Sudan University of Science and Technology

College of Graduate Studies

School of civil Engineering

MSc. In Construction Engineering

Production of High Strength Concrete
أنتاج الخرسانة عالية المقاومة

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

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....

....

...صيل . وباختياري أعطي حقوق طبع ونشر هذا العمل لكلية الدراسات العليا - جامعة السودان

... عليه يحق للجامعة نشر هذا العمل للأغراض العلمية .

الآية

بسم الله الرحمن الرحيم

{قَالَ يَا قَوْمِ أَرَأَيْتُمْ إِنْ كُنْتُ عَلَى بَيِّنَةٍ مِنْ رَبِّي وَرَزَقَنِي مِنْهُ رِزْقاً حَسَناً وَمَا أُرِيدُ أَنْ أُخَالِفَكُمْ إِلَى مَا أَنْهَاكُمْ عَنْهُ إِنْ أُرِيدُ إِلَّا الْإِصْلاحَ مَا اسْتَطَعْتُ وَمَا تَوْفِيقِي إِلَّا بِاللَّهِ عَلَيْهِ تَوَكَّلْتُ وَإِلَيْهِ أُنِيبُ}

صدق الله العظيم

سورة هود الآية (88)

Dedication

To my mother, my father and my sister for their support and guidance.

To my wife for her patience during the many hours in
writing, editing, and refining the research.

To my daughter Menn and my son Ahmed.

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I would like to thank all those people who have assisted me throughout the preparation and completion of this thesis. In particular, First and foremost, I wish to extend my gratitude and appreciation to my supervisors, Prof. Dr. Salih Elhadi Moh-Ahmed, who have guided and advised me from the very beginning of the research up to the completion of this dissertation. Their willingness to help expand my knowledge and expertise is deeply appreciated.

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Abstract

The aim of this study was to evaluate the performance of high strength concretes (HSC) containing supplementary cementitious materials. Now a days concrete had demanding requirements both in terms technical performance and economy. The main aim of the investigation program is first to prepare the strength of concrete of grade M80 with locally available ingredients and then to study the effects of different proportions of silica fume and silica fume in conjunction with fly ash in the mix and to find optimum range of silica fume and fly ash content in the mix. The silica fume and fly ash is added by weight of cement as a replacement. The concrete specimens were tested at different age levels,7-days and 28-days for mechanical properties of concrete, namely, cube compressive strength, and length change due to drying shrinkage tests also fresh concrete properties, using slump test has been made.

This research presents a part of an ongoing experimental laboratory investigation being carried out for production and characterization of high strength concrete (HSC) for heightening of an existing concrete dam in the south of Sudan, brief description of the main features of the dam and concrete works is presented. Hundreds of specimens were performed and tested using local Sudanese aggregates with addition of supplementary cementitious materials (Silica Fume and Fly Ash) and super plasticizers. Various percentages of silica fume (SF) and fly ash (FA) were added at different water/cementitious materials ratios (w/cm). Thirty three trial mix design of grade (80 MPa) HSC had been success fully produced and their mechanical properties were measured and documented. Two approaches were used in the study statistical approach which described in ACI 211.4 and another one is use JMP statistical program to make a modeling for predicting Compressive Strength and Slump for HSC.

The results have offered an important insight for optimizing the rheological characteristics of HSC and permitted to develop guidelines for optimum mix design methods for HSC from locally available aggregates in Sudan. Optimum w/cm ratio it ranges from 0.19 to 0.3. Optimum replacement percentage of SF is not a constant one but depends on the w/cm ratio of the mix it ranges between7 to 15% of cementitious materials. SF contributed to both short and long-term properties of concrete. It is concluded that local concrete materials, in combination with supplementary cementitious materials can be utilized in producing high strength concrete in Sudan.

مستخلص

الهدف من هذه الدراسة هو تقييم أداء الخرسانة عالية المقاومة التي تحتوي على المواد الأسمنتية التكميلية. فى هذه الايام الخرسانة مطالبة بمتطلبات فنية من حيث الأداء الفني والاقتصادى. الهدف الرئيسي من البحث هو ،أولاً انتاج خرسانة عالية المقاومة من الصنف 80 ميجا باسكال مع المكونات المتوفرة محليا ومن ثم دراسة آثار نسب مختلفة من غبار السيليكا وغبار السيليكا بالتزامن مع الرماد المتطاير في الخلطة الخرسانية وإيجاد المدى الأمثل من نسب غبار السيليكا و الرماد المتطاير في مزيج الخلطة الخرسانية. تم اختبار العينات الخرسانية على مستوى مختلف الأعمار(7أيام و28 يوم) للخواص الميكانيكية للخرسانة،تم أختبار مكعبات قوة الضغط.

يعرض هذا البحث جزء من التحقيق المختبرى التجريبي المستمر الذى يجري تنفيذه لإنتاج الخرسانة عالية المقاومة (HSC) لتعلية سد خرسانى موجود في جنوب السودان. ويرد وصف موجز من السمات الرئيسية من السد والأعمال الخرسانية. أجريت مئات العينات وتم إختبارها باستخدام الركام السودانى المحلى مع اضافة المواد الأسمنتية التكميلية (غبار السيليكا والرماد المتطاير) والملدنات المتقدمة. تمت إضافة نسب مختلفة من غبار السيليكا (SF) والرماد المتطاير (FA) مع نسب مختلفة من الماء /المواد الإسمنتية (w/cm). ثلاثة وثلاثين محاولة للخلطة الخرسانية للصنف (80 ميجا باسكال) أختبرت وتم قياس خواصها الميكانيكية وتوثيقها. تم أستخدام نهجين فى الدراسة الاول هو النموذج الاحصائى الذى وصف فى المدونة الامزيكية ACI 211.4 والثانى هو استخدام برنامج JMP الاحصائى وعمل نموذج لتوقع قوة الضغط وقابلية التشغيل.

وعرضت النتائج فكرة هامة لتحقيق الاستفادة المثلى من الريولوجية خصائص الخرسانة عالية المقاومة وسمحت لوضع مبادئ توجيهية لأساليب تصميم المزيج الأمثل للخرسانة عالية المقاومة من الركام المتاح محليا في السودان. كما سلط الضوء على تأثير نسبة (w/cm) على قوة الخرسانة عالية المقاومة وجدت النسبة المثلى 0.19 الى0.3 . نسبة الاستبدال المثلى لغبار السيلكا7% الى 15% من المواد الأسمنتية, ساهم غبار السليكا فى كل من خصائص الخرسانة قصيرة وطويلة الأجل. وخلص إلى أن المواد الخرسانية المحلية، إلى جانب المواد الأسمنتية التكميلية يمكن أن تستخدم في إنتاج الخرسانة عالية المقاومة في السودان.

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List of Abbreviations

ACI	American Concrete Institute
AEA	Air-entraining admixture
ASTM	American Society for Testing and Materials
BSI	British Standards Institute
CH	Calcium hydroxide
DIU	Dams implementation unit
FA	Fly Ash
HRWR	High-range water-reducing chemical admixture
HSC	High Strength Concrete
HPC	High Performance Concrete
JMP	Means jump, name of software
MLS	modified lignosulfonate
RSM	Response surface methodology
SCC	Self consolidating concrete
SCM	Supplementary cementitious material
SF	Silica Fume
SMF	sulfonated melamine–formaldehyde
SNF	sulfonated naphthalene–formaldehyde
SSD	Saturated surface dry condition
w/b	Water-binder (ratio)
W/cm	Water-cementious materials (ratio)

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CHAPTER ONE

INTRODUCTION

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INTRODUCTION

1.1General

High strength concrete is a relatively recent development in concrete technology made possibly by the introduction of efficient water-reducing admixtures and high strength cementitious materials. This thesis will discuss the materials technology underlying the development of high strength concrete, examining the selection of optimum constituent materials and considering the concrete mix design. The properties of both fresh and hardened high strength concrete will be discussed; finally, the production of high strength concrete, illustrated by trial mixes and two approaches will be examined. It is intended that this will lead to an understanding of the potential benefits and limitations of high strength concrete, together with the experience required to produce and use the material in a practical and effective manner.(18)

This thesis presents a part of an ongoing experimental laboratory investigation being carried out for production and characterization of high strength concrete for heightening of Roseires Dam, which, located on Blue Nile River in Sudan, was constructed in 1960s for power generation and irrigation purposes. It has been decided to heighten this composite concrete buttress and earth fill dam by 10m to increase its storage capacity.

The raising works of Roseires concrete dam comprise the addition of mass concrete, reinforced concrete, and post-tensioning requirements into both crest and the downstream portions of the dam. The concrete dam section is divided into 11 typical structures along its 1km length. The total numbers were 69 buttresses. Because each structure has its specific geometry and function different design methodologies are needed for each.

When considering high strength concrete one must first define what is meant by ‘ high strength ’ the perception of what level of compressive strength constitutes. ‘High strength ’ has been continually revised upwards over the past 20 years or so, and may be continued to rise in the near future. A simple definition for ‘High strength ’ would be ‘ concrete with a compressive strength greater than that covered by current codes and standards ’ . In the UK this would include concrete with a characteristic compressive strength of 60 MPa or more. [(1)] In USA concrete with a characteristic compressive strength of 55 MPa or more is considered to be a high strength concrete, but this is not a fixed level and may change with a time.

High-strength concrete mix proportioning is a more critical process than the design of normal strength concrete mixtures. Usually, specially selected pozzolanic and chemical admixtures are employed, and the attainment of a low water-cementitious ratio is considered essential. Many trial batches are often required to generate the data that enables the researcher to identify optimum mix proportions. [(4)]

There is no “scientific” method for proportioning. This means that there is no chart that can be used to derive the mixture ingredients to meet a specified level of performance. There are simply too many variables for such a chart to be developed. Here are some general rules for proportioning: [(26)]

Prescriptive specifications, means specify concrete mixture proportions to be used for all similar projects. This procedure may cause differences in performance from project to project because the performance of silica-fume concrete very much depends upon the interaction of the specific materials used. In this case one should follow the prescriptive proportions and test to verify that acceptable hardened concrete properties are achieved.

If the specification is performance based, one should remember that local materials will determine the final mixture performance. It should not be assumed that a mixture that was developed and used elsewhere will provide the same results when local materials are used. Mixtures used elsewhere are excellent starting points, but the influence of project materials on the results obtained must be determined. For a performance specification, time should not be wasted in developing a mixture if the project materials have not yet been identified. [26]

Tests should be done at both the laboratory and production scale during mixture development. The process is too complex to predict what the outcome will be without appropriate testing. A plenty of time should be allowed for the necessary testing. [26]

Finally, following the procedure described in the ACI 211.4. This procedure has evolved over many years and is the best recommendation currently available. [1]

Another approach is to use JMP statistical software program, response surface designs were used for modeling a curved quadratic surface to continuous factors, these factors and its ranges by kg/m^3 are present in table

(1), to modeling and predicting compressive strength and workability for high strength concrete depending on the test results.

Both methods need many of trial mixes design , cubes and slump test results for mix optimization.

Hence the purpose of this thesis was to study the potentiality and possibility of use Sudanese aggregate with supplementary cementitious materials silica fume and fly ash in high strength concrete mixes, and to study the effect of concrete ingredients on compressive strength, workability and cost of high strength concrete. It is also aimed to make a statistical modeling to predict compressive strength and workability of high strength concrete.

1.2Significance of the Study

There are some parts of many huge projects like dams, tall buildings and bridges were required high strength concrete, HSC, many applications of HSC have already been reported. Further growth on a much wider scale is anticipated in the near future because it offers cost efficient solutions to many structural design problems.

This section will provide brief description on the various significances of the study given on two categories, technological and economic. The proposed study serves the managers as their reference or guide. to engineers. The proposed study will help Engineers to have a deeper understanding to the high strength concrete. By this study they will come up with easier and powerful design of high strength concrete and production in Sudan. To future researcher, the proposed study will benefits and help the future researcher as their guide. The study can also open in development of this study.

1.3 Objectives of the Study

This research deals with HSC production, materials and the direct technical and economical benefits. To achieve the target of this research, the following specific objectives are proposed:-

1. The main aim of the investigation program is first to prepare the Strength of concrete of grade 80 MPa or grater with locally available ingredients.
2. To make a modeling to predicts concrete compressive strength and workability.
3. To investigate the effects of various replacement levels of silica fume, fly ash (class F) and silica fume and water- cementitious materials ratio on compressive strength and concrete properties.
4. To investigate the relationship between compressive strength and drying shrinkage for HSC.

1.4 Thesis questions and hypothesis

It is hypothesized that, if supplementary cementitious materials (silica fume and fly ash, class F) with local aggregate were used in concrete and special techniques like that described in ACI211.4-R-8were used, then can we obtain high strength concrete, grade 80 MPa and above or not?

1.5Statements of the problem

The purpose of this research was to produce high strength concrete by using local Sudanese aggregate with supplementary cementitious materials and investigate the use of statistical approach in concrete mixture proportioning. In many cases, the products are, like concrete, combinations of several components. Typically, these applications optimize a product to meet a number of performance criteria (user-specified constraints) simultaneously, at minimum cost. For concrete, these performance criteria could include fresh concrete properties such as viscosity and unit weight; mechanical properties such as strength.

The general approach to concrete mixture proportioning can be described by the following steps:

1. Identifying a starting set of mixture proportions.
2. Performing one or more trial batches, starting with the mixture identified in step 1 above, and adjusting the proportions in subsequent trial batches until all criteria are satisfied.

Current practice in the United States for developing new concrete mixtures often relies upon using historical information (i.e., what has worked for the producer in the past) or guidelines for mixture proportioning outlined in American Concrete Institute (ACI) 211.1. Following the ACI 211.1 guidelines, an engineer would select and run a first trial batch (selecting proportions using ACI 211.1 or historical data), evaluate the results, adjust the proportions of various components, and run further trial batches until all specified criteria are met. Typically, this is performed by varying one component at a time. While both historical information and ACI 211.1 can yield a starting point for trial batches, neither method is a comprehensive procedure for optimizing mixtures.

Trial batches are then carried out, test specimens are fabricated and tested, and results are analyzed using standard statistical methods. These methods include fitting empirical models to the data for each performance criterion. In these models, each response (resultant concrete property) such as strength, slump, or cost, is expressed as an algebraic function of factors (individual component proportions) such as w/cm, cement content, chemical admixture dosage, and percent of supplementary cementitious materials.

1.6 Thesis Methodology

The proposed methodology of the data collecting and analysis is as follow:-

1. Collecting adequate information about the basic science of HSC.

2. Collecting adequate information about HSC special materials and their mechanism of work, HSC special production techniques, properties of HSC concrete and its mix design guideline procedures and proportions.

3. Conducted experimental laboratory investigation, hundreds specimens had been carried out for production and characterization of high strength concrete (HSC) for heightening of an existing concrete dam in the south of Sudan, Thirty three of trial mixes were performed and tested using local Sudanese aggregates with addition of supplementary cementitious materials (Silica Fume and Fly Ash) and Super plasticizers. Various percentages of Silica Fume (SF) and Fly

Ash (FA) were added at different water/cementitious (w/cm) ratios.

4. Using the results of step 3 to present the optimum mix design of HSC. And present the relationship between strength and w/cm ratio, strength and sand content and relationship between 7 days and 28 days compressive strength of HSC. Estimated the cost for each trial mixes, and making comparative cost assessment, using different concrete strength alternatives. JMP software statistical program was used.
5. Drawing relevant conclusion and recommendations.

1.7Thesis organization

This thesis has been organized as follow:-

Chapter one is introduction, the definition of high strength concrete and general keys affecting regards to producing high strength concrete, special consideration to the factors affecting concrete strength and mix design are discussed and HSC special materials and their mechanism of work. This is the content of chapter (2).HSC special production techniques, HSC mix design procedures and proportions are discussed. This is the content of chapter (3).Statements of the research problem ,explain the purpose of the study, how to produce high strength concrete by using local Sudanese aggregate with supplementary cementitious materials and investigate the use of statistical approach in concrete mixture proportioning manually and JMP software program was used. This is the content of chapter (4).Result presentation and discussion, an evaluation of the performance of high strength concretes (HSC) containing supplementary cementitious materials, and the compressive strength result of concrete grade 80, 90 and 100MPa with locally available ingredients had been studied, the effects of different proportions of Silica fume and silica fume in conjunction with fly ash in the mixes and effects of different percentage of w/cm ratio and effects of different percentage of sand content and drawing a relationship between 7 days and 28 days compressive strength and cost estimation were conducted. This is the content of chapter (5). In the end of the study, the research summary and conclusions with recommendations for future researches are presented. This is the content of chapter (6).

CHAPTER TWO

LITERATURE REVIEW

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

2.1.1 Strength of concrete and high strength concrete

Strength of concrete is commonly considered its most valuable property, although, in many practical cases, other characteristics, such as durability and permeability, may in fact be more important. Nevertheless, strength usually gives an overall picture of the quality of concrete because strength is directly related to the structure of the hydrated cement paste. Moreover, the strength of concrete is almost invariably a vital element of structural design and is specified for compliance purposes. [6]

In this is chapter we are give the definition of high strength concrete and general keys affecting regards to producing high strength concrete, special consideration to the factors affecting concrete strength and mix design are discussed, proprieties related to high strength concrete and HSC special materials and their mechanism of work.

2.1.2 Mechanical strength of cement gel

There are two classical theories of hardening or development of strength of cement. That put forward by H. Le Chatelier in 1882 states that the products of hydration of cement have a lower solubility than the original compounds, so that the hydrates precipitate from a supersaturated solution. The precipitate is in the form of interlaced elongated crystals with high cohesive and adhesive properties.

The colloidal theory propounded by W. Michaëlis in 1893 states that the crystalline aluminate, sulfoaluminate and hydroxide of calcium give the initial strength. The lime-saturated water then attacks the silicates and forms a hydrated calcium silicate which, being almost insoluble, forms a gelatinous mass. This mass hardens gradually due to the loss of water either by external drying or by hydration of the inner unhydrated core of the cement grains: in this manner cohesion is obtained. [6]

2.1.3 High strength concrete

There are two fundamental distinctions between conventional-strength and high-strength concrete technology. First is the exchange in the relative strength and stiffness properties between paste and aggregate. On the low end of the strength spectrum, aggregate particles are bound by a weaker, more porous material. On the high end, aggregate particles are bound by a stronger, dense material. Going from conventional-strength to high strength concrete technology is tantamount to turning a composite material inside out. The second distinction centers on the properties of the interfacial transition zone. Bond strength and degree of stiffness compatibility between binder and aggregate is critically important with high-strength concrete. [22]

Being a two-component composite material consisting of paste and aggregate, it is understandable that the mechanical properties of concrete are highly dependent on the relative properties of these two materials. Overall, this and the manner in which bond at the interfacial transition zone is affected is probably the most important, but still underestimated characteristics influencing the service life of most concrete structures. Neville (1997) discusses how bond at the interfacial transition zone and modulus of elasticity are related, but nonetheless, treated separately. [22]

The definition of high-strength concrete is by no means static. Where high strength concrete has been defined in terms of a precise numerical value, its definition has changed over the years. In the 1984 version of ACI Committee Report 363R–92,4, 41 MPa (6,000 psi) was selected as a lower limit for high strength concrete. According to that report, although this value was selected as the lower limit, it was not intended to imply that any drastic change in material properties or production techniques occurs at this level of compressive strength. In reality, all of the gradual changes that take place represent a process that starts with very modest strength levels and continues well into the realm of ultra high-strength concrete. In the course of revising the 1992 version of the *State-of-the-Art of High-Strength Concrete* report, Committee 363 defined high-strength concrete as having a specified compressive strength for design of 55 MPa (8000) psi, or greater. Committee 363 also recognized that the definition of high-strength concrete varies on a geographical basis. The Committee recognized that material selection, concrete mix proportioning, batching, mixing, transporting, placing, curing, and quality control procedures are applicable across a wide range of concrete strengths. However, Committee 363 also agreed that material properties and structural design considerations addressed in the report should be concerned with concretes having the highest compressive strengths. [22]

European and UK standards for concrete define HPC as concrete that meets special performance and uniformity requirements that cannot always be achieved routinely by using only conventional materials and normal mixing, placing, and curing practices. The requirements may involve enhancements of characteristics such as placement and compaction without segregation, long-term mechanical properties, early-age strength, toughness, volume stability, or service life in severe environments. The term *high performance* could be attached to any type of concrete that exhibits fresh or hardened properties exceeding those of conventional concrete. In addition to high-strength concrete, other examples of high-performance concrete could include:

- flowing concrete;
- self consolidating concrete (SCC);
- lightweight concrete;
- heavyweight concrete;
- pervious (no-fines concrete);
- low permeability concrete; and
- shrinkage compensating concrete.

ACI provides the following definition and commentary:

High-performance concrete: Concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices.

A high-performance concrete is a concrete in which certain characteristics are developed for a particular application and environment. Examples of characteristics that may be considered critical for an application are:

- Ease of placement
- Compaction without segregation
- Early age strength
- Long-term mechanical properties
- Permeability
- Density
- Heat of hydration
- Toughness

• Volume stability

• Long life in severe environments

This following discussion is presented principally as a premise to providing definitions for the three strength-related terms that will be used most frequently in this thesis. They are:

• target strength;

• specified strength; and

• required average strength.

Target strength

Target strength simply refers to a desired level of measured strength at a given age, usually when evaluated under a standardized method of testing. It is important to recognize that target strength and design strength are unrelated terms.

Specified strength

Specified strength refers to a defined level of concrete compressive strength chosen by a code-recognized authority in the design of structures, when tested at a designated acceptance age, under standard testing conditions, and evaluated in accordance with the acceptance criteria of a legally adopted design code, such as ACI 318–05. For example, the specified compressive strength (f_c') for a series of columns in a tall building might be 70 MPa (10,000 psi) at 56 days.

Required average strength

The required average strength (f_{cr}') is the average compressive strength used as the basis for the selection of concrete proportions necessary to comply with the strength acceptance criteria of a legally adopted design code, such as ACI 318–05. If the measured strength of concrete equals or exceeds f_{cr}', there is a statistical probability of only about 1 in 100 that the concrete fails to comply with the following strength acceptance criteria:

• Every arithmetic average of any three consecutive strength tests equals or exceeds the specified compressive strength (f_c').

• No individual strength test (average of two cylinders) falls below f_c' by more than 0.10 f_c'.

2.1.3.1 Paste properties

In conventional concrete technology, the strength of the paste is a function of its water/ cement ratio. This is true also for high strength concrete but it is also the effect of the porosity within the paste, the particle size distribution of the crystalline phases and the presence of inhomogeneities within the hydrated paste that must be considered in detail. [18]

A reduction in water/cement ratio will produce a paste in which the cementitious particles are initially closer together in the freshly mixed concrete. This results in less capillary porosity in the hardened paste and hence a greater strength. This reduced capillary porosity also favours the formation of fine-textured hydration products that have a higher strength than the coarser equivalents. The capillary porosity can also be reduced by optimizing the particle size distribution of the cementitious materials in order to increase the potential packing density. Special high strength cements are available and the inclusion of finely divided reactive materials such as silica fume will also contribute to an increase in packing density and reduced capillary porosity. [18]

2.1.3.2 Transition zone properties

When fracture surfaces of failed conventional concretes are examined, it is often observed that the failure has occurred, either with the paste itself or, more often, at the interface between the paste and the coarse aggregate particles. Whilst it is possible to increase the strength of the paste significantly as described above, if the transition zone to the aggregate is weak, the strength of the concrete will not increase commensurately. In conventional (say, 40 MPa) concretes, this transition zone is quite large and is characterized by a high porosity and large crystalline hydration products (such as Portlandite Ca(OH)2). Reducing the water/paste ratio and the incorporation of silica fume into the concrete both contribute to reducing the width and improving the strength of the transition zone (Mindess et al., 1994). The rapid conversion of Ca(OH)2 to CSH by silica fume is thought to be of particular importance. Reduced bleeding within the paste also reduces the potential for accumulation of water around aggregate particles. [18]

2.1.3.3 Aggregate properties

When the transition zone between the paste and the aggregate is improved the transfer of stresses from the paste to the aggregate particles becomes more effective. Consequently the mechanical properties of the aggregate particles themselves may be the 'weakest link' leading to limitation of achievable concrete strength. Fracture surfaces in HSC often pass through aggregate particles rather than around them. [8]

Crushed rock aggregates are generally preferred to smooth gravels as there is some evidence that the strength of the transition zone is weakened by smooth aggregates (Aitcin and Mehta, 1990). The aggregate should have a high intrinsic strength and granites, basalts and limestones have been used successfully, as have crushed glacial gravels. [18]

2.2 Studies on High-Strength Concrete

Defining "high strength" in terms of a universally applicable numerical value is not possible, at least not with any sound degree of rationale. "High strength" is a relative term that is dependent on many things, such as the quality of locally available concreting materials and construction practices. High-strength concrete does not need to be defined in terms of one numerical value; however, at the end of this section, I present a range that most authorities might agree is a reasonable threshold for what would be considered “high-strength concrete,”.

Although high-strength concrete is often considered a relatively new material, its development has been gradual over many years. As the development has continued, the definition of high-strength concrete has changed. In the 1950s, concrete with a compressive strength of 5000 psi (34 MPa) was considered high strength. In the 1960s, concrete with 6000 and 7500 psi (41 and 52 MPa) compressive strengths were used commercially. In the early 1970s, 9000 psi (62 MPa) concrete was being produced. More recently, compressive strengths approaching 20,000 psi (138 MPa) have been used in cast-in-place buildings. [4]

For many years, concrete with compressive strength in excess of 6000 psi (41 MPa) was available at only a few locations. However, in recent years, the applications of high-strength concrete have increased, and high-strength concrete has now been used in many parts of the world. The growth has been possible as a result of recent developments in material technology and a demand for higher-strength concrete. The construction of Chicago’s Water Tower Place and 311 South Wacker Drive concrete buildings would not have been possible without the development of high-strength concrete. The use of concrete superstructures in long span cable-stayed bridges such as East Huntington, W.V., bridge over the Ohio River would not have taken place without the availability of high-strength concrete. [4]

Whilst a number of studies have considered the development of a rational or standardized method of concrete mix design for HSC (de Larrard, 1999; Mehta and Aitcin, 1990), no widely accepted method is currently available. The main requirements for successful and practical HSC are a low water/cement ratio combined with high workability and good workability retention characteristics. In the absence of a standard mix design method, the importance of trial mixes in achieving the desired concrete performance is increased.

The following factors should, however, be considered when designing a high strength concrete mix see Table (2.1):

*Table(2.1):*Commercial HSC mix designs from North America

	1	2	3	4	5
Cement(kg/m^3)	564	475	487	564	475
Fly Ash(kg/m^3)	-	59	-	-	104
Micro-silica(kg/m^3)	-	24	47	89	74
Coarse agg(kg/m^3)	1068	1068	1068	1068	1068
Fine agg(kg/m^3)	647	659	676	593	593
Water(L/m^3)	158	160	155	144	151
Superplasticizer (L/m^3)	11.61	11.61	11.22	20.12	16.45
Retarder(L/m^3)	1.12	1.04	0.97	1.47	1.51
w/c	0.281	0.287	0.291	0.22	0.231
90-day cylinder strength (MPa)	86.5	100.4	96.0	131.8	119.3

• The appropriate free water/cement ratio should be selected either from experience or by reference to published data. This will typically be in the range 0.25–0.30.

• The cement composition should be selected to maximize strength and other performance requirements. At its simplest this will be Portland cement blended with 5–10 per cent silica fume.

• Proportion coarse and fine aggregates to give a smooth overall grading curve in order to keep the water demand low. The proportion of fine aggregate is generally around 5 per cent lower (as a proportion of total aggregate) than for normal strength concrete. Care must be taken, however, not to make the mix too deficient in fine aggregate, particularly where the concrete is to be pumped.

• Use the saturation dosage of admixture (or admixtures), determined with a flow cone, to produce workability. It should be noted that most HSC is also high workability concrete, of, say, 600 mm flow table spread.

Trial mixes should be made and strength, workability and workability retention measured. Modifications can then be made to the mix to optimize the concrete's performance.

2.3Role of supplementary cementatious materials (scms) in High Strength Concrete

SCMs are materials that, when blended with portland cement, contribute to the properties of concrete through hydraulic activity, pozzolanic activity, or both (Kosmatka and Wilson 2011). Hydraulic activity occurs when phases in the SCM chemically react with water, forming cementitious hydration products similar to those formed through hydration of Portland cement. This is in contrast to pozzolanic activity, which is characterized by the reaction between siliceous or aluminosiliceous material in the SCM with calcium hydroxide (a reaction product from the hydration of Portland cement), forming calcium silicate hydrate and other cementitious compounds. Calcium silicate hydrate is a more desirable hydration product and thus the pozzolanic reaction is considered to have a positive impact on the long-term properties of the hardened concrete. Table (2. 2) summarizes properties of these common SCMs, noting that calcined clay, shale, and metakaolin are classified as Class N natural pozzolans. Tables (2.3) and (2.4) summarize how each SCM impacts the behavior of fresh and hardened concrete, respectively.

Table (2.2): Typical chemical compositions and select properties of common SCMs

	Type I cement	Class F fly ash	Class C fly ash	GGBF slag	Silica fume	Metakaolin
Silica (SiO_2) %	22	52	35	35	90	53
Alumina Al_2O_2) %	5	23	18	12	0.4	43
Iron oxide (Fe_2O_3) %	3.5	11	6	1	0.4	0.5
Calcium oxide (CaO) %	65	5	21	40	1.6	0.1
Sulfate (SO_4) %	1	0.8	4.1	9	0.4	0.1
Sodium oxide (Na_2O) %	0.2	1	5.8	0.3	0.5	0.05
Potassium oxide (K_2O) %	1	2	0.7	0.4	2.2	0.4
Total eq.alkali(as Na_2O) %	0.77	2.2	6.3	0.6	1.9	0.3
Loss on ignition %	0.2	2.8	0.5	1	3	0.7
Blaine fineness m^2/kg	350	420	420	400	20000	19000
Relative Density	3.15	2.38	2.65	2.94	2.4	2.5

Table (2.3): Effects of SCMs on the properties of fresh paving concrete

	Fly Ash		GGBF slag	Silica fume	Natural pozzolans		
	Class F	Class C			Calcined shale	Calcined clay	Metakaolin
Water requirements	⇊	⇊	↓	⇈	↔	↔	↑
Workability	↑	↑	↑	⇊	↑	↑	↓
Bleeding and segregation	⇊	↓	↕	⇊	↔	↔	↓
Air content	⇊	↓	↓	↔	↔	↔	↓
Heat of hydration	↓	↕	↓	↔	↓	↓	↓
Setting time	↑	↕	↑	↔ ↕	↑	↑	↔
Finishability	↑	↑	↑		↑	↑	↑
Pumpability	↑	↑	↑	↑	↑	↑	↑
Plastic shrinkage cracking	↔	↔	↔	↑	↔	↔	↔

Sources: Thomas and Wilson (2002)

Key	
↓	reduced
⇊	Significantly reduced
↑	increased
⇈	Significantly increased
↔	No Significantly change
↕	Effect varies

Table (2.4): Effects of SCMs on the properties of hardened paving concrete

	Fly Ash		GGBF slag	Silica fume	Natural pozzolans		
	Class F	Class C			Calcined shale	Calcined clay	Metakaolin
Early strength	↓	↔	↓	↑↑	↓	↓	↑↑
Long-term strength	↑	↑	↑	↑↑	↑	↑	↑↑
Permeability	↓	↓	↓	↓↓	↓	↓	↓↓
Chloride ingress	↓	↓	↓	↓↓	↓	↓	↓↓
ASR	↓↓	↕	↓↓	↓	↓	↓	↓
Sulfate resistance	↑↑	↕	↑↑	↑	↑	↑	↑
Freezing and thawing	↔	↔	↔	↔	↔	↔	↔
Abrasion resistance	↔	↔	↔	↔	↔	↔	↔
Drying shrinkage	↔	↔	↔	↔	↔	↔	↔

Sources: Thomas and Wilson (2002)

Key	
↓	reduced
↓↓	Significantly reduced
↑	increased
↑↑	Significantly increased
↔	No Significantly change
↕	Effect varies

2.4Principles of proportioning

A primary facet of high-strength concrete technology is that the empirical relationships best suited for determining the quantities of each constituent material is quite different than for conventional-strength concrete. The objectives of the proportioning process remain unchanged; however, the paths, or “principles” required to satisfy those objectives are often very different with high-strength concrete. For example, the size and quantity of coarse aggregate necessary to achieve optimum strength performance at a given age depends on the target strength under consideration. Common objectives include satisfying requirements for strength, durability consistency (slump or slump spread), pumpability, workability, or setting time. Less common, but equally important objectives, if necessary, might involve satisfying requirements for modulus of elasticity, creep, heat of hydration, or shrinkage. [22]

The various techniques of producing HSC are presented in Fig. 2.1

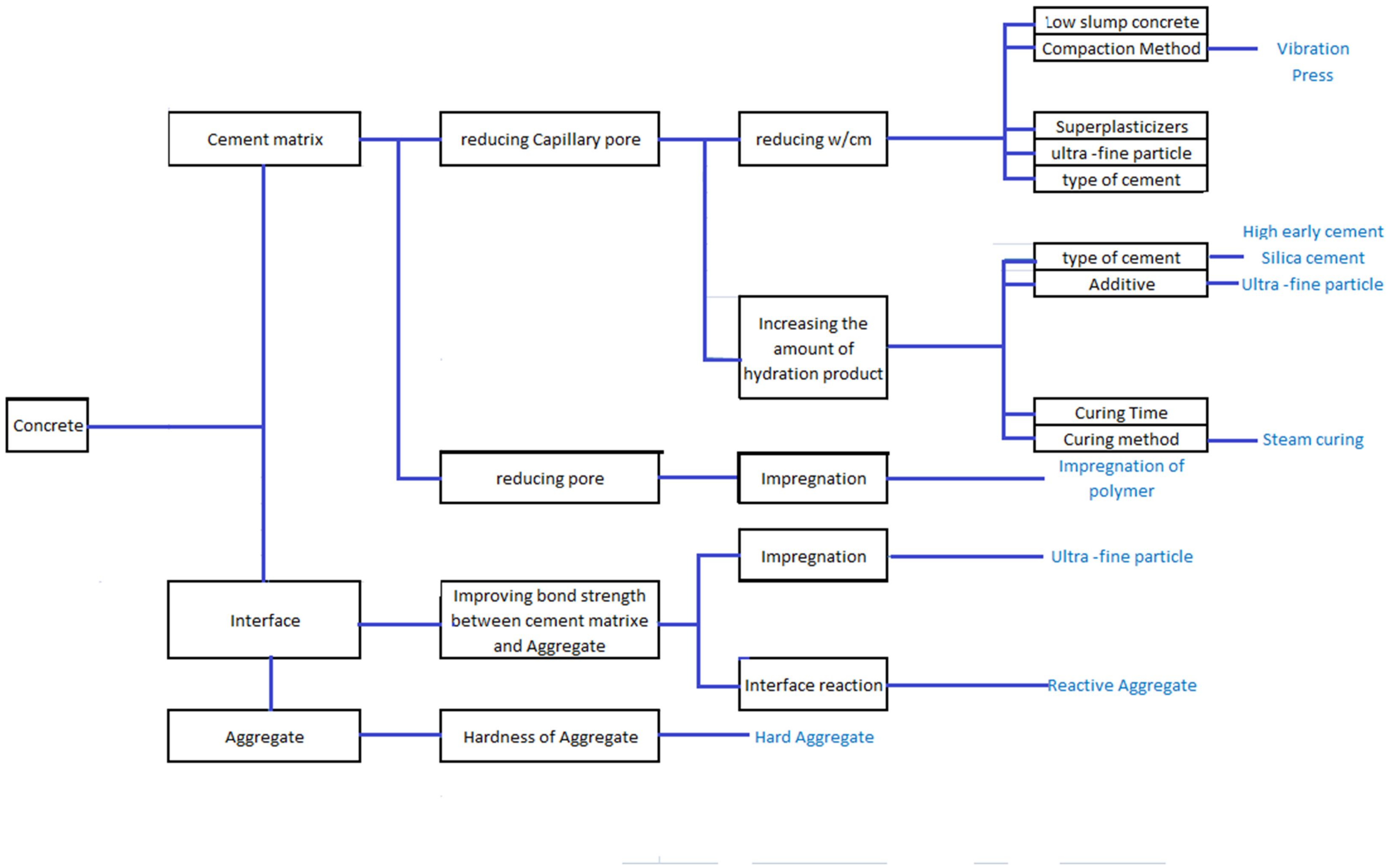


Figure (2-1) Techniques for attaining high strength in concrete (Nagataki and Sakai, 1994)

2.5 High Strength Concrete Proprieties

2.5.1 Stress-strain behavior in uniaxial compression

The stress–strain behavior of concrete is primarily influenced by the relative stiffness of the paste and aggregates, and the bond strength at the interfacial transition zone. All else equal, higher interfacial bond strength is achieved using rough as opposed to smooth textured aggregate. Therefore, for two coarse aggregates of the same size, shape, mineralogy, and stiffness, higher strength (and corresponding strain capacity) would be achieved using crushed stone compared to smooth gravel. [22]

Various investigators (Shah *et al.*, 1981, Jansen *et al.*, 1995) have reported higher strain capacities at maximum stress for high-strength compared to conventional-strength concretes. Curves representing typical stress–strain relationships for high, moderate, and conventional-strength concretes are shown in Figure (2.2).

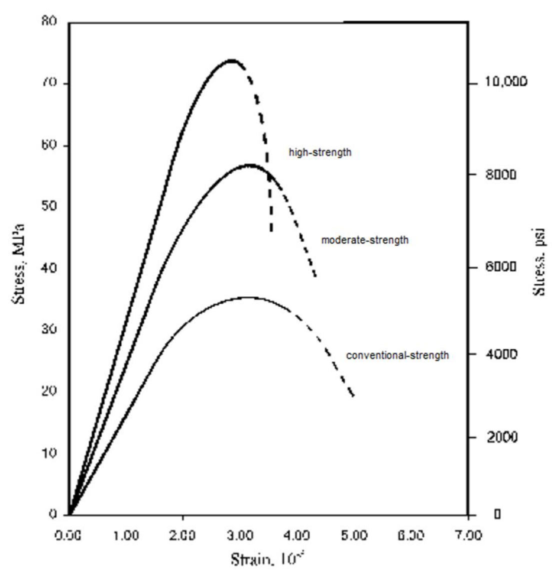


Figure (2.2)Typical stress–strain relationship for high-, moderate-, and conventional strength concrete.

2.5.2 Modulus of elasticity

Modulus of elasticity is defined as the ratio of normal stress to corresponding strain for tensile or compressive stresses below the proportional limit of a material. [22]

Thoman and Raede reported values for the modulus of elasticity determined as the slope of the tangent to the stress-strain curve in uniaxial compression at 25 percent of maximum stress from 4.2 x $l0^6$ to 5.2 x $l0^6$ psi (29 to 36 GPa) for concretes having compressive strengths ranging from (69 to 76 MPa).[22]

2.5.3 Poisson's ratio

Poisson's ratio under uniaxial loading conditions is defined as the ratio of transverse strain to the corresponding axial strain resulting from uniformly distributed axial stress below the proportional limit of the material. [12]

Experimental data on values of Poisson's ratio for high-strength concrete are very limited. Shideler and Carrasquillo reported values for Poisson's ratio of lightweight-aggregate high-strength concrete having uniaxial compressive strengths up to 10,570 psi (73 MPa) at 28 days to be 0.20 regardless of compressive strength, age, and moisture content. Values determined by the dynamic method were slightly higher. [4]

Based on the available information, Poisson's ratio of high-strength concrete in the elastic range seems comparable to the expected range of values for lower-strength concretes. [4]

2.5.4 Compressive strength

The strength of concrete depends on a number of factors, including the properties and proportions of the constituent materials, degree of hydration, rate of loading, method of testing and specimen geometry. The properties of the constituent materials that affect the strength are the quality of fine and coarse aggregate, the cement paste and the paste-aggregate bond at the interfacial transition, zone. These, in turn, depend on the macro and microscopic structural features including total porosity, pore size and shape, pore distribution and morphology of the hydration products, plus the bond between individual solid components. Testing conditions including age, rate of loading, method of testing, and specimen geometry, profoundly influence measured strength. [22]

The strength development characteristics of high-strength concrete are different from those of conventional-strength concrete. Tests by Wild *et al.* (1995) showed that high-strength concrete with a W/B ratio of 0.35 (without silica fume) had a 7-day compressive strength that averaged 86 percent of the 28-day strength when cured at 20°C (68°F). This same ratio for conventional-strength concrete was in the range 60 to 70 percent. When silica fume was added to the high-strength concrete in the range 12 to 28 percent mass fraction of cement, the average ratio of the 7-day to the 28-day strengths was 76 percent when cured at 20°C (68°F). When the curing temperature was increased to 50°C (122°F), this ratio increases significantly to 97 percent, indicating that high curing temperatures can be very beneficial to early strength development in silica-fume high-strength concrete (Meeks and Carino, 1999). Typically, strength gain in compression is much faster than strength gain in the transition zone bond. Changes in the strength of high-strength concrete over time are driven by two opposing factors— hydration and self-desiccation. Provided free moisture is available to unhydrated cementing particles, they will continue to form hydration products, and strength will continue to increase. Conversely, systems absent of free moisture may self-desiccate, in which case, measured strength over time could conceivably decrease. [22]

2.5.5 Tensile splitting strength

Dewar studied the relationship between the indirect tensile strength (cylinder splitting strength) and the compressive strength of concretes having compressive strengths of up to 12,105 psi (83.79 MPa) at 28 days. He concluded that at low strengths, the indirect tensile strength may be as high as 10 percent of the compressive strength but at higher strengths it may reduce to 5 percent. He observed that the tensile splitting strength was about 8 percent higher for crushed-rock-aggregate concrete than for gravel-aggregate concrete- In addition, he found that the indirect tensile strength was about 70 percent of the flexural strength at 28 days. The following equation for the prediction of the tensile splitting strength of normal weight concrete was recommended. [4]

$$f_{sp'} = 7.4\sqrt{f_c'}psi$$

For 3000psi $< f_c' <$ 12000 psi

$$f_{sp'} = 0.59\sqrt{f_c'}Mpa$$

For 21Mpa $< f_c' <$ 83Mpa……………………………………………...1.3

Figure(2.3) shows the non-linear exponential relation between the splitting tensile strength and the compressive strength of HSC.[25]

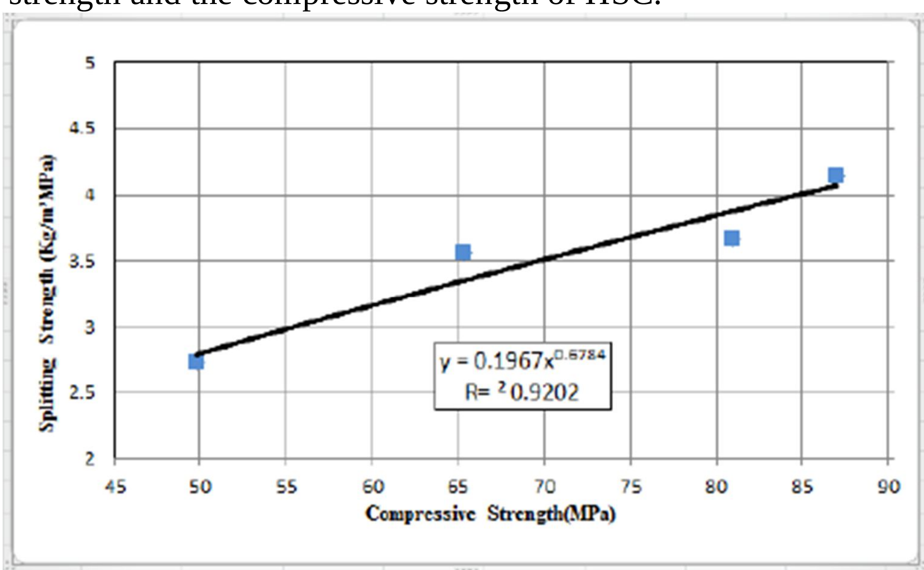
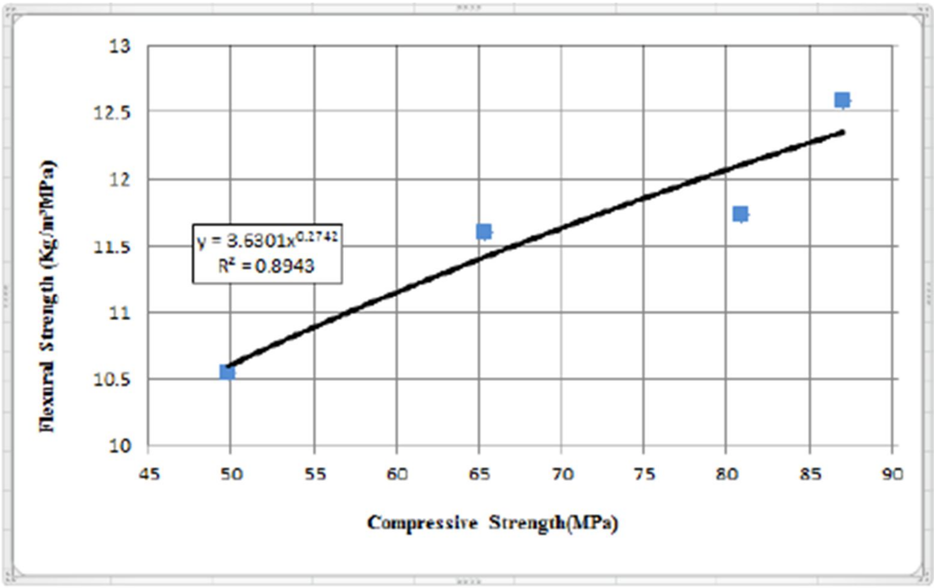


Figure (2.3) Variation of Splitting strength with Compressive Strength

2.5.6 Flexural Strength

*Figure (2.4)*shows an exponential correlation between flexural strength and compressive strength of HSC.[25]



Figure(2.4)Variation of Flexural strength with Compressive Strength

2.5.7 Shrinkage

Little information is available on the shrinkage behavior of high-strength concrete. A relatively high initial rate of shrinkage has been reported, but after drying for 180 days there is little difference between the shrinkage of high-strength and lower-strength concrete made with dolomite or limestone. Reducing the curing period from 28 to 7 days caused a slight increase in the shrinkage. Shrinkage was unaffected by changes in water-cement ratio but is approximately proportional to the percentage of water by volume in the concrete. Other laboratory studies and field studies have shown that shrinkage of high-strength concrete is similar to that of lower-strength concrete. Nagataki and Yonekuras reported that the shrinkage of high strength concrete containing high-range water reducers was less than for lower-strength concrete. [4]

2.5.8 Creep

Parrott reported that the total strain observed in sealed high-strength concrete under a sustained loading of 30 percent of the ultimate strength was the same as that of lower-strength concrete when expressed as a ratio of the short-term strain. Under drying conditions, this ratio was 25 percent lower than that of lower-strength concrete. The total long-term strains of drying and sealed high-strength concrete were 15 and 65 percent higher, respectively, than for a corresponding lower-strength concrete at a similar relative stress level. Ngab found little difference between the creep of high-strength concrete under drying and sealed conditions. The creepof high-strength concrete made with high-range water reducers is reported to be decreased significantly. The maximum specific creep was less for high-strength concrete than for lower-strength concrete loaded at the same age. [4]

2.5.9 Permeability and Water-tightness

Concrete used in water-retaining structures or exposed to weather or other severe exposure conditions must be virtually impermeable or watertight. Watertightness is often referred to as the ability of concrete to hold back or retain water without visible leakage. Permeability refers to the amount of water migration through concrete when the water is under pressure or to the ability of concrete to resist penetration by water or other substances (liquid, gas, or ions). Generally, the same properties of concrete that make it less permeable also make it more watertight. [23]

The overall permeability of concrete to water is a function of: (1) the permeability of the paste; (2) the permeability and gradation of the aggregate; (3) the quality of the paste and aggregate transition zone; and (4) the relative proportion of paste to aggregate. Decreased permeability improves concrete’s resistance to freezing and thawing, resaturation, sulfate, and chloride-ion penetration, and other chemical attack. [23]

The relationship between permeability, water-cement ratio, and initial curing for 100 x 200-mm (4 x 8-in.) cylindrical concrete specimens tested after 90 days of air dryingand subjected to 20 MPa (3000 psi) of water pressure is illustrated in Fig.(2-5). Although permeability values would be different for other liquids and gases, the relationship between water-cement ratio, curing period, and permeability would be similar. [23]

Test results obtained by subjecting 25-mm (1-in.) thick non-air-entrained mortar disks to 140-kPa (20-psi) water pressure are given in Fig. (2-6). [23]

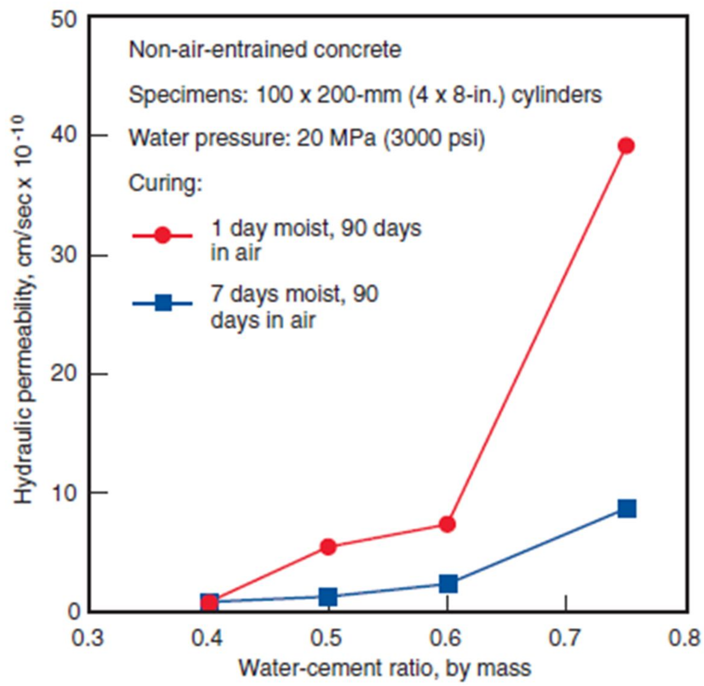


Figure (2.5) Relationship between hydraulic (water) permeability, water-cement ratio, and initial curing on concrete specimens (Whiting 1989).

A low water-cement ratio also reduces segregation and bleeding, further contributing to watertightness. Of course watertight concrete must also be free from cracks, honeycomb, or other large visible voids. [23]

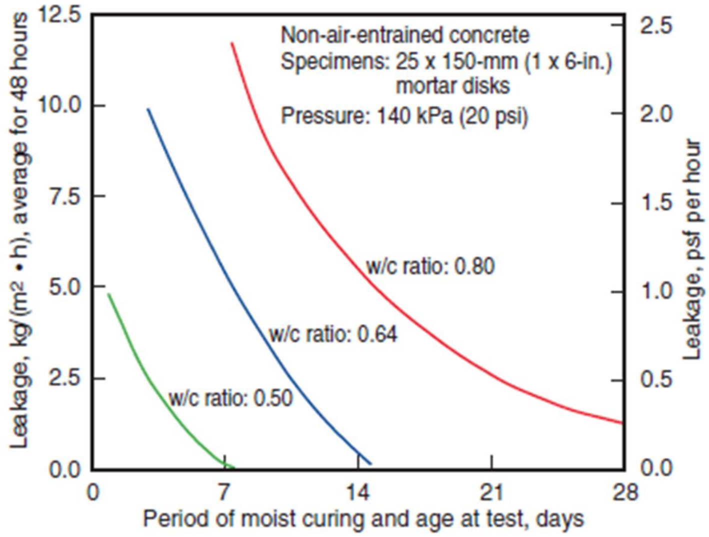


Figure (2.6) Effect of water-cement ratio (w/c) and curing duration on permeability of mortar.

2.6 High Strength Concrete Materials

A change in terminology has taken place. Prior versions all used the term “mineral admixture” throughout to describe the wide variety of materials that are commonly added to concrete to increase the paste content of the mixture. These same materials will now be referred to as “supplementary cementitious materials (SCMs)” throughout this chapter. This change was needed because the ASTM Subcommittee on Terminology (C09.90) could not reach a consensus on an adequate definition of the term “mineral admixture.” .[20]

Supplementary cementitious materials (SCMs) have undeniably played a significant role in the evolution of high-strength concrete. SCMs are important materials that contribute to the properties of concrete when used in conjunction with Portland cement by reacting either hydraulically or pozzolanically. [22]

Fly ash, ground granulated blast-furnace slag, silica fume, and natural pozzolans, such as calcined shale, calcined clay or metakaolin, are materials that, when used in conjunction with portland or blended cement, contribute to the properties of the hardened concrete through hydraulic or pozzolanic activity or both Fig.(2-7). A pozzolan is a siliceous or aluminosiliceous material that, in finely divided form and in the presence of moisture, chemically reacts with the calcium hydroxide released by the hydration of Portland cement to form calcium silicate hydrate and other cementitious compounds. Pozzolans and slags are generally catergorized as supplementary cementitious materials or mineral admixtures. [23]

Figure (2.7) Supplementary cementitious materials. From left to right, fly ash (Class C), metakaolin (calcined clay), silica fume, fly ash (Class F), slag, and calcined shale.

2.6.1 Portland and blended-hydraulic cements

Selecting Portland cements having the chemical and physical properties suitable for use in high strength concrete is one of the most important, but frequently underestimated considerations in the process of selecting appropriate materials for high strength concrete. Cements should be selected based on careful consideration of all performance requirements, not just strength. To avoid interaction related problems, the compatibility of the cement with chemical admixtures and other cementing materials should be confirmed. [12]

A list of the abbreviations used in cement chemistry and the primary compounds formed upon clinkering is shown in Tables (2.5) and (2.6), respectively. [22]

Table (2.5) Abbreviated notations used in cement chemistry

	Chemical formula	Notation
Lime	CaO	C
Silica	SiO_2	S
Alumina	Al_2O_3	A
Iron	Fe_2O_3	F
Titanium	TiO_2	T
Magnesia	MgO	M
Potassium	K_2O	K
Sodium	Na_2O	N
Sulfur	SO_3	S^-
Water	H_2O	H

Table (2.6) Primary compounds in Portland cement clinker

	Chemical composition	Abbreviated notation
Tricalcium silicate	3 $CaO.SiO_2$	C_3S
Dicalcium silicate	2 CaO. SiO_2	C_2S
Tricalcium aluminate	3 CaO.Al2O_3	C_3A
Tetracalcium alumino ferrite	4 CaO.Al_2O3.Fe_2O_3	C_4AF

The four primary cement compounds have the following properties:

tricalcium silicate (C_3S): hydrates and hardens rapidly and is largely responsible for initial set and early strength. In general, the early strength of Portland cement concrete is higher with increased percentages of C3S.

dicalcium silicate (C_2S):hydrates and hardens slowly and contributes largely to strength increase at ages beyond one week.

tricalcium aluminate (C_3A): liberates a large amount of heat during the first few days of hydration and hardening. It also contributes slightly to early strength development. Cements with low percentages of C3A are more resistant to soils and waters containing sulfates.

tetracalcium aluminoferrite (C_4AF):is the product resulting from the use of iron and aluminum raw materials to reduce the clinkering temperature during cement manufacture. It contributes little to strength. [12]
Most color effects that make cement gray are due to C4AF and its hydrates.

2.6.2 FLY ASH

Fly ash, the most widely used supplementary cementitious material in concrete, is a byproduct of the combustion of pulverized coal in electric power generating plants. Upon ignition in the furnace, most of the volatile coal's mineral impurities (such as clay, feldspar, quartz, and shale) fuse in suspension and are carried away from the combustion chamber by the exhaust gases. In the process, the fused material cools and solidifies into spherical glassy particles called fly ash Fig. (2-8). [23]

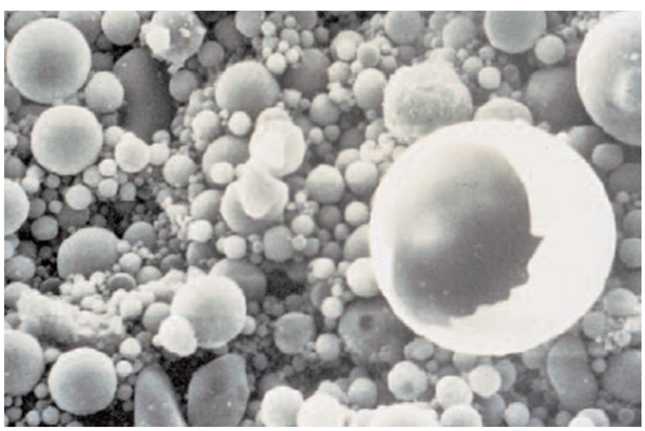


Figure (2.8) Scanning electron microscope (SEM) micrograph of fly ash particles at 1000X.

ASTM C 618 (AASHTO M 295) Class F and Class C fly ashes are commonly used as pozzolanic admixtures for general purpose concrete (Fig. 3-4). Class F materials are generally low-calcium (less than 10% CaO) fly ashes with carbon contents usually less than 5%, but some may be as high as 10%. Class C materials are often high-calcium (10% to 30% CaO) fly ashes with carbon contents less than 2%. Many Class C ashes when exposed to water will hydrate and harden in less than 45 minutes. Some fly ashes meet both Class F and Class C classifications. [23]

2.6.3 Silica Fume

2.6.3.1 Silica Fume Definition

The American Concrete Institute (ACI) defines silica fume as "very fine noncrystalline silica produced in electric arc furnaces as a by-product of the production of elemental silicon or alloys containing silicon" (ACI 116R). It is usually a gray colored powder, somewhat similar to Portland cement or some fly ashes. Figure (2.9)shows a typical silica fume as it appears after being collected from a furnace. [26]

Figure (2.9) As-produced silica fume. This is what the material looks like after it is collected.

2.6.3.2 Silica Fume –Reaction in Concrete

The benefits seen from adding silica fume are the result of changes to the microstructure of the concrete. These changes result from two different but equally important processes. The first of these is the physical aspect of silica fume and the second is its chemical contribution. Here is a brief description of both of these aspects: [26]

Physical contributions— Adding silica fume brings millions and millions of very small particles to a concrete mixture. Just like fine aggregate fills in the spaces between coarse aggregate particles, silica fume fills in the spaces between cement grains. This phenomenon is frequently referred to as particle packing or micro-filling. Even if silica fume did not react chemically, the micro-filler effect would bring about significant improvements in the nature of the concrete. Table (2.7) present a comparison of the size of silica-fume particles to other concrete ingredients to help understand how small these particles actually are.

Chemical contributions —Because of its very high amorphous silicon dioxide content, silica fume is a very reactive pozzolanic material in concrete. As the Portland cement in concrete begins to react chemically, it releases calcium hydroxide. The silica fume reacts with this calcium hydroxide to form additional binder material called calcium silicate hydrate, which is very similar to the calcium silicate hydrate formed from the Portland cement. It is largely this additional binder that gives silica-fume concrete its improved hardened properties.

Table (2.7) Comparison of Size of Silica Fume Particles and Other Concrete Ingredients

MATERIAL	NOMINALSIZE	SIUNITS
Silica fume particle	N/A	0.5µm
Cement grain	No.325sieve	45µm
Sand grain	No.8sieve	2.36 mm
Coarse aggregate particle	3/4inchsieve	19.0 mm

2.6.4 Uses for high-range water-reducing admixtures (Super-plasticizers)

General uses HRWRAs can be used in concrete to: increase slump; increase strength by decreasing water content and water cementitious materials ratio (w/cm); or decrease water and cement content, thus reducing temperature rise and volume change. These results are attainable in a wide variety of concrete mixtures, from conventional types to specialty concretes, and in a number of grouts and prepackaged concretes used for repair and rehabilitation. [2]

2.6.4.1 Effects on freshly mixed concrete

Concrete containing a HRWRA may require the use of procedures not normally required for conventional concrete. For instance, a flowing concrete, when placed rapidly, may increase the pressure on formwork. Other job site problem areas may involve slump loss, slow setting, or segregation and bleeding. Early identification of these problems is aided by using field trial batches, which will reflect job site conditions more accurately than laboratory testing. [2]

The rate of slump loss in concrete containing a HRWRA can be affected by the type of HRWRA, the dosage used, the simultaneous use of a C 494 Type A, B, or D admixture, the type and brand of cement, the class of concrete, and the concrete temperature.

2.6.4.2 Effects on hardened concrete

Compressive strength the primary effects of HRWRAs on concrete compressive strength are derived from their effect on the water-cementitious materials ratio (w/cm). When a HRWRA is used to lower water requirements at the same slump and cementitious materials content, the resulting decrease in w/cm will significantly increase concrete strength at all ages. If mixes with the same w/cm are compared, those containing HRWRA exhibit a slight increase in strength because of the cement dispersing effect. At early ages, this strength increase represents a significant percentage of total strength. [2]

2.6.5 Aggregates

Aggregates overwhelmingly occupy the largest volume of any constituent in concrete and profoundly influence concrete performance in both the fresh and hardened states. [22]

Fine aggregate The optimum gradation of fine aggregate for high-strength concrete is determined more by its effect on water demand than on particle packing. High-strength concretes typically contain high volumes of cementitious (i.e. powdery) sized material. As a result, fine sands that would be considered acceptable for use in conventional concretes may be less suited for high strength concrete due to the sticky consistency that may result [12]

Coarse aggregate Given the critical role that the interfacial transition zone plays in high-strength concrete, the mechanical properties of coarse aggregate will have a more pronounced effect than they would in conventional-strength concrete . Important parameters of coarse aggregate are shape, texture, grading, cleanliness, and nominal maximum size.

In the case of high-strength concrete, the effect of a weakened paste-to aggregate bond can be extremely detrimental to strength. For this reason, use of clean, washed aggregate in the production of high-strength concrete is highly suggested. [22]

2.6.6 Water

The requirements for water quality for high-strength concrete are no more stringent than those for conventional concrete. [4]

CHAPTER THREE

HIGH STRENGTH CONCRETE -PROPORTIONING

CHAPTER THREE
HIGH STRENGTH CONCRETE PROPORTIONING

3.1- Introduction

Concrete mix proportions for high-strength concrete have varied widely depending upon many factors. The strength level required, test age, material characteristics, and type of application have influenced mix proportions. In addition, economics, structural requirements, manufacturing practicality, anticipated curing environment, and even the time of year have affected the selection of mix proportions. [4]

High-strength concrete mix proportioning is a more critical process than the design of normal strength concrete mixtures. Usually, specially selected pozzolanic and chemical admixtures are employed, and the attainment of a low water-cementitious ratio is considered essential. Many trial batches are often required to generate the data that enables the researcher to identify optimum mix proportions.[4]

Proportioning Silica-fume Concrete Basic Considerations

Following are several basic considerations to keep in mind when proportioning silica-fume concrete:

Work to a fixed cementitious materials content and a fixed water-to-cementitious material ratio (w/cm.) In many cases with conventional concrete with a low specified w/cm, the cement content is raised to bring in additional water to provide slump. This practice is usually not the case for silica-fume concrete because it will result in very high contents of cementitious materials. Both the total amount of cementitious materials and the maximum water content will frequently be specified.

Will there be enough water to hydrate the cement? This question is frequently asked. Don’t worry about whether there is enough water. Concrete mixtures with w/cm of less than 0.25 have achieved over 120

MPa compressive strength. If the cement is not hydrated, it will serve as filler material to fill in void spaces in the mixture.

Don’t be particularly concerned with the slump resulting from water alone(“water slump” or “initial slump”.) Because silica-fume concrete mixtures usually contain so little water, there may not be enough water to develop a measurable slump until after the chemical admixtures are added.

Some specifies are uncomfortable about using a super-plasticizer without first verifying a water slump of 50 to 75 mm. This requirement is still seen in many specifications. For many high-performance concrete applications, the w/cm will be so low that there is not enough water to get a measurable slump and still develop a concrete with the desired performance characteristics.

Use chemical admixtures to achieve adequate slump for placement. Usually, both a water-reducer (normal setting or retarding) and a super-plasticizer will be used. The water-reducer is frequently added early in the mixing sequence to help loosen up the concrete and the super-plasticizer is added later to bring the concrete to the desired slump for transportation and placement.

In some cases it may be necessary to go above manufacturer’s recommended limits for chemical admixture dosages, particularly for super-plasticizers. For high-strength concrete with a very low w/cm, the necessary dose may be as much as twice there commended dose. In most cases such high dosages will retard the concrete; however, once the concrete begins to set, it will gain strength very rapidly. Testing at the high dose of admixture is recommended to ensure that other properties such as air content are not being affected.

Entrained air is required with silica-fume concrete if it will be exposed to freezing and thawing while saturated. Use the amount of air recommended in standard documents for conventional concrete, such as ACI 211.1, *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete,* or ACI 318,*Building Code Requirements for Structural Concrete* see Table (3.1). ACI 318 and most specifications allow a one percent reduction in air content if the compressive strength is above 35 MPa; this will almost always be the case for silica-fume concrete.[26]

Table (3.1): Recommended total air content for concrete exposed to freezing and thawing(from ACI 318)

NOMINAL MAXIMUM AGGREGATE SIZE		AIR CONTENT %	
mm	in.	SEVERE EXPOSURE	MODERATE EXPOSURE
9.5	⅜	7.5	6
12.5	½	7	5.5
19	¾	6	5
25	1	6	4.5
37.5	1½	5.5	4.5
50	2	5	4
75	3	4.5	3.5

Project Requirements

It is essential to understand the requirements for a particular project. While this may seem to be an obvious statement, it needs to said. Usually, all of the project requirements will be spelled out in the specifications. Take the time to read the entire concrete specification to be sure that all of the requirements are found. It is not unusual to find requirements on shrinkage, hardened air void parameters, and chloride permeability in addition to compressive strength. There may also be unusual requirements for the information that is to be submitted at the time of concrete mixture approval.[26]

If there are any questions regarding the project requirements, and particularly if some of the requirements seem to contradict one another, be sure to seek clarification from the specifier. It is always easier, and less expensive, to get questions answered before rather than after the concrete mixture is developed.

Construction Considerations

Once the project requirements are identified, it is critical to determine the requirements of the contractor who will actually be placing the concrete. Here are a few topics to consider:[26]

Slump: Silica-fume concrete is very cohesive and behaves somewhat differentlythan conventional concrete. A given slump will not be the same workability forconcrete with and without silica fume. Usually, the slump for the silica-fumeconcrete should be increased by about 40 to 50 mm over concrete without silicafume to achieve the same workability.

Maximum slump: A good rule of thumb for silica-fume concrete is to place it at as high a slump as possible for the placement. Using a higher slump will makeclosing the surface and achieving the desired finish much easier. Frequently, for bridge decks or parking structure flatwork, the slump will be determined by the slope of the structure. Place at the highest slump that will hold on the slope.

3.2- Proportioning Procedure

Proportions for silica-fume concrete are typically developed to meet specific project requirements. These requirements may be prescriptive in nature giving details about the mixture proportions or they may be purely performance giving only the requirements that must be met. In either case, it is best to follow a step-by-step procedure to develop the mixture proportions for a specific project.[26]

3.2.1 General Rules

There is no “scientific” method for proportioning. This means that there is no chart that can be used to derive the mixture ingredients to meet a specified level of performance. There are simply too many variables for such a chart to be developed. Here are some general rules for proportioning:[16]

Test at both the laboratory and production scale during mixture development. The process is too complex to predict what the outcome will be without appropriate testing. Allow plenty of time for the necessary testing.

Finally, follow the procedure described in the following section. This procedure has evolved over many years and is the best recommendation currently available.

3.2.2 Step-By-Step Procedure

This section presents a seven step procedure. Examples are given for each step. See Figure (3.1) for a summary of this procedure.[16]

STEP 1. Determine project requirements. Read the specifications carefully.Look for requirements not only for concrete performance but also for concreteproportioning. Items to look for include:

- Compressive strength
- Chloride exposure
- Freezing and thawing exposure, including specified air content
- Aggregate requirements, including nominal maximum size
- Chemical exposure
- Abrasion resistance
- Temperature restrictions

- Maximum water content
- Cementitious materials contents
- Percentages of fly ash, slag, and silica fume
- Slump

STEP 2. Coordinate with contractor who will be placing the concrete. Save timeand expense by getting input from the contractor early in the process. Items toconsider here include:

- Special constructability requirements
- Placing and finishing methods
- Nominal maximum allowable aggregate size
- Slump requirements — don’t forget to increase the slump for silica-fume concrete
- Responsibility for adding admixtures on the site, if necessary

STEP 3. Select starting mixture. Table (3.2) contains a number of silica-fume concrete mixtures that have been developed for a variety of applications. If the project specifications don’t include specifics on the mixture, use this table to find a concrete mixture that meets requirements that are similar to those on the current project.

STEP 4. Determine volume of entrained air required. It is essential that silica-fume concrete that will be exposed to freezing and thawing while saturated contain entrained air. Use an industry standard table such as found in ASTM or ACI to determine the volume of air required.

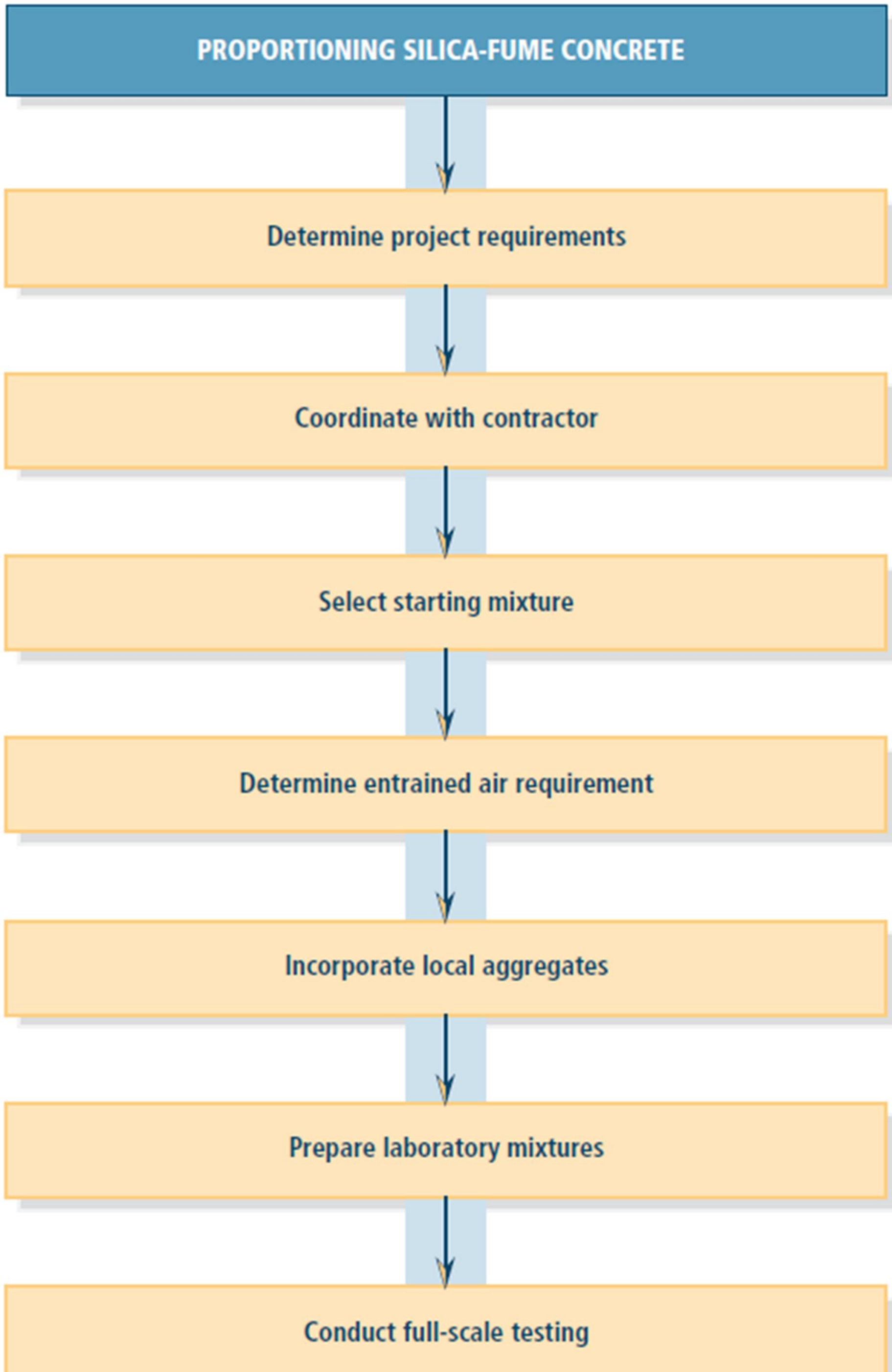


Figure (3.1) Steps in proportioning silica-fume concrete. Each of these steps is discussed in detail in the text.

Table (3.2) Recommended starting silica-fume concrete mixture proportions for various application

	HIGH-STRENGTH CONCRETE Key Tower, Cleveland	HIGH-STRENGTH CONCRETE Scotia Plaza, Toronto	BRIDGE DECK, WITH FLY ASH New York State DOT HP Mix	WET SHOTCRETE REPAIR	TEMPERATURE CONTROLLED CONCRETE Hanford Storage Facility
	MIXTURE 1	MIXTURE 2	MIXTURE 3	MIXTURE 4	MIXTURE 5
References	None	Bickley, et al, 1991	Alcompalle and Owens, 2000	Forrest, et al, 1995	Holland, 1998
Compressive strength *(Note 1)*	83 MPa @ 28 days	69 MPa @ 28 days	> 37 MPa @ 28 days	42 MPa @ 28 days	35 MPa @ 28 days 42 MPa @ 90 days
Rapid chloride test, coulombs	N/A	303 @ 1 year 258 @ 2 years	< 1,600	N/A	N/A
Other requirements	Pumpable, 57 stories	N/A	Minimize plastic and drying shrinkage cracking	59 kg/m³ of steel fibers to increase toughness	Max delivered < 21°C, Max @ 48 hr < 38°C, Pumpable, early strength for form removal
Entrained air *(Note 2)*	N/A	N/A	6.50%	8 to 10% as delivered 4 to 6% in place	2 to 6%
Slump	> 250 mm	100 mm	Unknown	50 to 100 mm	Unknown
Maximum aggregate size	13 mm	39 mm	39 mm	9.5 mm	25 mm
Cement, kg/m³	406	316	297	405	232
Fly ash, kg/m³	0	0	80, Class F	0	89, Class F
GGBFS, kg/m³	169	117	0	0	0
Silica fume kg/m³	47	37	24	42	35
Maximum w/cm	0.24	0.31	0.40	0.45	0.37
Water, kg/m³ *(Note 3)*	149	145	160	200	99

Note 1. Strength shown is f'c. Add appropriate overdesign for mixture development.
Note 2. Allowed reduction in air content for strength above 35 MPa has been taken.
Note 3. Includes water in HRWRA for mixes with very low w/cm.

TABLE (3.2)-continued

RECOMMENDED STARTING SILICA-FUME CONCRETE MIXTURE PROPORTIONS FOR VARIOUS APPLICATIONS

	HIGH-PERFORMANCE BRIDGE GIRDERS Colorado DOT	PARKING STRUCTURE Milwaukee Airport	TEST HIGH-STRENGTH MIX	TEST HIGH-STRENGTH MIX	BRIDGE DECK Colorado DOT
	MIXTURE 6	MIXTURE 7	MIXTURE 8	MIXTURE 9	MIXTURE 10
References	Leonard, 1999	Data from SFA Member	Burg & Ost, 1994	Burg & Ost, 1994	Xi, et al, 2003
Compressive strength *(Note 1)*	45 MPa @ release 69 MPa ultimate	14 MPa @ 36 hrs 39 MPa @ 56 days	89 MPa @ 28 days 115 MPa @ 3 yrs	107 MPa @ 28 days 126 MPa @ 3 yrs	32 MPa @ 28 days
Rapid chloride test, coulombs	N/A	< 1,000 from cores at 2-10 months	N/A	N/A	1,400–1,600 @ 56 days
Other requirements	N/A	N/A	N/A	N/A	N/A
Entrained air *(Note 2)*	Unknown	Unknown	N/A	N/A	8.5%
Slump	Unknown	160 to 190 mm	250 mm	240 mm	140 mm
Maximum aggregate size	Unknown	Unknown	13 mm	13 mm	Unknown
Cement, kg/m³	433	335	475	475	288
Fly ash, kg/m³	0	59, Class C	59, Class C	104, Class C	58, Class F
GGBFS, kg/m³	0	0	0	0	0
Silica fume kg/m³	21	23	24	74	12
Maximum w/cm	0.28	0.35	0.287	0.231	0.41
Water, kg/m³ *(Note 3)*	127	146	160	151	147

Note 1. Strength shown is f'c. Add appropriate overdesign for mixture development.
Note 2. Allowed reduction in air content for strength above 35 MPa has been taken.
Note 3. Includes water in HRWRA for mixes with very low w/cm.

STEP 5. Incorporate local aggregates into the starting mixture.

There are two considerations here:

- Calculate a total aggregate volume that will yield one cubic meter of concrete.* (Note: some concrete producers proportion their concrete mixtures to yield slightly more than one cubic meter. It is best to first proportion the concrete to develop the necessary fresh and hardened properties and then adjust the proportions for yield as appropriate.)

- Use a ratio of fine to coarse aggregate that works well for project materials. This ratio can always be adjusted while making trial mixtures. Although the ratio of fine to coarse aggregate will have an influence on the workability, small changes will not seriously affect hardened concrete properties. Because of the very fine nature of silica fume, it may be appropriate to start with a concrete mixture that is slightly “under sanded” compared to similar mixtures without silica fume. If an appropriate starting ratio of fine to coarse aggregate is not known, guidance on selecting starting aggregate proportions may be found in ACI 211.1, *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete.*

STEP 6. Prepare laboratory trial mixtures. This step is not all that different from what is normally done on a daily basis. However, the Silica Fume Association is aware of instances in which silica-fume concrete prepared in a laboratory has failed to produce the expected hardened concrete properties, whether the property is compressive strength or low permeability. This problem is particularly common in laboratories having small, and often less efficient, concrete mixers. Following are points to keep in mind when producing silica-fume concrete in a laboratory:

1. Silica fume is a very fine powder — the particles are approximately 1/100 the diameter of Portland cement grains. When used to produce high-performance concrete, silica fume is typically 4-15% of the cement weight. The exact addition rate depends upon the specific performance characteristic to be improved. Compared to the other

ingredients in concrete, the amount of silica fume used is small. For the silica fume to be effective, there are two issues that must be addressed:

- First, the agglomerations that make up the densified silica fume must be broken down.
- Second, the silica fume must be distributed uniformly throughout the concrete.

When making concrete in the laboratory, the key to both of these issues is batching the silica fume at the appropriate time and then mixing the concrete adequately. ASTM C192, Standard Practice for Making and Curing Concrete Test specimens in the Laboratory, see Figure (3.2):

- Silica fume must always be added with the coarse aggregate and some of the water. Batching silica fume alone or first can result in head packing or balling in the mixer. Mix silica fume, coarse aggregates, and water for11⁄2 minutes.
- Add the Portland cement and any other cementitious material such as flyash or slag cement. Mix for an additional 11⁄2 minutes.
- Add the fine aggregate and use the remaining water to wash in any chemical admixtures added at the end of the batching sequence. Mix for 5 minutes, rest for 3 minutes, and mix for 5 minutes. Actual mixing time may vary, depending upon the characteristics of a specific mixer. If there are any doubts that full dispersion and efficient mixing has been accomplished, mix longer. Silica-fume concrete cannot be over mixed.

Following these recommendations will help ensure that the results in the laboratory will closely resemble the results to be expected in actual silica-fume concrete production.

2. The Silica Fume Association's experience is that truck mixers or central plant mixers are much more efficient in breaking down the agglomerations and dispersing silica fume. However, remember to limit batch sizes to the rated mixing capacity of the equipment.
3. Batch the concrete at the maximum allowed water content. Remember that even with the maximum allowed water there may not be any measurable slump. Use chemical admixtures to achieve the necessary workability.
4. Review the properties of the fresh concrete and make adjustments as necessary to get the desired workability, air content, and other properties. Once the fresh properties are established, make specimens for hardened concrete testing.
5. Based upon the results of testing the hardened concrete, adjust the mixture proportions as necessary. At this point it may be necessary to make additional laboratory mixtures or it may be time to go to production-scale testing.

STEP 7. Conduct production-scale testing. There can always be minor differences between proportions developed in the laboratory and those used for concrete production, particularly in chemical admixture dosages. Making production batches of the concrete is the best way to work out the bugs. Keep in mind:

This is not a time to economize by making very small batches. Make enough concrete to be representative of what will be made during the project.

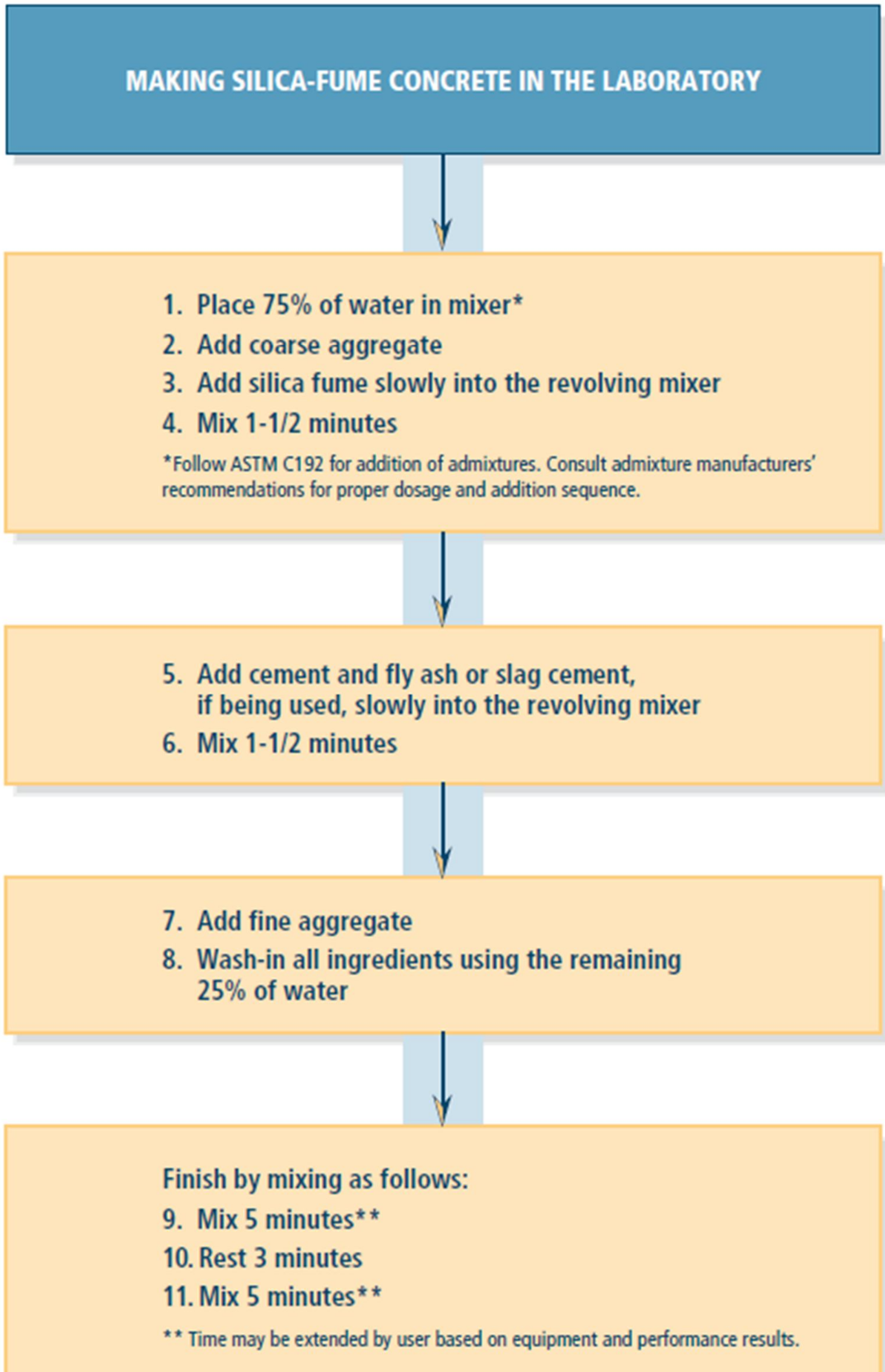


Figure (3.2) Recommendations for making silica-fume concrete in a laboratory mixer.

Test to determine whether the concrete meets the fresh and hardened requirements for the project. Because the mixture has already been fine tuned in the laboratory, major adjustments at this point should not be required. If it appears that the performance is not the same seen in the lab, examine the process carefully — there is no reason to expect major differences.

Make more than one batch. It is always good to confirm the performance of a particular concrete mixture.

3.3- Statistical Approach for Complex Mixtures

For projects with complex requirements and where Portland cement and silica fume may be used in conjunction with either fly ash or slag, development of mixture proportions in the laboratory may entail making a very large number of trial mixtures. Even with a large number of batches, the optimum mixture, in terms of best performance at the least cost, may not be found.[26]

In such a case, it may be better to use a statistical approach to mixture development. In essence, this approach consists of six steps:[26]

1. Determine the range of variables to be tested. For example, a set of variables could include a range of w/cm, a range of Portland cement contents, a range of Portland cement substitution by fly ash, and a range of silica fume contents.
2. Develop a suitable set of mixtures to be prepared to evaluate the various ranges define above.
3. Make the concrete mixtures in the laboratory and determine the fresh and hardened concrete properties of interest.

4. Review the test data to determine the concrete mixture that will best meet the requirements of the project at the least cost. This can be considered the optimum concrete mixture.
5. Confirm the performance of the optimum mixture in the laboratory. In all likelihood, this exact mixture will not have been prepared during the testing phase.
6. Move on to production-scale testing.

Most concrete producers don't have access to a statistician to help with the process described above. This type of service may be provided by the supplier of chemical admixtures.

3.4- Using JMP: Design of Experiments - Response Surface Designs

3.4.1 Creating a Response Surface Design

Response Surface Methodology (RSM) is an experimental technique invented to find the optimal response within specified ranges of the factors.

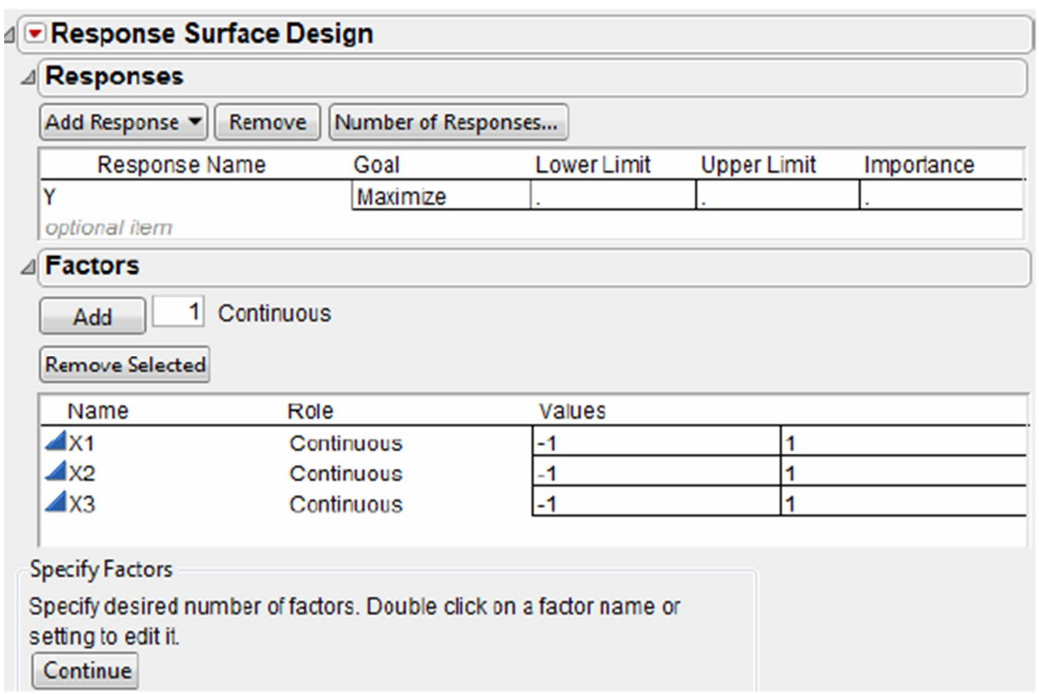
These designs are capable of fitting a second-order prediction equation for the response. The quadratic terms in these equations model the curvature in the true response function. If a maximum or minimum exists inside the factor region, RSM can estimate it. In industrial applications, RSM designs usually involve a small number of factors. This is because the required number of runs increases dramatically with the number of factors. Using the response surface designer, you choose to use well-known RSM designs for two to eight continuous factors. Some of these designs also allow blocking.

Response surface designs are useful for modeling and analyzing curved surfaces.

To start a response surface design, select **DOE > Response Surface Design**, or click the **Response Surface Design** button on the JMP Starter **DOE** page. Then, follow the steps described in the following sections.

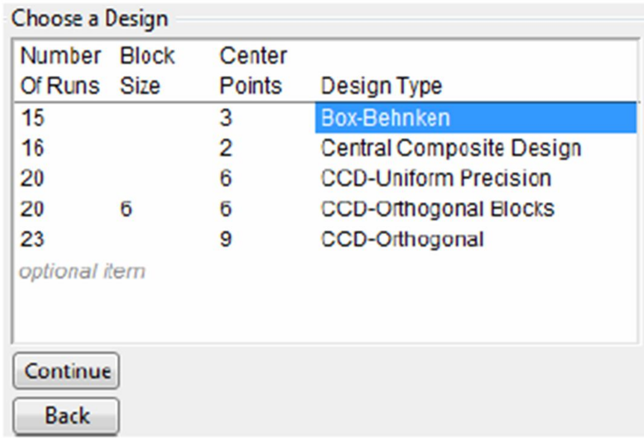
- "Enter Responses and Factors"
- "Choose a Design"
- "Specify Axial Value (Central Composite Designs Only)"
- "Specify Output Options"
- "View the Design Table"

Enter Factors into a Response Surface Design:



Click Continue to proceed to the next step.

Choose a Design *Type*:



Central Composite Designs

The response surface design list contains two types of central composite designs: uniform precision and orthogonal. These properties of central composite designs relate to the number of center points in the design and to the axial values:

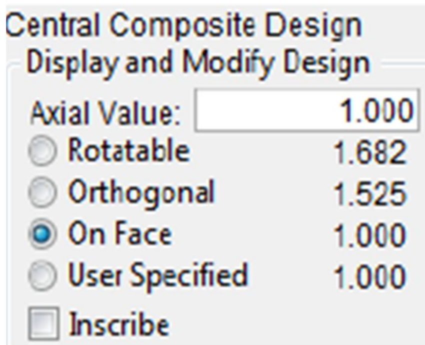
- Uniform precision means that the number of center points is chosen so that the prediction variance near the center of the design space is very flat.

- For orthogonal designs, the number of center points is chosen so that the second order parameter estimates are minimally correlated with the other parameter estimates.

Specify Axial Value (Central Composite Designs Only)

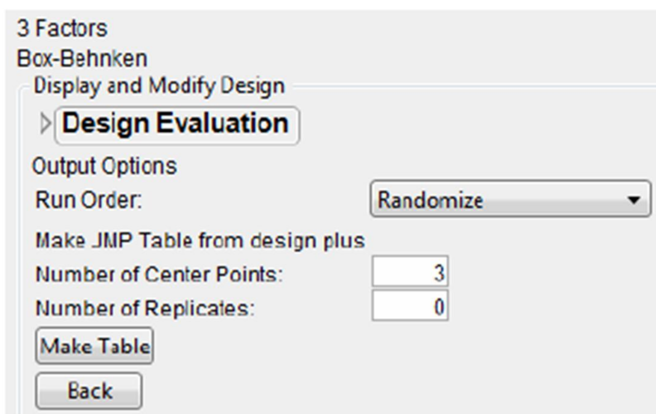
When you select a central composite (CCD-Uniform Precision) design and then click Continue, you see the panel in Display and Modify the central composite design. It supplies default axial scaling information. Entering 1.0in the text box instructs JMP to place the axial value on the face of the cube defined by the factors, which controls how far out the axial points are. You have the flexibility to enter the values you want to use.

Display and Modify the Central Composite Design:



Specify Output Options

Use the Output Options panel to specify how you want the output data table to appear. When the options are specified the way you want them, click Make Table.



View the Design Table

The Design Data Table

Box-Behnken
Design Box-Behnken
Model

Columns (5/0)
Pattern
X1
X2
X3
Y

Rows
All rows 15
Selected 0
Excluded 0
Hidden 0
Labelled 0

	Pattern	X1	X2	X3	Y
1	+0+	1	0	1	•
2	0+−	0	1	-1	•
3	−0+	-1	0	1	•
4	+0−	1	0	-1	•
5	0−+	0	-1	1	•
6	000	0	0	0	•
7	0++	0	1	1	•
8	−+0	-1	1	0	•
9	000	0	0	0	•
10	000	0	0	0	•
11	++0	1	1	0	•
12	0−−	0	-1	-1	•
13	−0−	-1	0	-1	•
14	+−0	1	-1	0	•
15	−−0	-1	-1	0	•

The name of the table is the design type that generated it.

Run the Model script to fit a model using the values in the design table. The column called Pattern identifies the coding of the factors. It shows all the codings with "+" for high, "–" for low factor, "a" and "A" for low and high axial values, and "0" for midrange. Pattern is suitable to use as a label variable in plots because when you hover over a point in a plot of the factors, the pattern value shows the factor coding of the point. The three rows whose values in the Pattern column are 000 are three center points.

The runs in the Pattern column are in the order you selected from the Run Order menu.

The Y column is for recording experimental results.

3.5- Adjusting the Mixture

There are two areas that frequently require adjustments during either the laboratory or the production-scale testing. These are compressive strength and the stickiness of the fresh concrete.[26]

Compressive strength. Failure to achieve a required compressive strength is most frequently the result of having too much water in the concrete. For very high strength concrete, don't be afraid to drop the w/cm well below customary levels. Look again at the starting mixtures in Table (3.2). To get into the very high strength range, there must be a very low water content.

Concrete stickiness. The most common complaint regarding silica-fume concrete is that it tends to be sticky. This stickiness is a result of the high fines content and the high super-plasticizer content. If stickiness a problem, here are some suggestions:

- Silica fume from a particular source can behave differently when used with a different super-plasticizers. Simply try a different super-plasticizer from your admixture supplier and see if that switch makes a difference in stickiness.
- Use of one of the mid-range water-reducing admixtures may also help reduce stickiness. Many of these products are usually based upon a lignin ingredient, which seems to help reduce stickiness. Try replacing about one-third of the super-plasticizer with the mid-range product. Since these mid-range products are priced about the same as super-plasticizers, there should be little impact on the cost of the concrete.
- Look at reducing the volume of fine aggregate by a small amount. As stated earlier, silica-fume concrete performs well when slightly under sanded. This success of this approach will depend upon the fineness of the aggregate.

- Look at the grading of the fine aggregate. If there are a lot of fines in the aggregate, replacing some or all of the fine aggregate with a coarser material may help reduce stickiness.

3.6- Placing and Consolidating

Silica-fume concrete has been successfully placed by all means of placing concrete. These include direct discharge from mixer trucks, crane and bucket, tremie under water, and pumping. Given the nature of the applications where silica-fume concrete tends to be used, the vast majority has been placed by pump. Overall, do not expect to see any significant differences when placing and consolidating silica-fume concrete.[26]

It is always easier to work with as high a slump as practical for a given placement. Use a slump for silica-fume concrete based upon actual job conditions and not based upon arbitrary recommendations that were probably developed for concrete without silica fume and super-plasticizer.

Because a lot of silica-fume concrete is placed by pump, there are the usual concerns over air loss. Silica-fume concrete is no more or no less susceptible to air loss than any concrete without silica fume placed under the same circumstances. Following good pumping practices, air loss of 1 to 2% going through the pump can be expected. If greater air loss is being seen, look at the procedures and configuration of the pump boom before blaming the concrete mixture. If higher air losses are being experienced, be very careful attempting to fix the problem by increasing the air content of the concrete going into the pump. What may work on one day may not work well the next day if the configuration of the boom is changed. See ACI 304.2R, *Placing Concrete by Pumping Methods*, for additional information on pumping and air loss.[26]

Silica-fume concrete is a very fluid material, particularly if the recommendations regarding increasing slump are followed. However, don't be fooled by the apparent workability — this concrete still needs to be adequately vibrated during placement. Do not assume that a vibratory screed will vibrate concrete in deeper sections such as beams cast integrally with slabs. An internal vibrator must be used in accordance with recommendations from ACI. For more information, see ACI 309R, *Guide for Consolidation of Concrete.*[26]

3.7- Curing

Curing is probably the most essential element when it comes to working with silica-fume concrete. The performance that is expected, and for which a premiumis being paid, will not be achieved if the concrete is not properly cured. This section addresses several aspects of curing silica-fume concrete and presents the Silica Fume Association recommendations for curing.[26]

Note that there is a difference between curing silica-fume concrete flatwork and structural elements. Because of its large surface to volume ratio, all concrete flatwork, with or without silica fume, is more susceptible to drying and shrinkage cracking. Structural elements such as columns or beams are less susceptible to this type of cracking. The Silica Fume Association is not aware of instances where cracking of structural members has been an issue on a project.[26]

Table (3.3) Protecting, Curing and preventing cracking of silica-fume concrete flatwork

MOST CRACKING OF SILICA-FUME CONCRETE FLATWORK CAN BE PREVENTED BY FOLLOWING THESE THREE STEPS:
1. Protect silica-fume concrete while it is still plastic ■ Fogging ■ Using evaporation retarder ■ Covering with plastic sheets ■ Applying curing compound
2. Cure silica-fume concrete as soon as possible ■ Wet cure for a minimum of 7 days
3. Never allow plastic or hardened silica-fume concrete to dry out until the wet curing has been completed

CHAPTER FOUR

STATEMENT OF THE RESEARCH PROBLEM

Chapter Four
Statement of Problem

4.1- Statement of Problem and Research Goals

The purpose of this research was to produce high strength concrete by using local Sudanese aggregate with supplementary cementitious materials and investigate the use of statistical approach in concrete mixture proportioning.

This study presents a part of an ongoing experimental laboratory investigation being carried out for production and characterization of high strength concrete (HSC) for heightening of an existing concrete dam in the south of Sudan. Brief description of the main features of the dam and concrete works is presented. Hundreds of trial mixes were performed and tested using local Sudanese aggregates with addition of Supplementary Cementitious Materials (Silica Fume and Fly Ash) and Super plasticizers. Three grades of HSC (80, 90, 100 MPa) had been success fully produced and their mechanical properties were measured and documented. Statistical analysis of tests results was performed. The results have offered an important insight for optimizing the rheological characteristics of HSC and permitted to develop guidelines for optimum mix design methods for HSC from locally available aggregates in Sudan. The effect of constituent materials on strength of HSC was also highlighted. It is concluded that local concrete materials, in combination with Supplementary Cementitious Materials can be utilized in producing High Strength Concrete in Sudan.

4.2- Roseires Dam Heightening

Roseires Dam, located on Blue Nile River in Sudan, was constructed in 1960s for power generation and irrigation purposes. It has been decided to heighten this composite concrete buttress and earth fill dam by 10m to increase its storage capacity.

The raising works of Roseires concrete dam comprise the addition of mass concrete, reinforced concrete, and post-tensioning requirements into both crest and the downstream portions of the dam. To commission the operation of Kenana and Dinder Headworks, some extra works have been programmed by DIU which, during the construction phase, have been put on hold by DIU.

The concrete dam section is divided into 11 typical structures along its 1km length. From east to west, the structures are East Transition, Dinder Canal Headworks, East Standard Buttresses, Deep Sluices, Central Standard Buttresses, Spillway, Service Power Station, Power Intakes, West Standard Buttresses, Kenana Canal Headworks and West Transition encompassing a total number of 69 buttresses. Because each structure has its specific geometry and function different design methodologies are needed for each.

4.2.1 Background

The economic prosperity of the Republic of the Sudan and her people depends to a large extent on the management of the waters of the Nile which provide the bulk of the water available for agriculture.

Over time, the storage capacity of Roseires reservoir is decreasing due to the accumulation of sediment in it. Additional storage capacity is sought by raising the FSL by 10m., Because the original dam designers made provision for such a future heightening, ,the Government of the Sudan, in 1991, decided to proceed with the implementation of the dam heightening. Subsequently, consultants were engaged to carry out the detailed site investigations and studies which led to the preparation of tender documents by 1993. Work started on the construction of the west (left) embankment of the dam but, due to some economic issues, it had to be temporarily halted. Earthworks continued at a slower pace due to the funding shortfall.

In 2005, previous economic studies for the project were reviewed and updated confirming its economic viability. Then, in October 2006, the Dams Implementation Unit (DIU) of the Presidency of the Republic engaged SMEC International Pty Ltd of Australia, in association with Coyne et Bellier of France, to carry out a review of the 1993 Tender Documents and previous design studies with the objective of letting a construction contract for the dam heightening and refurbishment of the associated mechanical and electrical works by the end of 2007. Following completion of Tender Design documents, SMEC was awarded a contract for the provision of Consulting Services for the Roseires Dam Heightening Contract Administration and Construction Supervision.

4.2.2 Project Description

Roseires Dam is located on the Blue Nile River, close to Damazin in the Blue Nile province of the Republic of the Sudan.

The Roseires Dam Heightening project will result in the raising of the dam to the maximum FSL of EL 493.02 (AD) with the following main objectives:

- to store a greater proportion of the annual flood of the Blue Nile to provide an assured supply for the extension of downstream irrigated reaches;
- to increase hydro-power generation; and
- to provide headworks and stilling basins for the future implementation of Kenana Canal and Dinder Canal irrigation schemes.

The heightening design intention was to add a 10m high concrete gravity section at the upstream end of the concrete dam's crest deck level to have the maximum dam height about 78m. It envisaged a strengthening of the buttress webs, generally from 3 to 5m thickness, with a horizontal extension of 7.2m in the downstream direction. Once raised to the final crest level, the earth embankments would have a total length of approximately 24km. After heightening, the dam reaches a nominal elevation EL 495.02 (AD).

The concrete dam section comprises 11 typical structures. The main features of the concrete dam and appurtenant structures are presented, sequentially from east to west, in Table (4.1).

Table (4.1) Summary of Roseires Dam Concrete Section

No	Structure	Total Length(m)	Buttresses	Description
1	East Transition	56.8	3B,4A,4B,5A	
2	Dinder Canal Headworks	56	5B,6,7,8	Three Outlets
3	East Standard Buttresses	56	9 to12	
4	Deep Sluices	84	13 to18	
5	Central Standard Buttresses	84	19 to24	
6	Spillway	112	25 to32	Seven Bays
7	Service Power Station	Between Buttresses 32 and 33		
8	Power Intake	142	33 to40	Seven Intakes
9	West Standard Buttresses	266	41 to59	
10	Kenana Canal Headworks	84	60 to65	Five Outlets
11	West Transition	60.3	66,67A,67B,68A	
Concrete Section of Roseires Dam		1001.1	69 Buttresses	

Figure (4.1) Roseires Dam Concrete Section downstream view

4.3- Experimental Program

The following subsections present the details of the materials used in the production of HSC and the related testing and specifications.

4.3.1 Concrete Ingredients

4.3.1.1 Cement

In this research, a locally produced ordinary Portland cement type I, conforming to ASTM C150 (OPC 42.5N) which is extensively used in Sudan, was used in the trial batches production. The specific gravity of cement used was 3.15, initial and final setting time were 2:12 and 3:38, other physical and mechanical properties test for cement are shown in Table(4.2).

Table (4.2) Physical and Mechanical Properties of Cement

Test according to BSEN196		Result
Normal Consistency		27.4%
Sitting Time	Initial Setting Time	2.2hour
	Final Setting Time	3.6hour
Loss on ignition		1.95%
Compressive Strength	2 days	32.1
	28 days	60.7

4.3.1.2 Aggregates

The coarse and fine aggregates used in this study were crushed marble processed from the local quarries around Damazin City, the quarry for Roseires Dam Heightening Project. The maximum aggregate size was 20 mm, the grading of the coarse and fine aggregates is shown in Figure 4. The specific gravity and absorption of the coarse aggregates, determined in according with ASTM C127 [10] were 2.84 and 0.25respectively, whereas those of fine aggregates, determined in accordance with ASTM C128 [11] were 2.839 and 0.45 respectively. All the sand samples were tested for their absorption percentage in saturated surface dry (SSD) condition. Organic impurities in sand were tested in accordance with ASTM C-40. The water-cement ration of all trial mixes were based on saturated surface dry condition (SSD) of the aggregates, different type of aggregates from another quarry was used. To compare with marble, granite aggregates from Merwei Dam (recently constructed another concrete dam in the north of Sudan) location were used.

Table (4.3) Summary of Test Results of Crushed Coarse Aggregate

Sample Source: Merowe Project		**Sample Type: Crushed Coarse Aggregate**			**Size (mm): 5 ～ 20**				
Test Item	Grading	Chloride %	Sulphate %	Soundness %	Alkali Reaction	Flakiness %	Shell Content %	Abrasion Value %	Water Absorption %
Test Result	see figure below	0.00305		2.06	/	27.5	Nil	29.72	0.44
Specification	/	⩽ 0.03	⩽ 0.4	⩽ 18	/	⩽ 35	Nil	⩽ 35	⩽ 2.5
Conclusion	Qualified	Qualified		Qualified	Qualified	Qualified	Qualified	Qualified	Qualified
Remarks	1、Crushed Coarse Aggregate (5-20mm) comes from Merowe Project and used for Merowe Project during all the Construction.								

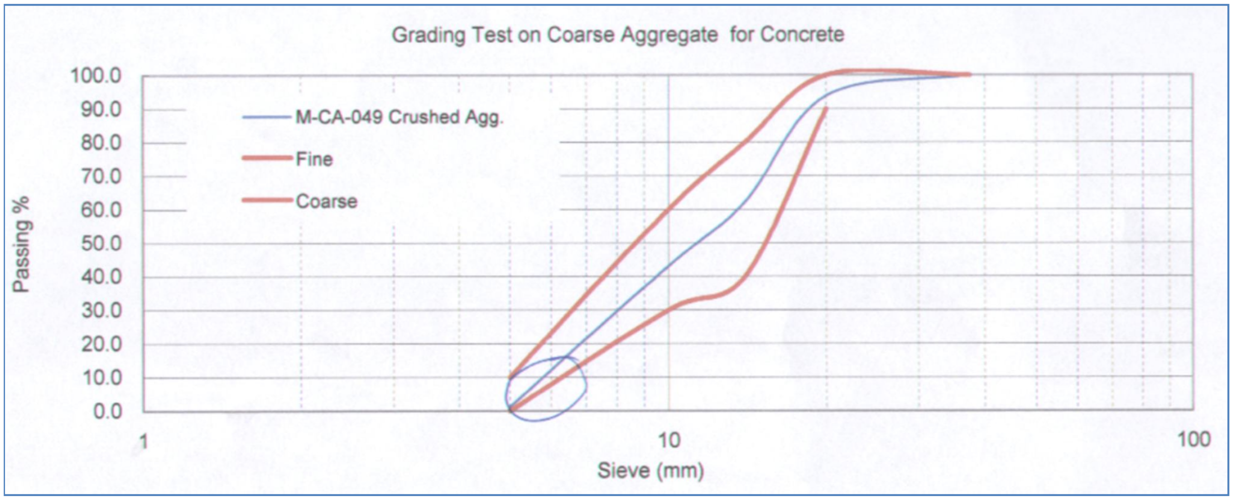


Figure (4.2) Different types of Aggregates production process

4.3.1.3 Chemical Admixtures (Super-plasticizer)

The superplasticizer used in this study has the trade name of “PCA-(I)” from Jiangsu Bote New Materials Company-China. PCA-(I) is a polycarboxylate polymer-basedcomposite admixture. It is a liquid which has the performance of high range water reduction, excellent slump retention and strengthening. The specific gravity of the super-plasticizer was 1.085 and the PH was 8.11 with nil chloride content percentage by weight. It is specially adapted for the production of high durability concrete, self-compacting concrete, high compressive strength concrete, and high workability concrete. PCA-(I) super-plasticizer is formulated to comply with the ASTM specifications for concrete admixture: ASTM494, Type G [11].

Figure (4.3) The super-plasticizer PCA-(I)

Table (4.4) Super-plasticizer PCA-(I)-Physical Properties

Item	**Specified limits according to ASTM494**
Appearance	Light yellowish viscous liquid
Solid content/wt.%	21.0±1
Density ; 20ºC	1.07±0.05
pH value	7±1
Chloride content/%	Below 0.01
Dosage(%),20% based	0.6-0.8

4.3.1.4 Silica Fume

Silica fume (SF) is ideally suited to the most demanding applications, such as concrete slipways, dam spillways and hard standings, where chloride, chemical or abrasion resistance are required. SF concretes have performed well under these circumstances, as they are chemically stable and have very low permeability. The SF used in this study was in accordance with the most international standards such the European BS EN 13263 Silica fume for concrete, Part 1:2005 Definitions, requirements and conformity criteria Part 2:2005 Conformity evaluation, and the American ASTM C1240-97b Standard specification for silica fume for use as a mineral admixture in hydraulic- cement concrete, mortar and grout. The specific gravity of the silica fume silica fume used in this study was 2.373. SF the pozzolanic high activity, which can be filled the gap between cement, increase the density of the system, so as enhance strength, impermeability, wear proof, anti-corrosion, anti-scour, antifreeze, and strong early performance.

Table (4.5) Physical Properties of KD-12 Silica Fume

Test items	**Specified limits according to ASTM C12405, BS EN13263**	**Test Results**
Absolute density (kg/m^3)	≥2200	2249
Loss on ignition (%)	≤3.5	1.88
Coarse particle	≤1.5	1.1
SiO_2 (%)	≥86	92
Carbon content (%)	≤2.5	2.3
Moisture (%)	≤1	0.85
Specific area (m^2/g)	≥15	20

4.3.1.5 Fly ash:

Fly ash used in this study was manufacture by Zouxian power plant-China.the specific gravity of the fly ash is 2.4, loss on ignition 0.48, the other properties of fly ash are presented in Table 5. ASTM C618; the requirement for Class F and Class C fly ashes, and the raw or calcined natural pozzolans, Class N, for use in concrete. Fly ash properties may vary considerably in different areas and from different sources within the same area. The preferred fly ashes for use in high strength concrete have a loss on ignition not greater than 3 percent, have a high fineness, and come from a source with a uniformity meeting ASTM C 618 requirements [12].

Table (4.6) Chemical Properties of Fly Ash

Test items	Specified limits according to BS 3892	Test Results
SO_3 (%)	Max.2.0%	1.68%
Chloride (%)	Max.0.1%	0.03%
Calcium Oxide (%)	Max.10%	8.4%

Table (4.7) Physical Properties of Fly Ash

Test items	Specified limits according to BS 3892	Test Results
Loss on ignition (%)	Max.7.0%	1.39%
Moisture Content	Max.0.5%	0.29%
Fineness	Max.12%	8.24%
Particle Density	Min.2000kg/m^3	2039kg/m^3
Water Requirement	Max.95% (30%Fly Ash+70%Cement)	92%
Soundness	Max.10mm	9.02mm
Strength Factor	Min.0.8	0.83

4.3.2 Proportioning, Mixing and Casting of Specimens

There is no empirical method available for proportioning high strength concrete. The procedure to get the proportions in this study is the approach that recommended in ACI 211.4R-08[1], by starting with mixture proportion that has been used successfully on other projects with similar requirements. Given this starting point, trial mixtures were made in the laboratory and under field conditions to verify performance with actual project materials this are presented in Table(4.9). Hundreds of trial batches were performed in the laboratory and several adjustments were carried out in order to identify the optimum proportions. The final optimum and best trials used in the construction will finalize a according to statistical approach was described in ACI 211.4R-08 and the concrete components cost shown presented in Table (4.12). A concrete fixed mixer with capacity of 0.125 $m^3$was used, the mixes from Table(4.9) were scaled down depending on number of molds for different tests, and the mixer was buttered by mixing amount of cement, sand with water because it is difficult to recover all the mortar from the mixer. The mortar adhering to the mixer after discharging is intended to compensate for loss of mortar from the test batch. The following steps were to mix each batch; all the mixing ingredients, including the mixtures, were scaled down and weight out. The coarse and fine aggregates, cement and other cementitous materials were added to the mixer. The mixer rotated for 2 minutes (dry mixing). Super-plasticizer was dispersed in about 2/3 of water before added to the mixer and started rotated the mixer again for 2 minutes. The mixer was shut off about 1 minute to let the aggregate absorb some of the paste, the aggregates were approximately in saturated surface dry condition (SSD) at the time the batch was prepared. The aggregates were sprayed with water and covered by burlaps for at least 24 hours.

4.3.3 Curing and Testing of Specimens

Lime saturated-water curing method was used in this study. After mixing, a portion of the fresh concrete was placed for fresh concrete properties determination. Slump was measured according to ASTM C143. Precautions were taken to keep the slump between 150-200 mm to obtain pumpable concrete for dam construction. Concrete casting was performed according to BS EN 12390-1:2000. Molds were covered to prevent loss of water from evaporation. Specimens were kept for 24 hours in molds at a temperature of about 23 C in casting room, and then cured for the specified time at approximately 23 C ± 2 C. The specimens were tested in dry state for compressive strengths, determination of length change of hardened concrete-drying shrinkage tests in accordance with BS EN 12390-2:2000[12], ASTM C-157 M respectively.

4.3.4 Step-by-step procedure for proportioning a high-strength concrete mixture for concrete dam in SI units:

Her by, we were present step by step procedure to produce a high strength concrete in a simple case, but in the complex mixes statistical approach essential.

Step 1: Determine project requirements—A review of the specifications develops

the following requirements:

- Design compressive strength of 80 MPa at 28 days
- No exposure to freezing and thawing

Step 2: Coordinate with contractor—Discussions with the contractor develop the

following additional requirements:

- Maximum size of coarse aggregate is 20 mm

- Desired slump is 50 to 200 mm
- Concrete will primarily be placed by pump

Step 3: Select a starting mixture—from historical experience select the high-strength mixture as being a good starting mixture. This mixture has the following characteristics:

Cement	500 kg/m^3
Silica Fume	56 kg/m^3
Fly Ash	zero
w/cm ratio	0.28
Super- plasticizer	8.8 kg/m^3

Step 4: Determine volume of air required—Assume that 1.5% will be entrapped in this mixture.

Step 5: Incorporate local aggregates—First, determine the volume the paste will occupy, as shown in the following table: (Remember: Specific gravity in SI units is expressed as Mg/m^3.)

Material	Mass(kg)	Specific Gravity	Volume,m^3
Cement	500	3.15	0.159
Fly Ash	-	2.5	-
Silica Fume	56	2.2	0.0255
Water(w/cm =0.28) cm=cement+ Silica fume +Fly Ash.	155	1	0.155
Air, 1.5%	N/A	N/A	0.015
Total paste volume = 0.3545 m^3			

Second, calculate aggregate volumes and masses:

Coarse aggregate density: 2.68
Fine aggregate density: 2.60
Aggregate volume=1.000m^3-0.3545m^3=0.6455m^3
Fine aggregate volume=0.41$\times 0.6455 = 0.265$
Fine aggregate mass=0.265$\times 2.6 = 0.689\ Mg = 689\ kg$
Coarse aggregate volume=0.6455-0.265=0.381m^3
Coarse aggregate mass=0.381$m3 \times 2.68 Mg\ m3 = 1.0206\ Mg = 1021\ kg$

Step 6: Prepare laboratory trial mixtures—Don't forget the following:

- Control silica fume dispersion.
- Carefully control and account for moisture on the aggregates
- Mix thoroughly
- Conduct necessary testing on fresh and hardened concrete
- Adjust mixture as necessary to obtain the properties that are required

Step 7: Conduct full-scale testing—Once satisfied with the results of the laboratory testing program, conduct production-scale testing. Consider these points:

- Use large enough batches to be representative
- Test more than once
- Work with the contractor to conduct placing and finishing trials as required

4.3.5 Statistical Approach for Complex Mixtures

4.3.5.1 Statistical Approach for Complex -ACI 211.4R-08.

For projects with complex requirements and where Portland cement and silica fume may be used in conjunction with either fly ash or slag, development of mixture proportions in the laboratory may entail making a very large number of trial mixtures. Even with a large number of batches, the optimum mixture, in terms of best performance at the least cost, may not be found.[16]

In such a case, it may be better to use a statistical approach to mixture development. In essence, this approach consists of six steps: [16]

1. Determine the range of variables to be tested. For example, a set of variables could include a range of w/cm, a range of Portland

cement contents, a range of Portland cement substitution by fly ash, and a range of silica fume contents.

Table (4.8) Range of Variables Mixtures Component

Component	ID	Minimum	Maximum
Water-cement ratio w/cm	x_1	0.19	0.3
Silica fume Type KD-12	x_2	50	126
Fly Ash Type F	x_3	0	83
Super Plasticizer type PCA(1)	x_4	7.77	13.44
Fine aggregate	x_5	268	704
Coarse aggregate	x_6	991	1235

2. Develop a suitable set of mixtures to be prepared to evaluate the various ranges define above.

Table (4.9) The suitable set of mixtures

Test No	Cement (kg/m^3)	Silica Fumetype KD-12 (kg/m^3)	Fly Ash (kg/m3)	Super Plasticizer type PCA(1) (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Coarse Aggregate (kg/m^3)
1	575	50	0	10	138	662	1177
2	585	65	0	10.4	140	641	1190
3	670	62	0	12.32	162	268	1231
4	708	62	0	12.32	169	385	1191
5	587	65	0	10.432	147	601	1045
6	587	115	77	10.75	154	443	1057
7	545	55	0	9.6	145	648	1042
8	500	56	0	8.88	155	689	1023
9	416	56	83	7.77	150	704	1003
10	647	126	67	13.44	168	399	1050
11	672	118	0	12.64	158	440	1025
12	528	72	0	9.6	138	593	1101
13	528	72	0	9.6	144	587	1091
14	540	78	32	10.4	143	521	1106
15	480	72	48	9.6	117	503	1233
16	616	84	0	11.2	133	436	1180
17	484	66	0	8.8	124	551	1225

Test No	Cement (kg/m^3)	Silica Fumetype KD-12 (kg/m^3)	Fly Ash (kg/m3)	Super Plasticizer type PCA(1) (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Coarse Aggregate (kg/m^3)
18	500	75	50	10	125	457	1235
19	528	72	0	9.6	126	500	1225
20	528	72	0	9.6	138	491	1202
21	572	78	0	9.6	130	451	1218
22	660	90	0	12	150	382	1145
23	572	78	0	10.4	150	469	1149
24	630	70	0	11.2	147	357	1195
25	655	77	39	9.6	146	296	1184
26	655	77	39	13.09	162	346	1095
27	660	90	0	12.75	165	467	992
28	595	70	35	11.9	161	498	1011
29	650	50	50	12	165	466	991
30	600	50	50	11.2	161	499	1013
31	550	50	50	9.6	163	586	1022
32	550	50	0	9.6	162	586	1022
33	495	55	0	9.6	165	615	1027

3. Make the concrete mixtures in the laboratory and determine the fresh and hardened concrete properties of interest. see table 3.9 and more details in chapter four.
4. Review the test data to determine the concrete mixture that will best meet the requirements of the project at the least cost. This can be considered the optimum concrete mixture.
5. Confirm the performance of the optimum mixture in the laboratory. In all likelihood, this exact mixture will not have been prepared during the testing phase.
6. Move on to production-scale testing.

Table (4.10) The result of fresh and hardened concrete properties Ave Compressive Strength (MPa) for 7days, Ave Compressive Strength (MPa) for 28days and Slump mm

Test No	Date	Ave Compressive Strength (MPa) for 7days	Ave Compressive Strength (MPa) for 28days	Slump mm
1	30-Oct-09	75.0	81.2	190.0
2	31-Oct-09	62.7	80.0	182.0
3	6-Nov-09	69.8	80.9	190.0
4	11-Nov-09	79.3	91.1	205.0
5	14-Nov-09	79.0	87.6	195.0
6	5-Dec-09	88.1	96.4	188.0
7	6-Dec-09	77.3	97.7	216.0
8	7-Dec-09	92.3	86.3	207.0
9	7-Dec-09	92.2	91.7	215.0
10	13-Jan-10	65.6	80.3	220.0
11	14-Jan-10	68.5	83.7	230.0
12	15-Jan-10	80.4	91.5	165.0
13	15-Jan-10	85.9	87.0	170.0
14	20-Jan-10	68.8	84.2	180
15	26-Jan-10	72.9	83.5	200.0
16	28-Jan-10	86.6	96.9	220.0
17	29-Jan-10	91.5	105.2	170.0
18	29-Jan-10	80.2	88.2	200.0
19	8-Feb-10	81.7	88.5	143.0
20	11-Feb-10	81.8	95.3	155.0
21	15-Feb-10	91.9	100.6	162.0
22	17-Feb-10	98.2	104.7	161.0
23	19-Feb-10	98.7	109.2	121.0
24	19-Feb-10	94.7	100.4	134.0
25	21-Feb-10	88.6	96.9	159.0
26	24-Feb-10	92.9	106.1	116.0
27	25-Feb-10	88.4	104.3	215.0
28	28-Feb-10	101.0	110.6	77.0
29	1-Mar-10	81.3	94.5	205.0
30	21-Mar-10	87.1	97.9	185.0
31	31-Mar-10	90.7	103.6	115.0
32	14-Apr-10	93.4	102.4	125.0
33	25-Apr-10	94.1	102.8	145.0

Table (4.11) The Mixtures Component cost$

Cost $	Cement kg	Silica Fumetype KD-12 kg	Fly Ash kg	Super Plasticizer type PCA(1) kg	Water kg	Fine Aggregate kg	Coarse Aggregate kg
	0.19	0.95	0.19	0.755	---------	0.007	0.0065

Table (4.12) The Trial Mixtures cost$ for m3

Test No	Cement (kg/m^3)	Silica Fumetype KD-12 (kg/m3)	Fly Ash (kg/m3)	Super Plasticizer type PCA(1) (kg/m3)	Water (kg/m3)	Sand (kg/m3)	Coarse Aggregate (kg/m3)	Cost of m3 $
1	575	50	0	10	138	662	1177	176.6
2	585	65	0	10.4	140	641	1190	193.0
3	670	62	0	12.32	162	268	1231	205.4
4	708	62	0	12.32	169	385	1191	213.2
5	587	65	0	10.432	147	601	1045	192.2
6	587	115	77	10.75	154	443	1057	253.5
7	545	55	0	9.6	145	648	1042	174.4
8	500	56	0	8.88	155	689	1023	166.4
9	416	56	83	7.77	150	704	1003	165.3
10	647	126	67	13.44	168	399	1050	275.1
11	672	118	0	12.64	158	440	1025	259.1
12	528	72	0	9.6	138	593	1101	187.3
13	528	72	0	9.6	144	587	1091	187.2
14	540	78	32	10.4	143	521	1106	201.5
15	480	72	48	9.6	117	503	1233	187.5
16	616	84	0	11.2	133	436	1180	216.0
17	484	66	0	8.8	124	551	1225	173.1
18	500	75	50	10	125	457	1235	194.5
19	528	72	0	9.6	126	500	1225	187.4
20	528	72	0	9.6	138	491	1202	187.2
21	572	78	0	9.6	130	451	1218	201.1
22	660	90	0	12	150	382	1145	230.1
23	572	78	0	10.4	150	469	1149	201.4
24	630	70	0	11.2	147	357	1195	204.9
25	655	77	39	9.6	146	296	1184	222.0
26	655	77	39	13.09	162	346	1095	224.4
27	660	90	0	12.75	165	467	992	230.2
28	595	70	35	11.9	161	498	1011	205.2
29	650	50	50	12	165	466	991	199.3
30	600	50	50	11.2	161	499	1013	189.5
31	550	50	50	9.6	163	586	1022	179.5
32	550	50	0	9.6	162	586	1022	170.0
33	495	55	0	9.6	165	615	1027	164.5

4.3.5.2 Using JMP Program Molding: Design of Experiments - Response Surface Designs

Creating a Response Surface Design

Response Surface Methodology (RSM) is an experimental technique invented to find the optimal response within specified ranges of the factors.

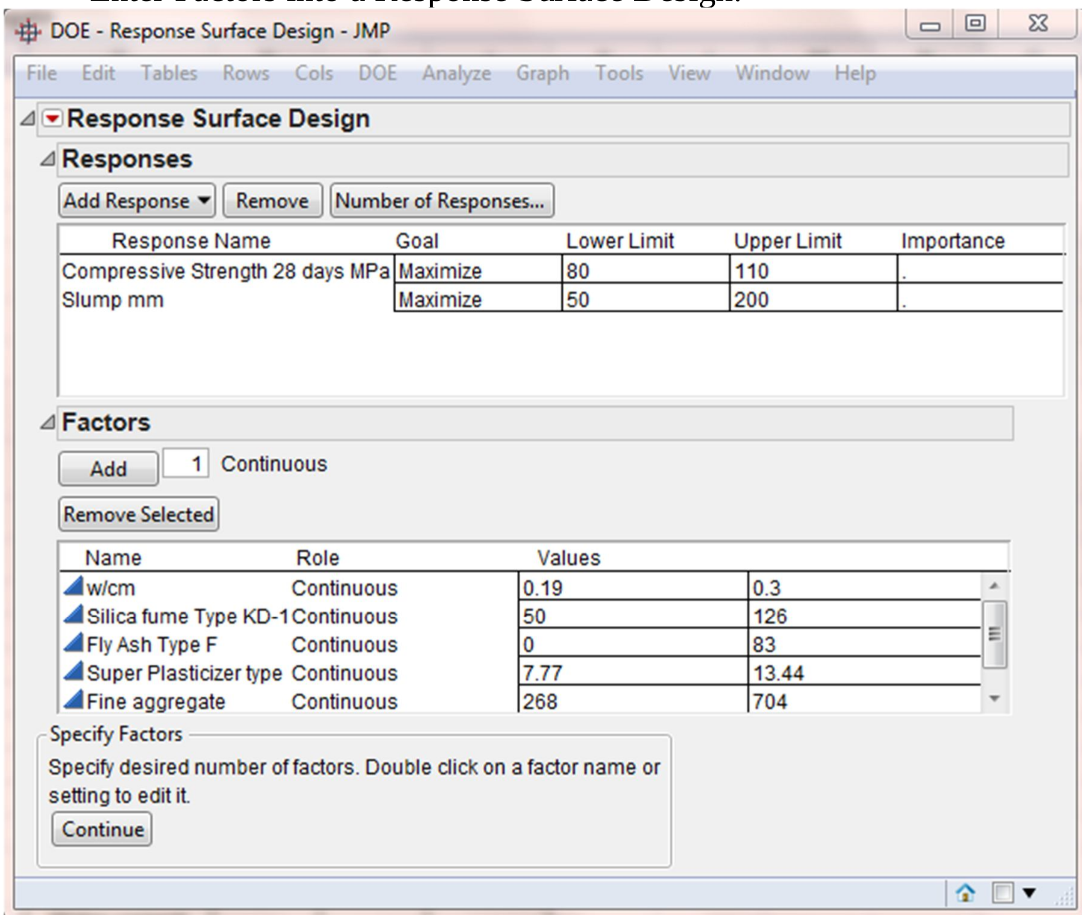
These designs are capable of fitting a second-order prediction equation for the response. The quadratic terms in these equations model the curvature in the true response function. If a maximum or minimum exists inside the factor region, RSM can estimate it. In industrial applications, RSM designs usually involve a small number of factors. This is because the required number of runs increases dramatically with the number of factors. Using the response surface designer, you choose to use well-known RSM designs for two to eight continuous factors. Some of these designs also allow blocking.

Response surface designs are useful for modeling and analyzing curved surfaces.

To start a response surface design, select **DOE > Response Surface Design**, or click the **Response Surface Design** button on the JMP Starter **DOE** page. Then, follow the steps described in the following sections.

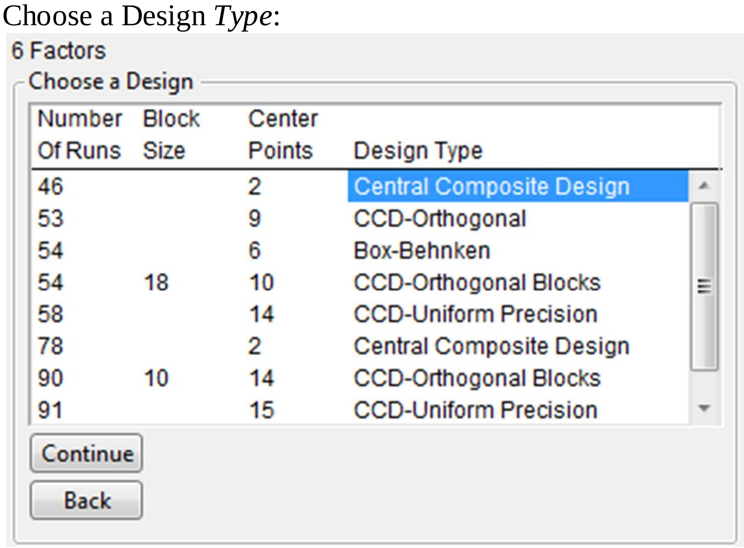
- "Enter Responses and Factors"
- "Choose a Design"
- "Specify Axial Value (Central Composite Designs Only)"
- "Specify Output Options"
- "View the Design Table"

Enter Factors into a Response Surface Design:



Click Continue to proceed to the next step.

Choose a Design *Type*:



Central Composite Designs

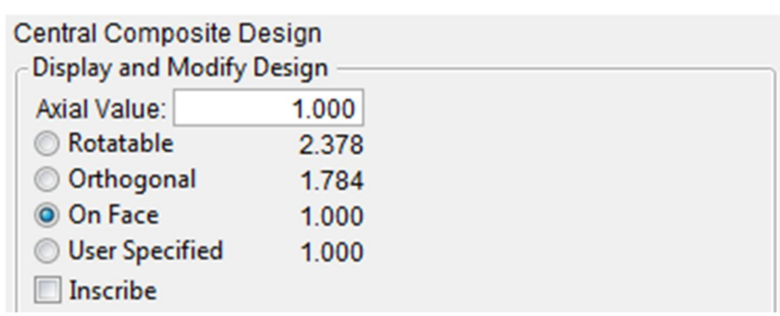
The response surface design list contains two types of central composite designs: uniform precision and orthogonal. These properties of central composite designs relate to the number of center points in the design and to the axial values:

- Uniform precision means that the number of center points is chosen so that the prediction variance near the center of the design space is very flat.
- For orthogonal designs, the number of center points is chosen so that the second order parameter estimates are minimally correlated with the other parameter estimates.

Specify Axial Value (Central Composite Designs Only)

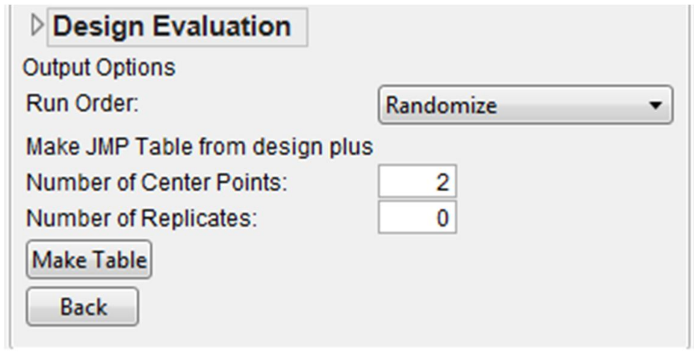
When you select a central composite (CCD-Uniform Precision) design and then click Continue, you see the panel in Display and Modify the Central Composite Design. It supplies default axial scaling information. Entering 1.0 in the text box instructs JMP to place the axial value on the face of the cube defined by the factors, which controls how far out the axial points are. You have the flexibility to enter the values you want to use.

Display and Modify the Central Composite Design:



Specify Output Options

Use the Output Options panel to specify how you want the output data table to appear. When the options are specified the way you want them, click Make Table.



View the Design Table

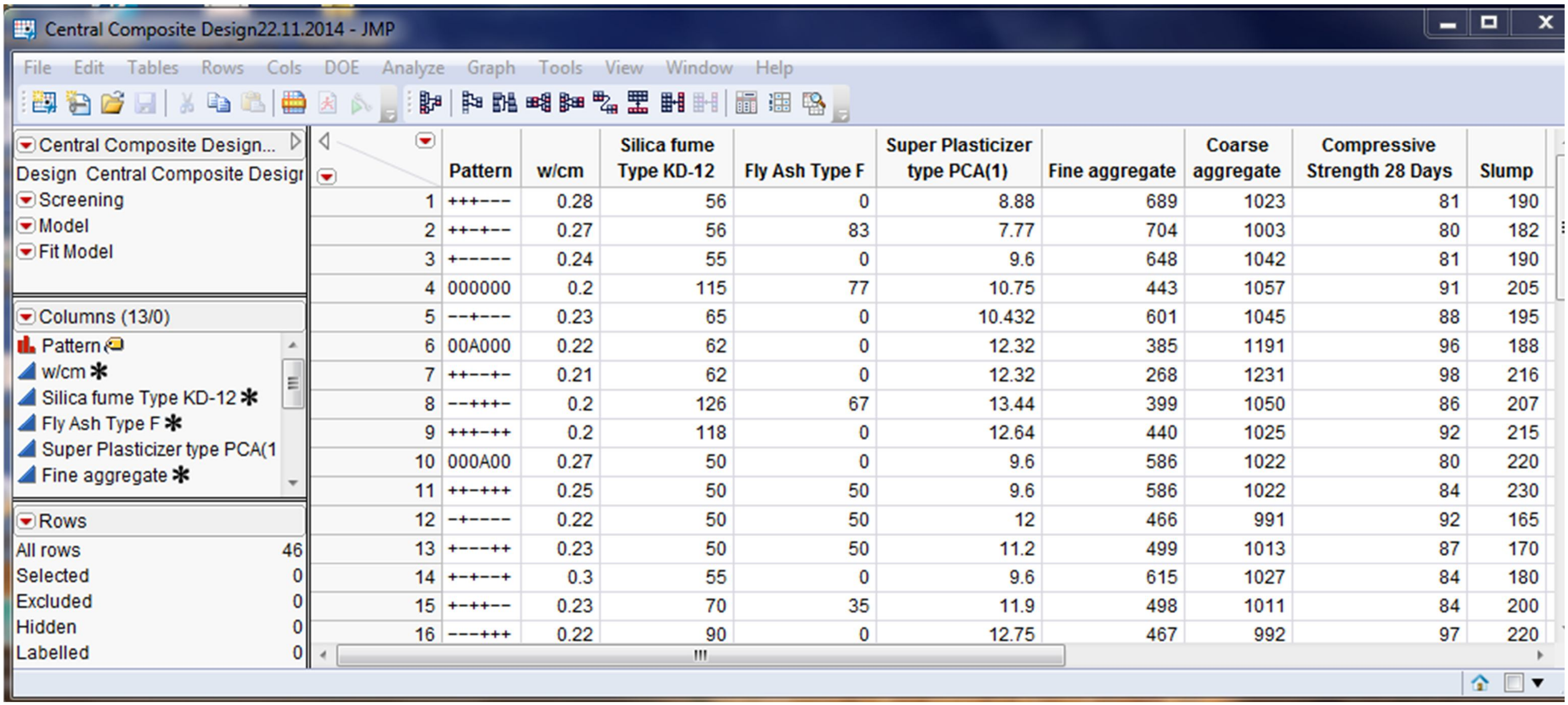
14/9 Cols 46/1 Rows	Pattern	w/cm	Silica fume Type KD-12	Fly Ash Type F	Super Plasticizer type PCA(1)	Fine aggregate	Coarse aggregate	Compressive Strength 28 Days	Slump
1	+++---	0.28	56	0	8.88	689	1023	81	190
2	++-+--	0.27	56	83	7.77	704	1003	80	182
3	+-----	0.24	55	0	9.6	648	1042	81	190
4	000000	0.2	115	77	10.75	443	1057	91	205
5	--+---	0.23	65	0	10.432	601	1045	88	195
6	00A000	0.22	62	0	12.32	385	1191	96	188
7	++--+-	0.21	62	0	12.32	268	1231	98	216
8	--+++-	0.2	126	67	13.44	399	1050	86	207
9	+++-++	0.2	118	0	12.64	440	1025	92	215
10	000A00	0.27	50	0	9.6	586	1022	80	220
11	++-+++	0.25	50	50	9.6	586	1022	84	230
12	-+----	0.22	50	50	12	466	991	92	165
13	+---++	0.23	50	50	11.2	499	1013	87	170
14	+-+--+	0.3	55	0	9.6	615	1027	84	180
15	+-++--	0.23	70	35	11.9	498	1011	84	200
16	---+++	0.22	90	0	12.75	467	992	97	220
17	-+++++	0.19	77	39	9.6	296	1184	105	170
18	-+-++-	0.21	77	39	13.09	346	1095	88	200
19	--+-++	0.21	70	0	11.2	357	1195	89	143
20	000000	0.23	78	0	10.4	469	1149	95	155
21	00000a	0.2	90	0	12	382	1145	101	162
22	00a000	0.23	72	0	9.6	491	1202	105	161
23	+-++++	0.2	75	50	10	457	1235	109	121
24	-++--+	0.2	78	0	9.6	451	1218	100	134
25	-+--++	0.21	72	0	9.6	500	1225	97	159
26	+++++-	0.19	84	0	11.2	436	1180	106	116
27	-++-+-	0.22	78	32	10.4	521	1106	104	215
28	0000A0	0.2	72	48	9.6	503	1233	111	77
29	-----+	0.24	72	0	9.6	587	1091	95	205
30	+-+-+-	0.23	72	0	9.6	593	1101	98	185
31	0000a0	0.23	66	0	8.8	551	1225	104	115
32	--++-+	0.22	65	0	10.4	641	1190	102	125
33	0a0000	0.22	50	0	10	662	1177	103	145
34	000a00	0.28	56	0	8.88	689	1023	81	190
35	----+-	0.27	56	83	7.77	704	1003	80	182
36	00000A	0.24	55	0	9.6	648	1042	81	190
37	++---+	0.2	115	77	10.75	443	1057	91	205
38	A00000	0.23	65	0	10.432	601	1045	88	195
39	a00000	0.22	62	0	12.32	385	1191	96	188
40	---+--	0.21	62	0	12.32	268	1231	98	216
41	-+-+-+	0.2	126	67	13.44	399	1050	86	207
42	++++-+	0.2	118	0	12.64	440	1025	92	215
43	-+++--	0.27	50	0	9.6	586	1022	80	220
44	+--+-+	0.25	50	50	9.6	586	1022	84	230

The name of the table is the design type that generated it.

Run the Model script to fit a model using the values in the design table. The column called Pattern identifies the coding of the factors. It shows all the coding with "+" for high, "–" for low factor, "a" and "A" for low and high axial values, and "0" for midrange. Pattern is suitable to use as a label variable in plots because when you hover over a point in a plot of the factors, the pattern value shows the factor coding of the point. The three rows whose values in the Pattern column are 000 are three center points.

The runs in the Pattern column are in the order you selected from the Run Order menu.

The Ys column is for recording experimental results.(Compressive strength 28 days MPa, Slump mm).



	Pattern	w/cm	Silica fume Type KD-12	Fly Ash Type F	Super Plasticizer type PCA(1)	Fine aggregate	Coarse aggregate	Compressive Strength 28 Days	Slump
1	+++−−−	0.28	56	0	8.88	689	1023	81	190
2	++−+−−	0.27	56	83	7.77	704	1003	80	182
3	+−−−−−	0.24	55	0	9.6	648	1042	81	190
4	000000	0.2	115	77	10.75	443	1057	91	205
5	−−+−−−	0.23	65	0	10.432	601	1045	88	195
6	00A000	0.22	62	0	12.32	385	1191	96	188
7	++−−+−	0.21	62	0	12.32	268	1231	98	216
8	−−+++−	0.2	126	67	13.44	399	1050	86	207
9	+++−++	0.2	118	0	12.64	440	1025	92	215
10	000A00	0.27	50	0	9.6	586	1022	80	220
11	++−+++	0.25	50	50	9.6	586	1022	84	230
12	−+−−−−	0.22	50	50	12	466	991	92	165
13	+−−−++	0.23	50	50	11.2	499	1013	87	170
14	+−+−−+	0.3	55	0	9.6	615	1027	84	180
15	+−++−−	0.23	70	35	11.9	498	1011	84	200
16	−−−+++	0.22	90	0	12.75	467	992	97	220

CHAPTER FIVE

PRESENTATION AND DISCUSSION OF RESULTS

CHAPTER FIVE
PRESENTATION AND DISCUSSION OF RESULTS

5.1- Introduction

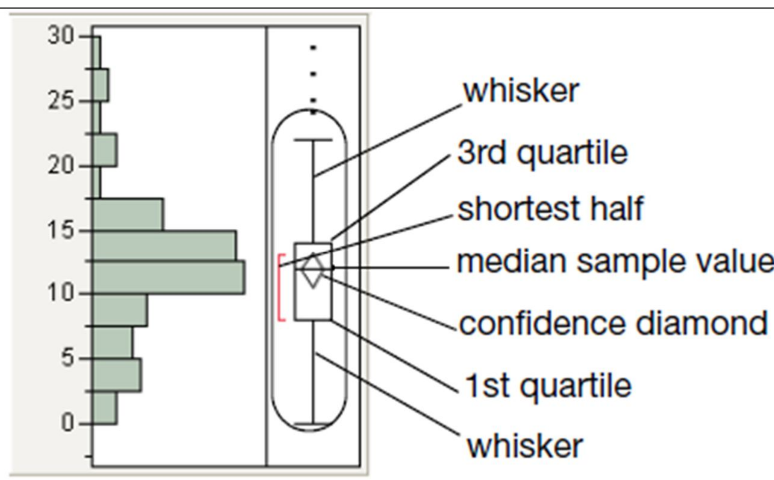
In this is chapter the tests results were present, cube compressive strength tests, slump tests and length change tests (drying shrinkage tests), different relationship from two statistical approaches which were given in chapter four are presented and discussed.

5.2- Compressive Strength

Fig.(5.1) shows the distributions of strength for 28 days concrete for the different grades. it is clear that it was possible to produce high strength concrete (up to 110 MPa) with stable and acceptable rate of strength gain. Different relations were obtained from data accumulated from the tests results. High strength concrete shows a higher rate of strength gain with age than normal strength, and Table(5.1) shows the results of concrete compressive strength for 28 days.

Key:

Outlier box plots:



Note the following aspects about outlier box plots:
The vertical line within the box represents the median sample value.

The confidence diamond contains the mean and the upper and lower 95% of the mean. If you drew a line through the middle of the diamond, you would have the mean. The top and bottom points of the diamond represent the upper and lower 95% of the mean.
The ends of the box represent the 25th and 75th quantiles, also expressed as the 1st and 3rd *quartile*, respectively.
The difference between the 1st and 3rd quartiles is called the *interquartile range*.
The box has lines that extend from each end, sometimes called *whiskers*. The whiskers extend from the ends of the box to the outermost data point that falls within the distances computed as follows: 1st quartile - 1.5*(interquartile range) 3rd quartile + 1.5*(interquartile range) If the data points do not reach the computed ranges, then the whiskers are determined by the upper and lower data point values (not including outliers).
The bracket outside of the box identifies the *shortest half*, which is the most dense 50% of the observations

Table (5.1) Concrete compressive strength for 28 days

Test No	Casting Date	Test Date	Measured Compressive Strength(Mpa) for 28 days									Ave Compressive Strength (Mpa) for 28days
1	30-Oct-09	27-Nov-09	82.6	81	79.6	72.3	82.4	80.4				81.2
2	31-Oct-09	28-Nov-09	82.4	82.3	80.9	77	78.9	78.4				80.0
3	6-Nov-09	4-Dec-09	79.9	89.7	83.5	76.2	78.2	77.9				80.9
4	11-Nov-09	9-Dec-09	87	76.6	90.5	90.8	88.2	98.9				91.1
5	14-Nov-09	12-Dec-09	92.8	65.8	85	85.4	85.5	89.4				87.6
6	5-Dec-09	2-Jan-10	102.2	85.9	93.6	97.9	92	96.2				96.4
7	6-Dec-09	3-Jan-10	90	102	85.6	102.9	91.2	102.5				97.7
8	7-Dec-09	4-Jan-10	85.1	88.5	85.2							86.3
9	7-Dec-09	4-Jan-10	91.8	94.7	88.6							91.7
10	13-Jan-10	10-Feb-10	82.7	66.6	85	71.3	76.3	86.2				80.3
11	14-Jan-10	11-Feb-10	79	81.8	87.4	91.8	89.1	73.4				83.7
12	15-Jan-10	12-Feb-10	79.5	97.5	83.8	102.4	85.9	100.1				91.5
13	15-Jan-10	12-Feb-10	83.4	80.3	84.7	81.4	100.2	91.7				87.0
14	20-Jan-10	17-Feb-10	82.8	85.1	80.7	79	93.5	84.2				84.2
15	26-Jan-10	23-Feb-10	74.4	75.6	85.2	94	94	77.6				83.5
16	28-Jan-10	25-Feb-10	100.9	96.4	92.4	102.6	97.5	91.7				96.9
17	29-Jan-10	26-Feb-10	107.8	102.4	109.8	98.4	108.1	104.9				105.2
18	29-Jan-10	26-Feb-10	88.9	85.6	85.9	85	84.5	99.2				88.2
19	8-Feb-10	8-Mar-10	79.6	90.5	80.9	95.5	91.3	93.2				88.5
20	11-Feb-10	11-Mar-10	106.7	99.6	93.8	93.7	85.2	92.4				95.3
21	15-Feb-10	15-Mar-10	103.9	90.6	101.6	103	102.3	102.2				100.6
22	17-Feb-10	17-Mar-10	116	103.5	103.4	94	99.2	112.3				104.7
23	19-Feb-10	19-Mar-10	116.7	110.1	109.3	105.5	106.1	107.5				109.2
24	19-Feb-10	19-Mar-10	91.1	113.9	94.5	94.7	93.8	114.3				100.4
25	21-Feb-10	21-Mar-10	99.7	99.6	97.7	96.7	85.6	102.4				96.9
26	24-Feb-10	24-Mar-10	106	105.6	107.9	103.6	105.6	108.2				106.1
27	25-Feb-10	25-Mar-10	108.2	98.2	113.2	96.9	105.4	103.8				104.3
28	28-Feb-10	28-Mar-10	110.9	106.9	109.6	109	107.5	107.6	115	112	116.7	110.6
29	1-Mar-10	29-Mar-10	102.1	105.5	107.6	84.9	81.7	85.2				94.5
30	21-Mar-10	18-Apr-10	106.7	104.1	100.5	83.3	106.8	85.9				97.9
31	31-Mar-10	28-Apr-10	106.4	98.6	105.8	103.3	100	104.6	98.9	106.6	107.8	103.6
32	14-Apr-10	12-May-10	103.1	95.1	102.9	108	104.9	100.5				102.4
33	25-Apr-10	23-May-10	101	105.2	101.9	103	101.7	104				102.8

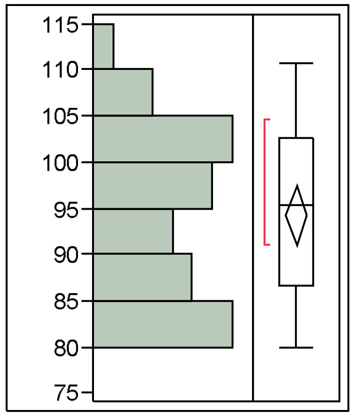


Figure (5.1) Distributions of Ave compressive strength for 28 days

Results Discussion:

From table (5.1) and figure (5.1), we can observe that, we have 33 trials mix design and we have 66 runs every three cube is consider one run, we are used local aggregate, 21 trials mix granite is blue font in the table4.1and 12 trials mix marble is blackfont in the table4.1, the minimum compressive strength for 28 days is 80(MPa), the maximum once up to 110 (MPa), these mean we are achieve the desired aim to produce high strength concrete.

5.3- Slump test results

Table (5.2) Concrete Slump Test Results

Test No	Casting Date	Measured Slump mm		Ave Slump mm
1	30-Oct-09	190	190	190.0
2	31-Oct-09	181	183	182.0
3	6-Nov-09	191	189	190.0
4	11-Nov-09	205	205	205.0
5	14-Nov-09	195	195	195.0
6	5-Dec-09	187	189	188.0
7	6-Dec-09	217	215	216.0
8	7-Dec-09	207	207	207.0
9	7-Dec-09	215	214	215.0
10	13-Jan-10	220	220	220.0
11	14-Jan-10	230	229	230.0
12	15-Jan-10	165	165	165.0
13	15-Jan-10	169	171	170.0
14	20-Jan-10	181	179	180
15	26-Jan-10	200	200	200.0
16	28-Jan-10	220	220	220.0
17	29-Jan-10	171	169	170.0
18	29-Jan-10	200	200	200.0
19	8-Feb-10	142	144	143.0
20	11-Feb-10	155	155	155.0
21	15-Feb-10	163	161	162.0
22	17-Feb-10	160	162	161.0
23	19-Feb-10	122	120	121.0
24	19-Feb-10	133	135	134.0
25	21-Feb-10	158	160	159.0
26	24-Feb-10	115	117	116.0
27	25-Feb-10	215	215	215.0
28	28-Feb-10	78	76	77.0
29	1-Mar-10	205	205	205.0
30	21-Mar-10	185	185	185.0
31	31-Mar-10	114	115	115.0
32	14-Apr-10	125	125	125.0
33	25-Apr-10	146	144	145.0

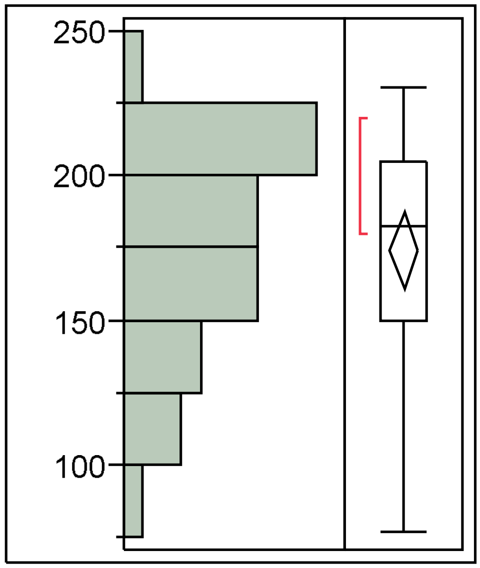


Figure (5.2) Distributions of Concrete Slump Test Result

Results Discussion:

The design slump range is (50~200mm) from table (5.2) and figure (5.2) above we can see all the results were above the minimum limit, minimum slump =77mm, but we had 8 test exceed the maximum limit slightly.

5.4- Concrete compressive strength for 28 days(MPa) vs. Mixtures components.

Table (5.3) Concrete compressive strength for 28 days, Slump Test Result, Cost and it components.

Test No	Casting Date	Test Date	Ave Compressive Strength (Mpa) for 28days	Slump mm	Aggregate Types	W/Cm Ratio	Cement (kg/m^3)	Silica Fumetype KD-12 (kg/m3)	Fly Ash (kg/m3)	Super Plasticizer type PCA(1) (kg/m3)	Water (kg/m3)	Fine Aggregate (kg/m3)	Coarse Aggregate (kg/m3)	Cost of m3 $
1	30-Oct-09	27-Nov-09	81.2	190.0	marble	0.28	500	56	0	8.88	155	689	1023	166.4
2	31-Oct-09	28-Nov-09	80.0	182.0	marble	0.27	416	56	83	7.77	150	704	1003	165.3
3	6-Nov-09	4-Dec-09	80.9	190.0	marble	0.24	545	55	0	9.6	145	648	1042	174.4
4	11-Nov-09	9-Dec-09	91.1	205.0	marble	0.2	587	115	77	10.75	154	443	1057	253.5
5	14-Nov-09	12-Dec-09	87.6	195.0	marble	0.23	587	65	0	10.432	147	601	1045	192.2
6	5-Dec-09	2-Jan-10	96.4	188.0	marble	0.22	708	62	0	12.32	169	385	1191	213.2
7	6-Dec-09	3-Jan-10	97.7	216.0	marble	0.21	670	62	0	12.32	162	268	1231	205.4
8	7-Dec-09	4-Jan-10	86.3	207.0	marble	0.2	647	126	67	13.44	168	399	1050	275.1
9	7-Dec-09	4-Jan-10	91.7	215.0	marble	0.2	672	118	0	12.64	158	440	1025	259.1
10	13-Jan-10	10-Feb-10	80.3	220.0	granite	0.27	550	50	0	9.6	162	586	1022	170.0
11	14-Jan-10	11-Feb-10	83.7	230.0	granite	0.25	550	50	50	9.6	163	586	1022	179.5
12	15-Jan-10	12-Feb-10	91.5	165.0	granite	0.22	650	50	50	12	165	466	991	199.3
13	15-Jan-10	12-Feb-10	87.0	170.0	granite	0.23	600	50	50	11.2	161	499	1013	189.5
14	20-Jan-10	17-Feb-10	84.2	180	granite	0.3	495	55	0	9.6	165	615	1027	164.5
15	26-Jan-10	23-Feb-10	83.5	200.0	granite	0.23	595	70	35	11.9	161	498	1011	205.2
16	28-Jan-10	25-Feb-10	96.9	220.0	granite	0.22	660	90	0	12.75	165	467	992	230.2
17	29-Jan-10	26-Feb-10	105.2	170.0	granite	0.19	655	77	39	9.6	146	296	1184	222.0
18	29-Jan-10	26-Feb-10	88.2	200.0	granite	0.21	655	77	39	13.09	162	346	1095	224.4
19	8-Feb-10	8-Mar-10	88.5	143.0	granite	0.21	630	70	0	11.2	147	357	1195	204.9
20	11-Feb-10	11-Mar-10	95.3	155.0	granite	0.23	572	78	0	10.4	150	469	1149	201.4
21	15-Feb-10	15-Mar-10	100.6	162.0	granite	0.2	660	90	0	12	150	382	1145	230.1
22	17-Feb-10	17-Mar-10	104.7	161.0	granite	0.23	528	72	0	9.6	138	491	1202	187.2
23	19-Feb-10	19-Mar-10	109.2	121.0	granite	0.2	500	75	50	10	125	457	1235	194.5
24	19-Feb-10	19-Mar-10	100.4	134.0	granite	0.2	572	78	0	9.6	130	451	1218	201.1
25	21-Feb-10	21-Mar-10	96.9	159.0	granite	0.21	528	72	0	9.6	126	500	1225	187.4
26	24-Feb-10	24-Mar-10	106.1	116.0	granite	0.19	616	84	0	11.2	133	436	1180	216.0
27	25-Feb-10	25-Mar-10	104.3	215.0	granite	0.22	540	78	32	10.4	143	521	1106	201.5
28	28-Feb-10	28-Mar-10	110.6	77.0	granite	0.2	480	72	48	9.6	117	503	1233	187.5
29	1-Mar-10	29-Mar-10	94.5	205.0	granite	0.24	528	72	0	9.6	144	587	1091	187.2
30	21-Mar-10	18-Apr-10	97.9	185.0	granite	0.23	528	72	0	9.6	138	593	1101	187.3
31	31-Mar-10	28-Apr-10	103.6	115.0	marble	0.23	484	66	0	8.8	124	551	1225	173.1
32	14-Apr-10	12-May-10	102.4	125.0	marble	0.22	585	65	0	10.4	140	641	1190	193.0
33	25-Apr-10	23-May-10	102.8	145.0	marble	0.22	575	50	0	10	138	662	1177	176.6

Result Discussion

Table (5.3) presents Concrete compressive strength for 28 days, Slump Test Results, Cost and it components, and we are used the table to analysis the data by JMP statistical program to show many relationships as presented below.

5.4.1 Concrete compressive strength for 28 days (MPa)vs. Aggregate types.

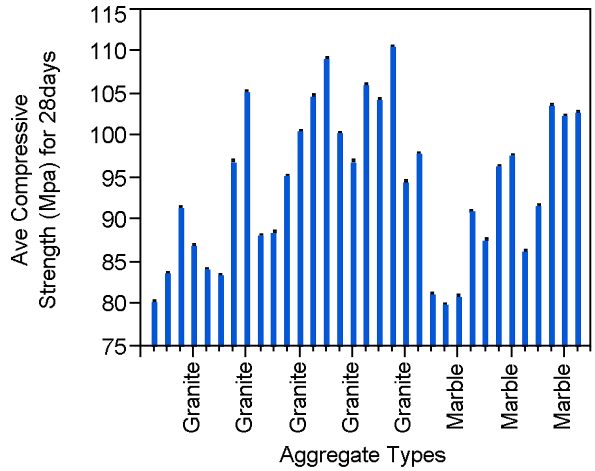


Figure (5.3)Distributions of Concrete compressive strength 28days (MPa) for two type of aggregate, Granite and Marble

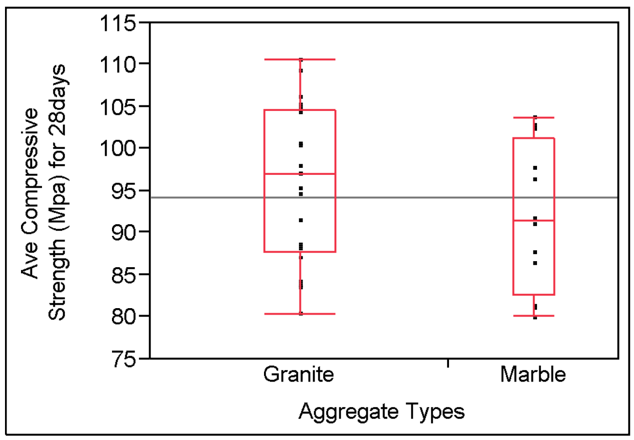


Figure (5.4) One-way Analysis of Ave Compressive Strength (MPa) for 28days by Aggregate Types

Result Discussion:

From figure (5.3) and (5.4) we can find that the minimum compressive strength for 28days is 80 (MPa) and the maximum compressive strength for 28days for granite is 110.6 (MPa) and maximum once for marble is 103.6 (MPa), we can conclude that both types of aggregate can produce high strength concrete.

5.4.2 Concrete compressive strength for 28 days(MPa) vs. w/cm ratio.

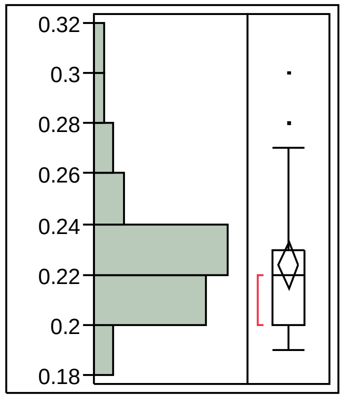
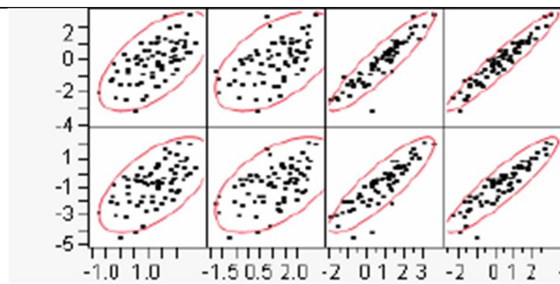


Figure (5.5) Distributions of w-cm ratio

Key:

Ellipse shape



By default, a 95% bivariate normal density ellipse is shown in each scatter-plot. Assuming the variables are bivariate normally distributed, this ellipse encloses approximately 95% of the points. The narrowness of the ellipse shows the correlation of the variables. If the ellipse is fairly round and is not diagonally oriented, the variables are uncorrelated. If the ellipse is narrow and diagonally oriented, the variables are correlated.

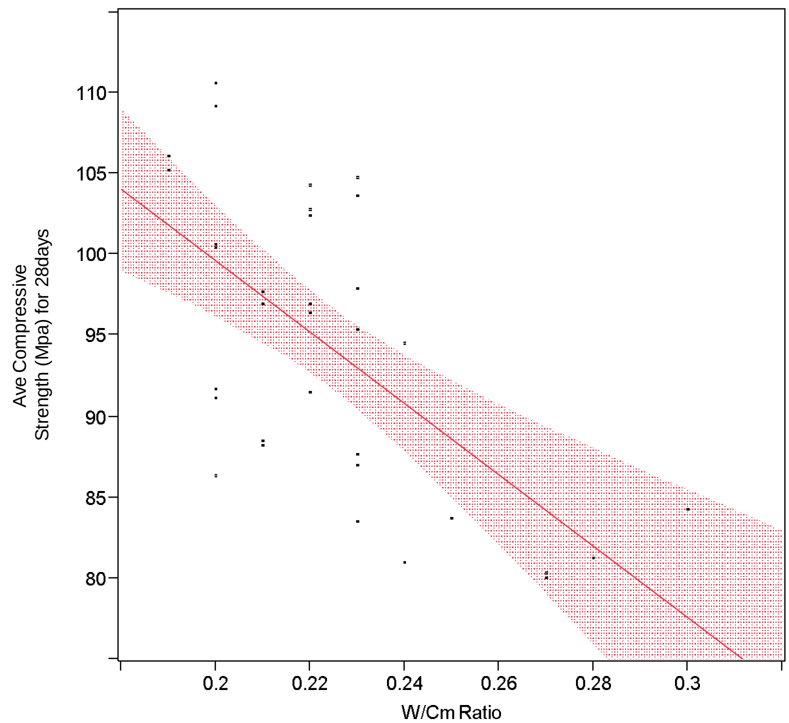


Figure (5.6) Multivariate relationship between 28 days compressive strength MPa and w/cm ratio

Result Discussion:

From figure (5.5) and (5.6) we can find that the minimum w/cm ratio used was 0.19 and the maximum once is 0.3 and from figure 4.5 we can observe that most of distribution between 0.2~0.24. And from figure 4.6 the relationship between compressive strength 28 days (MPa) and w/cm ratio is strong inverse relationship, when one quantity increases the other decreases. For example, when w/cm ratio is increased, the compressive strength decreases.

5.4.3Concrete compressive strength for 28 days(MPa) vs. Silica Fume type KD-12.

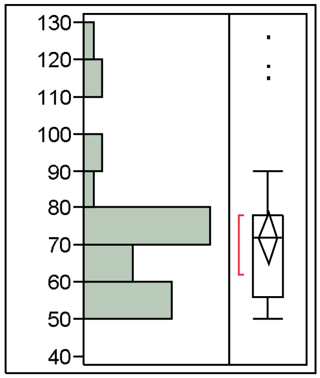


Figure (5.7)Distributions of silica fume type KD-12

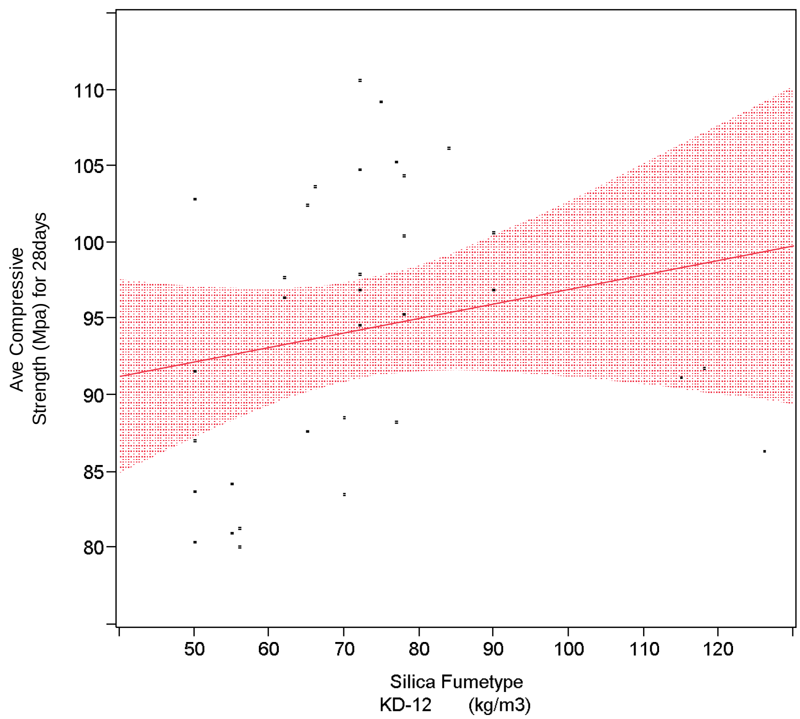


Figure (5.8) Multivariate relationship between 28 days compressive strength (MPa) and silica fume type KD-12

Result Discussion:

From figure 4.7 and 4.8 we can find that the minimum silica fume type KD-12 is 50 kg and this 6.7% of cementunise materials and the maximum is 126 kg and this 15% of cementunise materials.The relationship between compressive strength 28 days (MPa) and Silica fume type KD-12 is direct relationshipboth physical quantities may increase or decrease simultaneously.

5.4.4 Concrete compressive strength for 28 days(MPa) vs. Fly Ash type F.

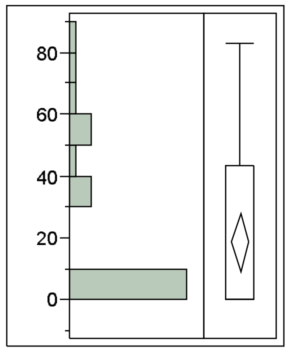


Figure (5.9) Distributions of fly ash

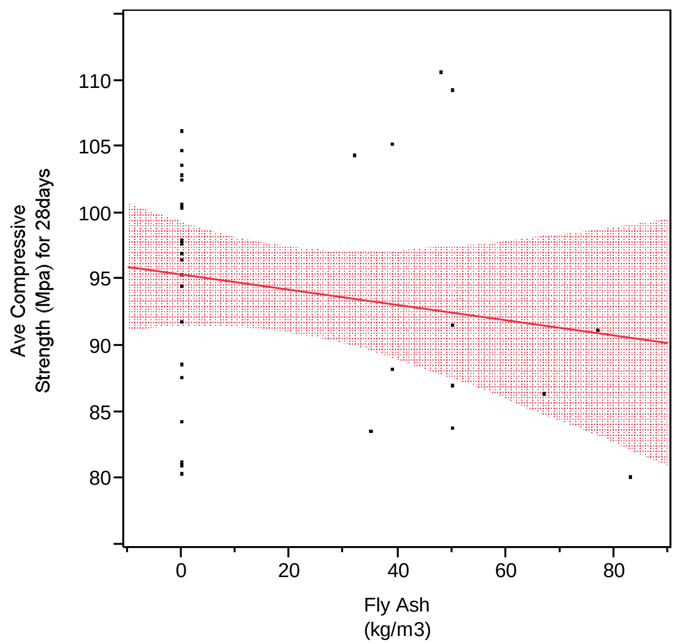


Figure (5.10) Multivariate relationship between 28 days compressive strength (MPa) and fly ash

Result Discussion:

From figure 4.9 and 4.10 we can find that the minimum fly ash is zero that means some trial mixes it used silica fume only and did not add fly ash, the maximum is 83 kg it is 15% of cementunise materials,The relationship between compressive strength 28 days (MPa) and fly ash type (F) is inverse relationship, because fly ash type (F) is effect in direct relationship when the age of concrete reach 90 days and above but in 28 days there are no positive effect.

5.4.5 Concrete compressive strength for 28 days (MPa)vs. super-plasticizer type PCA(1)

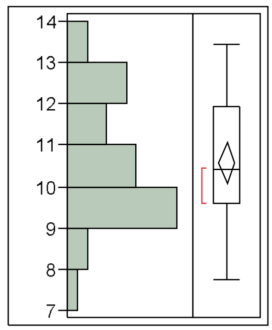


Figure (5.11) Distributions of *super-plasticizer type PCA(1)*

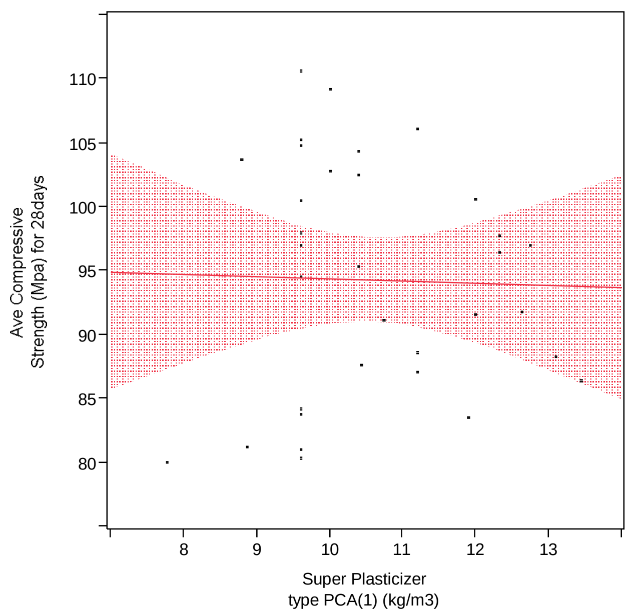


Figure (5.12) Multivariate relationship between 28 days compressive strength (MPa) and super-plasticizer type PCA(1)

Result Discussion:

From figure 4.11 and 4.12 we can find that the minimum super-plasticizer type PCA (1) is 7.77 kg and the maximum once is 13.44

kg,The relationship between compressive strength 28 days (MPa) and Super-plasticizer type PCA (1)is there is no effect.

5.4.6 Concrete compressive strength for 28 days(MPa) vs. Fine Aggregate

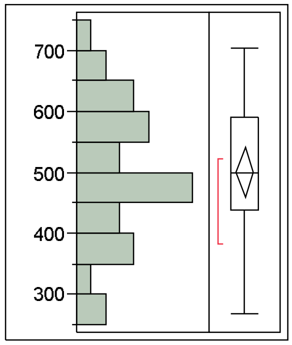


Figure (5.13) Distributions of Sand

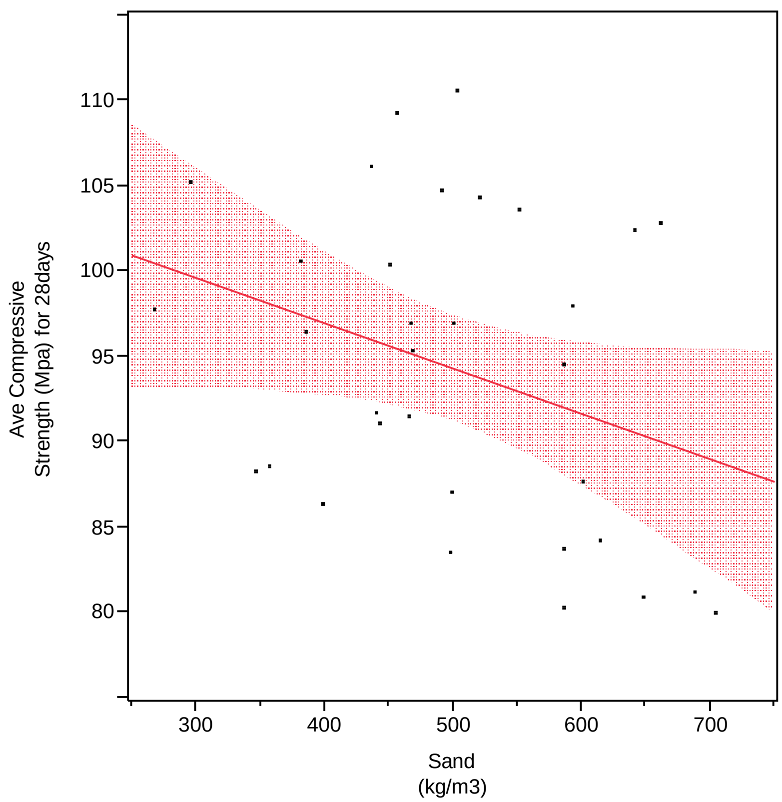


Figure (5.14) Multivariate relationship between 28 days compressive strength (MPa) and Sand

Result Discussion:

From figure 4.13 and 4.14 we can find that the minimum fine aggregate is 268 kg and the maximum once is 704kg,the relationship between compressive strength 28 days (MPa) and fine aggregateis inverse relationship.

5.4.7 Concrete compressive strength for 28 days (MPa)vs. Coarse Aggregate

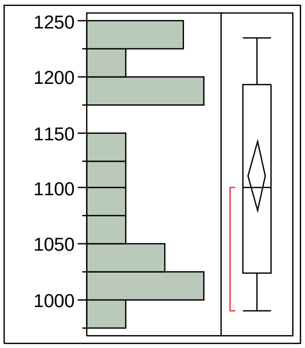


Figure (5.15) Distributions of Coarse aggregate

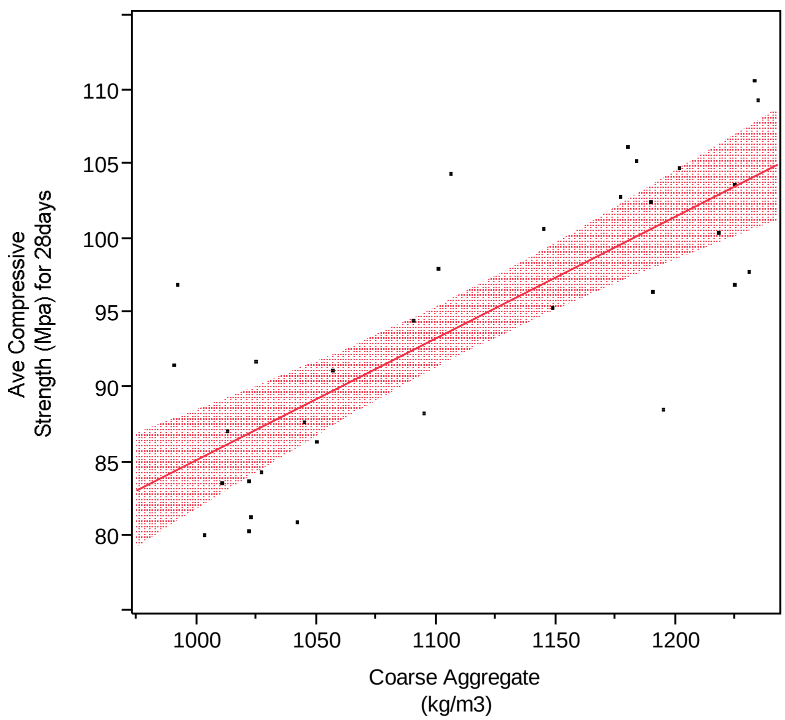


Figure (5.16) Multivariate relationship between 28 days compressive strength (MPa) and coarse aggregate

Result Discussion:

From figure (5.15) and(5.16)we can find that the minimum coarse aggregate is 991 kg and the maximum once is 1235kg,the relationship between compressive strength 28 days (MPa) and Coarse aggregate is strongdirect relationship. That means the local aggregate is main factor in produce high strength concrete.

5.5- Concrete compressive strength for 28 days(MPa) vs. Cost $m^3$$.

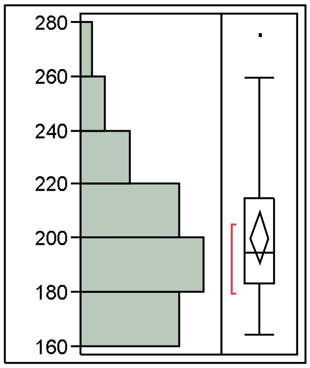


Figure (5.17) Distributions of Cost

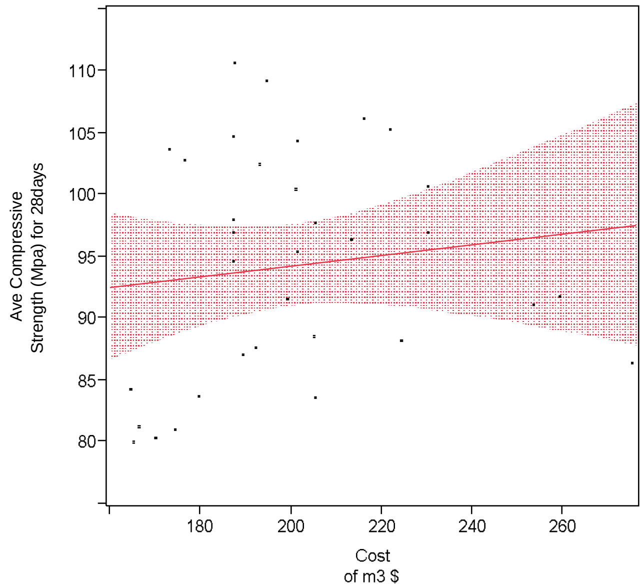


Figure (5.18) the relationship between 28 days compressive strength (MPa) and cost

Result Discussion:

From figure (5.17) and (5.18) we can find that the minimum cost is 164.5and the maximum once is 275.1,the relationship between compressive strength 28 days (MPa) and cost is direct relationship.

5.6- Concrete compressive strength for 28 days (MPa) vs. Concrete compressive strength for 7days (MPa).

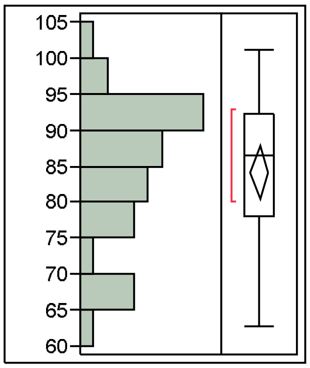


Figure (5.19) Ave Compressive Strength (MPa) for 7days

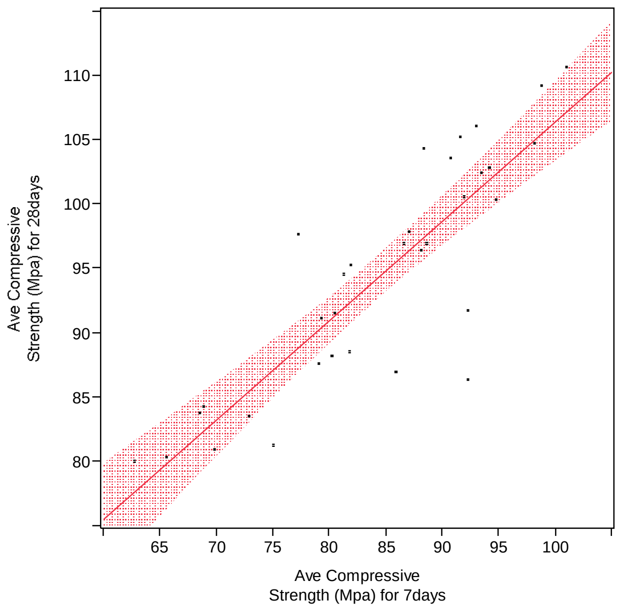


Figure (5.20) Multivariate relationship between 28 days compressive strength (MPa) and compressive strength 7 days (MPa)

Result Discussion:

From figure (5.19) and (5.20) we can find that the minimum compressive strength for 7 days is 62.7 (MPa) and the maximum once is 101(MPa),the relationship between compressive strength 28 days (MPa) and compressive strength for 7 days is strong direct relationship.

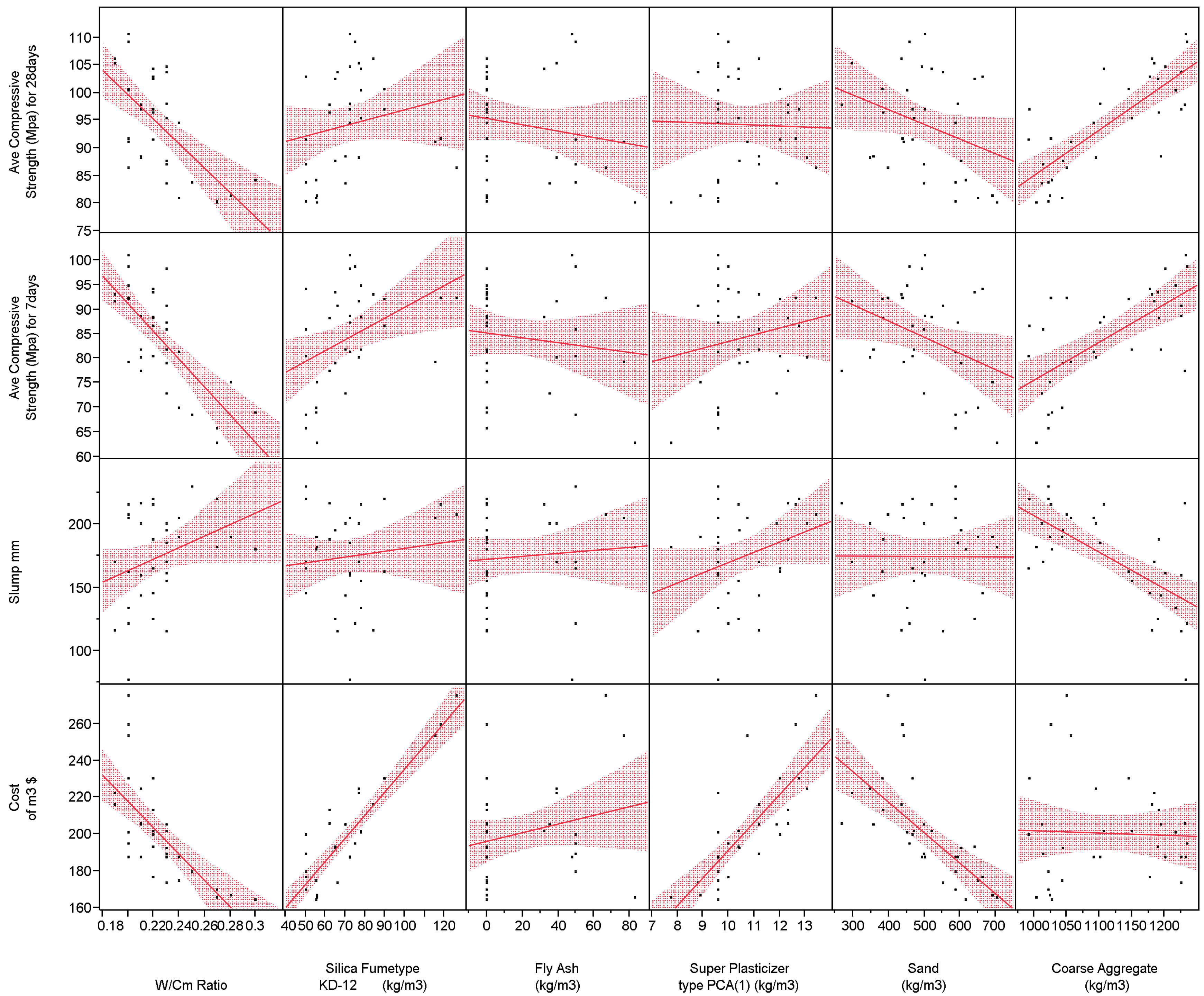


Figure (5.21) Multivariate relationship between 28 days compressive strength (MPa), compressive strength 7 days (MPa) and Cost with all mixture compounds.

5.7- Multivariate relationship between 28 days compressive strength (MPa), compressive strength 7 days (MPa) and Cost with all mixture compounds.

Result Discussion:

28 days Compressive strength (MPa) and other compounds:

From figure(5.21) we can observe that the relationship between 28 days compressive strength (MPa) and w/cm ratio is strong inverse relationship in an inverse relationship, when one quantity increases the other decreases. For example, when w/cm ratio is increased, the compressive strength decreases.

The relationship between 28 days compressive strength (MPa) and Silica fume type KD-12 is direct relationship both physical quantities may increase or decrease simultaneously.

The relationship between28 days compressive strength (MPa) and fly ash type (F) is inverse relationship, because fly ash type (F) is effect in direct relationship when the age of concrete reach 90 days and above but in 28 days there are no positive effect.

There is no effect in the relationship between28 days compressive strength (MPa) and Super-plasticizer type PCA (1).

The relationship between compressive strength 28 days (MPa) and Sandis inverse relationship.

The relationship between compressive strength 28 days (MPa) and Coarse aggregate is strongdirect relationship.

7 days Compressive strength (MPa) and other compounds:

From figure (5.21) we can observe that the relationship between compressive strength 7 days (MPa) and w/cm ratio is stronginverse relationshipin an inverse relationship, when one quantity increases the other decreases. For example, when w/cm ratio is increased, the compressive strength decreases.

The relationship between compressive strength 7 days (MPa) and Silica fume type KD-12 is direct relationshipboth physical quantities may increase or decrease simultaneously.

The relationship between compressive strength 7 days (MPa) and fly ash type (F) is inverse relationship, because fly ash type (F) is effect in direct relationship when the age of concrete reach 90 days and above but in 7days there are no positive effect.

The relationship between compressive strength 7 days (MPa) and Super-plasticizer type PCA (1)is direct relationship.

The relationship between compressive strength 7 days (MPa) and Sand is inverse relationship.

The relationship between compressive strength 7 days (MPa) and Coarse aggregate is strong direct relationship.

And we can observe that there are same effects at 7 days and 28 days that means the both in very strong relationship.

Slump (mm) and other compounds:

The relationship between Slump (mm) and w/cm is strong direct relationship.

The relationship between Slump (mm) and Silica fume type KD-12 is direct relationship.

The relationship between Slump (mm) andfly ash type (F) is direct relationship.

The relationship between Slump (mm) and Super-plasticizer type PCA (1) is direct relationship.

The relationship between Slump (mm) and sand is direct relationship.

The relationship between Slump (mm) and Coarse aggregate is strong inverse relationship.

Cost (m^3)$and other compounds:

From figure(5.21)we can observe that the relationship between cost (m^3)$ and w/cm ratio is stronginverse relationship.

The relationship between cost (m^3) $and Silica fume type KD-12 is strong direct relationship.

The relationship between cost (m^3) $andfly ash type (F) is direct relationship.

The relationship between cost (m^3) $and Super-plasticizer type PCA (1) is strong direct relationship.

The relationship between cost (m^3) $and Sand is stronginverse relationship.

The relationship between cost (m^3) $and Coarse aggregate is inverse relationship.

5.8 Optimum Proportions

Tables (5.5) presents the optimum mix proportions for the grade 80 (MPa),Tables (5.7)presents the optimum mix proportions for the grade 90 (MPa),Tables(5.9)presents the optimum mix proportions for the grade 100 (MPa)which were used in the dam construction project. From the tables it is clear that there are three different grades of high strength concrete (80, 90, 100MPa) were successfully produced using local Sudanese aggregates and silica fume and silica fume with fly ash. w/cm ratios 0.19~0.3 were found to produce the maximum values of strength in the different grades of concrete. SF and FA replacements in the range of 6.7 to 15% and zero to 15% of cementunise materials respectively, were found in the optimum combinations of ingredients to produce high strength concrete. Cement content between 390 and 560 Kg/m^3 for the three grades.

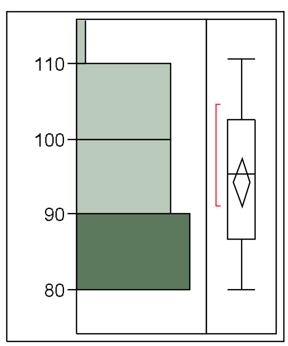


Figure (5.22) Categories of Ave Compressive Strength (MPa) for 28days (above 80 MPa, above 90 MPa and above 100 MPa)

Result Discussion:

From above result it is clear that all concrete compressive strength results were above 80 MPa (minimum concrete strength=80 MPa for all

33 trials tests), and we can divide it to three categories above 80, 90 and 100 MPa. Tables *(5.4, 5.6 and 5.8)* were present the result.

Table (5.4) Concrete Compressive strength above 80MPafor28days and Cost estimation

Test No	Casting Date	Test Date	Ave Compressive Strength (Mpa) for 28days	Slump mm	Aggregate Types	W/Cm Ratio	Cement (kg/m^3)	Silica Fumetype KD-12 (kg/m3)	Fly Ash (kg/m3)	Super Plasticizer type PCA(1) (kg/m3)	Water (kg/m3)	Fine Aggregate (kg/m3)	Coarse Aggregate (kg/m3)	Cost of m3 $
1	30-Oct-09	27-Nov-09	81.2	190	Marble	0.28	500	56	0	8.88	155	689	1023	166.4
2	31-Oct-09	28-Nov-09	80	182	Marble	0.27	416	56	83	7.77	150	704	1003	165.3
3	6-Nov-09	4-Dec-09	80.9	190	Marble	0.24	545	55	0	9.6	145	648	1042	174.4
5	14-Nov-09	12-Dec-09	87.6	195	Marble	0.23	587	65	0	10.432	147	601	1045	192.2
8	7-Dec-09	4-Jan-10	86.3	207	Marble	0.2	647	126	67	13.44	168	399	1050	275.1
10	13-Jan-10	10-Feb-10	80.3	220	Granite	0.27	550	50	0	9.6	162	586	1022	170
11	14-Jan-10	11-Feb-10	83.7	230	Granite	0.25	550	50	50	9.6	163	586	1022	179.5
13	15-Jan-10	12-Feb-10	87	170	Granite	0.23	600	50	50	11.2	161	499	1013	189.5
14	20-Jan-10	17-Feb-10	84.2	180	Granite	0.3	495	55	0	9.6	165	615	1027	164.5
15	26-Jan-10	23-Feb-10	83.5	200	Granite	0.23	595	70	35	11.9	161	498	1011	205.2
18	29-Jan-10	26-Feb-10	88.2	200	Granite	0.21	655	77	39	13.09	162	346	1095	224.4
19	8-Feb-10	8-Mar-10	88.5	143	Granite	0.21	630	70	0	11.2	147	357	1195	204.9

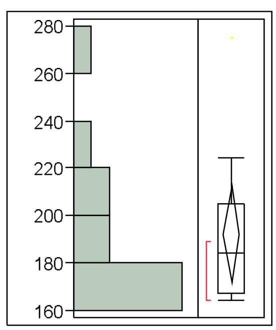


Figure (5.23) Distributions Cost of m^3 *$for compressive strength above 80 MPa*

Result Discussion:

We have 12 tests had achieved score above 80 MPa, and the cost for the concrete meter cube distributions show that the minimum cost=164.5$ mix design No.14, in the second order of least cost was mix design No.2 it cost is 165.3$ and In the third order of least cost was mix design No.1 it cost is 166.4$. So the best trial mix design for 80 MPa are: Mix No.14, 2and1.

Table (5.5)The optimum mix proportions for the grade 80 MPa.

No	Test No	Casting Date	Test Date	Ave Compressive Strength (Mpa) for 28days	Slump mm	Aggregate Types	W/Cm Ratio	Cement (kg/m^3)	Silica Fumetype KD-12 (kg/m3)	Fly Ash (kg/m3)	Super Plasticizer type PCA(1) (kg/m3)	Water (kg/m3)	Fine Aggregate (kg/m3)	Coarse Aggregate (kg/m3)	Cost of m3 $
1	14	20-Jan-10	17-Feb-10	84.2	180	Granite	0.3	495	55	0	9.6	165	615	1027	164.5
2	2	31-Oct-09	28-Nov-09	80	182	Marble	0.27	416	56	83	7.77	150	704	1003	165.3
3	1	30-Oct-09	27-Nov-09	81.2	190	Marble	0.28	500	56	0	8.88	155	689	1023	166.4

Table (5.6) Concrete Compressive strength above 90MPafor28days and Cost estimation

Test No	Casting Date	Test Date	Ave Compressive Strength (Mpa) for 28days	Slump mm	Aggregate Types	W/Cm Ratio	Cement (kg/m^3)	Silica Fumetype KD-12 (kg/m3)	Fly Ash (kg/m3)	Super Plasticizer type PCA(1) (kg/m3)	Water (kg/m3)	Fine Aggregate (kg/m3)	Coarse Aggregate (kg/m3)	Cost of m3 $
4	11-Nov-09	9-Dec-09	91.1	205	Marble	0.2	587	115	77	10.75	154	443	1057	253.5
6	5-Dec-09	2-Jan-10	96.4	188	Marble	0.22	708	62	0	12.32	169	385	1191	213.2
7	6-Dec-09	3-Jan-10	97.7	216	Marble	0.21	670	62	0	12.32	162	268	1231	205.4
9	7-Dec-09	4-Jan-10	91.7	215	Marble	0.2	672	118	0	12.64	158	440	1025	259.1
12	15-Jan-10	12-Feb-10	91.5	165	Granite	0.22	650	50	50	12	165	466	991	199.3
16	28-Jan-10	25-Feb-10	96.9	220	Granite	0.22	660	90	0	12.75	165	467	992	230.2
20	11-Feb-10	11-Mar-10	95.3	155	Granite	0.23	572	78	0	10.4	150	469	1149	201.4
25	21-Feb-10	21-Mar-10	96.9	159	Granite	0.21	528	72	0	9.6	126	500	1225	187.4
29	1-Mar-10	29-Mar-10	94.5	205	Granite	0.24	528	72	0	9.6	144	587	1091	187.2
30	21-Mar-10	18-Apr-10	97.9	185	Granite	0.23	528	72	0	9.6	138	593	1101	187.3

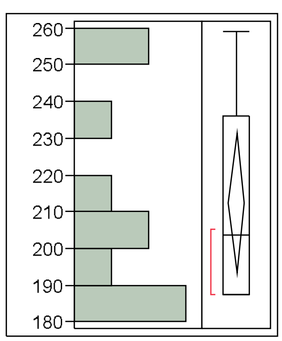


Figure (5.24) Distributions Cost of m3 $ for compressive strength above 90 MPa

Result Discussion:

We have 10 tests had achieved score above 90 MPa, and the cost for the concrete meter cube distributions show that the minimum cost=187.2$ mix design No.29, in the secondorder ofleastcost was mix design No.30 it cost is 187.3$ and In the thirdorder ofleastcost was mix design No.25 it cost is 187.4$. So the best trial mix design for 90 MPa are: Mix No.29, 30 and 25.

Table (5.7) The optimum mix proportions for the grade 90 MPa.

No	Test No	Casting Date	Test Date	Ave Compressive Strength (Mpa) for 28days	Slump mm	Aggregate Types	W/Cm Ratio	Cement (kg/m^3)	Silica Fumetype KD-12 (kg/m3)	Fly Ash (kg/m3)	Super Plasticizer type PCA(1) (kg/m3)	Water (kg/m3)	Fine Aggregate (kg/m3)	Coarse Aggregate (kg/m3)	Cost of m3 $
1	29	1-Mar-10	29-Mar-10	94.5	205	Granite	0.24	528	72	0	9.6	144	587	1091	187.2
2	30	21-Mar-10	18-Apr-10	97.9	185	Granite	0.23	528	72	0	9.6	138	593	1101	187.3
3	25	21-Feb-10	21-Mar-10	96.9	159	Granite	0.21	528	72	0	9.6	126	500	1225	187.4

Table (5.8) Concrete Compressive strength above 100MPafor28days and Cost estimation

Test No	Casting Date	Test Date	Ave Compressive Strength (Mpa) for 28days	Slump mm	Aggregate Types	W/Cm Ratio	Cement (kg/m^3)	Silica Fumetype KD-12 (kg/m3)	Fly Ash (kg/m3)	Super Plasticizer type PCA(1) (kg/m3)	Water (kg/m3)	Fine Aggregate (kg/m3)	Coarse Aggregate (kg/m3)	Cost of m3 $
17	29-Jan-10	26-Feb-10	105.2	170	Granite	0.19	655	77	39	9.6	146	296	1184	222
21	15-Feb-10	15-Mar-10	100.6	162	Granite	0.2	660	90	0	12	150	382	1145	230.1
22	17-Feb-10	17-Mar-10	104.7	161	Granite	0.23	528	72	0	9.6	138	491	1202	187.2
23	19-Feb-10	19-Mar-10	109.2	121	Granite	0.2	500	75	50	10	125	457	1235	194.5
24	19-Feb-10	19-Mar-10	100.4	134	Granite	0.2	572	78	0	9.6	130	451	1218	201.1
26	24-Feb-10	24-Mar-10	106.1	116	Granite	0.19	616	84	0	11.2	133	436	1180	216
27	25-Feb-10	25-Mar-10	104.3	215	Granite	0.22	540	78	32	10.4	143	521	1106	201.5
28	28-Feb-10	28-Mar-10	110.6	77	Granite	0.2	480	72	48	9.6	117	503	1233	187.5
31	31-Mar-10	28-Apr-10	103.6	115	Marble	0.23	484	66	0	8.8	124	551	1225	173.1
32	14-Apr-10	12-May-10	102.4	125	Marble	0.22	585	65	0	10.4	140	641	1190	193
33	25-Apr-10	23-May-10	102.8	145	Marble	0.22	575	50	0	10	138	662	1177	176.6

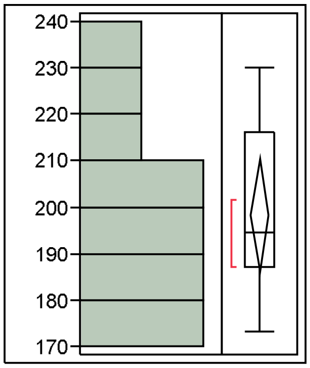


Figure (5.25) Distributions Cost of m3 $ for compressive strength above 100 MPa

Result Discussion:

We have 11 tests had achieved score above 100 MPa, and the cost for the concrete meter cube distributions show that the minimum cost=173.1$ mix design No.31, in the secondorder ofleastcost was mix design No.33 it cost is 176.6$ and In the thirdorder ofleastcost was mix design No.22 it cost is 187.2$. So the best trial mix design for 90 MPa are: Mix No.31, 33 and 22.

Table (5.9) The optimum mix proportions for the grade 100 MPa.

No	Test No	Casting Date	Test Date	Ave Compressive Strength (Mpa) for 28days	Slump mm	Aggregate Types	W/Cm Ratio	Cement (kg/m^3)	Silica Fumetype KD-12 (kg/m3)	Fly Ash (kg/m3)	Super Plasticizer type PCA(1) (kg/m3)	Water (kg/m3)	Fine Aggregate (kg/m3)	Coarse Aggregate (kg/m3)	Cost of m3 $
1	31	31-Mar-10	28-Apr-10	103.6	115	Marble	0.23	484	66	0	8.8	124	551	1225	173.1
2	33	25-Apr-10	23-May-10	102.8	145	Marble	0.22	575	50	0	10	138	662	1177	176.6
3	22	17-Feb-10	17-Mar-10	104.7	161	Granite	0.23	528	72	0	9.6	138	491	1202	187.2

Result Discussion:

From tables 4.5, 4.7 and4.9 we are calculate the least cost for m^3 according to statically approach which describe in ACI 211.4 and it consider the optimum mix design for the three grads(80,90 and 100MPa) for 80MPa the mixes No.14,2and 14,for 90MPa the mixes No.29,30and

25 and for 100MPa the mixes No.31,33and 22.Summary of tables(5.5,5.7 and 5.9) for optimum mixes are presented below:

Mix No	Cement (kg/m³)	Silica Fumetype KD-12 (kg/m³)	Fly Ash (kg/m3)	Super Plasticizer type PCA(1) (kg/m³)	Water (kg/m³)	Sand (kg/m³)	Coarse Aggregate (kg/m³)	
1	540	78	32	10.4	143	521	1106	80 MPa
2	585	65	0	10.4	140	641	1190	
3	575	50	0	10	138	662	1177	
4	650	50	50	12	165	466	991	90 MPa
5	600	50	50	11.2	161	499	1013	
6	655	77	39	9.6	146	296	1184	
7	550	50	50	9.6	163	586	1022	100 MPa
8	495	55	0	9.6	165	615	1027	
9	660	90	0	12	150	382	1145	

5.9- JMP statistical program Modeling result

5.9.1 Actual Compressive strength 28 days (MPa) and Predicted Compressive strength 28 days (MPa)

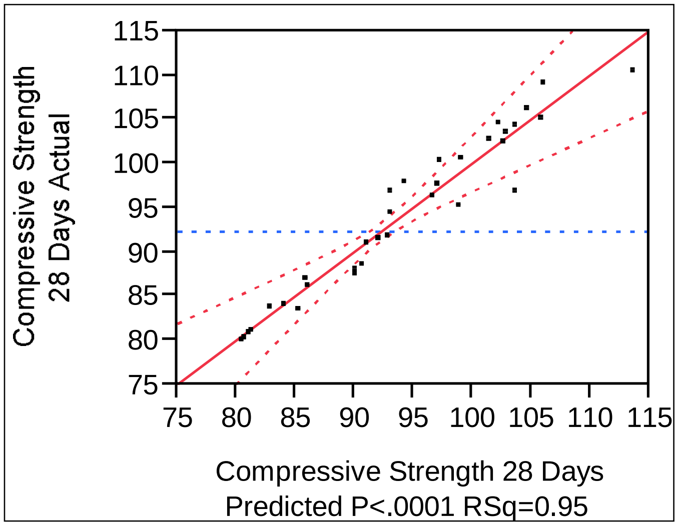


Figure (5.26) from JMP Modeling, Actual Compressive strength 28 days (MPa) and Predicted Compressive strength 28 days (MPa)

Predicted Compressive strength 28 days (MPa) equation:

Compressive Strength 28 days (MPa) =

96.3544184091129 + 4.11879756823741 * ((: Coarse Aggregate - 1113) / 122) + 8.81642084158031 * ((("w/cm") - 0.245) / 0.055) + 8.14096928246595 * ((:Sand - 486) / 218) + ((("w/cm") - 0.245) / 0.055) * (((("w/cm") - 0.245) / 0.055) * 8.46015019895674) + ((:Coarse Aggregate - 1113) / 122) * (((:Sand - 486) / 218) * 10.0704111144517) + ((:Coarse Aggregate - 1113) / 122) * (((:Fly Ash - 41.5) / 41.5) * 1.7719682883693) + ((("w/cm") - 0.245) / 0.055) * (((:Fly Ash - 41.5) / 41.5) * -4.08845461678596) + ((:Sand - 486) / 218) * (((:Fly Ash - 41.5) / 41.5) * 2.65469147864433) + ((:Fly Ash - 41.5) / 41.5) * (((:Fly Ash - 41.5) / 41.5) * 1.69669121462046) + ((("w/cm") - 0.245) / 0.055) * (((:Super-plasticizer - 10.605) / 2.835) * 0.060179037706117) + ((:Fly Ash - 41.5) / 41.5) * (((:Super- plasticizer - 10.605) / 2.835) * 0.373067435141173) + ((:Coarse Aggregate - 1113) / 122) * (((:Silica Fume - 88) / 38) * -7.07262372201201) + ((("w/cm") - 0.245) / 0.055) * (((:Silica Fume - 88) / 38) * 11.5797131450517) + ((:Sand - 486) / 218) * (((:Silica Fume - 88) / 38) * 9.37907602385322) + ((:Fly Ash - 41.5) / 41.5) * (((:Silica Fume - 88) / 38) * -3.30210318980605) + ((:Silica Fume - 88) / 38) * (((:Silica Fume - 88) / 38) * -2.06725192449431) + ((("w/cm") - 0.245) / 0.055) * (((("w/cm") - 0.245) / 0.055) * (((("w/cm") - 0.245) / 0.055) * -10.2044168811532))

5.9.2 Actual Slump (mm) and Predicted Slump (mm)

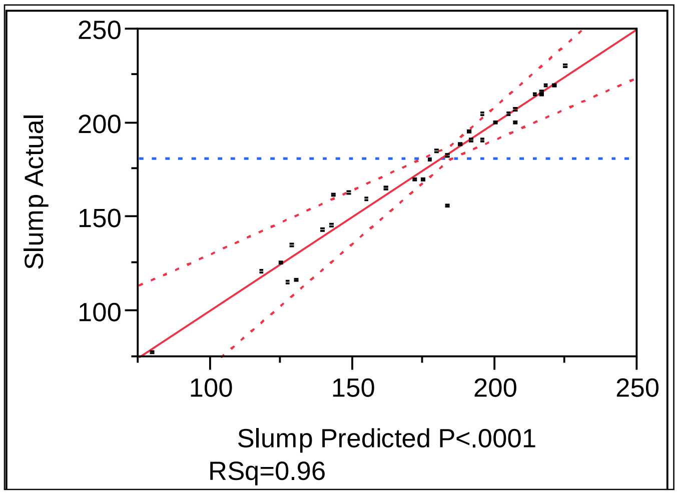


Figure (5.27) From JMP Modeling ,Actual Slump (mm) and Predicted Slump (mm)

Predicted Slump (mm) equation:

Slump (mm) =

181.028028387334 + -83.7732447036604 * ((: Coarse Aggregate - 1113) / 122) + 6.37648062036651 * ((:Sand - 486) / 218) + -4.74312539977284 * ((:Fly Ash - 41.5) / 41.5) + 18.8240310844349 * ((:Name("w/cm") - 0.245) / 0.055) + -17.1275465427219 * ((:Silica Fume - 88) / 38) + ((:Coarse Aggregate - 1113) / 122) * (((:Coarse Aggregate - 1113) / 122) * -6.23349509357676) + ((:Coarse Aggregate - 1113) / 122) * (((:Sand - 486) / 218) * 17.844980179676) + ((:Sand - 486) / 218) * (((:Sand - 486) / 218) * 26.7413753300967) + ((:Coarse Aggregate - 1113) / 122) * (((:Fly Ash - 41.5) / 41.5) * -11.4449723847269) + ((:Coarse Aggregate - 1113) / 122) * (((:Name("w/cm") - 0.245) / 0.055) * -13.6954482857792) + ((:Sand - 486) / 218) * (((:Name("w/cm") - 0.245) / 0.055) * -21.6564970275253) + ((:Coarse Aggregate - 1113) / 122) * (((:Silica Fume - 88) / 38) * -87.9806564606583) + ((:Name("w/cm") - 0.245) / 0.055) * (((:Silica Fume - 88) / 38) * 14.3690107928093) + ((:Coarse Aggregate - 1113) / 122) * (((:Super- plasticizer - 10.605) / 2.835) *

46.719323185576) + ((:Sand - 486) / 218) * (((:Super- plasticizer - 10.605) / 2.835) * 27.5144297260682) + ((:Fly Ash - 41.5) / 41.5) * (((:Super plasticizer - - 10.605) / 2.835) * 9.07661549276688) + ((:Coarse Aggregate - 1113) / 122) * (((:Coarse Aggregate - 1113) / 122) * (((:Coarse Aggregate - 1113) / 122) * - 9.49342563476495)) + ((:Coarse Aggregate - 1113) / 122) * (((:Coarse Aggregate - 1113) / 122) * (((:Sand - 486) / 218) * -41.3422828294282)) + ((:Coarse Aggregate - 1113) / 122) * (((:Sand - 486) / 218) * (((:Sand - 486) / 218) * -100.601423708651)) + ((:Sand - 486) / 218) * (((:Sand - 486) / 218) * (((:Sand - 486) / 218) * - 105.6361141195))

Table (5.10) From JMP Modeling The Predicted compressive strength28 days(MPa) and Predicted Slump(mm)

Test No	Compressive Strength 28days(Mpa)	Slump (mm)	Predicted Compressive Strength 28days(Mpa)	Predicted Slump (mm)
1	102.8	145	100.9347525	140.1424
2	102.4	125	103.9170139	126.9448
3	97.7	216	95.60168308	215.5752
4	96.4	188	97.06626875	186.9326
5	87.6	195	88.59024668	203.735
6	91.1	205	91.99175678	208.4006
7	80.9	190	82.30613001	194.1667
8	81.2	190	81.5225167	183.0659
9	80	182	80.60790439	184.4972
10	86.3	207	85.09439633	208.1903
11	91.7	215	93.42806932	214.788
12	97.9	185	94.82337872	193.9162
13	94.5	205	94.68673894	200.3792
14	104.3	215	96.16855335	185.579
15	110.6	77	113.1813267	107.3607
16	106.1	116	103.9656454	135.809
17	103.6	115	103.5263967	126.7868
18	109.2	121	109.2078038	103.2725
19	96.9	159	102.9670397	135.0619
20	104.7	161	99.16703301	150.4427
21	100.4	134	102.1214425	122.6285
22	100.6	162	94.61164179	145.2861
23	95.3	155	95.9896066	170.7396
24	88.5	143	96.47715012	166.6624

Test No	Compressive Strength 28days(Mpa)	Slump (mm)	Predicted Compressive Strength 28days(Mpa)	Predicted Slump (mm)
25	105.2	170	102.9417269	165.6175
26	88.2	200	95.17642906	196.492
27	96.9	220	92.87055685	210.2172
28	83.5	200	89.11081385	199.155
29	91.5	165	88.83504028	172.1097
30	87	170	86.86111848	183.6875
31	83.7	230	82.35797703	201.4051
32	80.3	220	81.93894773	202.4333
33	84.2	180	83.08203813	206.7856

Result Discussion:

From figure(5.24) and (5.25) we can find that we have strong direct relationship r^2=0.95 for actual and predicted compressive strength28 days (MPa) and r^2=0.96for actual and predicted Slump (mm).that means the model have strong value to predicted compressive strength and slum, and it can use it for further high strength concrete mix proportion in Sudan.

5.10- Relationship between HSC and drying shrinkage

Table (5.11) The result of concrete compressive strength and drying shrinkage

Date	Water (kg/m3)	w/cm	Ave Slump (mm)	Compressive Strength 28 days(MPa)	Drying Shrinkage % 28 days	Drying Shrinkage % 56 days
20.3.2011	168	0.28	150	88.7	0.012	0.04
10.4.2011	168	0.28	148	100.8	0.01	0.022
18.4.2011	168	0.28	148	114.4	0.0067	0.0253
27.4.2011	169	0.26	150	89	0.0164	0.042
28.4.2011	169	0.26	150	107.1	0.0208	0.0499
1.5.2011	168	0.28	121	109.1	0.016	0.032
6.5.2011	169	0.26	148	93.4	0.01	0.024
7.5.2011	169	0.26	138	101.5	0.018	0.024
12.5.2011	168	0.28	145	105.9	0.0213	0.0347
14.5.2011	169	0.26	150	95.6	0.0107	0.036
16.5.2011	169	0.26	145	100.1	0.0173	0.0267
17.5.2011	169	0.26	85	105.3	0.008	0.0233

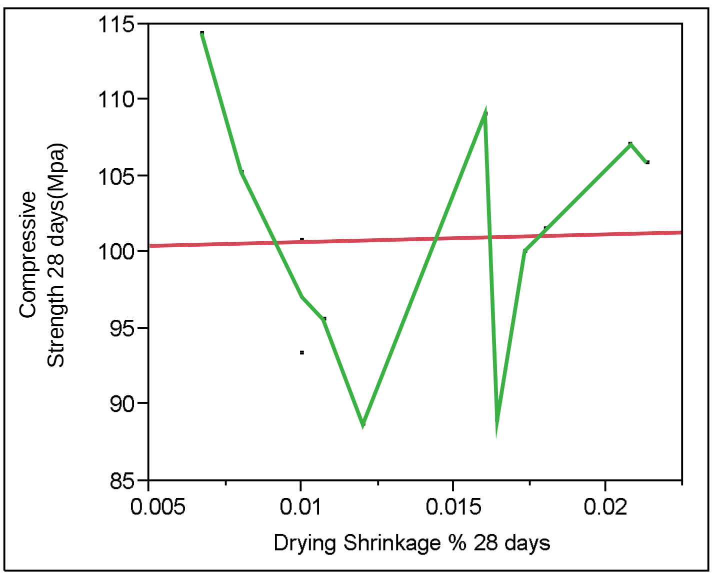


Figure (5.28) Relationship between compressive strength at 28 days (MPa) and drying shrinkage 28 days

Compressive Strength 28 days (MPa) = 100.21211 + 49.968173*Drying Shrinkage % 28 days

R Square	0.00096
Observations	12

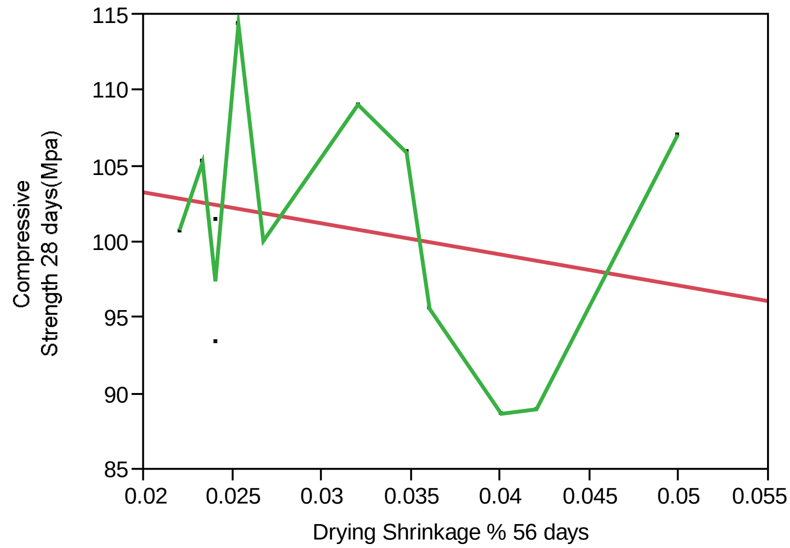


Figure (5.29) Relationship between compressive strength at 28 days (MPa) and drying shrinkage 56days

Compressive Strength 28 days (MPa) = 107.41863 - 205.64233*Drying Shrinkage % 56 days

R Square	0.052733
Observations	12

Result Discussion:

We have 12 tests for concrete compressive strength 28 days (MPa) and drying shrinkage percentage at 28 days and 56 days, we can observed that all compressive strength were above 80 MPa minimum is 88.7 and the drying shrinkage percentage increase with time at 28 days maximum is 0.0213 while 0.0499 at 56 days. the relationship between the compressive strength(MPa) for 28 days and the drying shrinkage percentage for 28 and 56 days were very weak r^2 =0.00096 and 0.052733 respectively .

We can conclusion that there are no relationship between HSC and drying shrinkage percentage.

5.11- Summary of results

1. We have 33 trials mixes designs, 21 trials mixes granite aggregate and 12 trials mixes marble aggregate, the minimum compressive strength for 28 days is 80(MPa), the maximum once up to 110 (MPa), this means that we achieved the desired aim to produce high strength concrete.
2. The design slump range is (50~200mm) the results which were obtained above the minimum limit, minimum slump =77mm, but we had 8 test exceed the maximum limit slightly.
3. From two points above we are satisfy hardened properties and fresh properties for high strength concrete.
4. For both type of aggregate granite from north of Sudan and marble from south of Sudan which we are used in the tests the minimum compressive strength for 28days is 80 (MPa) and the maximum compressive strength for 28days for granite is 110.6 (MPa) and maximum once for marble is 103.6 (MPa), we can conclusion that the both type of aggregate can produce high strength concrete.
5. The relationship between compressive strength 28 days (MPa) and w/cm ratio is stronginverse relationshipin an inverse relationship, when one quantity increases the other decreases. For example, when w/cm ratio is increased, the compressive strength decreases.
6. The relationship between compressive strength 28 days (MPa) and Silica fume type KD-12 is direct relationshipboth physical quantities may increase or decrease simultaneously.
7. The relationship between compressive strength 28 days (MPa) and fly ash type (F) is inverse relationship, because fly ash type (F) is effect in direct relationship when the age of concrete reach 90 days and above but in 28 days there are no positive effect.

8. The relationship between compressive strength 28 days (MPa) and Super-plasticizer type PCA (1)is there is no effect.
9. The relationship between compressive strength 28 days (MPa) and fine aggregateis inverse relationship.
10. The relationship between compressive strength 28 days (MPa) and Coarse aggregate is strongdirect relationship. That means the local aggregate is main factor in produce high strength concrete.
11. The relationship between compressive strength 28 days (MPa) and compressive strength for 7 days is strong direct relationship.
12. The relationship between compressive strength 28 days (MPa) and cost is direct relationship.
13. according to statically approach which describe in ACI 211.4 it consider the optimum mix design for the three grads(80,90 and 100MPa) for 80MPa the mixes No.14,2and 14, for 90MPa the mixes No.29,30and 25 and for 100MPa the mixes No.31,33and 22.
14. We are achieve predicted equations from JMP statistical program to predict compressive strength 28 days (MPa) and Slump(mm) for high strength concrete which is use local Sudanese aggregate granite and marble.
15. The drying shrinkage percentage increase with time, but there are no relationship between HSC and drying shrinkage percentage.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1CONCLUSIONS

Based on the findings of this study the following conclusions were made:

1. If we are use local aggregate with supplementary materials (silica fume and fly ash) and ordinary Portland cement with their optimum proportioning can be successfully used with other chemical admixtures (Super-plasticizer) to produce high strength concrete.
2. We are achieving predicted equations from JMP statistical program to predict 28 days compressive strength (MPa) and Slump (mm).
3. The results of the present investigation indicated that the maximum compressive strength occurred at about 6.7 to 15% Silica fume content.
4. The present study shows that the maximum values of compressive strength for different grades were obtained at water-cementitious materials ratios between 0.19 and 0.3.
5. The drying shrinkage percentage increase with time, but there are no relationship between HSC and drying shrinkage percentage.
6. both type of aggregate granite from north of Sudan and marble from south of Sudan which we are used in the tests the minimum compressive strength for 28days is 80 (MPa) and the maximum compressive strength for 28days for granite is 110.6 (MPa) and maximum once for marble is 103.6 (MPa), we can conclusion that the both type of aggregate can produce high strength concrete.
7. The relationship between 28 days compressive strength (MPa) and cost is direct relationship.

6.2 RECOMMENDATION

6.2.1 RECOMMENDATION FROM THE STUDY

1. Regards to cost consideration, try to reduce Silica fume content and Super-plasticizer or replace it by others local materials if available.
2. Recommended that to use marble and granite coarse aggregate in high strength concrete in Sudan.

6.2.2RECOMMENDATION FOR FURTHER RESEARCH

1. Use statistical approach and JMP statistical software to predict equations for high strength concrete proprieties for another type of aggregate in Sudan.
2. Use statistical approach and JMP statistical software to predict equation for splitting tensile strength and flexural strength.
3. Study the ability of use local supplementary materials in high strength concrete.
4. Study the effect of long term more than 90 days of supplementary materials.
5. Consideration of harm full effect of use of supplementary materials in special case.

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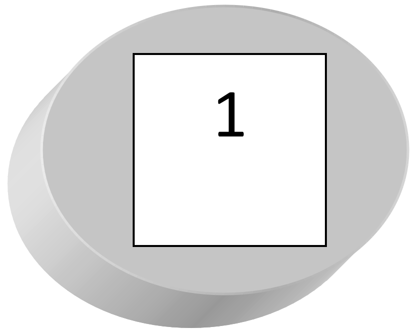
APPENDICES

Appendix A- Concrete Compressive Strength, Slump and Drying shrinkage Test Results



Trial Mix Design No.Q4-27

Quarry 4 Aggregate

Silica Fume % (10)

Fly Ash % (zero)

ROSEIRES DAM HEIGHTENING PROJECT

CONTRACT NO.1

Trial Test on Concrete Mix Design

CCMD JV SITE LABORATORY

Mix Design No.	Strength Class	Max Agg. Size (mm)	Design Slump (mm)	Testing Standard	Trial Test No.	Testing Date
Q4-27	M80/A20(fc'=80MPa)	20	150-200	BS EN 12390-2	Q4-27-4	30-Oct-09

Cement	Manufacturer	Guangxi Yufeng	Fly Ash	Manufaturer	Shandong Zouxian	Silica Fume	Manufacturer	Shanxi Kaidi		Water Reducing Agent	Manufacturer & Type	Beijing Lili, FS-G-III	Room Temp. (℃)	
	Type	CEM I		Grade	Grade I		Type	KD-12			Concentration (%)	20		
	Strength Class	52.5N		Dosage(%)	/		Dosage(%)	10			Dosage (%)	0.00	Water Temp. (℃)	
Super Plasticizer	Manufacturer	Jiangsu Bote	Non Shrinkage Agent	Manufacturer	Chongqing Jiangbei	Fine Aggregate	Type	Crushed	Natural	Coarse Aggregate	Type	Crushed (5-20mm)		
	Type	PCA (I)		Type	ZY (1)		Absorption(%)	1.02	1.19		Absorption (%)	0.61	Concrete Temp. (℃)	
	Dosage(%)	1.60		Dosage(%)	/		Free Water Content(%)	3.98	7.91		Free Water Content(%)	0.39		

Water (Kg/m³)	W/C	Sand Content %	Cement (Kg/m³)	Fly Ash (Kg/m³)	KD-12 (Kg/m³)	ZY(1) (Kg/m³)	FS-G-III (Kg/m³)	PCA(I) (Kg/m³)	Sand(Kg/m³)		Coarse Aggregate Ratio (%)				Coarse Aggregate(Kg/m³)				Unit Weight (Kg/m3)
									Crushed	Natural	5-10	5-20	20-40	40-75	5-10	5-20	20-40	40-75	
155	0.28	41	500	0	56	0	0.000	8.880	172	517	0	100	0	0	0	1023	0	0	2432

Material Weight per 40 dm³ of Concrete (Kg)

Cementitious Materials			Fine Aggregate		Coarse Aggregate				Non Shrinkage Agent ZY(I)	Water Reducing Agent (FS-G-III) (Solution)	Super Plasticizer PCA (I)	Water
Cement	Fly Ash	Silica Fume KD-12	Crushed	Natural	5~10	5~20	20~40	40~75				
20.000	0.000	2.240	6.880	20.680	0.000	40.920	0.000	0.000	0.000	0.000	0.355	6.200
			+ 0.274	+ 1.636	+ 0.000	+ 0.160						- 0.274
												- 1.636
												- 0.160
												- 0.000
20.00	0.00	2.24	7.15	22.32	0.00	41.08	0.00	0.00	0.00	0.00	0.355	4.13

Slump(mm)	Initial	200	After Min		After Min		After Min		Wet Density (kg/m³)	/	Air Content (%)	/

Remarks: 1、Crushed Aggregates from Quarry Site 4; 2、Natural Sand from Borrow Area Zone IV-A; 3、Crushed Sand : Natural Sand = 1:3.

Prepared by		Checked by		Laboratory Manager		SMEC Engineer	31/10/09

ROSEIRES DAM HEIGHTENING PROJECT

CONTRACT NO.1

Concrete Compressive Strength Test

中国水电集团 SINOHYDRO **CCMD JV** SITE LABORATORY WE

Mix Design No.	Specification Class	Project Identification	Design Slump (mm)	Testing Standard	Test Slump (mm)	Minimum Average Strength at 28 Days	Trial Test No.
Q4-27	M80/A20	PC80/20	150-200	BS EN 12390-2	190	80	Q4-27-4

Cement	Manufacturer	Guangxi Yufeng	Fly Ash	Manufaturer	Shandong Zouxian	Silica Fume	Manufacturer	Shanxi Kaidi	Water Reducing Agent	Manufacturer & Type	Beijing Lili, FS-G-III	Room Temp. (℃)
	Type	CEM I		Grade	Grade I		Type	KD-12		Concentration (%)	20	
	Strength Class	52.5N		Dosage(%)	/		Dosage(%)	10		Dosage (%)	0.00	Water Temp. (℃)
Super Plasticizer	Manufacturer	Jiangsu Bote	Non Shrinkage Agent	Manufacturer	Chongqing Jiangbei	Fine Aggregate	Type	Crushed / Natural	Coarse Aggregate	Type	Crushed (5-20mm)	
	Type	PCA (I)		Type	ZY (1)		Absorption(%)	1.02 / 1.19		Absorption (%)	0.61	Concrete Temp. (℃)
	Dosage(%)	1.60		Dosage(%)	7		Free Water Content(%)	3.98 / 7.91		Free Water Content(%)	0.39	

Water (Kg/m³)	W/C	Sand Content %	Cement (Kg/m³)	Fly Ash (Kg/m³)	KD-12 (Kg/m³)	ZY(1) (Kg/m³)	FS-G-III (Kg/m³)	PCA(I) (Kg/m³)	Sand(Kg/m³)		Coarse Aggregate Ratio (%)				Coarse Aggregate(Kg/m³)				Unit Weight (Kg/m3)
									Crushed	Natural	5-10	5-20	20-40	40-75	5-10	5-20	20-40	40-75	
155	0.28	41	500	0	56	0	0.000	8.880	172	517	0	100	0	0	0	1023	0	0	2432

Test Data Sheet

Specimen No.	Making Date	Testing Date	Age (days)	Load (KN)			Specimen Weight (kg)	Density (kg/m3)	Compressive Strength (Mpa)		
				Ultimate	Correction Factor	Calibration			Dimensions of Cube Specimens (mm)	Strength of Each Specimen (Mpa)	Average Strength (Mpa)
Q4-27-4	2009-10-30	2009-11-27	28	1864.0	0.9976	1859.5	8.286	2455	150×150×150	82.6	81.2
Q4-27-4	2009-10-30	2009-11-27	28	1827.0	0.9976	1822.6	8.395	2487	150×150×150	81.0	
Q4-27-4	2009-10-30	2009-11-27	28	1796.0	0.9976	1791.7	8.476	2511	150×150×150	79.6	
Q4-27-4	2009-10-30	2009-11-27	28	1631.0	0.9976	1627.1	8.695	2576	150×150×150	72.3×	
Q4-27-4	2009-10-30	2009-11-27	28	1859.0	0.9976	1854.5	8.486	2514	150×150×150	82.4	
Q4-27-4	2009-10-30	2009-11-27	28	1813.0	0.9976	1808.6	8.575	2541	150×150×150	80.4	

Remarks	1、Crushed Aggregates from Quarry Site 4; 2、Natural Sand from Borrow Area Zone IV-A; 3、Crushed Sand : Natural Sand = 1:3.

Prepared by	苏娟	Checked by	[illegible]	Laboratory Manager	[illegible]	SMEC Engineer	[illegible] 2009-11-28

Lab. Test form No.C-04

ROSEIRES DAM HEIGHTENING PROJECT

CONTRACT NO.1

Concrete Compressive Strength Test

CCMD JV SITE LABORATORY

Mix Design No.	Strength Class	Max Agg. Size (mm)	Design Slump (mm)	Testing Standard	Test Slump (mm)	Minimum Average Strength at 28 Days	Trial Test No.
Q4-27	M80/A20	20	150-200	BS EN 12390-2	190	80	Q4-27-4

Cement	Manufacturer	Guangxi Yufeng	Fly Ash	Manufaturer	Shandong Zouxian	Silica Fume	Manufacturer	Shanxi Kaidi		Water Reducing Agent	Manufacturer & Type	Beijing Lili, FS-G-III	Room Temp. (℃)
	Type	CEM I		Grade	Grade I		Type	KD-12			Concentration (%)	20	
	Strength Class	52.5N		Dosage(%)	/		Dosage(%)	10			Dosage (%)	0.00	Water Temp. (℃)
Super Plasticizer	Manufacturer	Jiangsu Bote	Non Shrinkage Agent	Manufacturer	Chongqing Jiangbei	Fine Aggregate	Type	Crushed	Natural	Coarse Aggregate	Type	Crushed (5-20mm)	
	Type	PCA (I)		Type	ZY (1)		Absorption(%)	1.02	1.19		Absorption (%)	0.61	Concrete Temp. (℃)
	Dosage(%)	1.60		Dosage(%)	7		Free Water Content(%)	3.98	7.91		Free Water Content(%)	0.39	

Water (Kg/m³)	W/C	Sand Content %	Cement (Kg/m³)	Fly Ash (Kg/m³)	KD-12 (Kg/m³)	ZY(1) (Kg/m³)	FS-G-III (Kg/m³)	PCA(I) (Kg/m³)	Sand(Kg/m³)		Coarse Aggregate Ratio (%)				Coarse Aggregate(Kg/m³)				Unit Weight (Kg/m3)
									Crushed	Natural	5-10	5-20	20-40	40-75	5-10	5-20	20-40	40-75	
155	0.28	41	500	0	56	0	0.000	8.880	172	517	0	100	0	0	0	1023	0	0	2432

Test Data Sheet

Specimen No.	Making Date	Testing Date	Age (days)	Load (KN) Ultimate	Correction Factor	Calibration	Specimen Weight (kg)	Density (kg/m3)	Compressive Strength (Mpa) Dimensions of Cube Specimens (mm)	Strength of Each Specimen (Mpa)	Average Strength (Mpa)
Q4-27-4	2009-10-30	2009-11-6	7	1697.0	0.9976	1692.9	8.234	2440	150×150×150	75.2	75.0
Q4-27-4	2009-10-30	2009-11-6	7	1654.0	0.9976	1650.0	8.271	2451	150×150×150	73.3	
Q4-27-4	2009-10-30	2009-11-6	7	1723.0	0.9976	1718.9	8.262	2448	150×150×150	76.4	

Remarks: 1、Crushed Aggregates from Quarry Site 4; 2、Natural Sand from Borrow Area Zone IV-A; 3、Crushed Sand : Natural Sand = 1:3.

Prepared by	[signature]	Checked by	[signature]	Laboratory Manager	[signature]	SMEC Engineer	[signature] 2009-11-7

Lab. Test form No.C-04

ROSEI[illegible] DAM HEIGHTENING PROJECT

CONTRACT NO.1

Concrete Drying Shrinkage Test

CCMD JV SITE LABORATORY

Test No.	Mix Design No.	Class	Pouring Place		Length of Calibration Rod(mm)	Testing Standard	Casting Date	
DS-B-1092	PW-82	M80/A20	DSB/14&15/C/01		292.5	ASTM C 157M	20-Mar-11	
Specimen No.	Testing Date	Age (d)	Reading of Calibration Rod (mm)	Reading of Specimen (mm)	Effective Length (mm)	Changes of Specimen Length (mm)	Drying Shrinkage (%)	
							Individual	Average
DS-B-1092-①	21-Mar-11	1	13.750	10.880	247.130	/	/	/
DS-B-1092-②			13.750	10.480	246.730	/	/	/
DS-B-1092-③			13.750	/	/	/	/	/
DS-B-1092-①	17-Apr-11	28	13.760	10.850	247.090	0.040	0.0160	0.0120
DS-B-1092-②			13.760	10.470	246.710	0.020	0.0080	
DS-B-1092-③			13.760	/	/	/	/	
DS-B-1092-①	15-May-11	56	18.720	15.710	246.990	0.140	0.0560	0.0400
DS-B-1092-②			18.720	15.390	246.670	0.060	0.0240	
DS-B-1092-③			18.720	/	/	/	/	
Remarks								

CCMD - Contractor			SMEC - Engineer		
Prepared by	Checked by	Approved by	Test & Inspection Witnessed	Test Results Reviewed	Work Verified
[signature]	[signature] RXM	Xiang Guojian	[signature] 16/4/11		

Lab. Test form No.C-22

Appendix B- JMP Statistical Software Program Creating a Response Surface Desig

Creating a Response Surface Design

Response Surface Methodology (RSM) is an experimental technique invented to find the optimal response within specified ranges of the factors. These designs are capable of fitting a second-order prediction equation for the response. The quadratic terms in these equations model the curvature in the true response function. If a maximum or minimum exists inside the factor region, RSM can estimate it. In industrial applications, RSM designs usually involve a small number of factors. This is because the required number of runs increases dramatically with the number of factors. Using the response surface designer, you choose to use well-known RSM designs for two to eight continuous factors. Some of these designs also allow blocking.

Response surface designs are useful for modeling and analyzing curved surfaces.

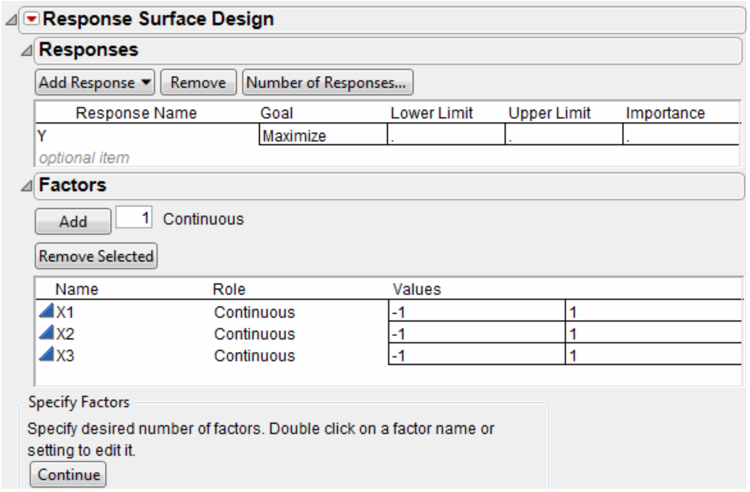
To start a response surface design, select **DOE > Response Surface Design**, or click the **Response Surface Design** button on the JMP Starter **DOE** page. Then, follow the steps described in the following sections.

Enter Responses and Factors

The steps for entering responses are the same in **Screening Design**, **Space Filling Design**, **Mixture Design**, **Response Surface Design**, **Custom Design**, and **Full Factorial Design**. These steps are outlined in "Enter Responses and Factors into the Custom Designer"

Factors in a response surface design can only be continuous. The Factors panel for a response surface design appears with two default continuous factors. To enter more factors, type the number you want in the Factors panel edit box and click **Add**, as shown in Enter Factors into a Response Surface Design.

Enter Factors into a Response Surface Design

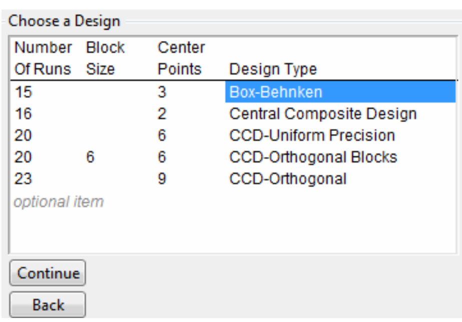


Click **Continue** to proceed to the next step.

Choose a Design

Highlight the type of response surface design you want and click **Continue**. The next sections describe the types of response surface designs shown in Choose a Design Type.

Choose a Design Type



Box-Behnken Designs

The Box-Behnken design has only three levels per factor and has no points at the vertices of the cube defined by the ranges of the factors. This is sometimes useful when it is desirable to avoid extreme points due to engineering considerations. The price of this characteristic is the higher uncertainty of prediction near the vertices compared to the central composite design.

Central Composite Designs

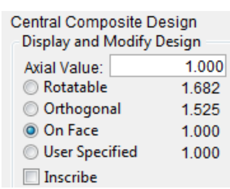
The response surface design list contains two types of central composite designs: *uniform precision* and *orthogonal*. These properties of central composite designs relate to the number of center points in the design and to the axial values:

- Uniform precision means that the number of center points is chosen so that the prediction variance near the center of the design space is very flat.
- For orthogonal designs, the number of center points is chosen so that the second order parameter estimates are minimally correlated with the other parameter estimates.

Specify Axial Value (Central Composite Designs Only)

When you select a central composite (CCD-Uniform Precision) design and then click **Continue**, you see the panel in Display and Modify the Central Composite Design. It supplies default axial scaling information. Entering 1.0 in the text box instructs JMP to place the axial value on the face of the cube defined by the factors, which controls how far out the axial points are. You have the flexibility to enter the values you want to use.

Display and Modify the Central Composite Design



Rotatable

makes the variance of prediction depend only on the scaled distance from the center of the design. This causes the axial points to be more extreme than the range of the factor. If this factor range cannot be practically achieved, it is recommended that you choose **On Face** or specify your own value.

Orthogonal

makes the effects orthogonal in the analysis. This causes the axial points to be more extreme than the –1 or 1 representing the range of the factor. If this factor range cannot be practically achieved, it is recommended that you choose **On Face** or specify your own value.

On Face

leaves the axial points at the end of the -1 and 1 ranges.

User Specified

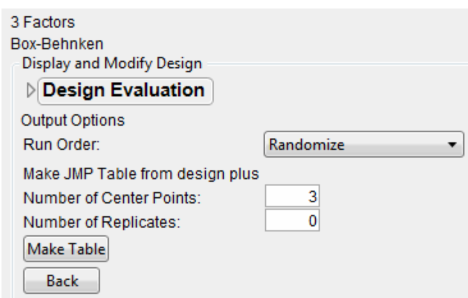
uses the value you enter in the Axial Value text box.

If you want to inscribe the design, click the box beside **Inscribe**. When checked, JMP rescales the whole design so that the axial points are at the low and high ends of the range (the axials are –1 and 1 and the factorials are shrunken based on that scaling).

Specify Output Options

Use the Output Options panel to specify how you want the output data table to appear. When the options are specified the way you want them, click **Make Table**. Note that the example shown in Select the Output Options is for a Box-Behnken design. The Box-Behnken design from the design list and the `Output Options` request 3 center points and no replicates.

Select the Output Options



`Run Order` provides a menu with options for designating the order you want the runs to appear in the data table when it is created. Menu choices are:

Keep the Same

the rows (runs) in the output table will appear in the standard order.

Sort Left to Right

the rows (runs) in the output table will appear sorted from left to right.

Randomize

the rows (runs) in the output table will appear in a random order.

Sort Right to Left

the rows (runs) in the output table will appear sorted from right to left.

Randomize within Blocks

the rows (runs) in the output table will appear in random order within the blocks you set up.

Add additional points with options given by Make JMP Table from design plus:

Number of Center Points

Specifies additional runs placed at the center points.

Number of Replicates

Specify the number of times to replicate the entire design, including center points. Type the number of times you want to replicate the design in the associated text box. One replicate doubles the number of runs.

View the Design Table

Now you have a data table that outlines your experiment, as described in The Design Data Table.

The Design Data Table

Box-Behnken
Design Box-Behnken
Model

Columns (5/0)
Pattern
X1
X2
X3
Y

Rows
All rows 15
Selected 0
Excluded 0
Hidden 0
Labelled 0

	Pattern	X1	X2	X3	Y
1	+0+	1	0	1	•
2	0+−	0	1	-1	•
3	−0+	-1	0	1	•
4	+0−	1	0	-1	•
5	0−+	0	-1	1	•
6	000	0	0	0	•
7	0++	0	1	1	•
8	−+0	-1	1	0	•
9	000	0	0	0	•
10	000	0	0	0	•
11	++0	1	1	0	•
12	0−−	0	-1	-1	•
13	−0−	-1	0	-1	•
14	+−0	1	-1	0	•
15	−−0	-1	-1	0	•

The name of the table is the design type that generated it.

Run the Model script to fit a model using the values in the design table.

The column called Pattern identifies the coding of the factors. It shows all the codings with “+” for high, “–” for low factor, “a” and “A” for low and high axial values, and “0” for midrange. Pattern is suitable to use as a label variable in plots because when you hover over a point in a plot of the factors, the pattern value shows the factor coding of the point.The three rows whose values in the Pattern column are 000 are three center points.

The runs in the Pattern column are in the order you selected from the **Run Order** menu.

The Y column is for recording experimental results.

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Help created on 12/23/2011.