of concrete because it is directly related to the structure of cement paste. (Neville, 2008)

The magnitude of variations in the strength of concrete test specimens is a direct result of the degree of control exerted over the constituent materials, the concrete production and transportation process, and the sampling, specimen preparation, curing and testing procedures. Variability in strength can be traced to two fundamentally different sources: variability in strength-producing properties of the concrete mixture and ingredients, including batching and production, and variability in the measured strength caused by variations inherent in the testing process. Table (2.3) summarizes the principal sources of strength variation. (ACI 214R-02, 1995)

Table (2.3) Principal Sources of Strength Variation.

Variations due to the concrete properties	Variations due to testing methods
• Changes in *w*/*c* caused by: -Poor control of water -Excessive variation of moisture in aggregate or variable aggregate moisture measurements -Retempering • Variations in water requirement	• Improper sampling procedures • Variations due to fabrication techniques: -Handling, storing, and curing of newly made cylinders

caused by: -Changes in aggregate grading, absorption, particle shape -Changes in cementitious and admixture properties -Changes in air content -Delivery time and temperature Changes • Variations in characteristics and proportions of ingredients: -Aggregates -Cementitious materials, including pozzolans -Admixtures • Variations in mixing, transporting, placing, and consolidation • Variations in concrete temperature	-Poor quality, damaged, or distorted molds • Changes in curing: -Temperature variation -Variable moisture control -Delays in bringing cylinders to the laboratory -Delays in beginning standard curing • Poor testing procedures: -Specimen preparation -Test procedure -Uncalibrated testing equipment

2.5.1 Normal Distribution

Test data from large concrete projects with many tests show a grouping around the average strength. A typical grouping is illustrated in Figure (2.1). To produce Figure (2.1), the strength tests are divided into cells. The cell width for Figure (2.1) is 200 psi. For example, the seven tests that fall between 3900 and 4099 psi have been plotted in the cell listed as 4000 psi. Similarly, all other strengths from the series of tests have been plotted in their respective cells. Since the grouping of tests on each side of the average is nearly symmetrical, it is called a normal distribution. It is possible to superimpose a normal distribution on the plot of individual strengths. As shown in Figure (2.2), this curve smooth's out the plot by reducing the effect of individual differences through averaging. The center of the curve is located at the average of all the tests. The area under the curve represents 100 percent of the tests. Figure (2.3) shows the normal distribution curve used to represent all of the tests, rather than using the individual tests plotted in their respective cells. This curve will be used to represent all of the strength tests without the individual plotted tests throughout the remainder of this report.

The example illustrated in this report is the compressive strength test, but the procedures outlined here may be used on test data from any test used to determine the strength of concrete. (ACI 214.3R-88, 1997)

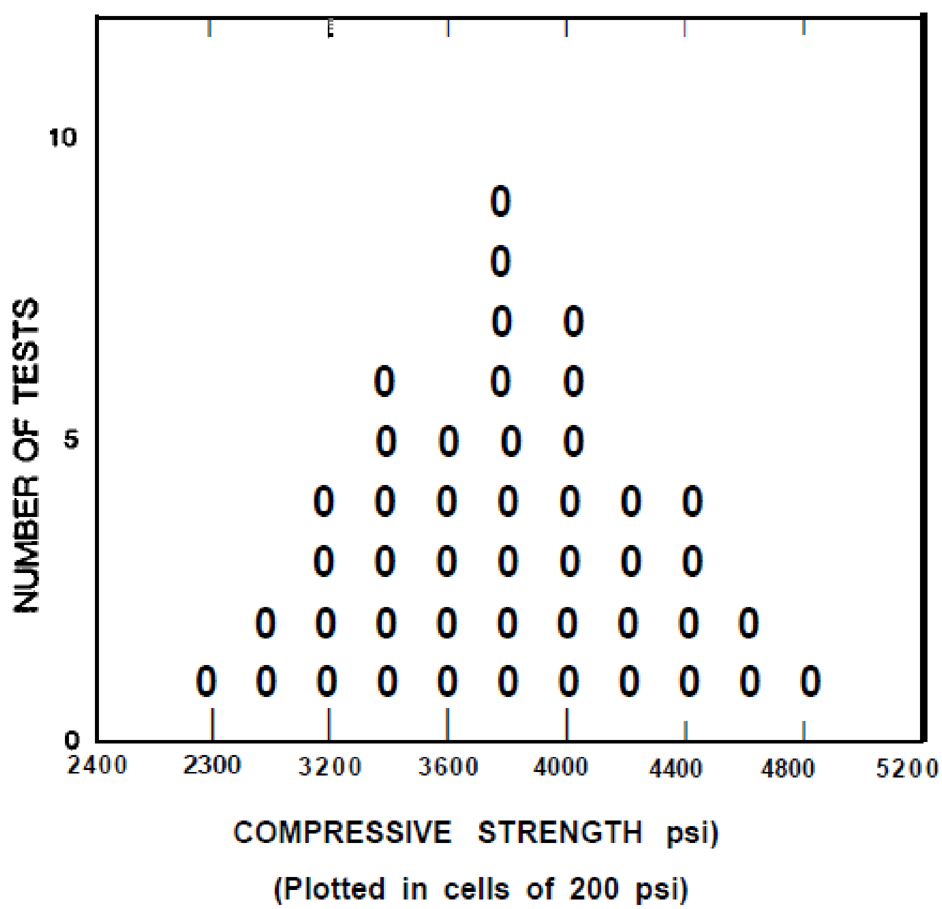


Figure (2.1) Plot of 45 strength tests in cell width of 200 psi

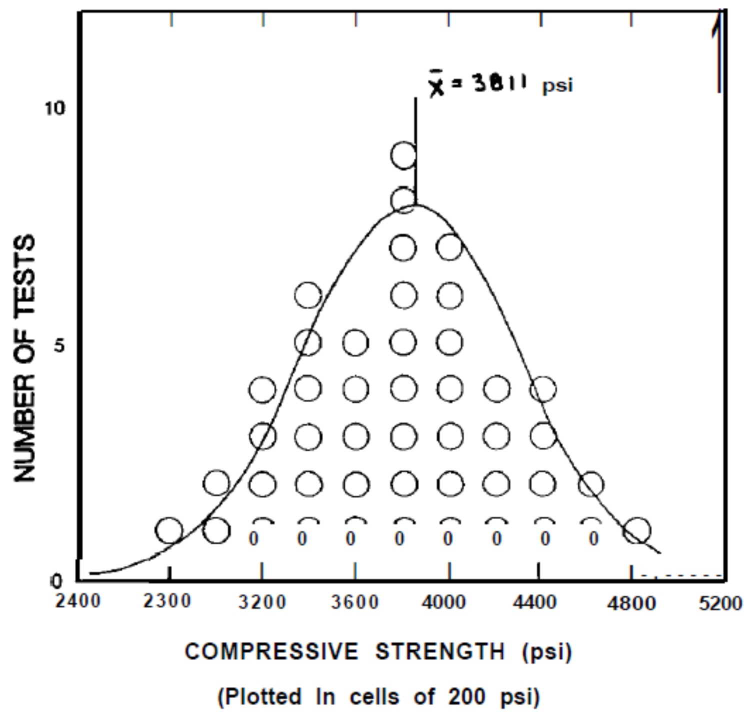


Figure (2.2) Strength tests plotted in Figure (2.1) with normal distribution curve superimposed on data

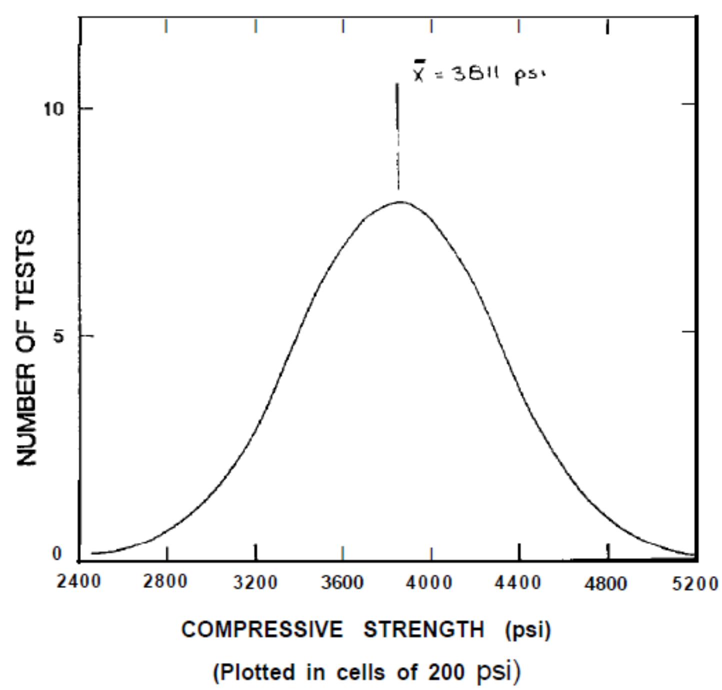


Figure (2.3) Normal distribution curve represents variation of individual test results plotted in Figure (2.1) and Figure (2.2).

2.5.2 Statistical Functions

A sufficient number of tests are needed to indicate accurately the variation in the concrete produced and to permit appropriate statistical procedures for interpreting the test results. Statistical procedures provide a sound basis for determining from such results the potential quality and strength of the concrete and for expressing results in the most useful form.
A strength test result is defined as the average strength of all specimens of the same age, fabricated from a sample taken from a single batch of concrete. A strength test cannot be based on only one cylinder; a minimum of two cylinders is required for each test.

Concrete tests for strength are typically treated as if they fall into a distribution pattern similar to the normal frequency distribution curve illustrated in Figure (2.4).

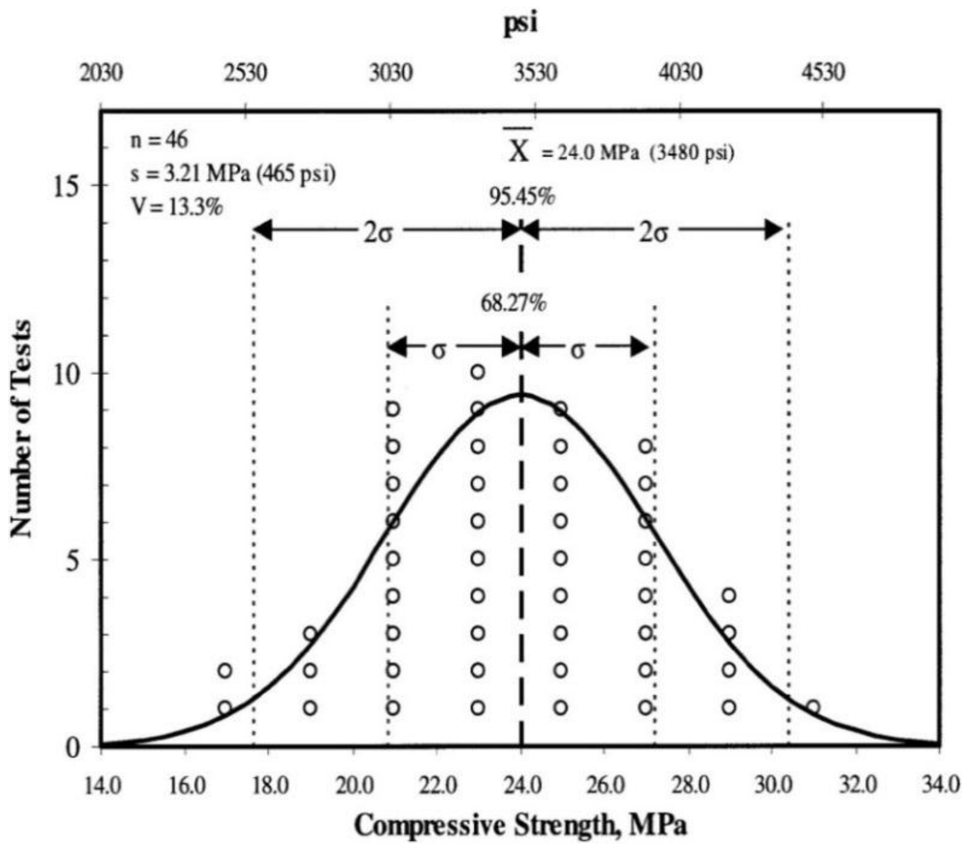


Figure (2.4) Frequency distribution of strength data and corresponding assumed normal distribution.

When there is good control, the strength test values will tend to cluster near to the average value, that is, the histogram of test results is tall and narrow.

The normal distribution can be fully defined mathematically by two statistical parameters: the mean and standard deviation. These statistical parameters of the strength can be calculated as shown below:

2.5.2.1 Mean *X*

The average strength tests result *X* is calculated using Equation (2-1)

$$\overline{X} = \frac{\sum_{i=1}^{n} X_i}{n} = \frac{1}{n}\sum X_i = \frac{1}{n}\left(X_1 + X_2 + X_3 + ... + X_n\right) \quad .... (2\text{-}1)$$

Where X_i is the i-th strength test result, the average of at least two cylinder strength tests. X_2 is the second strength test result in the record; ΣX_i is the sum of all strength test results and n is the number of tests in the record.

2.5.2.2 Standard deviation *S*

The standard deviation is the most generally recognized measure of dispersion of the individual test data from their average. An estimate of the population standard deviation σ is the sample standard deviation S. The population consists of all possible data, often considered to be an infinite number of data points. The sample is a portion of the population, consisting of a finite amount of data.

The sample standard deviation is obtained by Equation (2-2a), or by its algebraic equivalent, Equation (2-2b). The latter equation is preferable for computation purposes, because it is simpler and minimizes rounding errors. When using spreadsheet software, it is important to ensure that the sample standard deviation formula is used to calculate s.

$$s = \sqrt{\frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}{n-1}} = \sqrt{\frac{\left(X_1 - \overline{X}\right)^2 + \left(X_2 - \overline{X}\right)^2 + ...\left(X_n - \overline{X}\right)^2}{n-1}} \quad .... (2\text{-}2a)$$

Which is equivalent to

$$s=\sqrt{\frac{n\sum_{i=1}^{n}X_i^{\,2}-\left[\sum_{i=1}^{n}X_i\right]^2}{n(n-1)}}=\sqrt{\frac{\sum_{i=1}^{n}X_i^{\,2}-n\overline{X}^{\,2}}{n-1}} \quad \text{............... (2-2b)}$$

where *s* is the sample standard deviation, *n* is the number of strength test results in the record, *X* is the mean, or average, strength test result, and Σ*X* is the sum of the strength test results. When considering two separate records of concrete mixtures with similar strength test results, it is frequently necessary to determine the statistical average standard deviation, also termed the pooled standard deviation. The statistical average standard deviation of two records is calculated as shown in Equation (2-3).

$$\overline{s}=\sqrt{\frac{(n_A-1)(s_A)^2+(n_B-1)(s_B-1)(s_B)^2}{(n_A+n_B-2)}} \quad \text{..........(2-3)}$$

where $\overline{s}$ is the statistical average standard deviation, or pooled standard deviation, determined from two records, s_A and s_B are the standard deviations of Record A and Record B, respectively, and n_A and n_B are the number of tests in Record A and Record B, respectively.

2.5.2.3 Coefficient of variation *V*

The sample standard deviation expressed as a percentage of the average strength is called the coefficient of variation as shown in Equation (2-4).

$$V=\frac{s}{\overline{X}}\times 100 \quad \text{........... (2-4)}$$

Where *V* is the coefficient of variation, *s* is the sample standard deviation, and *X* is the average strength test result. The coefficient of variation is less affected by the magnitude of the strength level (Cook 1989; Anderson 1985), and is therefore more useful than the standard deviation in comparing the degree of control for a wide range of compressive strengths. The coefficient of variation is typically used when comparing the dispersion of strength test results of records with average compressive strengths more than about 7 MPa [1000 psi] different.

2.5.2.4 Range R

Range is the statistic found by subtracting the lowest value in a data set from the highest value in that data set.

In evaluation of concrete test results, **the within-test range R** of a strength test result is found by subtracting the lowest single cylinder strength from the highest single cylinder strength of the two or more cylinders used to comprise a strength test result. The average within-test range is used for estimating the within-test standard deviation.

2.6 Interpretation of Results

When the relationships between the individual test results, the normal distribution curve, and the statistical values produced from the test data are understood, it is possible to draw conclusions about the variability of the test data.

The area under the normal distribution curve represents 100 percent of the tests. A series of zones can be created under the curve by drawing vertical lines, each spaced a distance equal to a standard deviation on each side of the vertical line drawn at the average. Figure (2.5) shows a normal distribution curve with the percentage of tests expected to fall within each zone of the curve.

Each zone can be identified by standard-deviation limits on each side of the average. Fifty percent of the tests fall on each side of the center of the curve, or average strength. The zone bounded by one standard-deviation limit on each side of the average ($\pm s$) includes 68.2 percent of the tests. As soon as the average and the standard deviation are calculated, the shape of the normal distribution curve that represents the data can be visualized.
Moving a second standard-deviation limit on each side of the average will include an additional 27 percent of all the tests. Therefore, a total of 95.2 percent of all the tests fall within two standard-deviation limits ($\pm 2s$) on each side of the average. An additional 2.4 percent of all the tests fall between two and three standard deviation limits on each side of the average strength for a total of approximately 100 percent of the tests. These three

standard deviation limits each side of the average strength (± **3***s)* is normally considered to be the limits that include almost all test values. Engineers are not normally concerned with strengths that are too high. Therefore, only the standard-deviation limits below the average cause concern when evaluating the strength of concrete. Fig. 5 shows 15.9 percent of the tests, or approximately 1 in 6, will be below one standard-deviation limit; 2.4 percent of the tests, or approximately 1 in 42, will be below the two standard deviation limits. (ACI 214.3R-88, 1997)

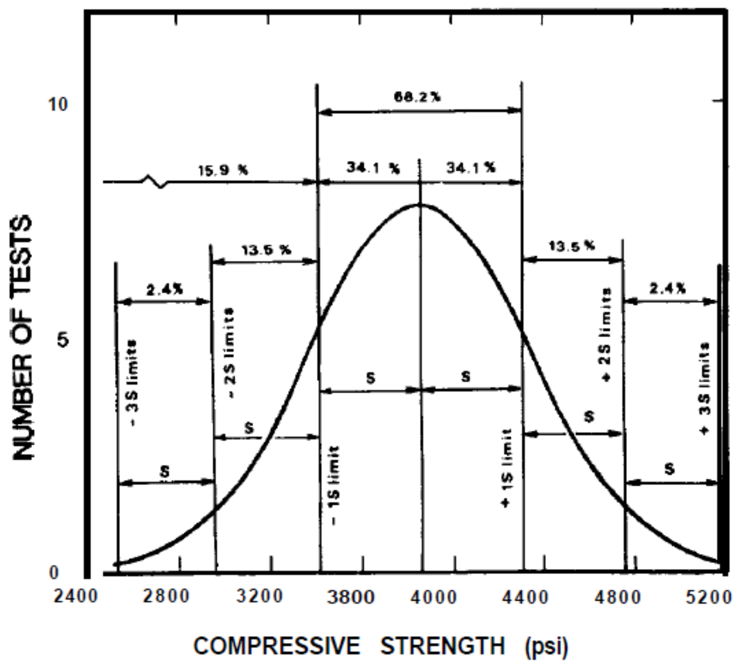


Figure (2.5) Percentages of tests expected to fall in each zone of normal distribution curve

2.7 Specifying the Strength of Concrete

It is the responsibility of the structural engineer to select the strength of concrete required for a structure. That strength is called the specified strength noted as *fc'*. Since the strength of concrete follows the normal distribution curve, if the average strength of the concrete is approximately equal to the specified strength, one-half of the concrete will have strength less than the specified strength. Because it is usually not acceptable to have one-half of the strength tests lower than specified strength, the average strength must be higher than the specified strength by some factor.

It is possible to use the statistical tools introduced here in all phases of concrete production – strength has been used as an example. Similar principles can be applied to other important characteristics of concrete such as entrained air, which relates to durability. The specification writer, in consultation with the engineer, selects a specified strength and the percentage of low tests that are considered acceptable for the class of concrete. ACI 318, "Building Code Requirements for Reinforced Concrete," provides guidelines for selecting the acceptable number of low tests.

An example of a statement for strength in the specification might read: The average of all strength tests shall be such that not more than one tests in ten (10 percent) shall fall below the specified strength fc' of 3500 psi. (ACI 214.3R-88, 1997)

2.8 Selecting the Strength of Concrete

Because of variability in the strength of concrete, it becomes necessary to produce a concrete with an average strength significantly greater than the specified strength to limit the percentage of low tests to the specified levels. The concrete producer must provide a strength that is higher than the specified strength, called the required average strength f_{cr} The required average strength can be determined from the following Equation (2-5)

$$f_{cr} = f_c' + ps \quad \text{……. (2-5)}$$

Use of the normal distribution curve to obtain the required average strength is illustrated in Figure (2.6). To calculate the required average strength, the engineer must decide the specified strength and what percentage of tests falling below the specified strength will be allowed. When the decision has been made on an acceptable percentage of low tests, the probability factor can be determined using the properties of the normal distribution curve. The probability factors for various percentages of low tests are given in Table (2.4).

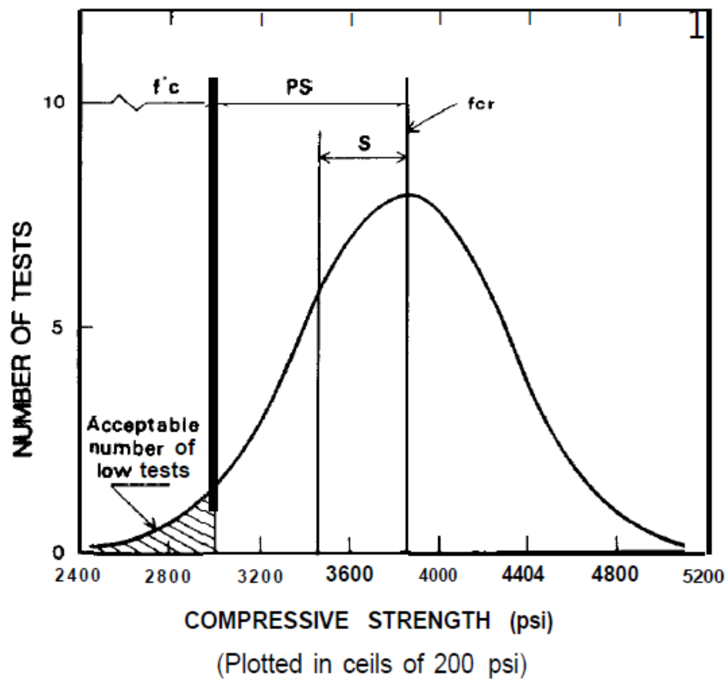


Figure (2.6) Illustration of determination of required average strength *fc′* = 3000 psi, product of probability factor **p**, and standard deviation s = 800 psi. The sum of fc′ and Ps = f_{cr} which is 3811 psi in this example

Table (2.4) Expected percentages of individual tests lower than *fc′*

Average strength μ	Expected percentage of low tests	Average strength μ	Expected percentage of low tests
fc′ + 0.10σ	46.0	*fc′* + 1.60σ	5.5
fc′ + 0.20σ	42.1	*fc′* + 1.70σ	4.5
fc′ + 0.30σ	38.2	*fc′* + 1.80σ	3.6
fc′ + 0.40σ	34.5	*fc′* + 1.90σ	2.9
fc′ + 0.50σ	30.9	*fc′* + 2.00σ	2.3
fc′ + 0.60σ	27.4	*fc′* + 2.10σ	1.8
fc′ + 0.70σ	24.2	*fc′* + 2.20σ	1.4
fc′ + 0.80σ	21.2	*fc′* + 2.30σ	1.1
fc′ + 0.90σ	18.4	*fc′* + 2.40σ	0.8
fc′ + 1.00σ	15.9	*fc′* + 2.50σ	0.6
fc′ + 1.10σ	13.6	*fc′* + 2.60σ	0.45
fc′ + 1.20σ	11.5	*fc′* + 2.70σ	0.35
fc′ + 1.30σ	9.7	*fc′* + 2.80σ	0.25
fc′ + 1.40σ	8.1	*fc′* + 2.90σ	0.19
fc′ + 1.50σ	6.7	*fc′* + 3.00σ	0.13

Where

f_{cr} = required average strength, psi

fc' = specified strength, psi

p = probability factor based on the percentage of tests the designer will allow to fall below fc'

s = expected standard deviation for the project, psi

The standard deviation is obtained by analyzing the concrete producer's data. Since the standard deviation for a project is not known at the beginning of a project, Chapter 4 of ACI 214.3R-88, 1997 permits the substitution of a standard deviation calculated from at least 30 consecutive strengths on concrete produced at the proposed concrete plant using similar materials and conditions.

Most concrete comes from plants with continuous testing programs. Quality-control personnel from these plants can supply standard deviation data on each class of concrete. Since three standard-deviation limits are generally considered to include all tests, the engineer who unrealistically refuses to recognize the variability that does exist, even in carefully controlled concreting operations, and demands that no tests fall below the specified strength, must realize that the required average strength must then be three standard-deviation limits above the specified strength. Even with the required average strength at three standard-deviation limits above the specified strength, there is a slight chance of a test falling below the specified strength. Table (2.4) indicates that using three standard-deviation limits does not completely insure that no test will fall below the specified strength. The predicted percentage of low tests where the average strength exceeds the specified strength by three standard deviation limits is 0.13 percent or 1.3 tests in 1000.

When the engineer understands the implications of the three standard-deviation limits, he may want to consider using several different probability factors for a given project, depending on the critical nature of the strength of each class of concrete. Table (2.5) lists criteria for selecting different probability factors based upon the risk if the concrete strength falls below the specified strength. (ACI 214.3R-88, 1997)

Table (2.5) Recommendations for *ps* to be used in computing the required average strength based on critical nature of strength of concrete.

Type of structural member	Probability of low test	Recommended values For *ps* for computing required average strength $f_{cr} = f'_c + ps$
Concrete strength below f'_c cannot be tolerated(minimum strength specification) Strength is critical	1.3 in 1000 1 in 100	3.00s 2.32s
Strength below f'_2 is not critical but a test below $f'_c - 500$ is critical. This requirement applies only where s is above 500 psi(ACI 318)	Variable	2.32s – 500 psi
Strength of concrete is not critical (ACI 214, ACI 318)	1 in 10	1.28s
Average of three consecutive tests does not fall below f'_c (ACI 318)	1 Test: 9 in 100 Average of three tests: 1 in 100	1.34s
Strength of concrete is of minor consequence in design	1 in 5	0.8%

2.9 Concrete Strength Control

At the beginning of a concreting operation, the strength level of the concrete being produced is based upon the calculation of the required average strength. This is hypothetical production strength. It assumes that the variables affecting the strength of concrete will be the same in the future as they have been in the past. As the first test data become available, the required average strength is replaced by the actual value-the project average strength. If the standard deviation from the project is approximately equal to the value used in the calculation of the required average strength, the project average strength should be maintained close to the required average strength.

If the project average strength is below the required average strength, the percentage of tests below the specified strength will be greater than the acceptable value and steps must be taken to increase the strength of the concrete. The strength of the concrete must also be increased if the standard deviation of the project is greater than the assumed standard deviation used in the determination of the required average strength. If the project standard deviation increases, the average strength of the concrete must be increased. An illustration of the ideal relationship between these values is shown in Figure (2.7).

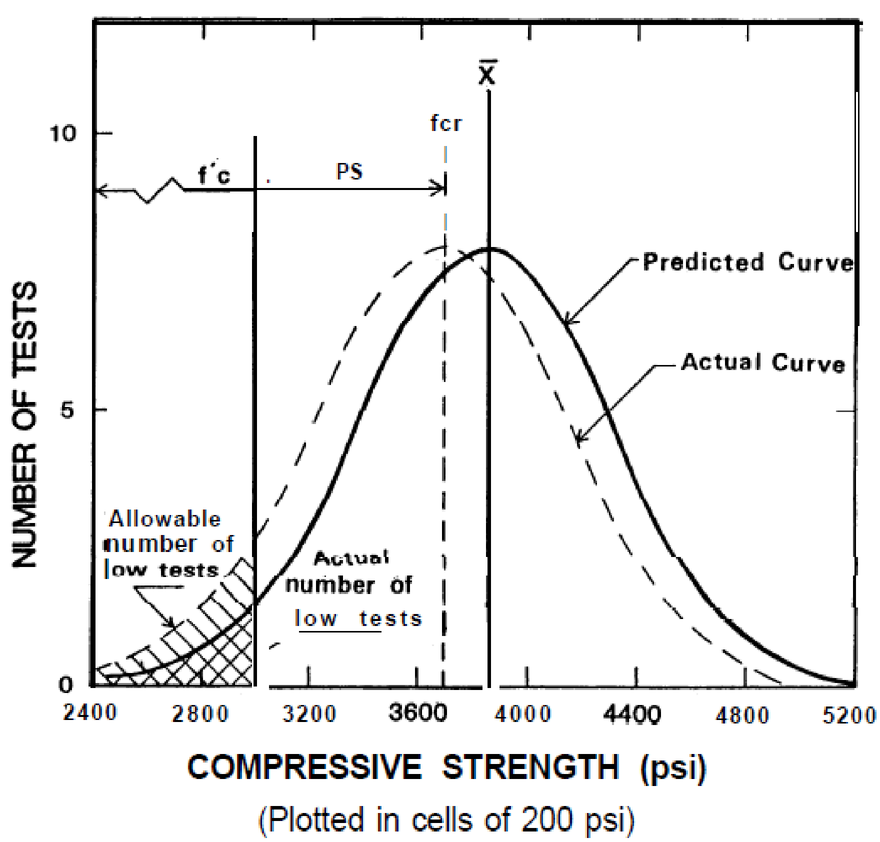


Figure (2.7) Approximate desired relationship between required average strength and average strength

Where
P = probability factor
$\overline{X}$ = average strength
f_c' = specified strength
S = standard deviation

2.10 Strength Test Variations

Variations in strength test results can be traced to two different sources:

1. Variations in testing methods; and
2. Variations in the properties or proportions of the constituent materials in the concrete mixture, variations in the production, delivery or handling procedures, and variations in climatic conditions. It is possible to compute the variations attributable to each source using analysis of variance (ANOVA) techniques or with simpler techniques.

2.10.1 Within-test variation

Variability due to testing is estimated by the within-test variation based on differences in strengths of companion (replicate) cylinders comprising a strength test result. The within-test variation is affected by variations in sampling, molding, consolidating, transporting, curing, capping, and testing specimens. A single strength test result of a concrete mixture, however, does not provide sufficient data for statistical analysis. As with any statistical estimator, the confidence in the estimate is a function of the number of test results.

The within-test standard deviation is estimated from the average range of at least 10, and preferably more, strength test results of a concrete mixture, tested at the same age, and the appropriate values of d_2 in Table (2.4) using Equation (2-6). In Equation (2-7), the within test coefficient of variation, in percent, is determined from the within-test standard deviation and the average strength.

$$s_1 = \frac{1}{d_2}\overline{R} \quad \text{……. (2-6)}$$

$$V_1 = \frac{s_1}{\overline{X}} \times 100 \quad \text{........ (2-7)}$$

Where s_1 is the sample within-test standard deviation, R is the average within-test range of at least 10 tests, d_2 is the factor for computing within-test standard deviation from the average range; V_1 is the sample within-test coefficient of variation, and ̄is the mean, or average, strength test result.

Table (2.6) Factors for computing within-test standard deviation from range

No. of specimens	d_2
2	1.128
3	1.693
4	2.059

2.10.2 Batch-to-Batch variation

These variations reflect differences in strength from batch to batch, which can be attributed to variations in:

(a) Characteristics and properties of the ingredients; and

(b) Batching, mixing, and sampling.

Batch-to-batch variation can be estimated from strength test results of a concrete mixture if each test result represents a separate batch of concrete. The overall variation s has two component variations, the within-test s_1, and batch-to-batch s_2 variations. The sample variance, the square of the sample standard deviation, is the sum of the sample within-test and sample batch-to-batch variances as shown in Equation (2-8)

$$s^2 = s_1^{\ 2} + s_2^{\ 2} \quad \text{....... (2-8)}$$

From which the batch – to – batch standard deviation can be computed as in Equation (2-9)

$$s_2 = \sqrt{s^2 - s_1^{\ 2}} \quad \text{...... (2-9)}$$

The within-test sample standard deviation estimates the variation attributable to sampling, specimen preparation, curing and testing, assuming proper testing methods are used. The batch-to-batch sample standard deviation estimates the variations attributable to constituent material suppliers, and the concrete producer. (ACI 214R-02, 1995)

2.11 Evaluating Concrete Strength

As the strength tests from a project become available, continuous evaluation of the data is desirable. Updated determination of the average strength and standard deviation will permit an evaluation of how well the actual project values compare with values used at the beginning of the project. An understanding of the percentage of tests falling within each zone, under the normal distribution curve illustrated in Fig. 5, will aid in this evaluation.

The approximate percentage of tests falling below the specified strength can be calculated any time after test data become available using Equation. (2-10) and Table (2.5) as follows

$$p = \frac{\overline{X} - f_c'}{s} \quad \ldots\ldots\ldots \text{(2-10)}$$

When the probability factor has been calculated from actual project data, the approximate percentage of low tests can be determined using Table (2.5) as follows.

Find the probability factor closest to the calculated value in the column labeled “Required average strength” of Table (2.5). The corresponding percentage can be read from the columns labeled “Percentage of low tests.” (ACI214.3R-88, 1997)

2.11.1 Standards of Control

One of the primary purposes of statistical evaluation of concrete data is to identify sources of variability. This knowledge can then be used to help determine appropriate steps to maintain the desired level of control. Several different techniques can be used to detect variations in concrete production, materials processing and handling, and contractor and testing agency operations. One simple approach is to compare overall variability and within-test variability, using either standard deviation or coefficient of variation, as appropriate, with previous performance.

Table (2.7) gives the standards of control which are appropriate for concrete having specified strengths up to 35 MPa (5000 psi), whereas Table (2.8) gives the appropriate standards of control for specified strengths over 35 MPa (5000 psi). These standards of control were adopted based on examination and analysis of compressive strength data by ACI Committee 214 and ACI Committee 363. The strength tests were conducted using 150 x 300 mm (6 x12 in.) cylinders. (ACI214.3R-88, 1997)

Table (2.7) Standards of concrete control

Overall variation					
Class of operation	**Standard deviation for different control standards. MPa (psi)**				
	Excellent	**Very good**	**Good**	**Fair**	**Poor**
General construction testing	Below 2.8 (below 400)	2.8 to 3.4 (400to 500)	3.4 to 4.1 (500 to600)	4.1 to 4.8 (600 to700)	Above 4.8 (above 700)
Laboratory trial batches	Below 1.4 (below 200)	1.4 to 1.7 (200 to250)	1.7 to 2.1 (250 to300)	2.1 to 2.4 (300 to350)	Above 2.4 (above 350)
Within-test variation					
Class of operation	**Coefficient of variation for different control standards, %**				
	Excellent	**Very good**	**Good**	**Fair**	**Poor**
Field control testing	Below 3.0	3.0 to 4.0	4.0 to 5.0	5.0 to 6.0	Above 6.0
Laboratory trial batches	Below 2.0	2.0 to 3.0	3.0 to 4.0	4.0 to 5.0	Above 5.0

* $f_c' \leq 34.5$ MPa (5000 psi).

Table (2.8) Standards of concrete control*

Overall variation					
Class of operation	**Coefficient of variation for different control standards, %**				
	Excellent	**Very good**	**Good**	**Fair**	**Poor**
General construction testing	Below 7.0	7.0 to 9.0	9.0 to 11.0	11.0 to 14.0	Above 14.0

Laboratory trial batches	Below 3.5	3.5 to 4.5	4.5 to 5.5	5.5 to 7.0	Above 7.0
Within-test variation					
Class of operation	**Coefficient of variation for different control standards, %**				
	Excellent	**Very good**	**Good**	**Fair**	**Poor**
Field control testing	Below 3.0	3.0 to 4.0	4.0 to 5.0	5.0 to 6.0	Above 6.0
Laboratory trial batches	Below 2.0	2.0 to 3.0	3.0 to 4.0	4.0 to 5.0	Above 5.0

* f_c' > 34.5 MPa (5000 psi).

2.12 Criteria for compressive strength according to ACI

The strength of concrete in a structure and the strength of test cylinders cast from a sample of that concrete are not necessarily the same. The strength of the cylinders obtained from that sample of concrete and used for contractual acceptance are to be cured and tested under tightly controlled conditions. The strengths of these cylinders are generally the primary evidence of the quality of concrete used in the structure. The engineer specifies the desired strength, the testing frequency, and the permitted tolerance in compressive strength.

Any specified quantity, including strength, should also have a tolerance. It is impractical to specify an absolute minimum strength, because there is always the possibility of even lower strengths simply due to random variation, even when control is good. There will always be a certain probability of tests falling below fc′. ACI 318 and most other building codes and specifications establish tolerances for meeting the specified compressive strength acceptance criteria, analogous to the tolerances for other building materials.

To satisfy statistically based strength-performance requirements, the average strength of the concrete should be in excess of the specified compressive strength fc′. The required average strength fcr′ which is the strength used in mixture proportioning, depends on the expected variability of test results as measured by the coefficient of variation or standard deviation, and on the allowable proportion of tests below the appropriate, specified acceptance criteria.

2.12.1 Data used to establish the minimum required average strength

To establish the required average strength fcr′ (target strength), an estimate of the variability of the concrete to be supplied for construction is needed. The strength test record used to estimate the standard deviation or coefficient of variation should represent a group of at least 30 consecutive tests.

The requirement for 30 consecutive strength tests can be satisfied by using a test record of 30 consecutive batches of the same class of concrete or the statistical average of two test records totaling 30 or more tests. If the number of test results available is less than 30, a more conservative approach is needed. Test records with as few as 15 tests can be used to estimate the standard deviation; however, the calculated standard deviation should be increased by as much as 15% to account for the uncertainty in the estimate of the standard deviation. In the absence of sufficient information, a very conservative approach is required and the concrete is proportioned to produce relatively high average strengths.

If only a small number of test results are available, the estimates of the standard deviation and coefficient of variation become less reliable. When the number of strength test results is between 15 and 30, the calculated standard deviation, multiplied by the appropriate modification factors obtained from Table (2.9), which was taken from ACI 318, provides a sufficiently conservative estimate to account for the uncertainty in the calculated standard deviation.

Table (2.9) Modification factors for standard deviation

Number of tests	Modification factors
Less than 15	See Table (2.10)
15	1.16
20	1.08
25	1.03
30 or more	1.00

Table (2.10) Minimum required average strength without sufficient historical data

$f'_{cr} = f'_c + 6.9$ MPa (1000 psi)	When $f'_c < 20.7$ MPa (3000 psi)
$f'_{cr} = f'_c + 8.3$ MPa (1200 psi)	When $f'_c \geq 20.7$ MPa (3000 psi) and $f'_c \leq$ 34.5 MPa (5000 psi)
$f'_{cr} = 1.10 f'_c + 4.8$ MPa (700 psi)	When $f'_c > 34.5$ MPa (5000 psi)

2.12.2 Strength Requirements Criteria

The minimum required average strength f_{cr}' can be computed using Equation (2-11a), (2-11b), Table (2.10), depending on whether the coefficient of variation or standard deviation is used. The value of f_{cr}' will be the same for a given set of strength test results regardless of whether the coefficient of variation or standard deviation is used.

$$f'_{cr} = f'_c / (1 - zV) \quad \text{........ (2-11a)}$$

$$f'_{cr} = f'_c + zs \quad \text{....... (2-11-b)}$$

where z is selected to provide a sufficiently high probability of meeting the specified strength, assuming a normal distribution of strength test results. In most cases, fc′ is replaced by a specified acceptance criterion, such as fc′ – 3.5 MPa or 0.90fc′.

Figure (2.8) shows that as the variability increases, fcr′ increases and thereby illustrates the economic value of good control.

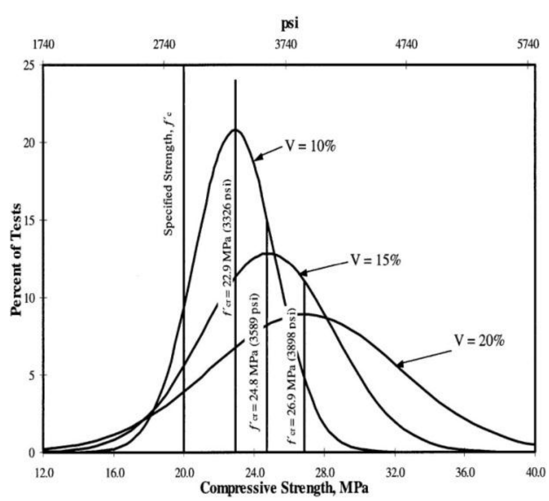


Figure (2.8) Normal frequency curves for coefficients of variation of 10, 15, and 20%.

Table (2.11) provides values of z for various percentages of tests falling between the mean + zσ and the mean –zσ.

Percentages of tests within $\pm z\sigma$	Chances of falling below lower limit	Z
40	3 in 10 (30%)	0.52
50	2.5 in 10 (25%)	0.67
60	2 in 10 (20%)	0.84
68.27	1 in 6.3 (15.9%)	1.00
70	1.5 in 10 (15%)	1.04
80	1 in 10 (10%)	1.28
90	1 in 20 (5%)	1.65
95	1 in 40 (2.5%)	1.96
95.45	1 in 44 (2.3%)	2.00
98	1 in 100 (1%)	2.33
99	1 in 200 (0.5%)	2.58
99.73	1 in 741 (0.13%)	3.00

The amount by which the required average strength f_{cr}' should exceed the specified compressive strength f_c' depends on the acceptance criteria specified for a particular project. The following are criteria examples used to determine the required average strength for various specifications or elements of specifications. The numerical examples are presented in both SI and inch-pound units in a parallel format that have been hard converted and so are not exactly equivalent numerically.

2.12.2.1 Criterion No.1

The engineer may specify a stated maximum percentage of individual, random strength tests results that will be permitted to fall below the specified compressive strength. This criterion is no longer used in the ACI 318 Building Code, but does occur from time to time in specifications based on allowable strength methods or in situations where the average strength is a fundamental part of the design methodology, such as in some pavement specifications. A typical requirement is to permit no more than 10%of the strength tests to fall below fc′. The specified strength in these situations will generally be between 21 and 35 MPa.

Standard deviation method—Assume sufficient data exist for which a standard deviation of 3.58 MPa has been calculated for a concrete mixture with a specified strength of 28 MPa. From Table 4.3, 10% of the normal probability distribution lies more than 1.28 standard deviations below the mean. Using Equation (2-11b)

$$f'_{cr} = f'_c + zs \quad \ldots\ldots\ (2\text{-}11\text{-}b)$$

Therefore, for a specified compressive strength of 28 MPa, the concrete mixture should be proportioned for an average strength of not less than 32.6 MPa so that, on average, no more than 10% of the results will fall below fc′.
Coefficient of variation method—Assume sufficient data exist for which a coefficient of variation of 10.5% has been calculated for a concrete mixture with a specified strength of 28 MPa. From Table 4.3, 10% of the normal probability distribution lies more than 1.28 standard deviations below the mean. Using Eq. (2-11a)

$$f'_{cr} = f'_c / (1 - zV) \quad \ldots\ldots\ldots\ (2\text{-}11a)$$

Therefore, for a specified compressive strength of 28 MPa, the concrete mixture should be proportioned for an average strength of not less than 32.3 MPa so that, on average, no more than 10% of the results will fall below fc′.

2.13 Conformity criteria for compressive strength according to BS EN 206-1

2.13.1 General

For normal-weight and heavy-weight concrete of strength classes from C8/10 to C55/67 or light-weight concrete from LC8/9 to LC 55/60, sampling and testing shall be performed either on individual concrete compositions or on concrete families of established suitability as determined by the producer unless agreed otherwise. The family concept shall not be applied to concrete with higher strength classes. Light-weight concrete shall not be mixed into families containing normal-weight concrete. Light-weight concrete with demonstrably similar aggregates may be grouped into its own family.

In the sampling and testing plan and the conformity criteria of individual concrete compositions or concrete families, distinction is made between initial production and continuous production.

Initial production covers the production until at least 35 test results are available and Continuous production is achieved when at least 35 test results are obtained over a period not exceeding12 months.

2.13.2 Compressive Strength Conformity Criteria

Conformity assessment shall be made on test results taken during an assessment period that shall not exceed the last twelve months. Conformity of concrete compressive strength is assessed on specimens tested at 28 days for:

1. groups of n non-overlapping or overlapping consecutive test results f_{cm} (Criterion 1)
2. Each individual test result f_{ci} (Criterion 2).

Conformity is confirmed if both the criteria given in Table (2.13) for either initial or continuous production are satisfied.

Where conformity is assessed on the basis of a concrete family, Criterion 1 is to be applied to the reference concrete taking into account all transposed test results of the family; Criterion 2 is to be applied to the original test results.

To confirm that each individual member belongs to the family, the mean of all non-transposed test results (f_{cm}) for a single family member shall be assessed against Criterion 3 as given in Table 18. Any concrete failing this criterion shall be removed from the family and assessed individually for conformity.

Table (2.12) Confirmation criterion for family members

Number n of test results for compressive strength for a single family member	**Mean of n results (f_{cm}) for a single family member** N/mm^2
2	$\geq f_{ck} - 1{,}0$
3	$\geq f_{ck} + 1{,}0$
4	$\geq f_{ck} + 2{,}0$

5	$\geq f_{ck} + 2{,}5$
6	$\geq f_{ck} + 3{,}0$
7 to 9	$\geq f_{ck} + 3{,}5$
10 to 12	$\geq f_{ck} + 4{,}0$
13,14	$\geq f_{ck} + 4{,}5$
≥ 15	$\geq f_{ck} + 1{,}48\sigma$

At the end of initial production, the standard deviation (σ) of the population shall be estimated from at least 35 consecutive test results taken over a period exceeding three months. When continuous production commences, this value of standard deviation shall be used to check the conformity over the first assessment period. At the end of the first and subsequent assessment periods, the standard deviation is checked to determine whether it has changed significantly using the limits given in Table (2.14). If it has not changed significantly, the current estimate of the standard deviation applies to the following assessment period. When there is a significant change in standard deviation, a new standard deviation is calculated from the most recent 35 consecutive results and applied to the following assessment period.

Table (2.13) Conformity criteria for compressive strength

Production	**Number n of test results for compressive strength in the group**	**Criterion 1**	**Criterion 2**
		Mean of n results (f_{cm}) N/mm^2	**Any individual test result (f_{ci}) N/mm^2**
Initial	3	$f_{cm} \geq (f_{ck} + 4)$	$f_{ci} \geq (f_{ck} - 4)$
Continuous	Not less than 15	$f_{cm} \geq (f_{ck} + 1{,}48\sigma)$	$f_{ci} \geq (f_{ck} - 4)$

Table (2.14) Values for verification of standard deviation

Number of test results	**Limits for s_n**
15 to 19	$0{,}63\sigma \leq s_n \leq 1{,}37\sigma$
20 to 24	$0{,}68\sigma \leq s_n \leq 1{,}31\sigma$
25 to 29	$0{,}72\sigma \leq s_n \leq 1{,}28\sigma$
30 to 34	$0{,}74\sigma \leq s_n \leq 1{,}26\sigma$
35^a	$0{,}76\sigma \leq s_n \leq 1{,}24\sigma$

2.14 Use of control charts in the production of concrete

2.14.1 Simple Data Charts

Simple data control charts are used to routinely monitor quality. There are two basic types of control charts. Univariate – a control chart of one quality characteristic (e.g. mean strength) and Multivariate - control chart of a statistic that summarises or represents more than one quality characteristic (e.g. coefficient of variation). If a single quality characteristic has been measured or computed from a sample, the control chart shows the value of the quality characteristic versus the sample number or versus time.
Simple data charts are useful in providing a visual image of production and unusual results. Simple charts may also give an indication of trends but the general scatter of the data may also mask trends that can be identified only by more in-depth analysis of the data.

2.14.2 Shewhart Charts

2.14.2.1 Introduction

While graphical plots can give useful information about the pattern of a production process, the control chart becomes a much more powerful tool if statistical rules are also applied to the data. Shewhart control systems measure variables in the production processes (e.g. target mean strength).They make use of calculated control limits and apply warning limits based on the measured variation in the production process. ISO 8258 gives general information on Shewhart control charts and ISO 7966 gives general information on Shewhart control charts for acceptance control.
The Shewhart chart will have a horizontal central line which represents the expected mean value of the test results on the samples taken from production; in the case of concrete, the Target Mean Strength for a chart controlling compressive strength. Lines representing the upper control limit (UCL) lower control limit (LCL), upper warning limit (UWL) and lower warning limit (LWL) may also be added. Generally action is required if a result is beyond either of the control limits.
The UWL and LWL are set at a level so that most of the results will fall between the lines when a system is running in control. These are not

specification limits but 'warning' limits based on the variability of the production process. While for conformity to a specified characteristic strength a high value is not significant, from the viewpoint of economic production it does matter. Therefore in practice, both upper and lower warnings limits are used even for a variable that has a single limit value, e.g. concrete strength.

A Shewhart control chart can be constructed with
UCL = TMS + 3 x σ
LCL = TMS – 3 x σ
UWL = TMS + 2 x σ
LWL = TMS – 2 x σ
Where TMS is target mean strength

2.14.2.2 Shewhart action criteria

2.14.2.2.1 Points beyond UCL or LCL

The presence of one or more points lying outside of the UCL or LCL is primary evidence that the system is out of control at that point. Since there is only a 0.3% chance that this result is due to natural variation, it is probable that special variation will account for the extreme value and an immediate investigation into the cause should be undertaken.

2.14.2.2.2 Points beyond UWL or LWL

The presence of two consecutive, or more than 1 in 40, points beyond either warning line is evidence that the process is out of control and an investigation of the data should be undertaken. (Gibb, et al, 2010)

2.14.2.3 Patterns within control limits

It is also possible to analyse data that doesn't breach either the control or warning limits to evaluate whether any trends are significant. Runs analysis can give the first warning of a system going out of control before points are seen beyond the warning limits.

The following simple rules of thumb have been proposed for sequences of results that remain within the warning limits. (BS 5703, 2003)

1. Seven or more consecutive results on the same side of the target mean strength
2. At least 10 out of 11 results on the same side of the target mean strength
3. At least 12 out of 14 results on the same side of the target mean strength
4. At least 14 out of 17 results on the same side of the target mean strength

2.15 Previous Studies

A countless number of papers and applied researches dealing with this topic were published, in this section we present and surmise some of them.

(S. Silvestri, 2008) Carried out a statistical inference analysis upon the compressive strength values of an extensive population set of concrete cubic specimens, which have been obtained with reference to an homogenous production of about half a million cubic meters of concrete. Such production has been obtained over a five-year period. The results of the statistical analysis clearly show that the probability density function which best interprets the experimental measurements is the Lognormal one and not the Normal (Gaussian) one. The Italian code and, in certain measure, the Eurocode make explicit reference to Normal distributions, thus leading to a usually penalizing evaluation of the characteristic strength (5% percentile). It is therefore advisable that design codes will encompass the possibility for the engineer to evaluate the concrete characteristics based upon these more refined statistical models.

(Yasish, 2000) Presented a statistical analysis dealing with compressive strength of cores sampled from existing building structures in japan, which were inspected for the purpose of seismic diagnosis. And he find out that a considerable numbers of buildings with low strength concrete were found in existing buildings and the variations of strength were significant, Buildings of recent completion showed larger strength and smaller coefficient of variation and also buildings designed in a higher concrete strength showed stable concrete quality with less variation in strength.

(WafaSiddig, 2015) evaluate the quality of concrete in some selected recent projects in Sudan through studying the measured results of concrete compressive strength test that have been performed by (BRRI) for 5 years (2008 to 2012) at ages 7 and 28 days. And then classified and analyzed the collected measured results using two computer software’s; Microsoft excel and Statistical Package for Social Science (SPSS) mainly to assess the compatibility of the quality of these projects concrete with some international standard methods of quality evaluation; ACI, BS code and shewhart charts.

Concrete quality control and quality evaluation had become part of everyday practice in the advanced countries. While in the young countries there is still a lack of awareness regarding this matter. Researches and papers published in the quality of concrete field have, and still, one of the main factors that greatly contribute in the ongoing major developments in the field.

Chapter Three
Theoretical Evaluation of the Case Study

3.1 General overview of DCUAP

The Dam Complex of the Upper Atbara Project (DCUAP) involved damning the Atbara River and the Setit River approximately 13 km upstream of their confluence and 80 km upstream of the Kashm el Girba reservoir. The project is located in the Gadaref governorate in eastern Sudan.

The Dam Complex of the Upper Atbara Project is a multipurpose project designed to provide irriga-tion, power generation, flood control, and a reliable water supply. The reservoir is dimensioned to store enough water to potentially irrigate about 300,000 ha of farm land which is equivalent to about 2,150 x 106 m^3 per year. This water supply will be utilized in a future Upper Atbara Irrigation Project (UAIP). The city of Gedaref will be reliably supplied with 150,000 m^3per day drinking water. The dam complex will also mitigate silting of the Atbara and Setit rivers, thereby, benefitting the downstream Khashm El Girba reservoir. The project includes 320 MW of power generation capacity which can supplement the national elec-tric grid during the peak demands which mainly occur for about 6 hours per day.

The DCUAP consists of two spillways: 1) at Rumela on the Atbara River, and 2) at Burdana on the Setit River. The power generating structures include the intakes, penstocks, powerhouse and outlet pool. They are situated near Rumela on the Atbara River. The intake and the two spillways are integrated into an approximately 13 km earth-fill dam.

3.2 The Project Main Features and Structures

The main components of the DCUAP are from West to East:

1- Concrete Structures
- Rumela Spillway C1-A,
- Rumela Power Station with Water Intake in the dam, C1-A and C2-A Contractors,
- Rumela Headworks, Intake for Upper Atbara Irrigation Project (UAIP) and Gedaref water supply embedded into the dam,
- Burdana Spillway C1-B,

2- Embankment Structures

- Rumela left bank dyke, length ca. 5,340 m, height 0 m up to 25 m,
- Rumela left bank dam of Atbara River, length ca. 230 m, height 25 m up to 50 m,
- Rumela right bank and river bed dam, length ca. 695 m, height up to 50 m,
- Burdana left bank dam of Setit River and dyke, length ca. 1,140 m, height 25 m up to 50 m,
- Burdana right bank and river bed dam, length ca. 410 m, height 25 m up to 50 m,
- Burdana right bank dyke length ca. 5,685 m, height 0 m up to 25 m.

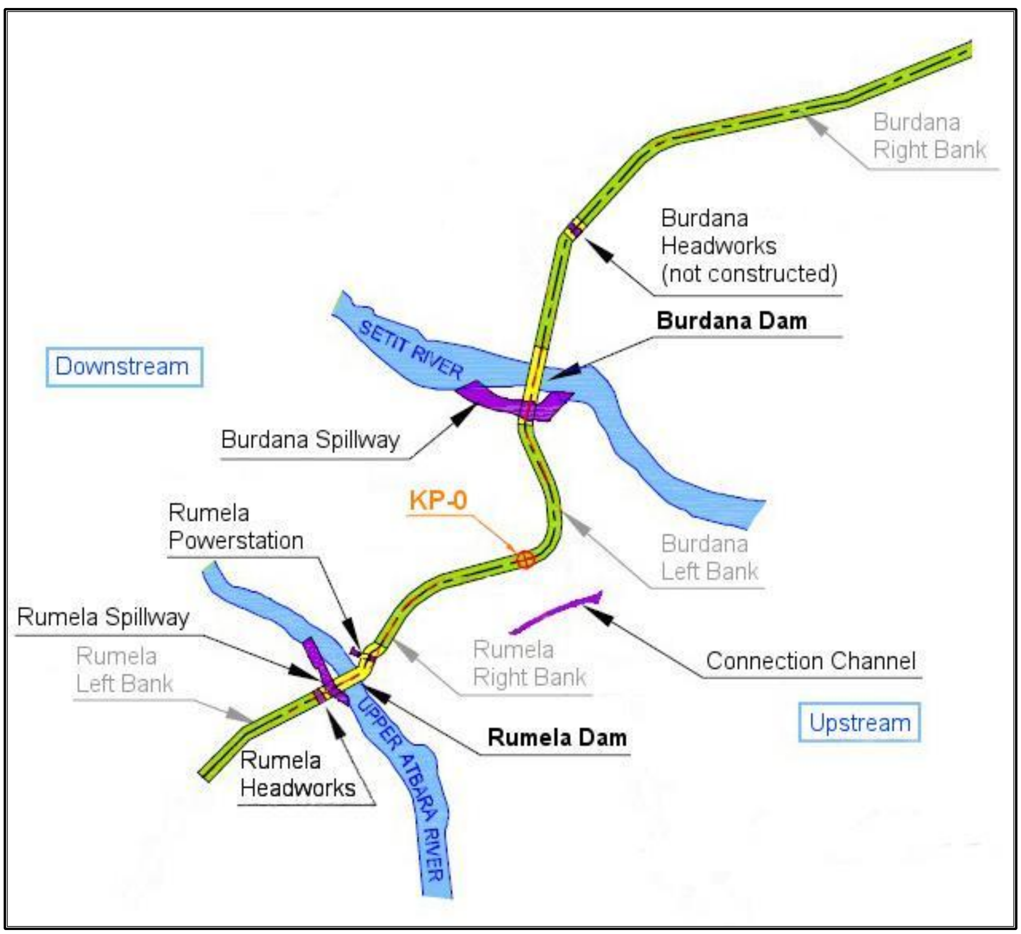


Figure (3.1) General Project Layout Plan

3.3 Main Characteristics of Concrete Structures of DCUAP

All concrete structures of the Spillways, the Headwork, the Power Intake, and the Power House are founded on rock and sealed with contact grouting. The rock impermeability is assured with grout curtains. Drainage bore holes have been applied from the low foundation galleries. In total, about 1,000,000 m³ concrete have been used for all concrete structures. (Lahmeyer International Consultant Reports)

The concrete structures were designed and executed in accordance with the Eurocode EN. The concrete strength classes used in the concrete structures were as follows:

1. Mass and backfill concrete: C12/15
2. Structural concrete C20/25
3. Structural concrete C25/30
4. Concrete exposed to considerable weir C35/45
5. Abrasion resistant concrete C70/85

3.3.1 Cement used in DCUAP

- **Type of cement**

  Different types of cement were used in DCUAP like Ordinary Portland cement type OPC 42.5N and OPC 52.5N and Ground Granulated Blast-Furnace Slag cement type CEM III B.

- **Quality control over cement**

  All cement used in the Permanent Works were tested by the manufacturer and the Contractor at the laboratory on Site and at another laboratory approved by the Engineer. The tests were in accordance with DIN EN 196, the frequency of testing was one set of tests for every 200 tons of cement delivered to Site from each plant.

  Cement which was stored on Site for longer than two months were retested and those who did not complying with the Specification were rejected. Table (3.1) below states the cement tests carried out at DCUAP site.

Table (3.1) Cement tests carried out at DCUAP

Material	Test	Test Standard
Cement	Chemical and physical properties	EN 196
	Temperature/Inspection for lumps/Weight of bagged material	Visual inspection
	Compressive strength	EN196-1
	Setting time	EN196-3
	Soundness	EN196-3
	Fineness	EN196-6
	Specific density	EN196-6

3.3.2 Aggregate used in DCUAP

- **Source of Aggregate**

  The coarse and fine aggregates used in DCUAP were crushed Granite and Basalt processed from Proposed Quarry Site at Jebel Aklayit which located 16 km northeast to the dam site.

- **Quality control over Aggregate**

  The Contractor carried out routine testing of aggregates for compliance with the specification during the period in which concrete was being produced for the permanent works. The tests set out in Table (3.2) below were performed on aggregates provided that the aggregates are of uniform quality. In addition to the mentioned below routine tests, the contractor did carry out moisture content tests as frequent as necessary in order to control the water content of the concrete.

Table (3.2) Aggregate tests carried out at DCUAP

Material	Test	Test Standard
Both Course and Fine Aggregate	Gradation	EN933-1
	Organic Impurities	DIN 4226-2
	Soundness	EN1367-2
	Specific Density & Water absorption	EN1097-6
	Potential Alkali Reactivity	ASTM C 289

	Clay, Silt, Shell and Dust content	EN993-7
Course Aggregate	Los-Angeles Test	EN1097-2
	Flakiness Index Flakiness / Value	EN933-4

3.3.3 Water used for concrete in DCUAP

Water for concrete at DCUAP comes from a treatment plant located at site, and it is clean, fresh and free from matter in solution or suspension that may adversely affect the strength, durability or appearance of the concrete or cause corrosion on reinforcement and embedded items. The suitability of the water for concrete was evaluated according to DIN EN 1008 (mixing water).

The water was retested at intervals of one month initially until sufficient results were available to determine the suitability of the source. Then the frequency of testing was reduced to one sample every three month.

3.3.4 Admixtures used in DCUAP

At DCUAP site varies types of admixtures were used, like retarder, accelerator, superplasticizer and Shrinkage-reducing admixtures.

Admixtures proposed by the Contractor were tested for their suitability with the cement and materials used in the production of concrete process and under proposed construction conditions. The performance of admixtures was determined by using reference concrete. The test mix (with admixture) was compared with the control mix (without admixture). The chloride and alkali contents also was measured and declared. Test procedures for admixtures were complying with EN 480.

3.3.5 Fly Ash and Silica Fume at DCUAP

The fly ash and silica fume were tested in combination with the cement and aggregates used in the Works to determine the advantage or disadvantages with respect to quality and economy of the concrete. And they were tested in accordance with EN 450 (Fly ash) and EN 13263 (Silica fume).

3.3.6 Concrete Mix Design at DCUAP

In total 21 concrete mixeswere developed by the Contractor's concrete department under close supervision by the Engineer. The parameters to be considered for the different purposes were as follows:

- Different strength classes C12/15 up to C70/85.
- Aggregates with maximum size16mm and 32mm.
- Cement type (Ordinary Portland cement 42.5N, Slag cement, Ordinary Portland cement 52.5N).
- Usage which Mainly was pumped concrete
- Workability/Design Flow from non-plastic to high flow slump concrete.

Depending on the specific conditions of the structure, with regard to strength requirements and favorable compaction, the selection of mix design took place for each concrete pour.

3.3.7 Production of Concrete at DCUAP

The Contractor provide, operate, and maintain at the Site automatic batching plant fully equipped and designed for such capacities, which permitted performance of the concrete work in accordance with approved program and conforming to the relevant standard. Concrete mixing trucks were used to transport concrete from the batching plant to the casting location.

3.3.8Compressive strength test conducted on DCUAP

Random samples were taken from site every $200m^3$ concrete in accordance with the European standard EN 12350-1, then the samples were stored and tested for compressive strength at the age of 7 and 28 days in accordance with the European standard EN 12390.

3.3.9 Evaluation Techniques of DCUAP Strength Data

As stated in chapter two, evaluating strength data is required in many situations such as evaluation for mixture submittal purposes, evaluation of level of control (typically called quality control); and evaluation to determine compliance with specifications.

In all cases, the usefulness of the evaluation will be a function of the amount of test data and the statistical rigor of the analysis. Applications for routine quality control and compliance overlap considerably. Many of the evaluation tools or techniques used in one application are appropriate for use in the other.

Chapter Four
Analysis of Data and Discussion of the Results

4.1 Introduction

After excluding the anomalies, out of 4289 concrete compressive strength test results 3166 test results were collected from Dam Complex of Upper Atbara Project is sorted out into concrete classes, each class of concrete is separated into two groups biased on the cement type used in the mentioned class. Then an analysis of the compressive strength is conducted for each concrete class to determine the quality level of the concrete in the project, and also to make comparison between the different types of cement used in the same concrete class.

Additionally, the above mentioned strength test results is subjected to shewhart chart analysis using the rules stated in chapter two clause 2.14.2.3, in order assess whether the process is in control or not and also to predict whether the actual mean strength is higher or lower than the required one.

Briefly a full description of the results and analysis of the research problem is presented.

4.2 DCUAP Concrete Compressive strength test results:

After conducting a number of trial mixes, using different type of cement, different aggregate size and different admixtures (Plastsizers, Retarders, and non-shrinkage agent), a concrete mixes, that serves the function which the concrete block is supposed to fulfill, were selected for each concrete class.

As stated in chapter three, samples for compressive strength test were taken each 200m^3 produced concrete from the project different concrete structures Burdana Spillway, Rumela Spillway, Rumela Headwork, Rumela Power Intake and Power Station.

Samples of Concrete compressive strength tests are in the tables (4.1) to (4.5).

Table (4.1) Class 12/15 compressive strength test result samples

Sample No.	Class	Mix Design No	Cement Type	Sampling Date	Testing Date		Strength (MPa)		Location
					7 days	28 days	7 days	28 days	
1	C12/15	C15-32--L	OPC 42.5N	4-Oct-11	11-Oct-11	1-Nov-11	8.6	17.2	Burdana Spillway
2	C12/15	PPC-1	OPC 42.5N	8-Oct-11	15-Oct-11	5-Nov-11	13.6	22.0	Rumela Spillway
3	C12/15	PPC-1	OPC 42.5N	9-Jul-12	16-Jul-12	6-Aug-12	20.5	27.3	Rumela Power Intake
4	C12/15	PPC-1	OPC 42.5N	21-Feb-12	28-Feb-12	20-Mar-12	15.0	34.8	Rumela Power Station
5	C12/15	PPC-1-27	OPC 42.5N	26-Feb-12	4-Mar-12	25-Mar-12	24.6	40.8	Burdana Spillway
6	C12/15	PPC-1-27	OPC 42.5N	26-Feb-12	4-Mar-12	25-Mar-12	26.8	38.9	Burdana Spillway
7	C12/15	TPC-1	OPC 42.5N	27-Jul-12	3-Aug-12	24-Aug-12	11.5	32.5	Rumela Power Station
8	C12/15	TPC-1	OPC 42.5N	8-Oct-12	15-Oct-12	5-Nov-12	25.1	36.7	Rumela Spillway
9	C12/15	PPC-1-31	OPC 42.5N	29-Oct-15	5-Nov-15	26-Nov-15	19.0	22.4	Burdana Spillway
10	C12/15	PPC-1-35	OPC 42.5N	3-Nov-15	10-Nov-15	1-Dec-15	19.6	23.4	Burdana Spillway
11	C12/15	SPC-1-1	Slag 42.5N	12-May-13	19-May-13	9-Jun-13	13.7	28.8	Burdana Spillway
12	C12/15	SPC-1-1	Slag 42.5N	12-May-13	19-May-13	9-Jun-13	14.1	31.0	Burdana Spillway
13	C12/15	SPC-1-1	Slag 42.5N	21-Jul-13	28-Jul-13	18-Aug-13	12.9	26.5	Burdana Spillway
14	C12/15	SPC-1-1	Slag 42.5N	5-Aug-13	12-Aug-13	2-Sep-13	10.9	23.6	Rumela Power Station
15	C12/15	SPC-1-1	Slag 42.5N	7-Aug-13	14-Aug-13	4-Sep-13	13.5	24.5	Rumela Spillway
16	C12/15	SPC-1-1	Slag 42.5N	8-Oct-13	15-Oct-13	5-Nov-13	9.5	21.3	Rumela Power Station
17	C12/15	SPC-1-1	Slag 42.5N	13-Oct-13	20-Oct-13	10-Nov-13	10.9	20.1	Rumela Power Intake
18	C12/15	SPC-1-1	Slag 42.5N	1-Nov-13	8-Nov-13	29-Nov-13	8.6	18.5	Rumela Power Intake
19	C12/15	SPC-1-1	Slag 42.5N	18-Nov-13	25-Nov-13	16-Dec-13	13.6	28.8	Rumela Power Intake
20	C12/15	SPC-1-1	Slag 42.5N	6-Dec-13	13-Dec-13	3-Jan-14	13.8	23.1	Rumela Power Station

(Lahmeyer International Consultant Reports)

Table (4.2) Class 20/25 compressive strength test result samples

Sample No.	Class	Mix Design No	Cement Type	Sampling Date	Testing Date		Strength (MPa)		Location
					7 days	28 days	7 days	28 days	
1	C20/25	PPC-3	OPC 42.5N	15-Dec-11	22-Dec-11	12-Jan-12	27.3	40.4	Rumela Spillway
2	C20/25	PPC-3	OPC 42.5N	16-Dec-11	23-Dec-11	13-Jan-12	29.5	42.0	Rumela Spillway
3	C20/25	PPC-3-32	OPC 42.5N	19-Dec-11	26-Dec-11	16-Jan-12	28.9	41.2	Burdana Spillway
4	C20/25	PPC-3-32	OPC 42.5N	19-Dec-11	26-Dec-11	16-Jan-12	25.1	41.4	Burdana Spillway
5	C20/25	PPC-3(3)	OPC 42.5N	1-Feb-12	8-Feb-12	29-Feb-12	22.1	40.7	Rumela Power Station
6	C20/25	PPC-3(3)	OPC 42.5N	1-Feb-12	8-Feb-12	29-Feb-12	23.1	40.9	Rumela Spillway
7	C20/25	PPC-3(5)	OPC 42.5N	15-Apr-12	22-Apr-12	13-May-12	26.0	45.7	Rumela Power Station
8	C20/25	PPC-3(5)	OPC 42.5N	15-Apr-12	22-Apr-12	13-May-12	30.4	44.9	Rumela Spillway
9	C20/25	TPC-1-1	OPC 42.5N	26-Apr-12	3-May-12	24-May-12	16.9	35.2	Rumela Spillway
10	C20/25	TPC-3	OPC 42.5N	29-Apr-12	6-May-12	27-May-12	18.8	40.9	Rumela Spillway
11	C20/25	SPC-3-6	Slag 42.5N	21-Jan-13	28-Jan-13	18-Feb-13	22.5	33.6	Burdana Spillway
12	C20/25	SPC-3-6	Slag 42.5N	21-Jan-13	28-Jan-13	18-Feb-13	21.5	36.0	Burdana Spillway
13	C20/25	SPC-14	Slag 42.5N	23-Jan-13	30-Jan-13	20-Feb-13	24.7	33.7	Rumela Power Station
14	C20/25	SPC-14	Slag 42.5N	5-Mar-13	12-Mar-13	2-Apr-13	25.5	44.2	Rumela Spillway
15	C20/25	SPC-26	Slag 42.5N	18-Jun-13	25-Jun-13	16-Jul-13	21.4	41.3	Rumela Spillway
16	C20/25	SPC-26	Slag 42.5N	24-Jun-13	1-Jul-13	22-Jul-13	19.6	40.5	Rumela Spillway
17	C20/25	SPC-3-15	Slag 42.5N	12-Apr-15	19-Apr-15	10-May-15	22.6	33.3	Burdana Spillway
18	C20/25	SPC-3-15	Slag 42.5N	16-Oct-15	23-Oct-15	13-Nov-15	24.2	36.2	Burdana Spillway
19	C20/25	SPC-14	Slag 42.5N	16-Apr-16	23-Apr-16	14-May-16	29.3	49.8	Rumela Power Intake
20	C20/25	SPC-3-6	Slag 42.5N	29-Dec-14	5-Jan-15	26-Jan-15	16.3	25.7	Rumela Power Intake

(Lahmeyer International Consultant Reports)

Table (4.3) Class 25/30 compressive strength test result samples

Sample No.	Class	Mix Design No	Cement Type	Sampling Date	Testing Date		Strength (MPa)		Location
					7 days	28 days	7 days	28 days	
1	C25/30	TPC-4-3	OPC 42.5N	30-Jul-12	6-Aug-12	27-Aug-12	25.6	53.2	Rumela Power Intake
2	C25/30	TPC-4-3	OPC 42.5N	31-Jul-12	7-Aug-12	28-Aug-12	28.0	57.4	Rumela Power Intake
3	C25/30	PPC-4-3	OPC 42.5N	28-Aug-12	4-Sep-12	25-Sep-12	22.5	54.3	Burdana Spillway
4	C25/30	PPC-4-3	OPC 42.5N	6-Sep-12	13-Sep-12	4-Oct-12	27.7	43.4	Burdana Spillway
5	C25/30	TPC-3	OPC 42.5N	23-Aug-12	30-Aug-12	20-Sep-12	34.3	54.8	Rumela Spillway
6	C25/30	TPC-3	OPC 42.5N	11-Sep-12	18-Sep-12	9-Oct-12	37.2	55.2	Rumela Spillway
7	C25/30	PPC-3-51	OPC 42.5N	7-Nov-12	14-Nov-12	5-Dec-12	34.2	40.6	Rumela Power Station
8	C25/30	PPC-3-51	OPC 42.5N	7-Nov-12	14-Nov-12	5-Dec-12	33.1	44.4	Rumela Power Station
9	C25/30	PPC-4-74	OPC 42.5N	7-Dec-12	14-Dec-12	4-Jan-13	32.1	49.4	Burdana Spillway
10	C25/30	PPC-8-6	OPC 42.5N	7-May-15	14-May-15	4-Jun-15	22.5	33.1	Burdana Spillway
11	C25/30	SPC-4	Slag 42.5N	22-Dec-12	29-Dec-12	19-Jan-13	40.1	51.5	Burdana Spillway
12	C25/30	SPC-4	Slag 42.5N	22-Dec-12	29-Dec-12	19-Jan-13	31.5	44.3	Burdana Spillway
13	C25/30	SPC-20	Slag 42.5N	10-Jan-13	17-Jan-13	7-Feb-13	18.7	30.5	Burdana Spillway
14	C25/30	SPC-20	Slag 42.5N	11-Jan-13	18-Jan-13	8-Feb-13	19.5	32.1	Rumela Power Station
15	C25/30	SPC-16	Slag 42.5N	16-Jan-13	23-Jan-13	13-Feb-13	31.1	50.3	Rumela Power Station
16	C25/30	SPC-16	Slag 42.5N	19-Jan-13	26-Jan-13	16-Feb-13	28.7	46.8	Rumela Spillway
17	C25/30	SPC-5-1	Slag 42.5N	22-Jan-13	29-Jan-13	19-Feb-13	28.9	43.4	Burdana Spillway
18	C25/30	SPC-5-1	Slag 42.5N	23-Jan-13	30-Jan-13	20-Feb-13	32.1	50.3	Burdana Spillway
19	C25/30	SPC-21	Slag 42.5N	23-Apr-13	30-Apr-13	21-May-13	28.0	40.7	Burdana Spillway
20	C25/30	SPC-23	Slag 42.5N	23-Apr-13	30-Apr-13	21-May-13	26.1	44.8	Burdana Spillway

(Lahmeyer International Consultant Reports)

Table (4.4) Class 35/45 compressive strength test result samples

Sample No.	Class	Mix Design No	Cement Type	Sampling Date	Testing Date		Strength (MPa)		Location
					7 days	28 days	7 days	28 days	
1	C35/45	PPC-4-7	OPC 52.5N	3-Jan-13	10-Jan-13	31-Jan-13	26.8	46.2	Rumela Spillway
2	C35/45	PPC-4-7	OPC 52.5N	3-Jan-13	10-Jan-13	31-Jan-13	25.3	45.0	Rumela Spillway
3	C35/45	PPC-4-7	OPC 52.5N	29-Dec-13	5-Jan-14	26-Jan-14	33.8	58.0	Rumela Power Station
4	C35/45	PPC-4-7	OPC 52.5N	29-Dec-13	5-Jan-14	26-Jan-14	34.0	52.8	Rumela Power Station
5	C35/45	PPC-4-7	OPC 52.5N	5-Jan-13	12-Jan-13	2-Feb-13	22.9	38.7	Rumela Spillway
6	C35/45	PPC-6-4	OPC 52.5N	10-May-13	17-May-13	7-Jun-13	34.3	48.4	Rumela Power Intake
7	C35/45	PPC-6-4	OPC 52.5N	21-May-13	28-May-13	18-Jun-13	34.0	48.2	Rumela Spillway
8	C35/45	PPC-6-4	OPC 52.5N	21-May-13	28-May-13	18-Jun-13	33.0	48.5	Rumela Spillway
9	C35/45	PPC-6-4	OPC 52.5N	21-Aug-15	28-Aug-15	18-Sep-15	25.0	49.6	Burdana Spillway
10	C35/45	PPC-6-4	OPC 52.5N	31-Aug-15	7-Sep-15	28-Sep-15	36.2	50.0	Rumela Power Intake
11	C35/45	SPC-6-1	Slag 42.5N	21-Oct-13	28-Oct-13	18-Nov-13	34.7	55.9	Rumela Power Station
12	C35/45	SPC-6-1	Slag 42.5N	24-Apr-14	1-May-14	22-May-14	27.3	49.8	Rumela Power Intake
13	C35/45	SPC-6-1	Slag 42.5N	2-Nov-13	9-Nov-13	30-Nov-13	31.9	50.9	Rumela Power Station
14	C35/45	SPC-6-1	Slag 42.5N	1-Jul-14	8-Jul-14	29-Jul-14	40.8	57.9	Rumela Spillway
15	C35/45	SPC-6-1	Slag 42.5N	1-Jul-14	8-Jul-14	29-Jul-14	39.2	54.3	Rumela Spillway
16	C35/45	SPC-8-9	Slag 42.5N	6-Apr-14	13-Apr-14	4-May-14	37.1	57.7	Rumela Spillway
17	C35/45	SPC-8-9	Slag 42.5N	26-Nov-15	3-Dec-15	24-Dec-15	31.7	52.7	Rumela Power Intake
18	C35/45	PPC-6-1-1	Slag 42.5N	21-May-16	28-May-16	18-Jun-16	23.7	40.7	Rumela Power Station
19	C35/45	PPC-6-1-1	Slag 42.5N	19-Jun-16	26-Jun-16	17-Jul-16	27.5	47.3	Rumela Power Station
20	C35/45	PPC-6-1-1	Slag 42.5N	19-Jul-16	26-Jul-16	16-Aug-16	29.1	46.7	Rumela Power Station

(Lahmeyer International Consultant Reports)

Table (4.5) Class 70/85 compressive strength test result samples

Sample No.	Class	Mix Design No	Cement Type	Sampling Date	Testing Date		Strength (MPa)		Location
					7 days	28 days	7 days	28 days	
1	C70/85	PAC-1-31	OPC 52.5N	26-Oct-12	2-Nov-12	23-Nov-12	58.2	80.8	Rumela Spillway
2	C70/85	PAC-1-31	OPC 52.5N	29-Oct-12	5-Nov-12	26-Nov-12	59.2	80.4	Rumela Spillway
3	C70/85	PAC-1-31	OPC 52.5N	10-Jan-13	17-Jan-13	7-Feb-13	73.3	88.4	Rumela Spillway
4	C70/85	PAC-1-31	OPC 52.5N	10-Jan-13	17-Jan-13	7-Feb-13	77.3	96.7	Rumela Spillway
5	C70/85	PAC-1-31	OPC 52.5N	10-Mar-13	17-Mar-13	7-Apr-13	60.1	75.1	Burdana Spillway
6	C70/85	PAC-1-31	OPC 52.5N	11-Mar-13	18-Mar-13	8-Apr-13	62.1	86.0	Rumela Spillway
7	C70/85	PAC-1-31	OPC 52.5N	14-Mar-13	21-Mar-13	11-Apr-13	64.8	90.0	Rumela Spillway
8	C70/85	PAC-1-31	OPC 52.5N	15-Mar-13	22-Mar-13	12-Apr-13	63.9	77.1	Burdana Spillway
9	C70/85	PAC-1-31	OPC 52.5N	17-Aug-13	24-Aug-13	14-Sep-13	60.3	93.7	Burdana Spillway
10	C70/85	PAC-1-31	OPC 52.5N	17-Aug-13	24-Aug-13	14-Sep-13	60.5	95.8	Burdana Spillway
11	C70/85	PAC-1-31	OPC 52.5N	20-Aug-13	27-Aug-13	17-Sep-13	67.0	97.6	Burdana Spillway
12	C70/85	PAC-1-31	OPC 52.5N	22-Aug-13	29-Aug-13	19-Sep-13	61.4	95.4	Burdana Spillway
13	C70/85	PAC-1-31	OPC 52.5N	24-Sep-13	1-Oct-13	22-Oct-13	63.0	94.6	Burdana Spillway
14	C70/85	PAC-1-31	OPC 52.5N	25-Sep-13	2-Oct-13	23-Oct-13	65.2	95.5	Burdana Spillway
15	C70/85	PAC-1-31	OPC 52.5N	14-Dec-13	21-Dec-13	11-Jan-14	60.4	91.2	Rumela Spillway
16	C70/85	PAC-1-31	OPC 52.5N	16-Dec-13	23-Dec-13	13-Jan-14	84.1	96.8	Rumela Spillway
17	C70/85	PAC-1-31	OPC 52.5N	8-Feb-14	15-Feb-14	8-Mar-14	69.9	90.6	Rumela Spillway
18	C70/85	PAC-1-31	OPC 52.5N	24-Feb-14	3-Mar-14	24-Mar-14	76.0	97.4	Rumela Spillway
19	C70/85	PAC-1-31	OPC 52.5N	12-Apr-16	19-Apr-16	10-May-16	59.3	89.8	Rumela Power Station
20	C70/85	PAC-1-31	OPC 52.5N	13-Apr-16	20-Apr-16	11-May-16	51.0	86.3	Rumela Power Station

(Lahmeyer International Consultant Reports)

Table (4.6) Summary of strength test result where Ordinary Portland Cement was used

Concrete Class		Samples No.	Maximum Strength	Minimum Strength	Average Mean Strength	Standard Deviation
C12/15	7day	152	30.3	13	20.3	3.8
	28day		37.5	21.8	30.9	3.8
C20/25	7day	796	39.5	13.5	26.7	4.7
	28day		57	25.8	41.5	5.3
C25/30	7day	336	37.4	17.7	25.6	3.7
	28day		46	30.3	38	4.4
C35/45	7day	220	45	24.7	36.4	4
	28day		62	44.7	52.3	4.2
C70/85	7day	158	75.9	57.1	65.81	4.6
	28day		95.8	76.6	88.4	3.9

Table (4.7) Summary of strength test result where Slag Cement was used

Concrete Class		Samples No.	Maximum Strength	Minimum Strength	Average Mean Strength	Standard Deviation
C12/15	7day	152	23.9	10.1	14.2	2.6
	28day		37.1	20.1	26.7	3.5
C20/25	7day	796	33.2	10.5	19.25	3.4
	28day		46.9	24.4	34.6	4.6
C25/30	7day	336	37.4	14	23.9	3.7
	28day		50.3	30	40.2	4.4
C35/45	7day	220	42.5	27.6	36.5	3.6
	28day		60.5	46.7	53.1	3.2

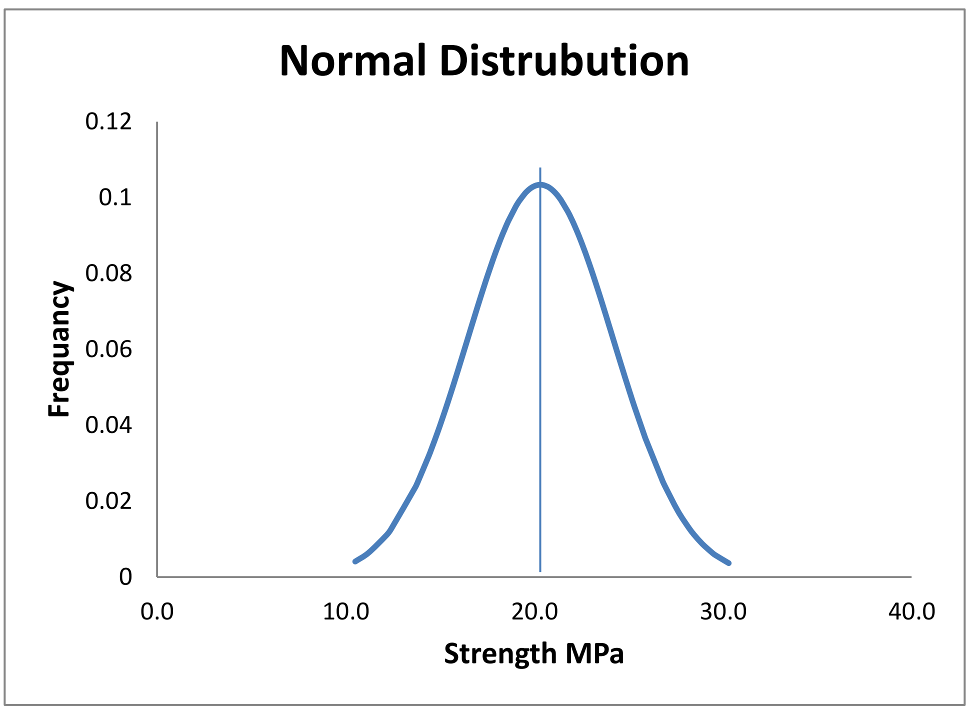
From the above tables (4.6) and (4.7) we get that the number of concrete samples tested for compressive strength in DCUAP is 3166 sample.

4.3Evaluation to determine level of quality

4.3.1Concrete Class 12/15

The followings procedures were abide by for concrete class 12/15:

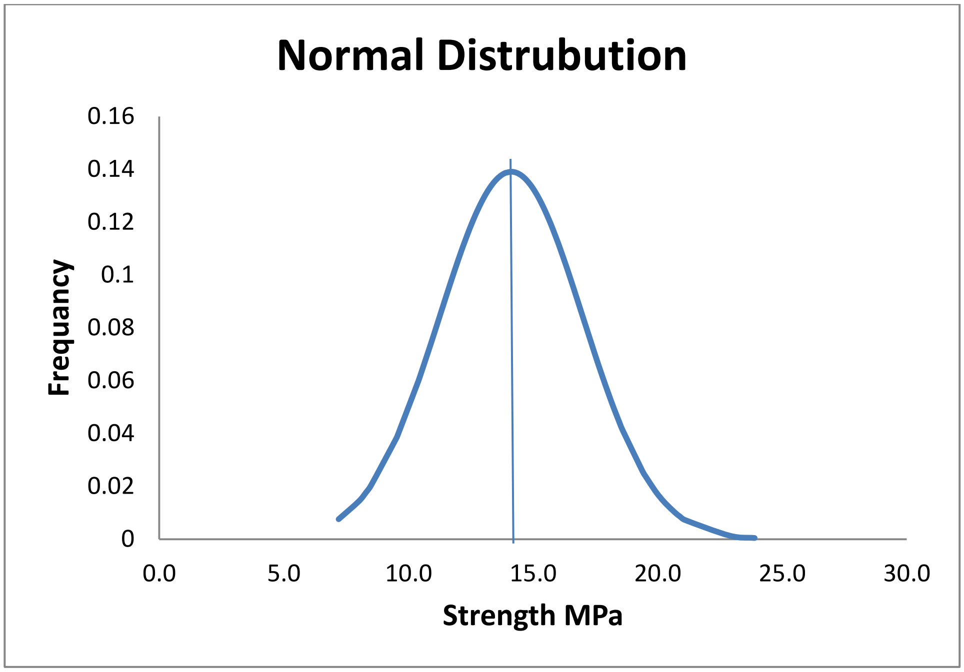
- 152 concrete samples were taken from DCUAP site where 42.5N ordinary Portland cement was used.
- 152 concrete samples were taken from DCUAP site where 42.5N Slag cement was used.
- Compressive strength test was conducted for booth batches of samples at age 7 and 28 days.
- The results of the tests were collected and analyzed and the following charts are drawn as plots in figure (4.1), (4.2), (4.3) and (4.4)



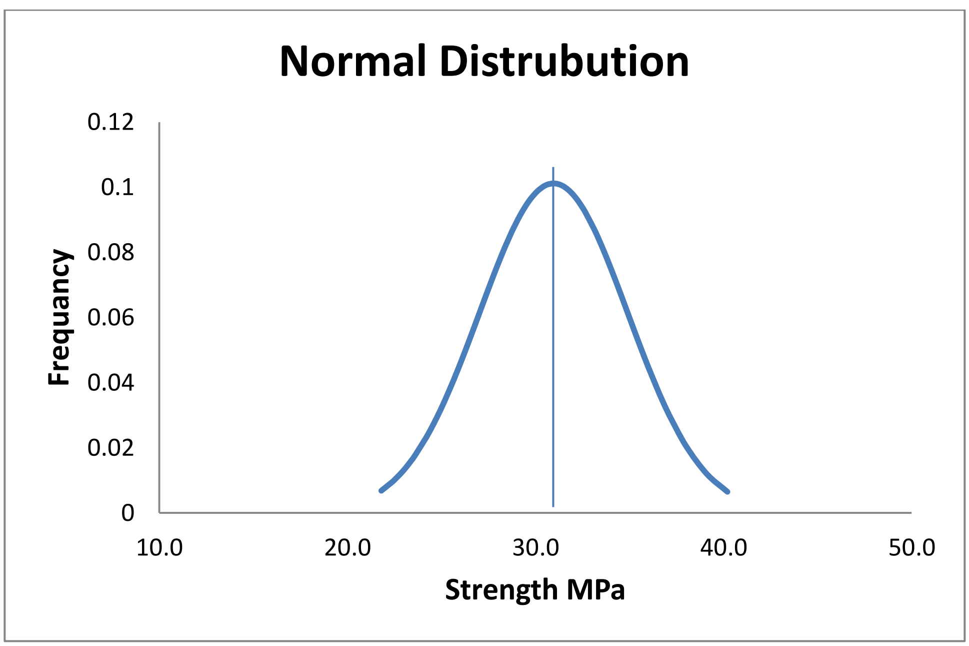
Mean X =20.3 N/mm^2

Standard deviation σ = 3.8

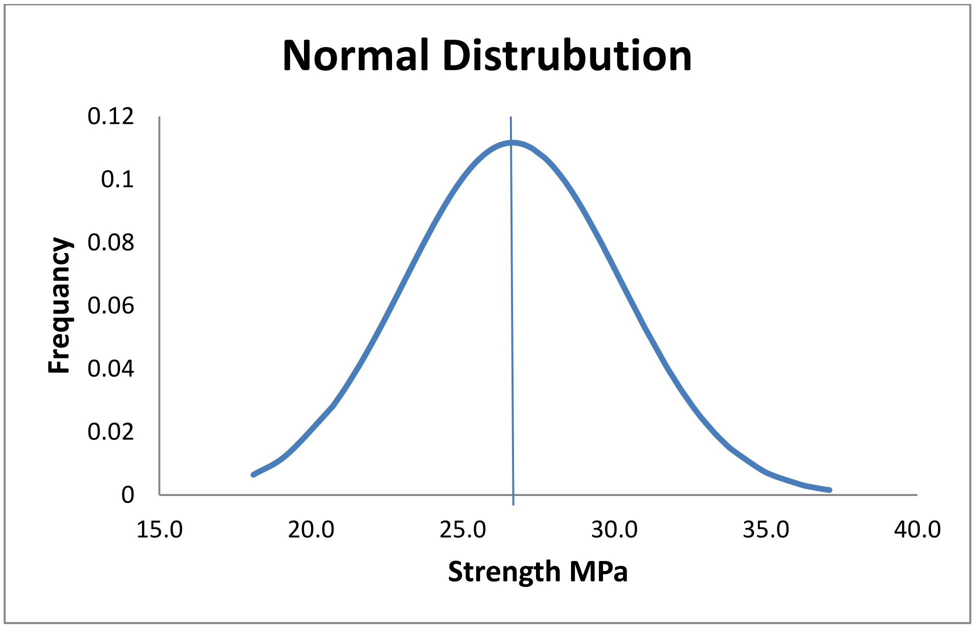
Figure (4.1): Normal distribution curve for 7day test using Ordinary Portland Cement 42.5N



Mean X =14.2 N/mm^2
Standard deviation σ = 2.6
Figure (4.2): Normal distribution curve for 7day test Slag Cement 42.5N



Mean X =30.9 N/mm^2
Standard deviation σ = 3.8
Figure (4.3): Normal distribution curve for 28day test using Ordinary Portland Cement 42.5N



Mean X =26.7 N/mm^2

Standard deviation σ = 3.5

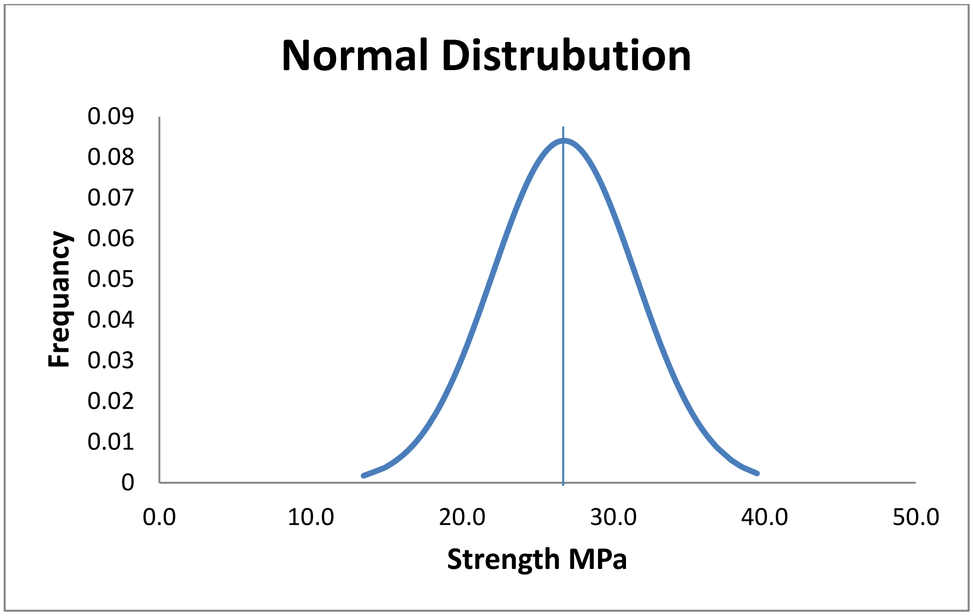
Figure (4.4): Normal distribution curve for 28day test using Slag Cement 42.5N

Applying the standard deviation results for the concrete class 12/15 to table (2.7) at chapter two obtained from ACI214.3R-88, 1997, we find that the degree of quality is classified as good for the Ordinary Portland Cement for both 7 and 28 days. And As for the Slag cement, the degree of quality was excellent for the 7 days result and good for the 28 days result.

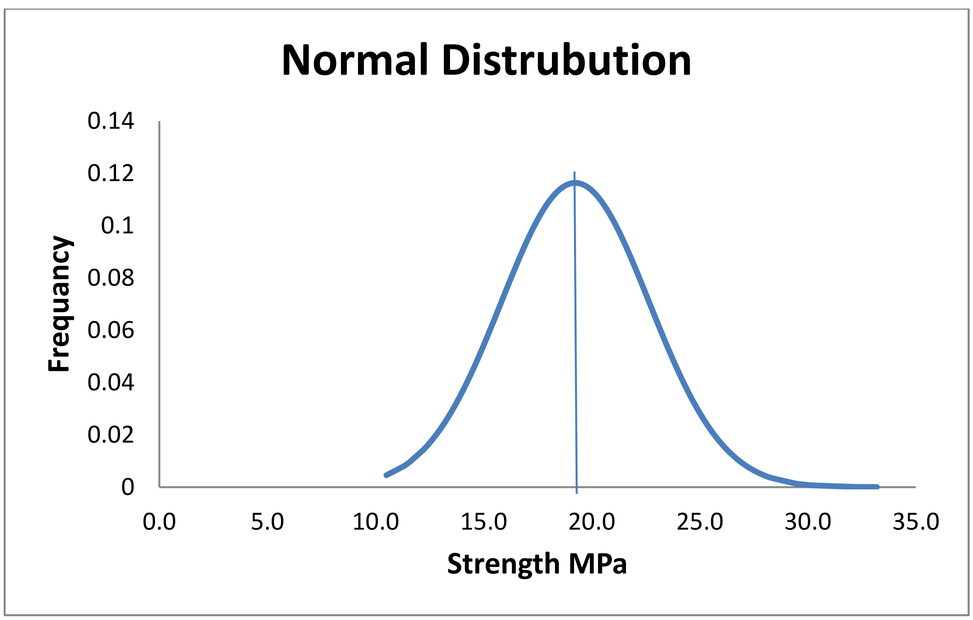
4.3.2 Concrete Class 20/25

The followings procedures were abide by for concrete class 20/25:

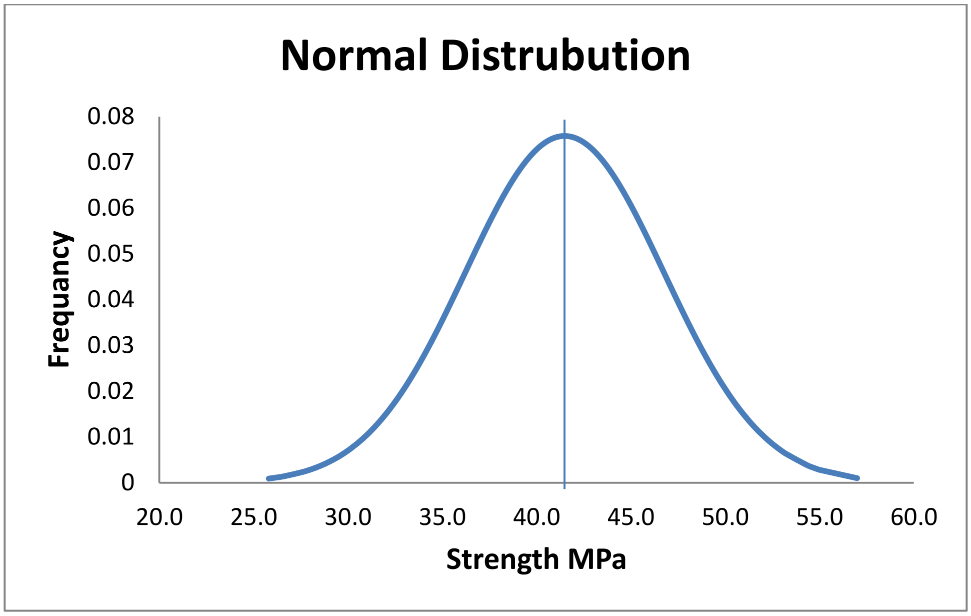
- 796 concrete samples were taken from DCUAP site where 42.5N ordinary Portland cement was used.
- 757 concrete samples were taken from DCUAP site where 42.5N Slag cement was used.
- Compressive strength test was conducted for booth batches of samples at age 7 and 28 days.
- The results of the tests were collected and analyzed and the following charts are drawn as plots in figure (4.5), (4.6), (4.7) and (4.8)



Mean X =26.7 N/mm^2
Standard deviation σ = 4.7
Figure (4.5): Normal distribution curve for 7day test using Ordinary Portland Cement 42.5N



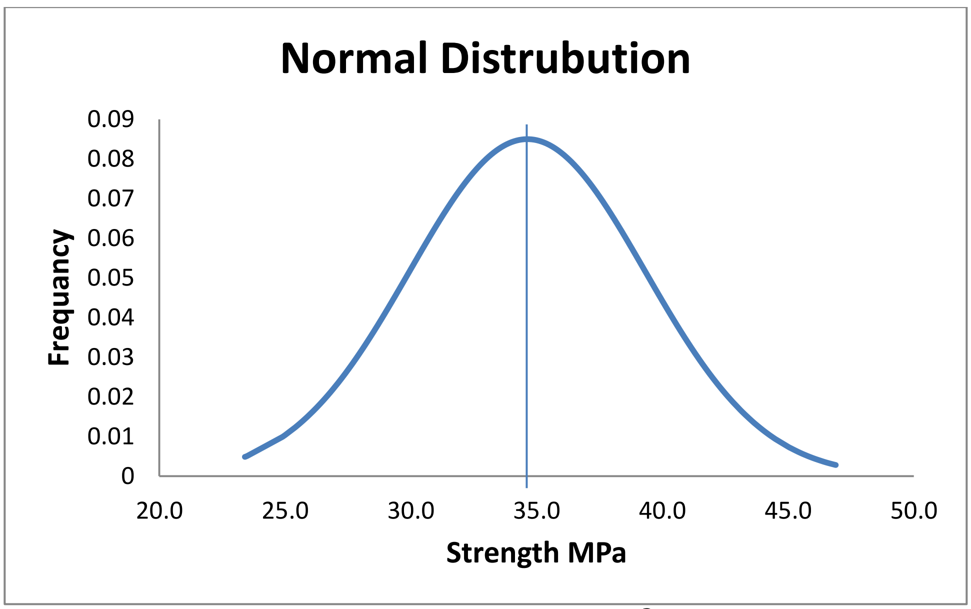
Mean X =19.25 N/mm^2
Standard deviation σ = 3.4
Figure (4.6): Normal distribution curve for 7day test using Slag Cement 42.5N



Mean X =41.5 N/mm^2

Standard deviation σ = 5.3

Figure (4.7): Normal distribution curve for 28day test using Ordinary Portland Cement 42.5N



Mean X =34.6 N/mm^2

Standard deviation σ = 4.6

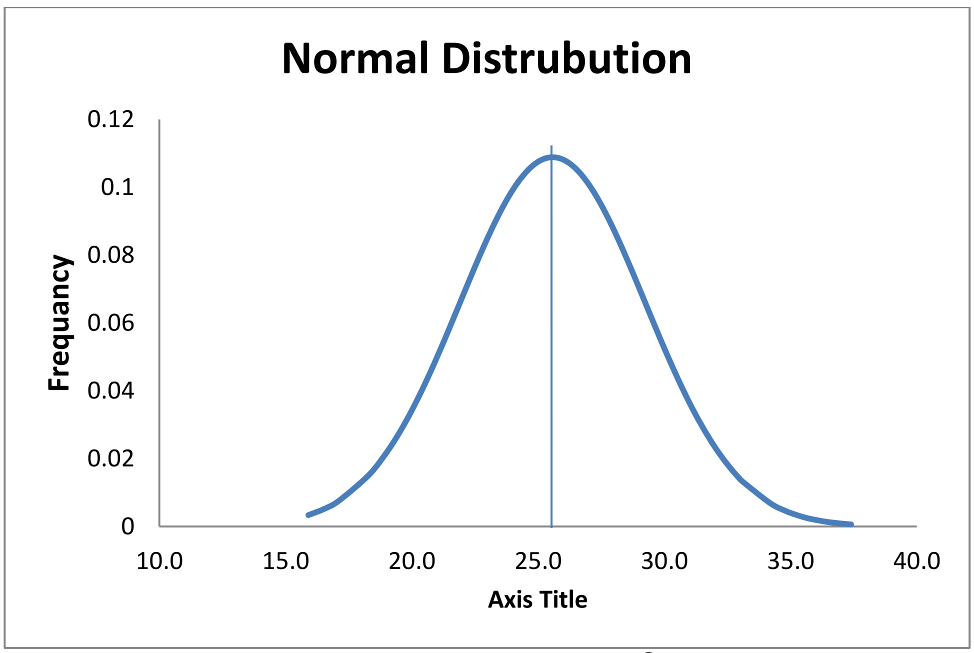
Figure (4.8): Normal distribution curve for 28day test using Slag Cement 42.5N

Applying the standard deviation results for the concrete class 20/25, to table (2.7) at chapter two obtained from ACI214.3R-88, 1997, we find that the degree of quality is classified as poor for the Ordinary Portland Cement for both 7 and 28 days. And As for the Slag cement, the degree of quality was good for the 7 days result and fair for the 28 days result.

4.3.3 Concrete Class 25/30

The followings procedures were abide by for concrete class 25/30:

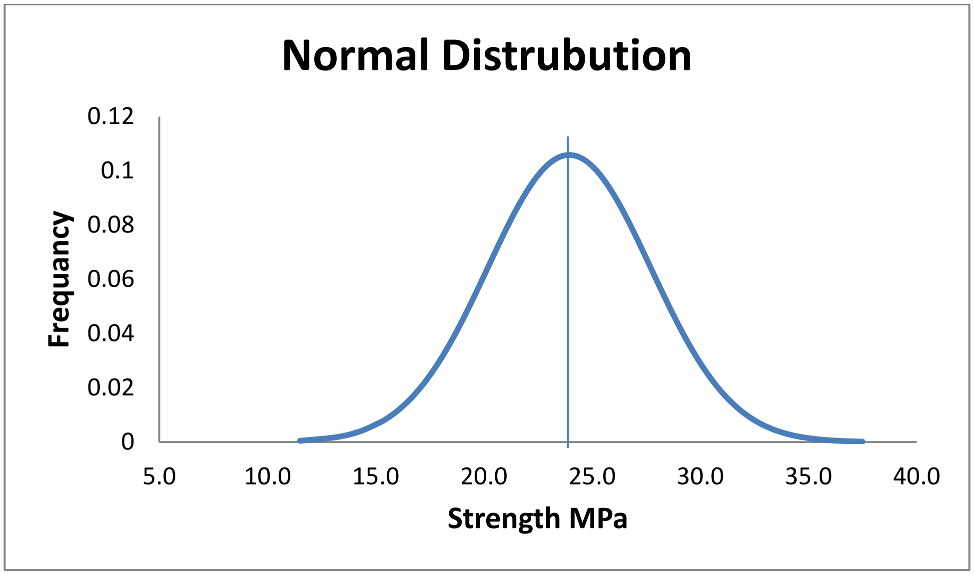
- 336 concrete samples were taken from DCUAP site where 42.5N ordinary Portland cement was used.
- 1487 concrete samples were taken from DCUAP site where 42.5N Slag cement was used.
- Compressive strength test was conducted for booth batches of samples at age 7 and 28 days.
- The results of the tests were collected and analyzed and the following charts are drawn as plots in figure (4.9), (4.10), (4.11) and (4.12)



Mean X =25.6 N/mm^2

Standard deviation σ = 3.7

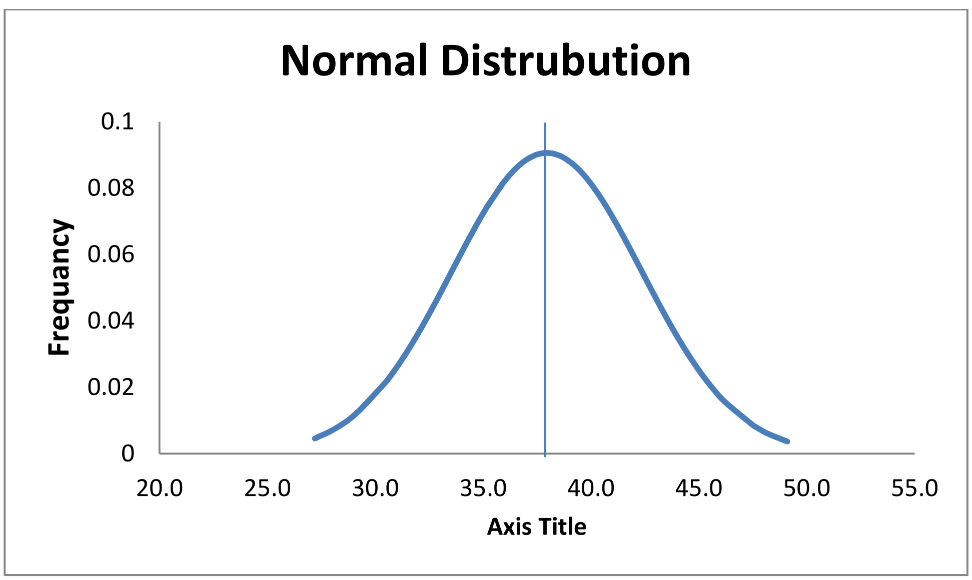
Figure (4.9): Normal distribution curve for 7day test using Ordinary Portland Cement 42.5N



Mean X =23.9/mm^2

Standard deviation σ = 3.7

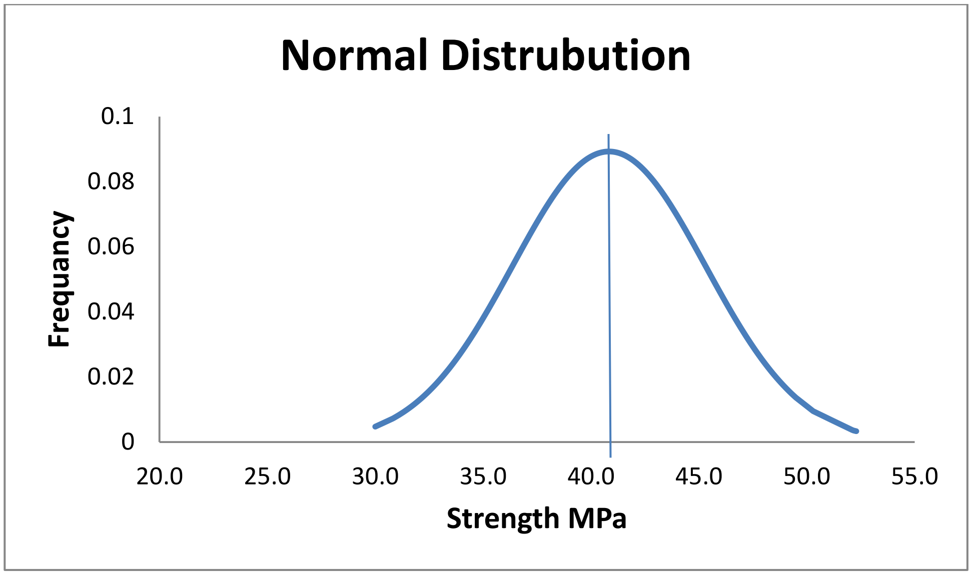
Figure (4.10): Normal distribution curve for 7day test using Slag Cement 42.5N



Mean X =38.0 N/mm^2

Standard deviation σ = 4.4

Figure (4.11): Normal distribution curve for 28day test using Ordinary Portland Cement 42.5N



Mean X =40.2 N/mm^2

Standard deviation σ = 4.4

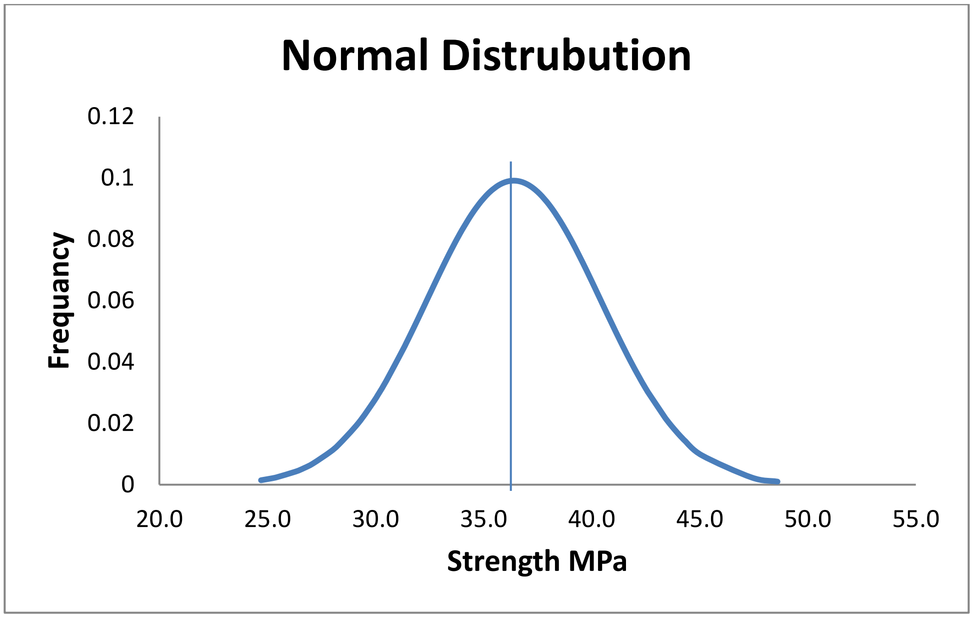
Figure (4.12): Normal distribution curve for 28day test using Slag Cement 42.5N

Applying the standard deviation results for the concrete class 25/30 to table (2.7) at chapter two obtained from ACI214.3R-88, 1997, we find that the degree of quality is classified as good for the Ordinary Portland Cement for 7 days result and fair for the 28 days result. And As for the Slag cement, the degree of quality was good for the 7 days result and fair for the 28 days result.

4.3.4 Concrete Class 35/45

The followings procedures were abide by for concrete class 35/45:

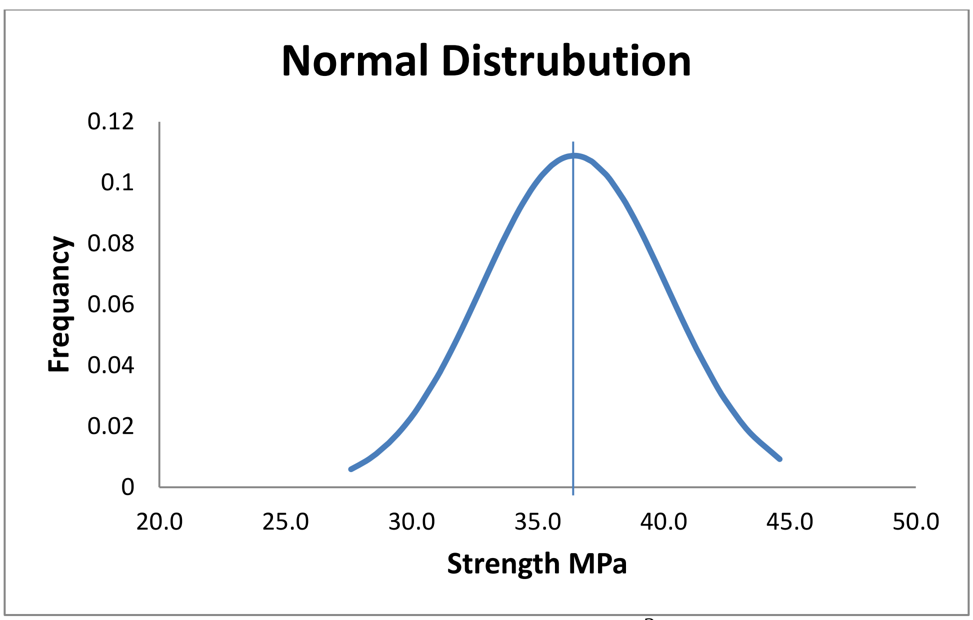
- 220 concrete samples were taken from DCUAP site where 42.5N ordinary Portland cement was used.
- 90 concrete samples were taken from DCUAP site where 42.5N Slag cement was used.
- Compressive strength test was conducted for booth batches of samples at age 7 and 28 days.
- The results of the tests were collected and analyzed and the following charts are drawn as plots in figure (4.13), (4.14), (4.15) and (4.16)



Mean X =36.4 N/mm^2

Standard deviation σ = 4.0

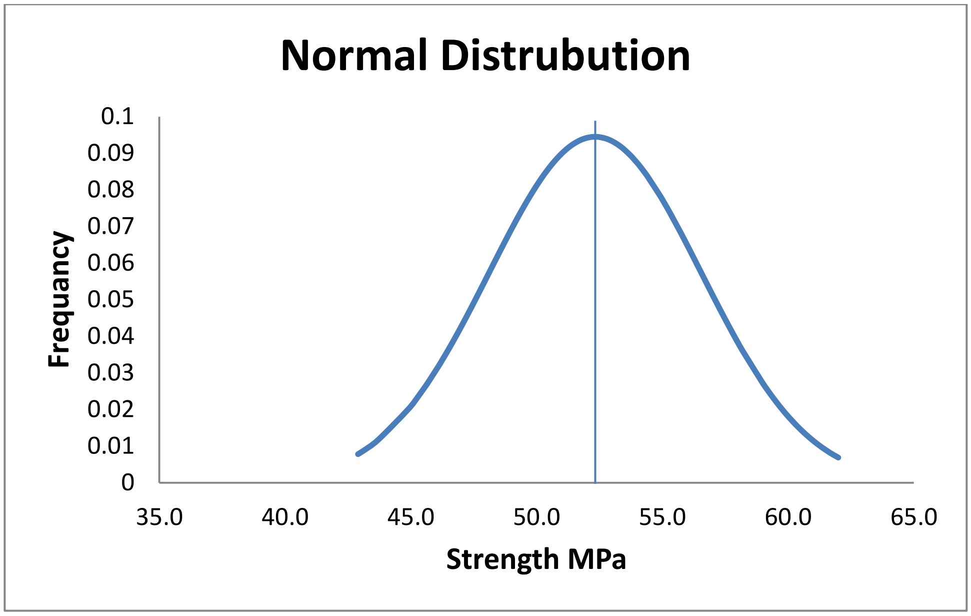
Figure (4.13): Normal distribution curve for 7day test using Ordinary Portland Cement 42.5N



Mean X =36.5 N/mm^2

Standard deviation σ = 3.6

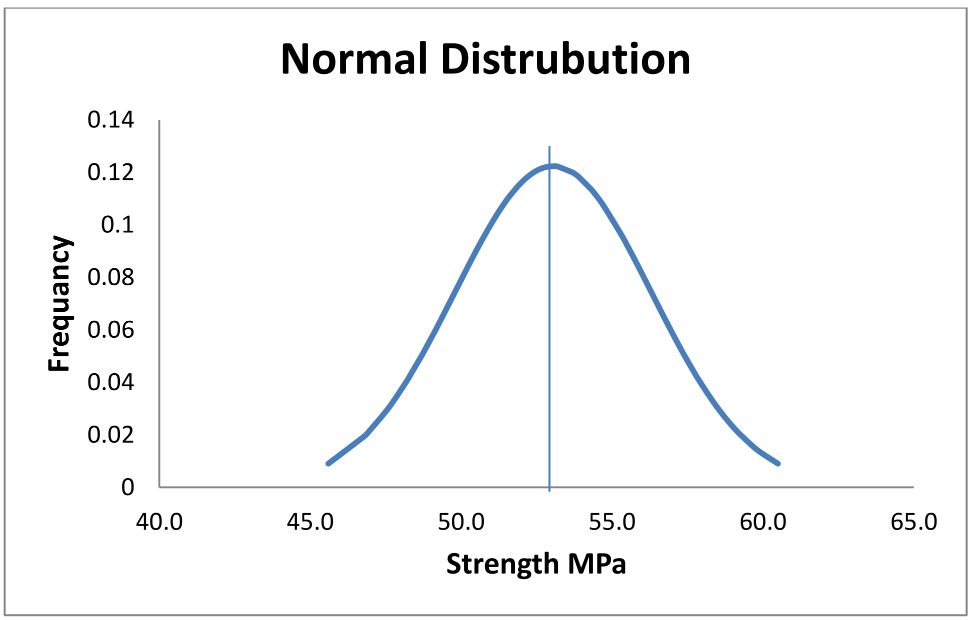
Figure (4.14): Normal distribution curve for 7day test using Slag Cement 42.5N



Mean X =52.3N/mm^2

Standard deviation σ = 4.2

Figure (4.15): Normal distribution curve for 28 day test using Ordinary Portland Cement 42.5N



Mean X =53.1N/mm^2

Standard deviation σ = 3.2

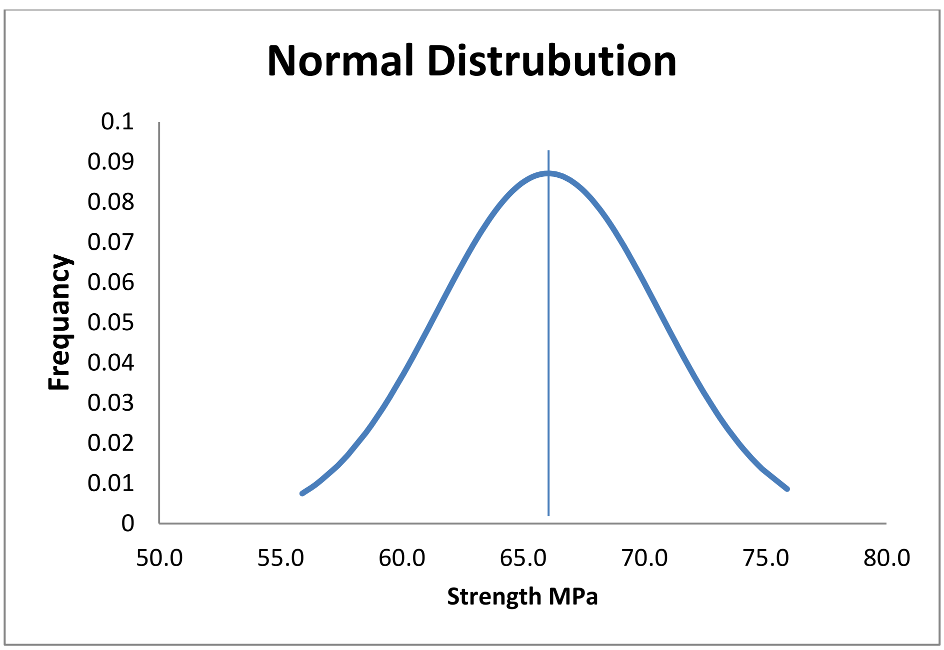
Figure (4.16): Normal distribution curve for 28 day test using Slag Cement 42.5N

Applying the standard deviation results for the concrete class 35/45, to table (2.7) at chapter two obtained from ACI214.3R-88, 1997, we find that the degree of quality is classified as fair for the Ordinary Portland Cement for both 7 days and 28 days test result. And As for the Slag cement, the degree of quality was good for the7 day's result and very good for the 28 days result.

4.3.5 Concrete Class 70/85

The followings procedures were abide by for concrete class 70/85:

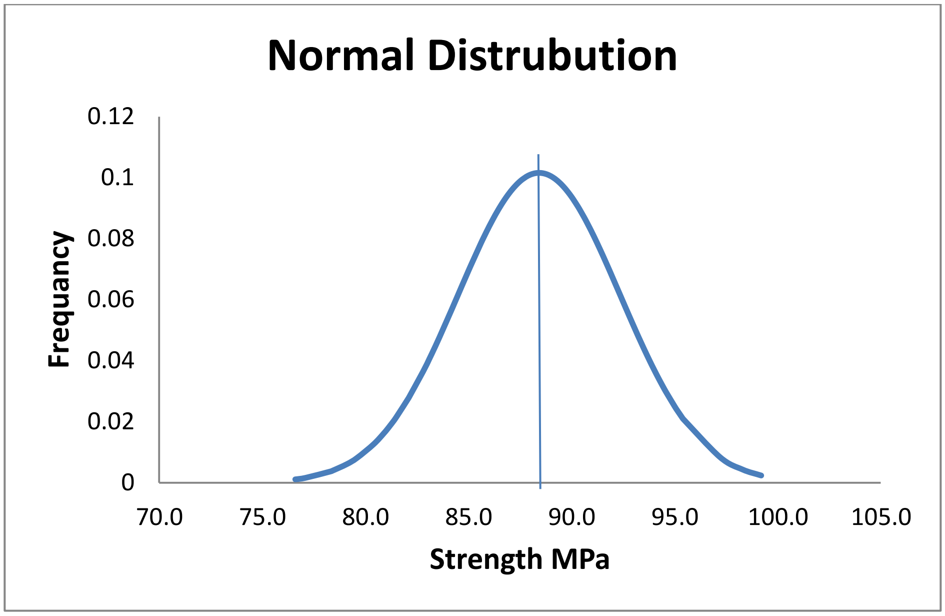
- 158 concrete samples were taken from DCUAP site where 52.5N ordinary Portland cement was used.
- Compressive strength test was conducted for booth batches of samples at age 7 and 28 days.
- The results of the tests were collected and analyzed and the following charts are drawn as plots in figure (4.17) and (4.18)



Mean X =65.8N/mm^2

Standard deviation σ = 4.6

Figure (4.17): Normal distribution curve for 7day test using Ordinary Portland Cement 52.5N



Mean X =88.4N/mm^2

Standard deviation σ = 3.9

Figure (4.18): Normal distribution curve for 28day test using Ordinary Portland Cement 52.5N

Applying the standard deviation results for the concrete class 70/85, to table (2.7) at chapter two obtained from ACI214.3R-88, 1997, we find that the degree of quality is classified as fair for the Ordinary Portland Cement for 7 days result and good for the 28 days result.

Table (4.8) Summery of Standard of concrete control at DCUAP

Concrete Class		Samples No.	Different Control Standard	
			OPC	Slag
C12/15	7day	152	Good	Excellent
	28day		Good	Good
C20/25	7day	796	Fair	V. Good
	28day		Poor	Fair
C25/30	7day	336	Good	Good
	28day		Fair	Fair
C35/45	7day	220	Fair	Good
	28day		Fair	Fair
C70/85	7day	158	Fair	Good
	28day		Good	V. Good

4.4 Evaluation of Level of Control using Shewhart Chart

Application of shewhart chart was based on the assumption that all the data collected represent an overall single process of concrete production. Then control limit were calculated and warning limits were apply based on the measured variation in the production process. After the calculation of the control and warning limits, the charts were drawn for evaluating purpose and to measure the variables in the production process using the rules stated in chapter two.

4.4.1 Concrete Class 12/15

- **For 7day test using Ordinary Portland Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn in figure (4.19) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$
$$UCL = 20.3 + 3 \times 3.8 = 31.9 N/mm^2$$
$$LCL = TMS - 3 \times \sigma$$
$$LCL = 20.3 - 3 \times 3.8 = 8.7 N/mm^2$$
$$UWL = TMS + 2 \times \sigma$$
$$UWL = 20.3 + 2 \times 3.8 = 28.1 N/mm^2$$
$$LWL = TMS - 2 \times \sigma$$
$$LWL = 20.3 - 2 \times 3.8 = 12.6 N/mm^2$$

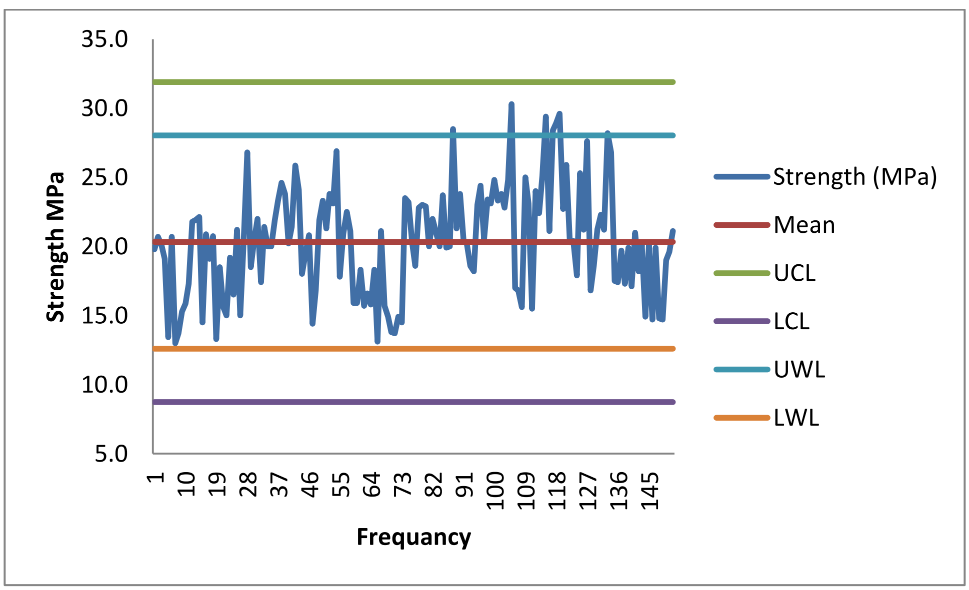


Figure (4.19): chart 7day test using Ordinary Portland Cement 42.5N

The chart shows that the process was in control except for three points where the UWL was exceeded.

- **For 7day test using Slag Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.20) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$
$$UCL = 14.2 + 3 \times 2.6 = 22.3 N/mm^2$$
$$LCL = TMS - 3 \times \sigma$$
$$LCL = 14.2 - 3 \times 2.6 = 6.2 N/mm^2$$
$$UWL = TMS + 2 \times \sigma$$
$$UWL = 14.2 + 2 \times 2.6 = 19.6 N/mm^2$$
$$LWL = TMS - 2 \times \sigma$$
$$LWL = 14.2 - 2 \times 2.6 = 8.9 N/mm^2$$

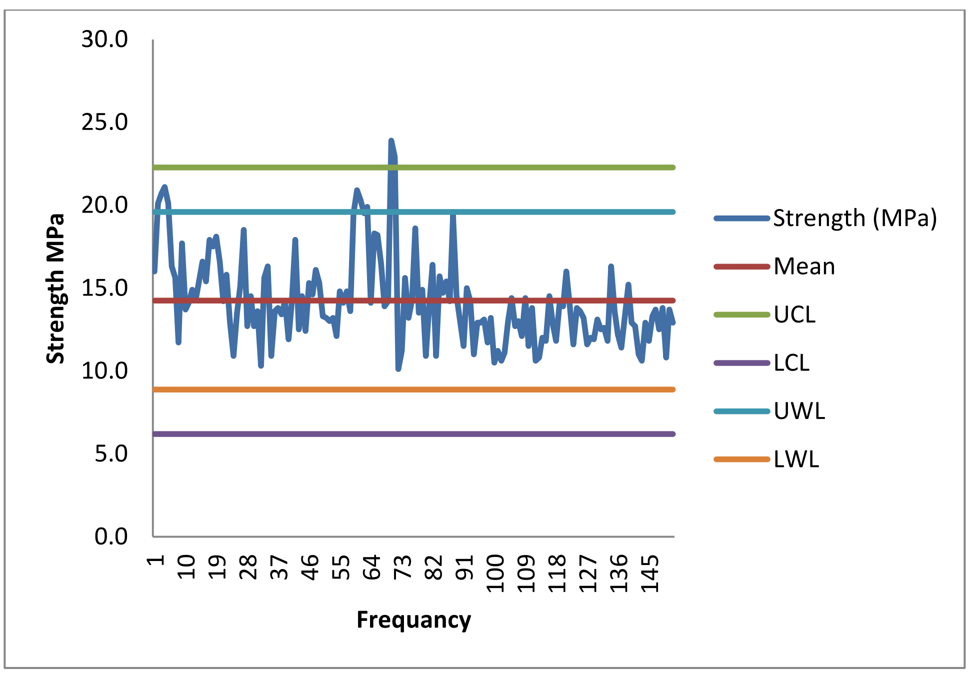


Figure (4.20): chart 7day test using slag Cement 42.5N

The chart show that the process was in control except for some points where the UWL was exceeded and at one point the UCL was exceeded.

- **For 28day test using Ordinary Portland Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.21) according to the calculated limits.

$$UCL = TMS + 3 \text{ x } \sigma$$
$$UCL = 30.9 + 3 \text{ x } 3.8 = 42.6 N/mm^2$$
$$LCL = TMS - 3 \text{ x } \sigma$$
$$LCL = 30.9 - 3 \text{ x } 3.8 = 19.3 N/mm^2$$
$$UWL = TMS + 2 \text{ x } \sigma$$
$$UWL = 30.9 + 2 \text{ x } 3.8 = 38.7 N/mm^2$$
$$LWL = TMS - 2 \text{ x } \sigma$$
$$LWL = 30.9 - 2 \text{ x } 3.8 = 23.2 N/mm^2$$

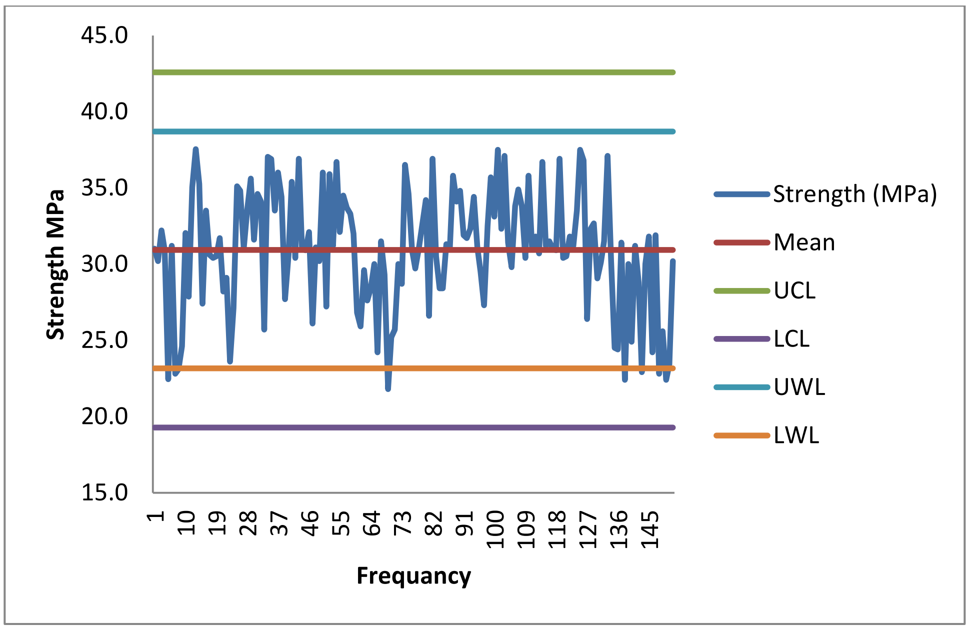


Figure (4.21): chart 28 day test using Ordinary Portland Cement 42.5N

The chart shows that the process was out of control at the beginning, and for the rest of the period it was controlled except for some points where the UWL was exceeded.

- **For 28day test using Slag Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.22) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$

$$UCL = 26.7 + 3 \times 3.5 = 37.2N/mm^2$$

$$LCL = TMS – 3 \times \sigma$$

$$LCL = 26.7 – 3 \times 3.5 = 16.1N/mm^2$$

$$UWL = TMS + 2 \times \sigma$$

$$UWL = 26.7 + 2 \times 3.5 = 33.7N/mm^2$$

$$LWL = TMS – 2 \times \sigma$$

$$LWL = 26.7 – 2 \times 3.5 = 19.6N/mm^2$$

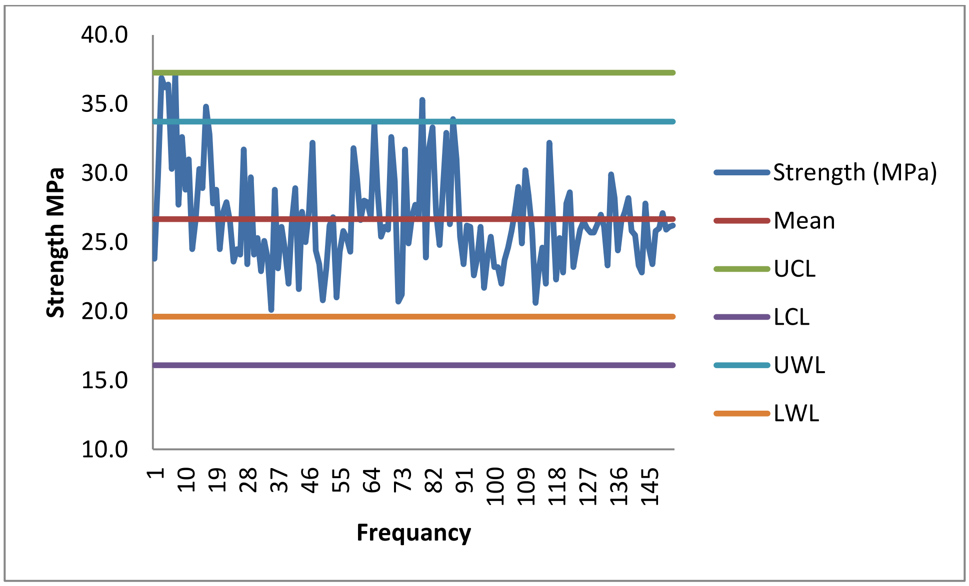


Figure (4.22): chart 28 day test using slag Cement 42.5N

The chart shows that the process was out of control through several stages at the beginning of the period, and then it was controlled for the rest of the period.

4.4.2 Concrete Class 20/25

- **For 7day test using Ordinary Portland Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.23) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$

$$UCL = 26.7 + 3 \times 4.7 = 40.9N/mm^2$$

$$LCL = TMS – 3 \times \sigma$$

$$LCL = 26.7 – 3 \times 4.7 = 12.5 N/mm^2$$

$$UWL = TMS + 2 \times \sigma$$

$$UWL = 26.7 + 2 \times 4.7 = 36.2 N/mm^2$$

$$LWL = TMS – 2 \times \sigma$$

$$LWL = 26.7 – 2 \times 4.7 = 17.2 N/mm^2$$

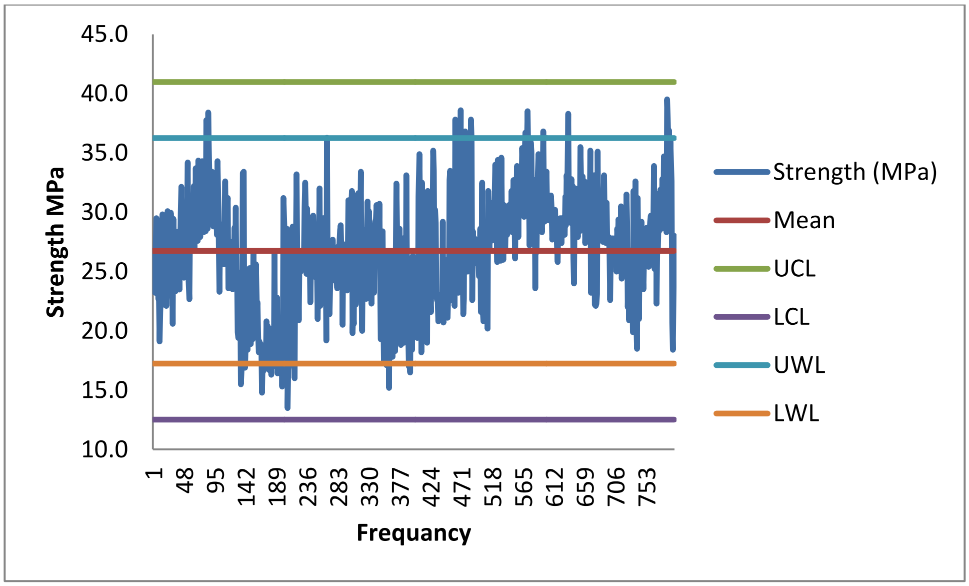


Figure (4.23): chart 7day test using Ordinary Portland Cement 42.5N

The chart shows that the process was out of control for many separated points through the period.

- **For 7day test using Slag Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.24) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$
$$UCL = 19.25 + 3 \times 3.4 = 2.5 N/mm^2$$
$$LCL = TMS – 3 \times \sigma$$
$$LCL = 19.25 – 3 \times 3.4 = 8.9 N/mm^2$$
$$UWL = TMS + 2 \times \sigma$$
$$UWL = 19.25 + 2 \times 3.4 = 26.1 N/mm^2$$

$$LWL = TMS - 2 \times \sigma$$
$$LWL = 19.25 - 2 \times 3.4 = 12.3 N/mm^2$$

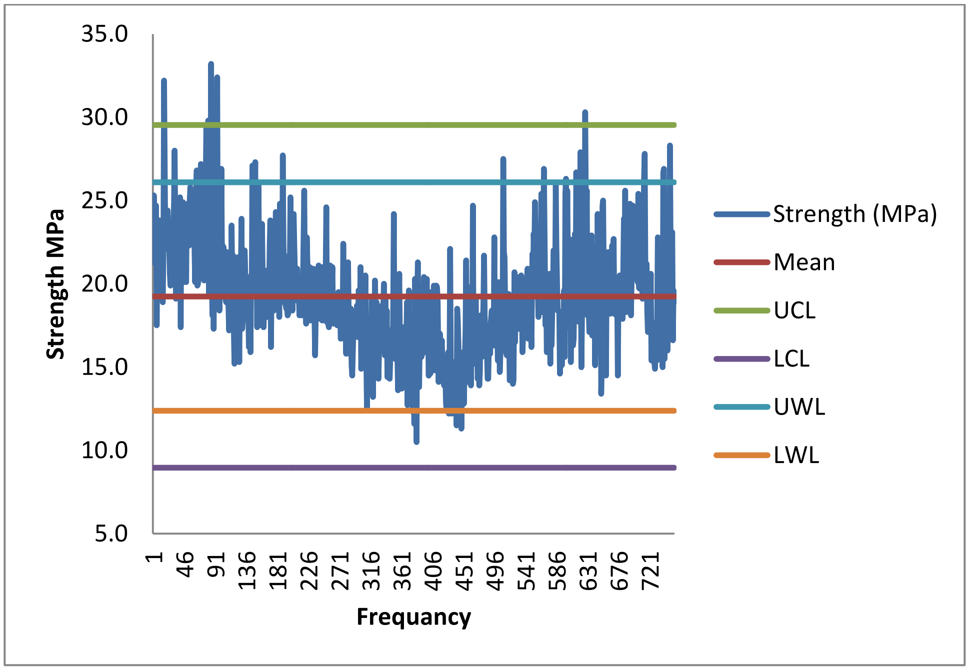


Figure (4.24): chart 7day test using slag Cement 42.5N

The chart shows that the process was out of control for many separated points through the period.

- **For 28day test using Ordinary Portland Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.25) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$
$$UCL = 41.5 + 3 \times 5.3 = 57.2 N/mm^2$$
$$LCL = TMS - 3 \times \sigma$$
$$LCL = 41.5 - 3 \times 5.3 = 25.6 N/mm^2$$
$$UWL = TMS + 2 \times \sigma$$
$$UWL = 41.5 + 2 \times 5.3 = 52.1 N/mm^2$$
$$LWL = TMS - 2 \times \sigma$$
$$LWL = 41.5 - 2 \times 5.3 = 30.9 N/mm^2$$

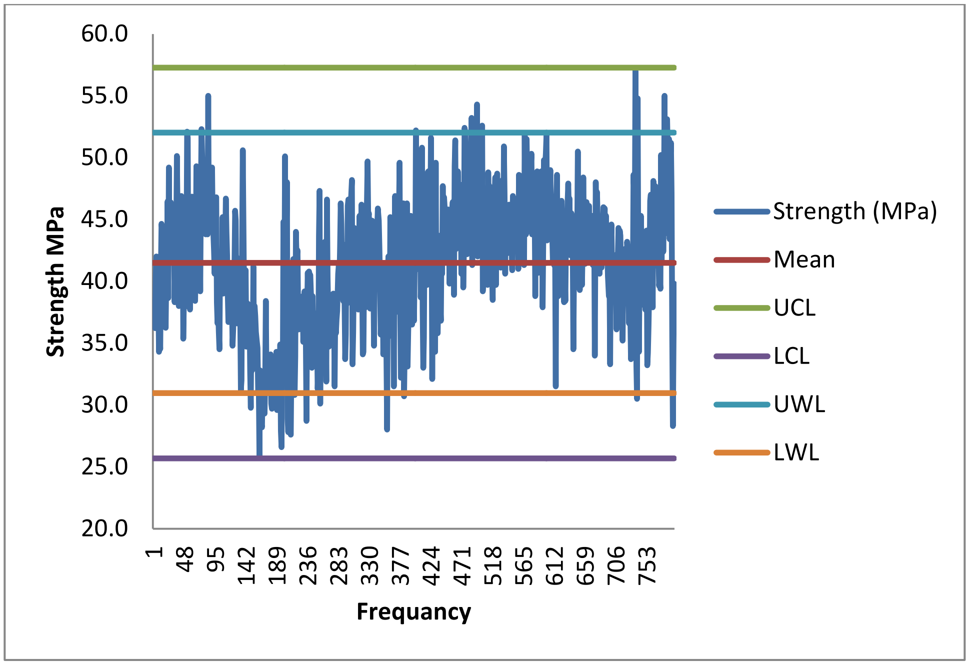


Figure (4.25): chart 28 day test using Ordinary Portland Cement 42.5N

The chart shows that the process was out of control for many separated points through the period.

- **For 28day test using Slag Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.26) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$

$$UCL = 34.6 + 3 \times 4.6 = 48.7 N/mm^2$$

$$LCL = TMS - 3 \times \sigma$$

$$LCL = 34.6 - 3 \times 4.6 = 20.5 N/mm^2$$

$$UWL = TMS + 2 \times \sigma$$

$$UWL = 34.6 + 2 \times 4.6 = 44.1 N/mm^2$$

$$LWL = TMS - 2 \times \sigma$$

$$LWL = 34.6 - 2 \times 4.6 = 25.2 N/mm^2$$

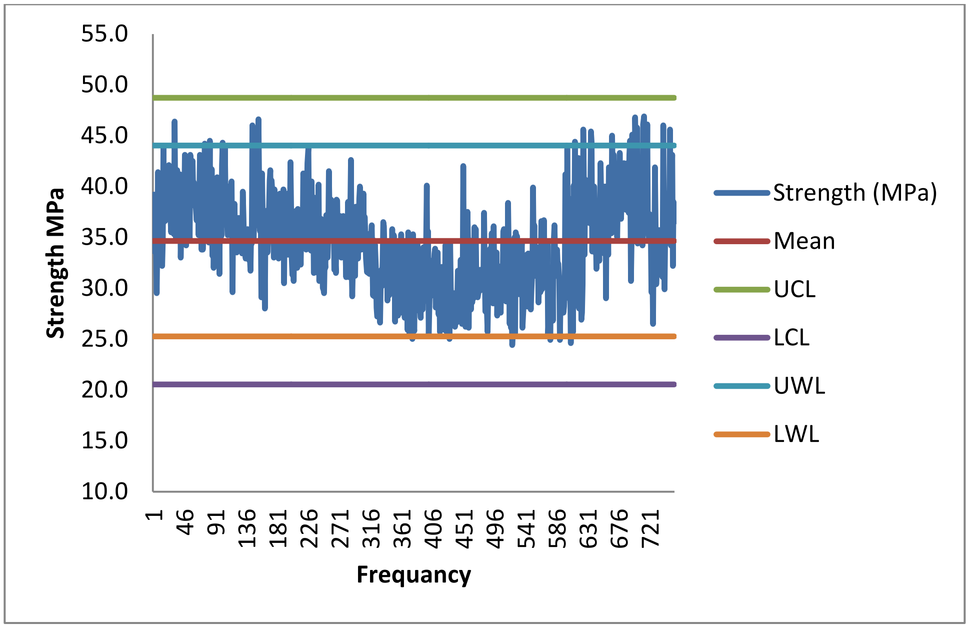


Figure (4.26): chart 28day test using slag Cement 42.5N

The chart shows that the process was out of control for many separated points through the period.

4.4.3 Concrete Class 25/30

- **For 7day test using Ordinary Portland Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.27) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$

$$UCL = 25.6 + 3 \times 3.7 = 36.5 N/mm^2$$

$$LCL = TMS - 3 \times \sigma$$

$$LCL = 25.6 - 3 \times 3.7 = 14.5 N/mm^2$$

$$UWL = TMS + 2 \times \sigma$$

$$UWL = 25.6 + 2 \times 3.7 = 32.9 N/mm^2$$

$$LWL = TMS - 2 \times \sigma$$

$$LWL = 25.6 - 2 \times 3.7 = 18.2 N/mm^2$$

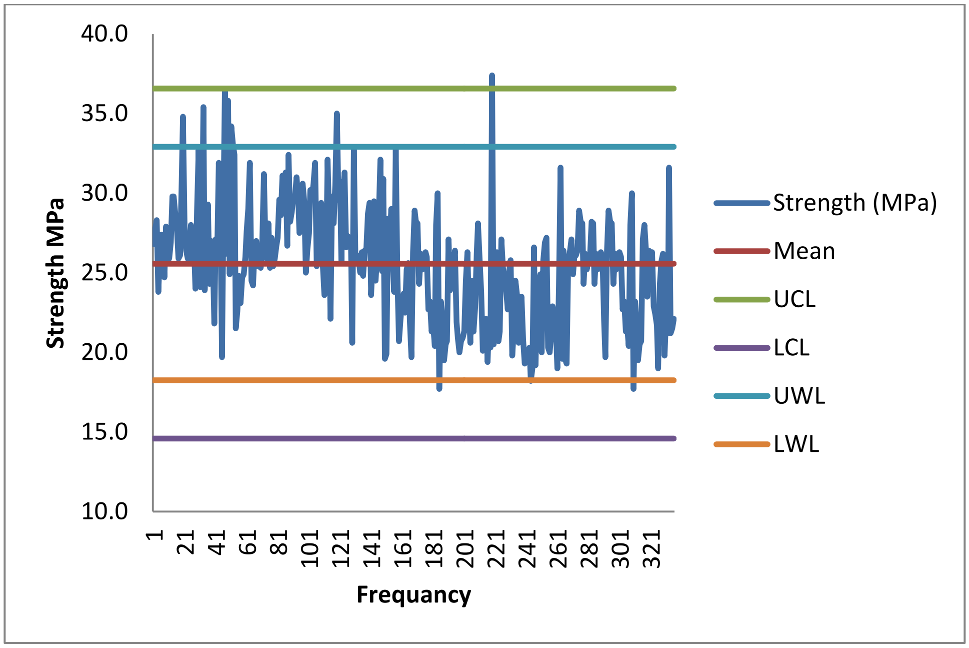


Figure (4.27): chart 7day test using Ordinary Portland Cement 42.5N

The chart shows that the actual Mean strength was higher at the first half of the period and lower at the second half than the required Mean strength.

- **For 7day test using Slag Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.28) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$

$$UCL = 23.9 + 3 \times 3.7 = 35.2 N/mm^2$$

$$LCL = TMS - 3 \times \sigma$$

$$LCL = 23.9 - 3 \times 3.7 = 12.6 N/mm^2$$

$$UWL = TMS + 2 \times \sigma$$

$$UWL = 23.9 + 2 \times 3.7 = 31.4 N/mm^2$$

$$LWL = TMS - 2 \times \sigma$$

$$LWL = 23.9 - 2 \times 3.7 = 16.4 N/mm^2$$

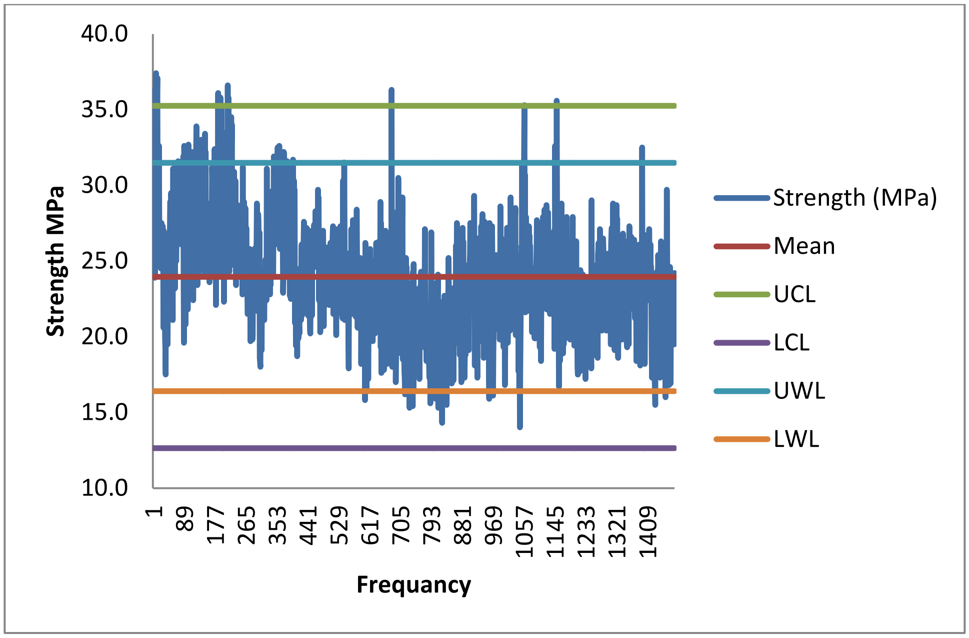


Figure (4.28): chart 7day test using slag Cement 42.5N

The chart shows that the process was out of control for several points throw the period and the actual Mean strength is higher than the required one.

- **For 28day test using Ordinary Portland Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.29) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$

$$UCL = 38.0 + 3 \times 4.4 = 51.1 N/mm^2$$

$$LCL = TMS - 3 \times \sigma$$

$$LCL = 38.0 - 3 \times 4.4 = 24.7 N/mm^2$$

$$UWL = TMS + 2 \times \sigma$$

$$UWL = 38.0 + 2 \times 4.4 = 46.7 N/mm^2$$

$$LWL = TMS - 2 \times \sigma$$

$$LWL = 38.0 - 2 \times 4.4 = 29.1 N/mm^2$$

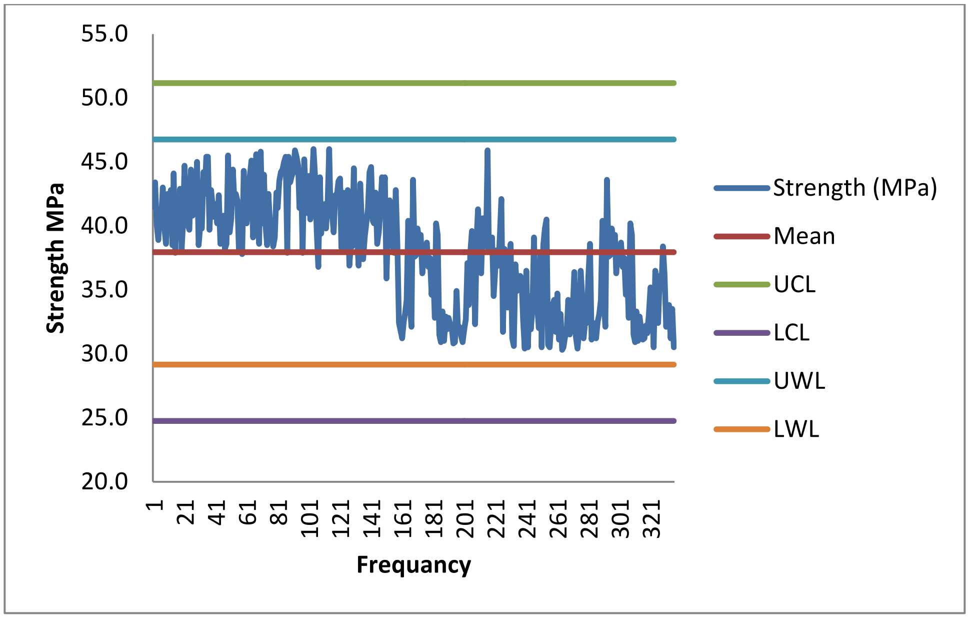


Figure (4.29): chart 28 day test using Ordinary Portland Cement 42.5N

The chart shows that the process was in control except at some points at the beginning of the period and that the actual Mean strength was higher at the first half of the period and lower at the second half than the required Mean strength.

- **For 28day test using Slag Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.30) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$

$$UCL = 40.2 + 3 \times 4.4 = 54.2 N/mm^2$$

$$LCL = TMS - 3 \times \sigma$$

$$LCL = 40.2 - 3 \times 4.4 = 27.4 N/mm^2$$

$$UWL = TMS + 2 \times \sigma$$

$$UWL = 40.2 + 2 \times 4.4 = 49.7 N/mm^2$$

$$LWL = TMS - 2 \times \sigma$$

$$LWL = 40.2 - 2 \times 4.4 = 31.8 N/mm^2$$

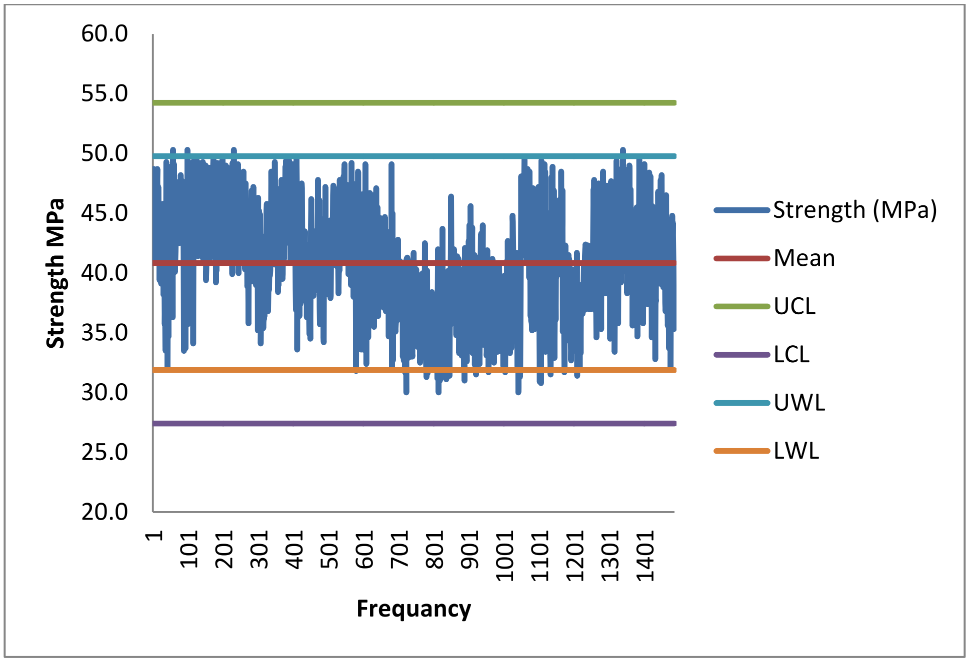


Figure (4.30): chart 28 day test using slag Cement 42.5N

The chart shows that the process is way out of control and the actual Mean strength is higher than the required one.

4.4.4 Concrete Class 35/45

- **For 7day test using Ordinary Portland Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.31) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$

$$UCL = 36.4 + 3 \times 4.0 = 48.4 N/mm^2$$

$$LCL = TMS - 3 \times \sigma$$

$$LCL = 36.4 - 3 \times 4.0 = 24.3 N/mm^2$$

$$UWL = TMS + 2 \times \sigma$$

$$UWL = 36.4 + 2 \times 4.0 = 44.4 N/mm^2$$

$$LWL = TMS - 2 \times \sigma$$

$$LWL = 36.4 - 2 \times 4.0 = 28.3 N/mm^2$$

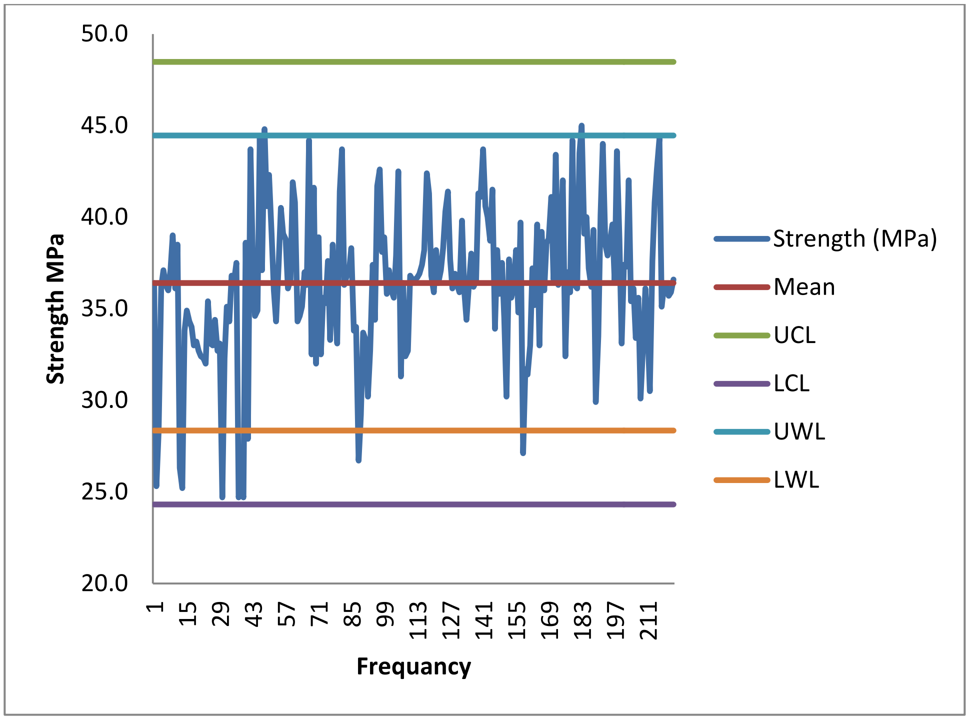


Figure (4.31): chart 7day test using Ordinary Portland Cement 42.5N

The chart shows that the process was out of control for several points through the entire period.

- **For 7day test using Slag Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.32) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$

$$UCL = 36.5 + 3 \times 3.6 = 47.4 N/mm^2$$

$$LCL = TMS - 3 \times \sigma$$

$$LCL = 36.5 - 3 \times 3.6 = 25.4 N/mm^2$$

$$UWL = TMS + 2 \times \sigma$$

$$UWL = 36.5 + 2 \times 3.6 = 43.7 N/mm^2$$

$$LWL = TMS - 2 \times \sigma$$

$$LWL = 36.5 - 2 \times 3.6 = 29.1 N/mm^2$$

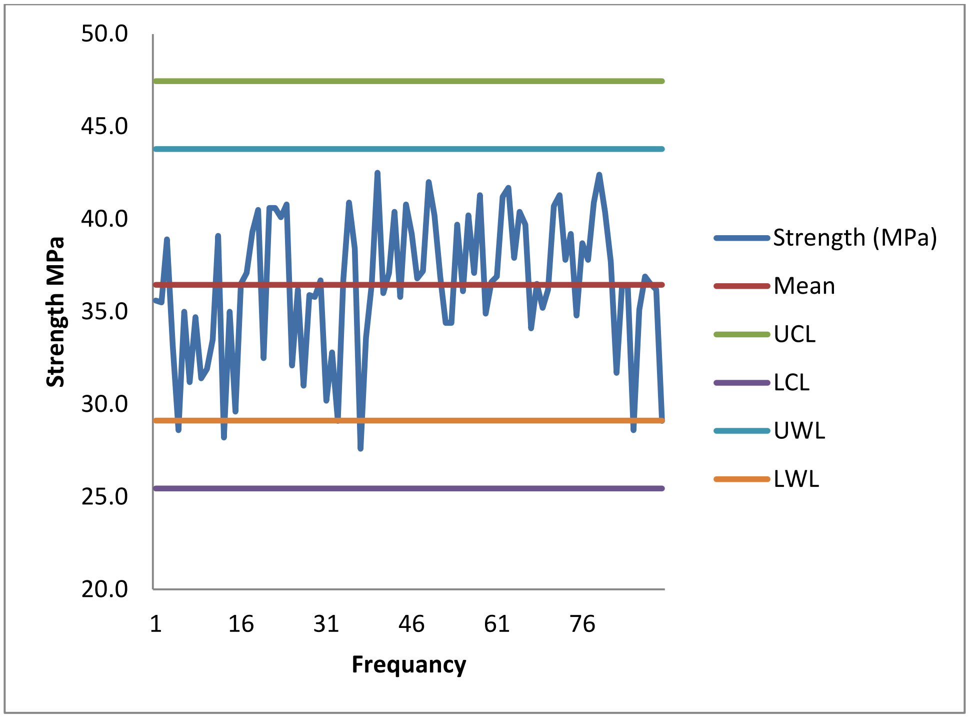


Figure (4.32): chart 7day test using slag Cement 42.5N

The chart shows that the process was in control through most of the period except for some points which have exceeded the LWL.

- **For 28day test using Ordinary Portland Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.33) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$

$$UCL = 52.3 + 3 \times 4.2 = 64.9 N/mm^2$$

$$LCL = TMS - 3 \times \sigma$$

$$LCL = 52.3 - 3 \times 4.2 = 39.6 N/mm^2$$

$$UWL = TMS + 2 \times \sigma$$

$$UWL = 52.3 + 2 \times 4.2 = 60.7 N/mm^2$$

$$LWL = TMS - 2 \times \sigma$$

$$LWL = 52.3 - 2 \times 4.2 = 43.8 N/mm^2$$

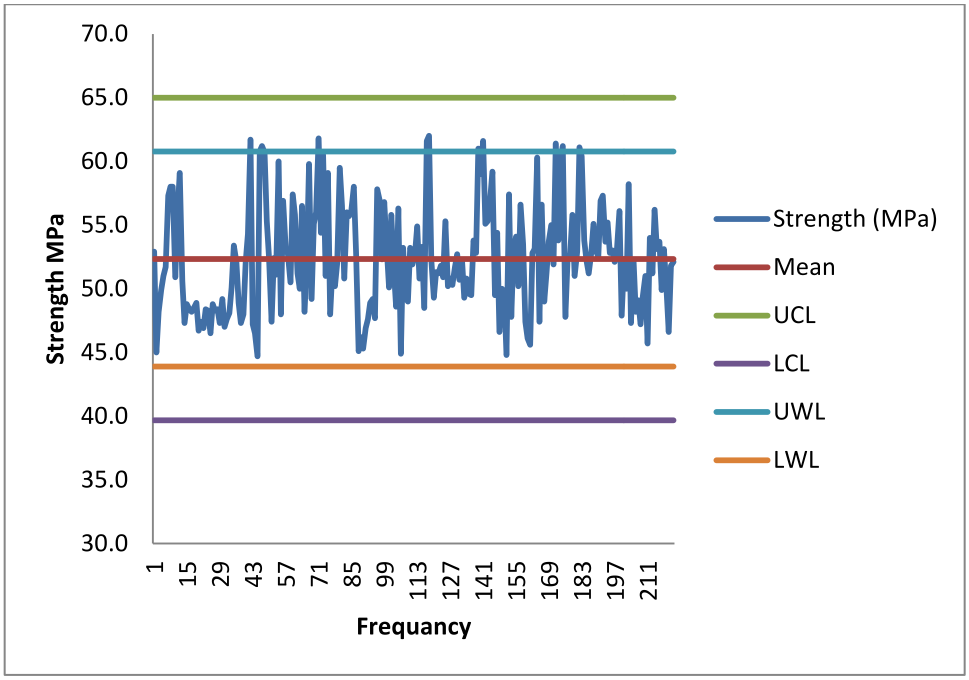


Figure (4.33): chart 28 day test using Ordinary Portland Cement 42.5N

The chart shows that the process was out of control for several points through the entire period.

- **For 28day test using Slag Cement 42.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.34) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$

$$UCL = 53.1 + 3 \times 3.2 = 62.8 N/mm^2$$

$$LCL = TMS - 3 \times \sigma$$

$$LCL = 53.1 - 3 \times 3.2 = 43.2 N/mm^2$$

$$UWL = TMS + 2 \times \sigma$$

$$UWL = 53.1 + 2 \times 3.2 = 59.5 N/mm^2$$

$$LWL = TMS - 2 \times \sigma$$

$$LWL = 53.1 - 2 \times 3.2 = 46.5 N/mm^2$$

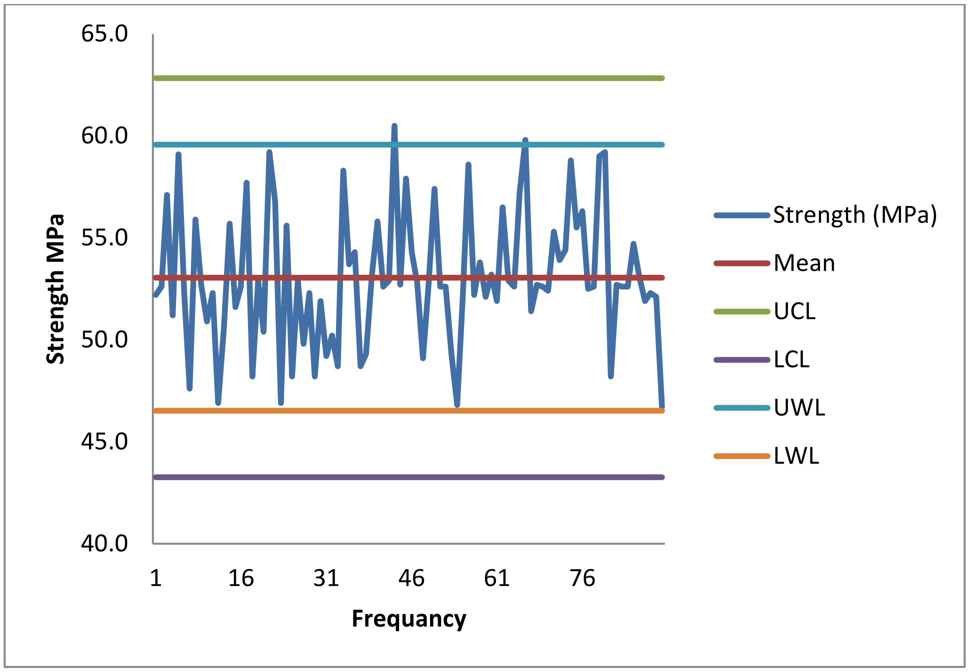


Figure (4.34): chart 28 day test using slag Cement 42.5N

The chart shows that the process was in control through the entire period.

4.4.5Concrete Class 70/85

- **For 7day test using Ordinary Portland Cement 52.5N**

Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.35) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$

$$UCL = 65.8 + 3 \times 4.6 = 79.7 N/mm^2$$

$$LCL = TMS - 3 \times \sigma$$

$$LCL = 65.8 - 3 \times 4.6 = 52.3 N/mm^2$$

$$UWL = TMS + 2 \times \sigma$$

$$UWL = 65.8 + 2 \times 4.6 = 75.2 N/mm^2$$

$$LWL = TMS - 2 \times \sigma$$

$$LWL = 65.8 - 2 \times 4.6 = 56.8 N/mm^2$$

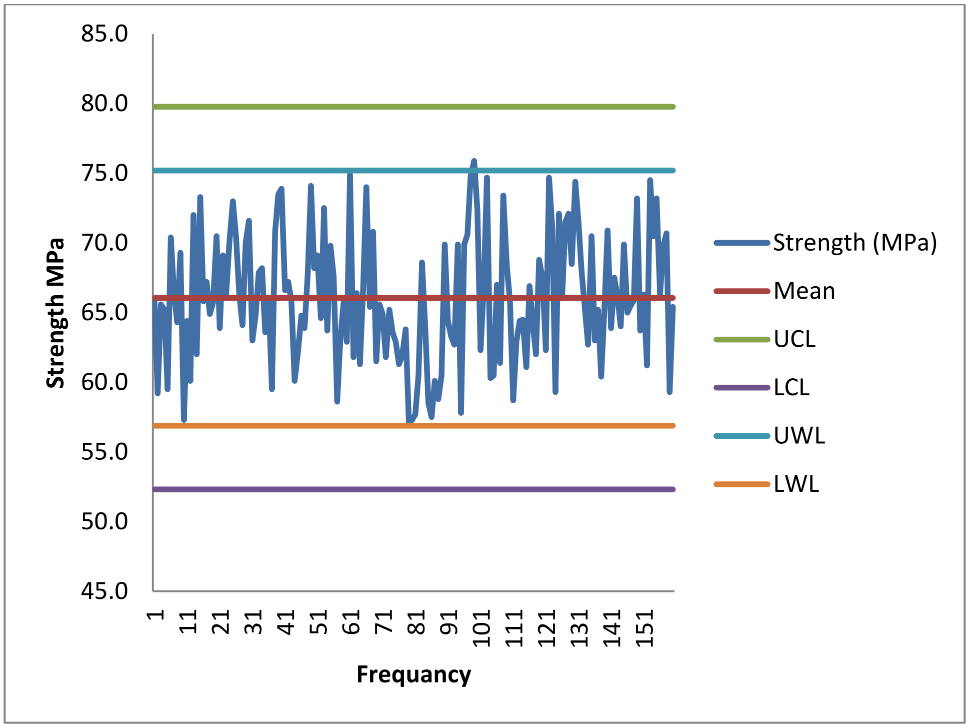


Figure (4.35): chart 7day test using Ordinary Portland Cement 52.5N

The chart shows that the process was in control through the entire period.

- **For 28day test using Ordinary Portland Cement 52.5N**
  Calculating the limits from the equations stated in chapter two and then the chart is drawn figure (4.36) according to the calculated limits.

$$UCL = TMS + 3 \times \sigma$$

$$UCL = 88.4 + 3 \times 3.9 = 100.2 N/mm^2$$

$$LCL = TMS - 3 \times \sigma$$

$$LCL = 88.4 - 3 \times 3.9 = 76.6 N/mm^2$$

$$UWL = TMS + 2 \times \sigma$$

$$UWL = 88.4 + 2 \times 3.9 = 96.2 N/mm^2$$

$$LWL = TMS - 2 \times \sigma$$

$$LWL = 88.4 - 2 \times 3.9 = 80.5 N/mm^2$$

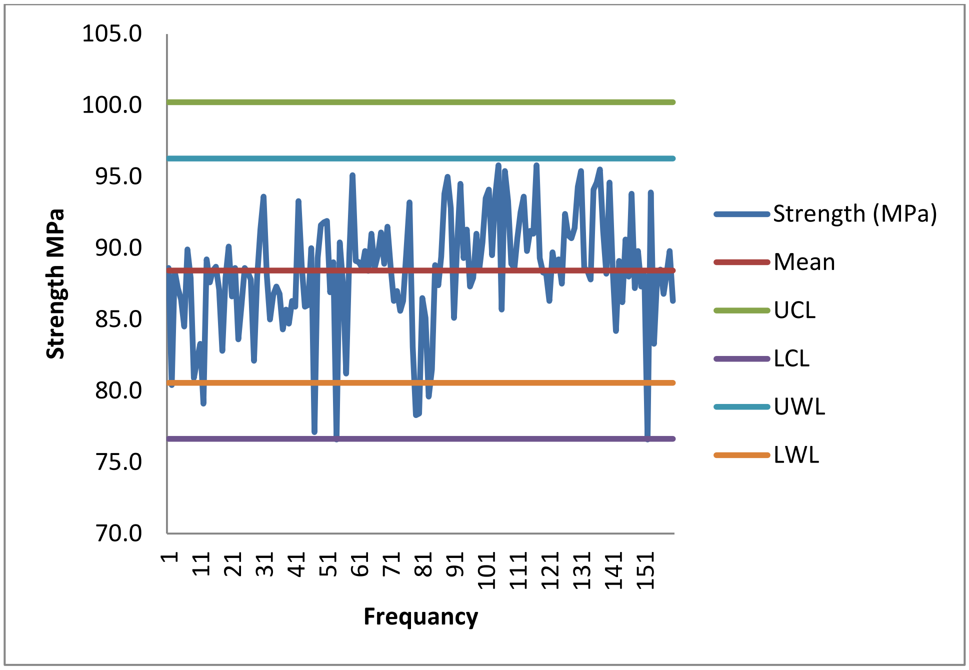


Figure (4.36): chart 28 day test using Ordinary Portland Cement 52.5N

The chart shows that the process was out of control for several points through the entire period.

Chapter Five
Conclusions and Recommendations

5.1 Introduction

The main objective of this research is to evaluate the quality of the concrete produced in Dam Complex of Upper Atbara Project through measuring the concrete compressive strength test result conducted at the above mentioned project. The measured results were collected, classified and analyzed mainly to assess the compatibility of the quality of concrete used in DCUAP with some international standard methods of quality evaluation; ACI codes, BS-EN codes and shewhart charts.

5.2 Conclusions

The following conclusions were obtained after implementing the mentioned above international standard methods to the collected strength data:

1. It is clear that, after applying the ACI and BS technique for determining the degree of quality, the best quality level was achieved when the slag cement was used.
2. In general the degree of quality varies between very good and good through the entire period of the project for the different classes of concrete with the exception of very excellent quality level for concrete class 12/15 with slag cement used at the age of 7 day and poor for class 20/25 with ordinary Portland cement 52.5N used at the age of 28 day.
3. Applying shewhart charts to the strength data collected shows that, the production control of the concrete is non-uniform and vary through the different stages of the project.
4. Shewhart charts indicate that the process for most of the concrete classes was out of control through the earlier stage of the project and went down to be controlled for the rest of the period with some exceptions, this can clearly be seen for class 12/15 charts.

5. Shewhart charts also show that, most of the control breaks occur for the UWL and UCL which is unacceptable from an economic point of view.

5.3 Recommendations

The following recommendations were obtained based on the results and findings of this study.

1. With the fact that the slag cement was introduced at later stage of DCUAP, further investigations are needed to find whether the improvement in the degree of quality comes with the use of the mentioned cement type or it was due to other reasons.
2. More studies also are needed, to reveal the deficiencies in the process of concrete production at DCUAP in order to increase the level of quality from good, fair and poor to excellent in the upcoming projects.
3. It is also recommended to increase the awareness concerned with the general knowledge of the quality control process to improve the uniformity of the concrete produced.
4. More studies and tests to be executed at earlier stage of any projects are also recommended in order to avoided been out of control at that stage of any project.
5. From the point number 5 in the conclusion, it is clear that adapting the concept of quality control is recommended in order to reduce the expenses in the construction industry.

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Appendices

Table (A1) Concrete Mixes used at DCUAP

S/NO	Mix Design No.	Strength Class	Cement Type &Class	Max Aggregate Size(mm)	Concrete Type	Design Flow (mm) / Slump (cm)	Admixture Type	Admixture Dosage %	Expansive Agent (HME-III) Type	Expansive Agent (HME-III) Dosage %	Silica Fume %	Fly Ash %	W/(C+P) ACI211	S.C %	Materials Required per 1 m^3 Concrete (Kg): Water	Cement	Silica Fume	HME-III	PCA(I) / MF2000	SR(Ⅰ)	Fly Ash	Crushed Sand	5-16 mm	16-32 mm	5-12.5mm	Accelerating Agent(SBT®-NT)
1	TPC-01-01	C12/15	Thatta OPC 42.5N	32	Pump	15 ± 2.5	PCA(I)	1.00	/	/	/	25	0.52	44	155	225	/	/	3.0	/	75	825	420	630	/	/
2	PPC-3-4	C20/25	Y.Feng OPC 42.5N	32	Pump	450~520	PCA(I)	1.00	/	/	/	30	0.46	40	158	240	/	/	3.42	0.68	102	736	552	552	/	/
3	TPC-3-1	C20/25	Thatta OPC 42.5N	32	Pump	450~520	PCA(I)	1.00	/	/	/	30	0.46	40	158	240	/	/	3.42	0.68	102	736	552	552	/	/
4	TPC-4-3	C25/30	Thatta OPC 42.5N	32	Pump	450~520	PCA(I)	1.00	/	/	/	25	0.40	38	150	281	/	/	3.75	0.75	94	694	453	679	/	/
5	SPC-4	C25/30	Sharjah Slag	32	Pump	450~520	PCA(I)	1.00	/	/	/	/	0.46	40	165	359	/	/	3.59	0.72	/	727	545	545	/	/
6	PPC-6-4	C35/45	Y.Feng OPC 52.5N	16	Pump	600-700	PCA(I)	1.00	HME-Ⅲ	10	/	25	0.38	45	172	317	/	45	4.53	0.91	91	776	949	/	/	/
7	PAC-1-31	C70/85	Y.Feng OPC 52.5N	16	Pump	420~530	PCA(I)	1.60	/	/	8	12	0.25	36	155	496	50	/	9.92	1.24	74	567	1008	/	/	/
8	SPC-16	C25/30	Sharjah Slag	16	Pump	450~520	PCA(I)	0.80	/	/	/	/	0.47	40	186	396	/	/	3.17	0.79	/	727	1091	/	/	/
9	SPC-20	C25/30	Sharjah Slag	32	Pump	450~520	PCA(I)	1.00	/	/	/	/	0.48	40	165	344	/	/	3.44	0.69	/	749	561	561	/	/
10	SPC-21	C20/25	Sharjah Slag	32	Pump	450~520	MegaFlow 2000	0.50	/	/	/	/	0.54	40	160	296	/	/	1.48	0.296	/	757	568	568	/	/
11	SPC-23	C25/30	Sharjah Slag	32	Pump	450~520	MegaFlow 2000	0.50	/	/	/	/	0.46	39	160	348	/	/	1.74	0.348	/	718	562	562	/	/
12	SPC-17	C20/25	Sharjah Slag	16	Pump	500 ± 50	PCA(I)	1.00	HME-Ⅲ	8	/	/	0.52	40	186	329	/	29	3.58	0.658	/	742	1114	/	/	/
13	SPC-26	C20/25	Sharjah Slag	16	Pump	650 ± 50	PCA(I)	1.20	/	/	/	/	0.52	42	195	375	/	/	4.50	/	/	769	1061	/	/	/
14	PPC-4-74	C25/30	Thatta OPC 42.5N	32	Pump	450~520	PCA(I)	1.00	/	/	/	25	0.42	41	158	282	/	/	2.63	0.75	94	766	550	550	/	/
15	SPC-1-1	C12/15	Sharjah Slag	32	Pump	450~520	PCA(I)	1.00	/	/	/	/	0.68	43	172	253	/	/	2.53	0.51	/	815	540	540	/	/
16	SPC-3-15	C20/25	Sharjah Slag	16	Pump	450~520	PCA(I)	1.00	/	/	/	/	0.54	42	173	320	/	/	3.20	0.64	/	776	1071	/	/	/
17	SPC-5-1	C25/30	Sharjah Slag	16	Pump	450~520	PCA(I)	1.00	/	/	/	/	0.47	41	173	368	/	/	3.68	0.74	/	736	1061	/	/	/
18	SPC-6-1	C35/45	Sharjah Slag	16	Pump	600-700	PCA(I)	1.00	HME-Ⅲ	8.00	/	/	0.38	44	190	460	/	40	5.00	1.00	/	726	924	/	/	/
19	SPC-8-9	C35/45	Sharjah Slag	16	Pump	450-520	PCA(I)	1.00	/	/	/	/	0.34	39	168	494	/	/	4.94	0.99	/	658	1030	/	/	/
20	S-10	C25/30	Sharjah Slag	12.5	Pump	120-180	PCA(I)	1.00	/	/	/	/	0.44	70	220	500	/	/	5.00	/	/	1071	/	/	459	25
21	PARC-1-8	C70/85	Y.Feng OPC 52.5N	16	Pump	420~530	Megaflow2000	1.00	/	/	8	10	0.25	39	138	453	44	/	5.52(MEGA2000)	/	55	644	1006	/	/	2.76(VE)

Table (A2) Class 12/15 compressive strength test result when OPC is used

Sample No.	Class	Mix Design No	Cement Type	Sampling Date	Testing Date		Strength 7day (MPa)	Strength 28 day (MPa)
1	C12/15	PPC-1	OPC 42.5N	8-Oct-11	15-Oct-11	5-ov-11	19.8	31.0
2	C12/15	C15-32--L	OPC 42.5N	19-Oct-11	26-Oct-11	16-Nov-11	20.7	30.2
3	C12/15	C15-32--L	OPC 42.5N	23-Oct-11	30-Oct-11	20-Nov-11	20.1	32.2
4	C12/15	PPC-1	OPC 42.5N	25-Oct-11	1-Nov-11	22-Nov-11	19.1	30.9
5	C12/15	C15-32--L	OPC 42.5N	1-Nov-11	8-Nov-11	29-Nov-11	13.4	22.5
6	C12/15	PPC-1	OPC 42.5N	5-Nov-11	12-Nov-11	3-Dec-11	20.7	31.2
7	C12/15	PPC-1	OPC 42.5N	8-Nov-11	15-Nov-11	6-Dec-11	13.0	22.8
8	C12/15	PPC-1	OPC 42.5N	9-Nov-11	16-Nov-11	7-Dec-11	13.7	23.1
9	C12/15	C15-32--L	OPC 42.5N	10-Nov-11	17-Nov-11	8-Dec-11	15.3	24.6
10	C12/15	PPC-1-27	OPC 42.5N	24-Nov-11	1-Dec-11	22-Dec-11	15.9	32.0
11	C12/15	PPC-1-27	OPC 42.5N	22-Dec-11	29-Dec-11	19-Jan-12	17.3	27.9
12	C12/15	PPC-1-27	OPC 42.5N	31-Dec-11	7-Jan-12	28-Jan-12	21.8	35.0
13	C12/15	PPC-1-27	OPC 42.5N	12-Jan-12	19-Jan-12	9-Feb-12	21.9	37.5
14	C12/15	PPC-1-27	OPC 42.5N	16-Jan-12	23-Jan-12	13-Feb-12	22.1	35.3
15	C12/15	PPC-1	OPC 42.5N	21-Jan-12	28-Jan-12	18-Feb-12	14.5	27.4
16	C12/15	PPC-1-27	OPC 42.5N	21-Jan-12	28-Jan-12	18-Feb-12	20.9	33.5
17	C12/15	PPC-1	OPC 42.5N	26-Jan-12	2-Feb-12	23-Feb-12	19.1	30.6
18	C12/15	PPC-1-27	OPC 42.5N	29-Jan-12	5-Feb-12	26-Feb-12	20.7	30.4
19	C12/15	PPC-1	OPC 42.5N	1-Feb-12	8-Feb-12	29-Feb-12	13.3	30.5
20	C12/15	PPC-1	OPC 42.5N	4-Feb-12	11-Feb-12	3-Mar-12	18.5	31.7
21	C12/15	PPC-1	OPC 42.5N	8-Feb-12	15-Feb-12	7-Mar-12	15.6	28.2
22	C12/15	PPC-1	OPC 42.5N	10-Feb-12	17-Feb-12	9-Mar-12	15.0	29.1
23	C12/15	PPC-1	OPC 42.5N	11-Feb-12	18-Feb-12	10-Mar-12	19.2	23.6
24	C12/15	PPC-1	OPC 42.5N	14-Feb-12	21-Feb-12	13-Mar-12	16.5	27.1
25	C12/15	PPC-1	OPC 42.5N	19-Feb-12	26-Feb-12	18-Mar-12	21.2	35.1
26	C12/15	PPC-1	OPC 42.5N	21-Feb-12	28-Feb-12	20-Mar-12	15.0	34.8
27	C12/15	PPC-1-27	OPC 42.5N	26-Feb-12	4-Mar-12	25-Mar-12	20.5	31.0
28	C12/15	PPC-1-27	OPC 42.5N	26-Feb-12	4-Mar-12	25-Mar-12	26.8	33.6
29	C12/15	PPC-1	OPC 42.5N	28-Feb-12	6-Mar-12	27-Mar-12	18.5	35.6
30	C12/15	PPC-1-27	OPC 42.5N	7-Mar-12	14-Mar-12	4-Apr-12	20.4	31.6
31	C12/15	PPC-1	OPC 42.5N	8-Mar-12	15-Mar-12	5-Apr-12	22.0	34.6
32	C12/15	PPC-1	OPC 42.5N	12-Mar-12	19-Mar-12	9-Apr-12	17.4	34.1
33	C12/15	PPC-1	OPC 42.5N	16-Mar-12	23-Mar-12	13-Apr-12	21.4	25.7
34	C12/15	PPC-2-10	OPC 42.5N	16-Mar-12	23-Mar-12	13-Apr-12	20.0	37.0
35	C12/15	PPC-2-10	OPC 42.5N	16-Mar-12	23-Mar-12	13-Apr-12	20.0	36.9
36	C12/15	PPC-1	OPC 42.5N	22-Mar-12	29-Mar-12	19-Apr-12	21.9	33.5
37	C12/15	PPC-1	OPC 42.5N	27-Mar-12	3-Apr-12	24-Apr-12	23.3	36.0
38	C12/15	PPC-1	OPC 42.5N	28-Mar-12	4-Apr-12	25-Apr-12	24.6	34.4
39	C12/15	PPC-1	OPC 42.5N	30-Mar-12	6-Apr-12	27-Apr-12	23.8	27.7
40	C12/15	PPC-1	OPC 42.5N	30-Mar-12	6-Apr-12	27-Apr-12	20.2	30.6
41	C12/15	PPC-1	OPC 42.5N	2-Apr-12	9-Apr-12	30-Apr-12	21.4	35.4
42	C12/15	PPC-1-27	OPC 42.5N	4-Apr-12	11-Apr-12	2-May-12	25.9	30.4
43	C12/15	PPC-1	OPC 42.5N	5-Apr-12	12-Apr-12	3-May-12	24.1	36.9
44	C12/15	PPC-1	OPC 42.5N	7-Apr-12	14-Apr-12	5-May-12	18.0	31.0
45	C12/15	PPC-1	OPC 42.5N	7-Apr-12	14-Apr-12	5-May-12	19.5	30.9
46	C12/15	PPC-1-27	OPC 42.5N	8-Apr-12	15-Apr-12	6-May-12	20.8	32.1
47	C12/15	PPC-1-27	OPC 42.5N	12-Apr-12	19-Apr-12	10-May-12	14.4	26.1
48	C12/15	PPC-1-27	OPC 42.5N	13-Apr-12	20-Apr-12	11-May-12	16.8	31.1
49	C12/15	PPC-1	OPC 42.5N	14-Apr-12	21-Apr-12	12-May-12	21.9	30.2
50	C12/15	PPC-1-27	OPC 42.5N	16-Apr-12	23-Apr-12	14-May-12	23.3	36.0
51	C12/15	PPC-1	OPC 42.5N	17-Apr-12	24-Apr-12	15-May-12	21.3	27.2
52	C12/15	PPC-1	OPC 42.5N	18-Apr-12	25-Apr-12	16-May-12	23.8	35.9
53	C12/15	PPC-1	OPC 42.5N	18-Apr-12	25-Apr-12	16-May-12	23.1	31.2
54	C12/15	PPC-1	OPC 42.5N	20-Apr-12	27-Apr-12	18-May-12	26.9	36.7

55	C12/15	PPC-1-27	OPC 42.5N	21-Apr-12	28-Apr-12	19-May-12	17.8	32.1
56	C12/15	PPC-1	OPC 42.5N	22-Apr-12	29-Apr-12	20-May-12	20.9	34.5
57	C12/15	PPC-1	OPC 42.5N	22-Apr-12	29-Apr-12	20-May-12	22.5	33.7
58	C12/15	PPC-1-27	OPC 42.5N	24-Apr-12	1-May-12	22-May-12	21.1	33.3
59	C12/15	PPC-1-27	OPC 42.5N	25-Apr-12	2-May-12	23-May-12	15.9	32.0
60	C12/15	TPC-3	OPC 42.5N	26-Apr-12	3-May-12	24-May-12	15.9	26.8
61	C12/15	TPC-1	OPC 42.5N	27-Apr-12	4-May-12	25-May-12	18.3	25.9
62	C12/15	TPC-1	OPC 42.5N	28-Apr-12	5-May-12	26-May-12	15.7	29.6
63	C12/15	PPC-1-27	OPC 42.5N	30-Apr-12	7-May-12	28-May-12	16.6	27.6
64	C12/15	PPC-1-27	OPC 42.5N	5-May-12	12-May-12	2-Jun-12	15.8	28.4
65	C12/15	TPC-1	OPC 42.5N	6-May-12	13-May-12	3-Jun-12	18.3	30.0
66	C12/15	TPC-1	OPC 42.5N	6-May-12	13-May-12	3-Jun-12	13.1	24.2
67	C12/15	TPC-1	OPC 42.5N	8-May-12	15-May-12	5-Jun-12	21.1	31.5
68	C12/15	PPC-1-27	OPC 42.5N	12-May-12	19-May-12	9-Jun-12	15.7	29.3
69	C12/15	TPC-1	OPC 42.5N	19-May-12	26-May-12	16-Jun-12	14.9	21.8
70	C12/15	TPC-1	OPC 42.5N	21-May-12	28-May-12	18-Jun-12	13.8	25.2
71	C12/15	TPC-1	OPC 42.5N	22-May-12	29-May-12	19-Jun-12	13.7	25.7
72	C12/15	PPC-1	OPC 42.5N	29-May-12	5-Jun-12	26-Jun-12	14.9	30.0
73	C12/15	TPC-1	OPC 42.5N	6-Jun-12	13-Jun-12	4-Jul-12	14.5	28.7
74	C12/15	PPC-1	OPC 42.5N	10-Jun-12	17-Jun-12	8-Jul-12	23.5	36.5
75	C12/15	PPC-1	OPC 42.5N	12-Jun-12	19-Jun-12	10-Jul-12	23.2	34.6
76	C12/15	PPC-1-27	OPC 42.5N	12-Jun-12	19-Jun-12	10-Jul-12	20.3	30.9
77	C12/15	PPC-1	OPC 42.5N	16-Jun-12	23-Jun-12	14-Jul-12	18.6	29.7
78	C12/15	PPC-1-27	OPC 42.5N	17-Jun-12	24-Jun-12	15-Jul-12	22.8	31.0
79	C12/15	PPC-1-27	OPC 42.5N	18-Jun-12	25-Jun-12	16-Jul-12	23.0	32.6
80	C12/15	PPC-1-27	OPC 42.5N	20-Jun-12	27-Jun-12	18-Jul-12	22.9	34.2
81	C12/15	TPC-1	OPC 42.5N	21-Jun-12	28-Jun-12	19-Jul-12	20.0	26.6
82	C12/15	PPC-1-27	OPC 42.5N	21-Jun-12	28-Jun-12	19-Jul-12	22.0	36.9
83	C12/15	PPC-1-27	OPC 42.5N	21-Jun-12	28-Jun-12	19-Jul-12	21.0	30.5
84	C12/15	TPC-1	OPC 42.5N	22-Jun-12	29-Jun-12	20-Jul-12	20.0	28.4
85	C12/15	PPC-1	OPC 42.5N	23-Jun-12	30-Jun-12	21-Jul-12	23.7	28.4
86	C12/15	PPC-1	OPC 42.5N	25-Jun-12	2-Jul-12	23-Jul-12	19.9	31.3
87	C12/15	PPC-1	OPC 42.5N	26-Jun-12	3-Jul-12	24-Jul-12	20.0	31.0
88	C12/15	PPC-1-27	OPC 42.5N	27-Jun-12	4-Jul-12	25-Jul-12	28.5	35.8
89	C12/15	PPC-1	OPC 42.5N	30-Jun-12	7-Jul-12	28-Jul-12	21.3	34.1
90	C12/15	PPC-1-27	OPC 42.5N	30-Jun-12	7-Jul-12	28-Jul-12	23.8	34.8
91	C12/15	PPC-1	OPC 42.5N	1-Jul-12	8-Jul-12	29-Jul-12	20.4	31.9
92	C12/15	PPC-1-27	OPC 42.5N	1-Jul-12	8-Jul-12	29-Jul-12	20.2	31.7
93	C12/15	PPC-1	OPC 42.5N	2-Jul-12	9-Jul-12	30-Jul-12	18.6	32.3
94	C12/15	PPC-1	OPC 42.5N	4-Jul-12	11-Jul-12	1-Aug-12	18.2	34.4
95	C12/15	PPC-1	OPC 42.5N	7-Jul-12	14-Jul-12	4-Aug-12	23.0	31.1
96	C12/15	PPC-1-27	OPC 42.5N	8-Jul-12	15-Jul-12	5-Aug-12	24.4	29.5
97	C12/15	PPC-1	OPC 42.5N	9-Jul-12	16-Jul-12	6-Aug-12	20.5	27.3
98	C12/15	PPC-1	OPC 42.5N	10-Jul-12	17-Jul-12	7-Aug-12	23.4	32.5
99	C12/15	PPC-1-27	OPC 42.5N	10-Jul-12	17-Jul-12	7-Aug-12	23.1	35.7
100	C12/15	PPC-1-27	OPC 42.5N	13-Jul-12	20-Jul-12	10-Aug-12	24.8	33.1
101	C12/15	PPC-1-27	OPC 42.5N	13-Jul-12	20-Jul-12	10-Aug-12	23.3	37.5
102	C12/15	TPC-1	OPC 42.5N	15-Jul-12	22-Jul-12	12-Aug-12	23.8	32.3
103	C12/15	PPC-1	OPC 42.5N	15-Jul-12	22-Jul-12	12-Aug-12	22.8	37.1
104	C12/15	TPC-1	OPC 42.5N	17-Jul-12	24-Jul-12	14-Aug-12	24.8	31.4
105	C12/15	PPC-1-27	OPC 42.5N	17-Jul-12	24-Jul-12	14-Aug-12	30.3	29.8
106	C12/15	PPC-1	OPC 42.5N	27-Jul-12	3-Aug-12	24-Aug-12	17.0	33.8
107	C12/15	PPC-1-27	OPC 42.5N	2-Sep-12	9-Sep-12	30-Sep-12	16.8	34.9
108	C12/15	PPC-1-27	OPC 42.5N	2-Sep-12	9-Sep-12	30-Sep-12	15.6	33.8
109	C12/15	PPC-1-27	OPC 42.5N	18-Sep-12	25-Sep-12	16-Oct-12	25.0	30.4
110	C12/15	PPC-1-27	OPC 42.5N	24-Sep-12	1-Oct-12	22-Oct-12	23.1	35.8
111	C12/15	PPC-1-27	OPC 42.5N	1-Oct-12	8-Oct-12	29-Oct-12	15.5	31.0
112	C12/15	PPC-1-27	OPC 42.5N	1-Oct-12	8-Oct-12	29-Oct-12	24.0	31.8
113	C12/15	PPC-1-27	OPC 42.5N	4-Oct-12	11-Oct-12	1-Nov-12	22.4	30.7
114	C12/15	TPC-1	OPC 42.5N	8-Oct-12	15-Oct-12	5-Nov-12	25.1	36.7

115	C12/15	PPC-1-27	OPC 42.5N	8-Oct-12	15-Oct-12	5-Nov-12	29.4	31.2
116	C12/15	PPC-1-27	OPC 42.5N	8-Oct-12	15-Oct-12	5-Nov-12	21.1	31.5
117	C12/15	PPC-1-27	OPC 42.5N	10-Oct-12	17-Oct-12	7-Nov-12	28.4	31.0
118	C12/15	PPC-1-27	OPC 42.5N	21-Oct-12	28-Oct-12	18-Nov-12	28.9	30.9
119	C12/15	PPC-1-27	OPC 42.5N	23-Oct-12	30-Oct-12	20-Nov-12	29.6	36.9
120	C12/15	PPC-1-27	OPC 42.5N	23-Oct-12	30-Oct-12	20-Nov-12	22.7	30.4
121	C12/15	PPC-1-27	OPC 42.5N	23-Oct-12	30-Oct-12	20-Nov-12	25.9	30.5
122	C12/15	TPC-1	OPC 42.5N	25-Oct-12	1-Nov-12	22-Nov-12	20.3	31.8
123	C12/15	TPC-1	OPC 42.5N	25-Oct-12	1-Nov-12	22-Nov-12	20.4	31.2
124	C12/15	PPC-1-27	OPC 42.5N	29-Oct-12	5-Nov-12	26-Nov-12	17.9	33.5
125	C12/15	PPC-1-27	OPC 42.5N	7-Nov-12	14-Nov-12	5-Dec-12	25.3	37.5
126	C12/15	PPC-1-27	OPC 42.5N	16-Nov-12	23-Nov-12	14-Dec-12	21.2	36.8
127	C12/15	TPC-1	OPC 42.5N	25-Nov-12	2-Dec-12	23-Dec-12	27.6	26.4
128	C12/15	PPC-1-27	OPC 42.5N	10-Dec-12	17-Dec-12	7-Jan-13	16.8	32.3
129	C12/15	PPC-1-27	OPC 42.5N	23-Dec-12	30-Dec-12	20-Jan-13	18.6	32.7
130	C12/15	PPC-1-27	OPC 42.5N	31-Dec-12	7-Jan-13	28-Jan-13	21.2	29.1
131	C12/15	PPC-1	OPC 42.5N	2-Jan-13	9-Jan-13	30-Jan-13	22.3	30.1
132	C12/15	PPC-1	OPC 42.5N	26-Jan-13	2-Feb-13	23-Feb-13	21.2	31.5
133	C12/15	PPC-1	OPC 42.5N	31-Jan-13	7-Feb-13	28-Feb-13	28.2	37.1
134	C12/15	PPC-1	OPC 42.5N	5-Mar-13	12-Mar-13	2-Apr-13	26.8	30.2
135	C12/15	PPC-1-35	OPC 42.5N	26-Jan-15	2-Feb-15	23-Feb-15	17.5	24.5
136	C12/15	PPC-1-35	OPC 42.5N	2-Feb-15	9-Feb-15	2-Mar-15	17.4	24.4
137	C12/15	PPC-1-35	OPC 42.5N	3-Feb-15	10-Feb-15	3-Mar-15	19.7	31.4
138	C12/15	PPC-1-35	OPC 42.5N	26-Feb-15	5-Mar-15	26-Mar-15	17.3	22.4
139	C12/15	PPC-1-35	OPC 42.5N	5-May-15	12-May-15	2-Jun-15	19.9	30.0
140	C12/15	PPC-1-35	OPC 42.5N	14-May-15	21-May-15	11-Jun-15	17.1	24.9
141	C12/15	PPC-1-35	OPC 42.5N	18-May-15	25-May-15	15-Jun-15	21.0	31.2
142	C12/15	PPC-1-35	OPC 42.5N	21-May-15	28-May-15	18-Jun-15	18.2	28.8
143	C12/15	PPC-1-35	OPC 42.5N	3-Jul-15	10-Jul-15	31-Jul-15	20.1	22.9
144	C12/15	PPC-1-35	OPC 42.5N	12-Jul-15	19-Jul-15	9-Aug-15	14.9	30.0
145	C12/15	PPC-1-35	OPC 42.5N	24-Jul-15	31-Jul-15	21-Aug-15	20.1	31.8
146	C12/15	PPC-1-35	OPC 42.5N	10-Aug-15	17-Aug-15	7-Sep-15	14.7	24.2
147	C12/15	PPC-1-35	OPC 42.5N	14-Aug-15	21-Aug-15	11-Sep-15	19.9	31.9
148	C12/15	PPC-1-35	OPC 42.5N	5-Sep-15	12-Sep-15	3-Oct-15	14.8	22.8
149	C12/15	PPC-1-35	OPC 42.5N	10-Sep-15	17-Sep-15	8-Oct-15	14.7	25.6
150	C12/15	PPC-1-31	OPC 42.5N	29-Oct-15	5-Nov-15	26-Nov-15	19.0	22.4
151	C12/15	PPC-1-35	OPC 42.5N	3-Nov-15	10-Nov-15	1-Dec-15	19.6	23.4
152	C12/15	PPC-1-35	OPC 42.5N	13-Dec-15	20-Dec-15	10-Jan-16	21.1	30.2
Average							**20.3**	**30.9**
Standard Deviation							**3.85955**	**3.88204**
Maximum Strength							**30.3**	**37.5**
Minimum Strength							**13.0**	**21.8**

Table (A3) Class 35/45 compressive strength test result when Slag Cement was used

Sample No.	Class	Mix Design No	Cement type	Sampling Date	Testing Date		Strength 7day (MPa)	Strength2 8day (MPa)
1	C35/45	SPC-6-1	Slag 42.5N	21-Mar-13	28-Mar-13	18-Apr-13	35.6	52.2
2	C35/45	SPC-6-1	Slag 42.5N	26-Mar-13	2-Apr-13	23-Apr-13	35.5	52.6
3	C35/45	SPC-6-1	Slag 42.5N	28-Mar-13	4-Apr-13	25-Apr-13	38.9	57.1
4	C35/45	SPC-6-1	Slag 42.5N	30-Mar-13	6-Apr-13	27-Apr-13	33.2	51.2
5	C35/45	SPC-6-1	Slag 42.5N	3-Apr-13	10-Apr-13	1-May-13	28.6	59.1
6	C35/45	SPC-6-1	Slag 42.5N	8-Apr-13	15-Apr-13	6-May-13	35.0	52.3
7	C35/45	SPC-6-1	Slag 42.5N	17-Oct-13	24-Oct-13	14-Nov-13	31.2	47.6
8	C35/45	SPC-6-1	Slag 42.5N	21-Oct-13	28-Oct-13	18-Nov-13	34.7	55.9
9	C35/45	SPC-6-1	Slag 42.5N	29-Oct-13	5-Nov-13	26-Nov-13	31.4	52.7
10	C35/45	SPC-6-1	Slag 42.5N	2-Nov-13	9-Nov-13	30-Nov-13	31.9	50.9
11	C35/45	SPC-6-1	Slag 42.5N	23-Dec-13	30-Dec-13	20-Jan-14	33.5	52.3
12	C35/45	SPC-6-1	Slag 42.5N	30-Dec-13	6-Jan-14	27-Jan-14	39.1	46.9
13	C35/45	SPC-6-1	Slag 42.5N	11-Feb-14	18-Feb-14	11-Mar-14	28.2	50.6
14	C35/45	SPC-6-1	Slag 42.5N	17-Feb-14	24-Feb-14	17-Mar-14	35.0	55.7
15	C35/45	SPC-6-1	Slag 42.5N	8-Mar-14	15-Mar-14	5-Apr-14	29.6	51.6
16	C35/45	SPC-6-1	Slag 42.5N	23-Mar-14	30-Mar-14	20-Apr-14	36.5	52.6
17	C35/45	SPC-8-9	Slag 42.5N	6-Apr-14	13-Apr-14	4-May-14	37.1	57.7
18	C35/45	SPC-6-1	Slag 42.5N	7-Apr-14	14-Apr-14	5-May-14	39.3	48.2
19	C35/45	SPC-6-1	Slag 42.5N	9-Apr-14	16-Apr-14	7-May-14	40.5	52.9
20	C35/45	SPC-6-1	Slag 42.5N	16-Apr-14	23-Apr-14	14-May-14	32.5	50.4
21	C35/45	SPC-6-1	Slag 42.5N	17-Apr-14	24-Apr-14	15-May-14	40.6	59.2
22	C35/45	SPC-6-1	Slag 42.5N	18-Apr-14	25-Apr-14	16-May-14	40.6	56.8
23	C35/45	SPC-6-1	Slag 42.5N	18-Apr-14	25-Apr-14	16-May-14	40.1	46.9
24	C35/45	SPC-6-1	Slag 42.5N	19-Apr-14	26-Apr-14	17-May-14	40.8	55.6
25	C35/45	SPC-6-1	Slag 42.5N	23-Apr-14	30-Apr-14	21-May-14	32.1	48.2
26	C35/45	SPC-6-1	Slag 42.5N	24-Apr-14	1-May-14	22-May-14	36.2	52.9
27	C35/45	SPC-6-1	Slag 42.5N	27-Apr-14	4-May-14	25-May-14	31.0	49.8
28	C35/45	SPC-6-1	Slag 42.5N	28-Apr-14	5-May-14	26-May-14	35.9	52.3
29	C35/45	SPC-6-1	Slag 42.5N	30-Apr-14	7-May-14	28-May-14	35.8	48.2
30	C35/45	SPC-6-1	Slag 42.5N	4-May-14	11-May-14	1-Jun-14	36.7	51.9
31	C35/45	SPC-6-1	Slag 42.5N	5-May-14	12-May-14	2-Jun-14	30.2	49.2
32	C35/45	SPC-6-1	Slag 42.5N	6-May-14	13-May-14	3-Jun-14	32.8	50.2
33	C35/45	SPC-6-1	Slag 42.5N	7-May-14	14-May-14	4-Jun-14	29.1	48.7
34	C35/45	SPC-6-1	Slag 42.5N	12-May-14	19-May-14	9-Jun-14	36.7	58.3
35	C35/45	SPC-6-1	Slag 42.5N	19-May-14	26-May-14	16-Jun-14	40.9	53.7
36	C35/45	SPC-6-1	Slag 42.5N	24-May-14	31-May-14	21-Jun-14	38.4	54.3
37	C35/45	SPC-6-1	Slag 42.5N	24-May-14	31-May-14	21-Jun-14	27.6	48.7
38	C35/45	SPC-6-1	Slag 42.5N	29-May-14	5-Jun-14	26-Jun-14	33.6	49.3
39	C35/45	SPC-6-1	Slag 42.5N	9-Jun-14	16-Jun-14	7-Jul-14	36.5	53.1
40	C35/45	SPC-6-1	Slag 42.5N	10-Jun-14	17-Jun-14	8-Jul-14	42.5	55.8
41	C35/45	SPC-6-1	Slag 42.5N	15-Jun-14	22-Jun-14	13-Jul-14	36.0	52.6
42	C35/45	SPC-6-1	Slag 42.5N	16-Jun-14	23-Jun-14	14-Jul-14	37.1	52.9
43	C35/45	SPC-6-1	Slag 42.5N	23-Jun-14	30-Jun-14	21-Jul-14	40.4	60.5
44	C35/45	SPC-6-1	Slag 42.5N	25-Jun-14	2-Jul-14	23-Jul-14	35.8	52.7
45	C35/45	SPC-6-1	Slag 42.5N	1-Jul-14	8-Jul-14	29-Jul-14	40.8	57.9
46	C35/45	SPC-6-1	Slag 42.5N	1-Jul-14	8-Jul-14	29-Jul-14	39.2	54.3
47	C35/45	SPC-6-1	Slag 42.5N	1-Jul-14	8-Jul-14	29-Jul-14	36.8	52.8
48	C35/45	SPC-6-1	Slag 42.5N	3-Jul-14	10-Jul-14	31-Jul-14	37.2	49.1
49	C35/45	SPC-6-1	Slag 42.5N	5-Jul-14	12-Jul-14	2-Aug-14	42.0	52.8
50	C35/45	SPC-6-1	Slag 42.5N	10-Jul-14	17-Jul-14	7-Aug-14	40.2	57.4
51	C35/45	SPC-6-1	Slag 42.5N	24-Oct-14	31-Oct-14	21-Nov-14	36.9	52.6
52	C35/45	SPC-6-1	Slag 42.5N	2-Nov-14	9-Nov-14	30-Nov-14	34.4	52.6
53	C35/45	SPC-6-1	Slag 42.5N	8-Nov-14	15-Nov-14	6-Dec-14	34.4	49.3
54	C35/45	SPC-6-1	Slag 42.5N	11-Nov-14	18-Nov-14	9-Dec-14	39.7	46.8
55	C35/45	SPC-6-1	Slag 42.5N	18-Nov-14	25-Nov-14	16-Dec-14	36.1	52.3

56	C35/45	SPC-6-1	Slag 42.5N	18-Nov-14	25-Nov-14	16-Dec-14	40.2	58.6
57	C35/45	SPC-6-1	Slag 42.5N	18-Nov-14	25-Nov-14	16-Dec-14	37.1	52.2
58	C35/45	SPC-6-1	Slag 42.5N	18-Nov-14	25-Nov-14	16-Dec-14	41.3	53.8
59	C35/45	SPC-6-1	Slag 42.5N	21-Nov-14	28-Nov-14	19-Dec-14	34.9	52.1
60	C35/45	SPC-6-1	Slag 42.5N	21-Nov-14	28-Nov-14	19-Dec-14	36.6	53.2
61	C35/45	SPC-6-1	Slag 42.5N	22-Nov-14	29-Nov-14	20-Dec-14	36.9	51.9
62	C35/45	SPC-6-1	Slag 42.5N	22-Nov-14	29-Nov-14	20-Dec-14	41.2	56.5
63	C35/45	SPC-6-1	Slag 42.5N	22-Nov-14	29-Nov-14	20-Dec-14	41.7	52.9
64	C35/45	SPC-6-1	Slag 42.5N	23-Nov-14	30-Nov-14	21-Dec-14	37.9	52.6
65	C35/45	SPC-6-1	Slag 42.5N	24-Nov-14	1-Dec-14	22-Dec-14	40.4	57.2
66	C35/45	SPC-6-1	Slag 42.5N	29-Nov-14	6-Dec-14	27-Dec-14	39.7	59.8
67	C35/45	SPC-6-1	Slag 42.5N	1-Dec-14	8-Dec-14	29-Dec-14	34.1	51.4
68	C35/45	SPC-6-1	Slag 42.5N	2-Dec-14	9-Dec-14	30-Dec-14	36.5	52.7
69	C35/45	SPC-6-1	Slag 42.5N	3-Dec-14	10-Dec-14	31-Dec-14	35.2	52.6
70	C35/45	SPC-6-1	Slag 42.5N	4-Dec-14	11-Dec-14	1-Jan-15	36.2	52.4
71	C35/45	SPC-6-1	Slag 42.5N	4-Dec-14	11-Dec-14	1-Jan-15	40.7	55.3
72	C35/45	SPC-6-1	Slag 42.5N	7-Dec-14	14-Dec-14	4-Jan-15	41.3	53.9
73	C35/45	SPC-6-1	Slag 42.5N	7-Dec-14	14-Dec-14	4-Jan-15	37.8	54.4
74	C35/45	SPC-6-1	Slag 42.5N	8-Dec-14	15-Dec-14	5-Jan-15	39.2	58.8
75	C35/45	SPC-6-1	Slag 42.5N	9-Dec-14	16-Dec-14	6-Jan-15	34.8	55.5
76	C35/45	SPC-6-1	Slag 42.5N	10-Dec-14	17-Dec-14	7-Jan-15	38.7	56.3
77	C35/45	SPC-6-1	Slag 42.5N	11-Dec-14	18-Dec-14	8-Jan-15	37.8	52.5
78	C35/45	SPC-6-1	Slag 42.5N	11-Dec-14	18-Dec-14	8-Jan-15	40.9	52.6
79	C35/45	SPC-6-1	Slag 42.5N	12-Dec-14	19-Dec-14	9-Jan-15	42.4	59.0
80	C35/45	SPC-6-1	Slag 42.5N	15-Dec-14	22-Dec-14	12-Jan-15	40.4	59.2
81	C35/45	SPC-6-1	Slag 42.5N	17-Dec-14	24-Dec-14	14-Jan-15	37.7	48.2
82	C35/45	SPC-8-9	Slag 42.5N	26-Nov-15	3-Dec-15	24-Dec-15	31.7	52.7
83	C35/45	SPC-6-1	Slag 42.5N	28-Feb-16	6-Mar-16	27-Mar-16	36.4	52.6
84	C35/45	SPC-6-1	Slag 42.5N	5-Mar-16	12-Mar-16	2-Apr-16	36.4	52.6
85	C35/45	SPC-6-1	Slag 42.5N	6-Mar-16	13-Mar-16	3-Apr-16	28.6	54.7
86	C35/45(SCC	PPC-6-1-1	Slag 42.5N	21-May-16	28-May-16	18-Jun-16	35.1	53.1
87	C35/45(SCC	PPC-6-1-1	Slag 42.5N	22-May-16	29-May-16	19-Jun-16	36.9	51.9
88	C35/45(SCC	PPC-6-1-1	Slag 42.5N	19-Jun-16	26-Jun-16	17-Jul-16	36.5	52.3
89	C35/45(SCC	SPC-6-1-1	Slag 42.5N	1-Jul-16	8-Jul-16	29-Jul-16	36.2	52.1
90	C35/45(SCC	PPC-6-1-1	Slag 42.5N	19-Jul-16	26-Jul-16	16-Aug-16	29.1	46.7
Average							36.5	53.1
Standard Deviation							3.6648	3.26143
Maximum Strength							27.6	46.7
Minimum Strength							42.5	60.5