MIX DESIGN FOR DURABLE CONCRETE USING FLY ASH, SLAG AND LOCALLY AVAILABLE AGGREGATE

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September 2019

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by

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A Thesis submitted to the Department of Civil Engineering, Bangladesh University of Engineering and Technology, in partial fulfillment of the requirements for the degree of

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BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY, DHAKA
BANGLADESH

September 2019

The thesis titled "Mix Design for Durable Concrete using Fly Ash, Slag and Locally Available Aggregate" submitted by Meraj Rubayat Kamal, Roll No. 101402324 (P), Session: October 2014, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering (Structural) on the 19th September, 2019.

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Meraj Rubayat Kamal

DEDICATION

to

My Son
Rudayeef Rubayat

ACKNOWLEDGEMENT

The preparation of the thesis was undertaken to meet the need for the partial fulfillment of the Degree of Master of Science in Civil Engineering (Structural) from BUET. All praise to The Almighty for blessing to lead this thesis work towards successful completion.

The author would like to express his thankfulness to his supervisor Dr. Md. Shafiul Bari, Professor, Department of Civil Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka for his constant inspiration, motivation and support.

The author wishes to offer his profound gratitude to Dr. Munaz Ahmed Noor, Vice Chancellor, Bangabandhu Sheikh Mujibur Rahman Digital University, Bangladesh and Professor, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Dhaka who shared his latest ideas regarding concrete technology along with demonstrations, necessary guidance, and invaluable suggestions in every phase of this work.

The entire work has been carried out in the Concrete Laboratory of the Department of Civil Engineering of BUET. The author would like to express his gratitude to the lab technicians of concrete laboratory for their help.

The author would like to thank his wife, Rubaiya Rumman, Assistant Professor of Civil Engineering, BUET, for her invaluable support, encouragement and ideas at every stage of this research. Finally, the author would like to convey his obedient gratitude to his parents and in-laws for their continuous moral support.

ABSTRACT

Concrete is a low maintenance composite material consisting mainly of cementitious material, water and aggregate. It is a popular construction material in Bangladesh also in the world. Concrete mix design works as a major determining factor for the properties of concrete. Many countries have already developed their own methods of concrete mix designs. But at present there is very few concrete mix design guideline for Bangladesh that use locally available materials. Ashraf (2012) proposed a mix design guideline using aggregate gradation bands of local materials which considered compressive strength and workability as required parameters. Ashraf (2012) observed that contemporary band gradations of aggregates result in better strength and workability compared to conventional gradations (ASTM C33, BS 882) and developed two band aggregate gradations- ‗5-10-14-18' and ‗5-10-18-22'. Rumman (2018) updated Ashraf's (2012) mix design process considering both strength and durability parameters using Rice Husk Ash (RHA) as Supplementary Cementing Material (SCM). Although RHA performed well in terms of durability, commercial viability of using RHA as supplementary cementing material is yet to be assessed. On the other hand, fly ash and blast furnace slags are widely used SCM all over the world. In this research, a mix design guideline incorporating durability criteria is developed for Bangladesh considering fly ash and blast furnace slag as SCM and using aggregate gradation bands of local materials.

Three water cement ratios (0.4, 0.5 and 0.6) have been used in this research work and cement content range has been kept between 350 to 500 kg/m^3. The fly ash replacement levels were 0%, 20% and 35% and the slag replacement levels were 0%, 20%, 65% and 90%. A slag replacement level of 90% can also work as green cement which is an effective approach to control the heat release rate, reduce the material cost and enhance the durability which will help to produce greener environment. It has been found that with increase of fly ash replacement, 28 day compressive strength reduced slightly but the durability increased greatly. Concrete prepared with 35% fly ash replacement had 14% to 22% less strength than the control concrete but it showed much higher durability than the control one. For blast furnace slag, concrete prepared with 20% replacement showed the highest strength and 65% slag replacement level also showed compatible strength. But green cement prepared with 90% slag replacement showed the lowest compressive strength. On the other hand, concrete durability increased with increase of slag replacement level. 90% slag replacement resulted in highest durability whereas the control concrete had the lowest durability.

A mix design process has been developed after analyzing the results of different mixes. 28 day compressive strength, Rapid Chloride Permeability Test result and slump value have been used as mix design parameters. Contour diagrams have been used in the mix design steps for easier interpretation. Finally the proposed mix design method has been validated by preparing six different mixes and comparing their test results with target values.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
A/C	Aggregate Cement Ratio
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BS	British Standard
EN	European Norms
FA/TA	Fine Aggregate/Total Aggregate
FM	Fineness Modulus
GGBS	Ground Granulated Blast Furnace Slag
IPR	Individual Percent Retained
IS	Indian Standard
OPC	Ordinary Portland Cement
PCC	Portland Composite Cement
RCPT	Rapid Chloride Permeability Test
RHA	Rice Husk Ash
SCM	Supplementary Cementing Material
SSD	Saturated Surface Dry
UHVFA	Ultra-High Vacuum Fly Ash
USBR	United States Bureau of Reclamation
W/C	Water Cement Ratio

Chapter 1
INTRODUCTION

1.1 General

Concrete is a popularly used man made construction material. Concrete is being used to build structures from thousands of years ago and with the passage of time the knowledge of concrete technology has flourished. Concrete is a composite material, consisting mainly of cement, water and aggregate (coarse aggregate and fine aggregate). When these materials are mixed together, they form a workable paste which then gradually hardens over time. Fly ash, blast furnace slag, rice husk ash etc. supplementary cementing materials are sometimes used in concrete to improve its durability properties.

Concrete mix design is the process of finding right proportions of cement, sand and coarse aggregates for concrete to achieve target strength and workability in structures in an economic but sustainable manner.

1.2 Background and Present State of the Problem

The purpose of concrete mix design is to achieve a desired workability in the plastic stage, a desired minimum strength in the hardened stage and a desired durability in the given environment condition. Though the earliest recordings of concrete structures date back to 6500BC, the history of concrete mix design is not that old. In fact there were no standard practices for developing concrete mix designs back in the early 1900‘s. Fuller and Thompson (1907) performed their studies on concrete mix design based on optimized aggregate grading. Since then, numerous researches have been accomplished in many countries to find out the optimum proportions of the ingredients of concrete. Apparently there were also studies by others based on maximum density, but Abrams (1918) dismissed them in Design of Concrete Mixtures. Instead Abrams developed the Fineness Modulus and based his mix design theories on combined fineness modulus of both coarse and fine aggregate. Professor Arvo Nykanen developed a mix proportion method in 1945.

Many countries have already developed their own methods of concrete mix designs. Some of the common concrete mix design methods used in different countries of the world are: ACI Mix Design Method, British Mix design Method, USBR Mix design practice, ISI Recommended guidelines etc. These methods are being used successfully by the engineers over the years. However, the British or American methods are not properly suited for mix design and construction technology in Bangladesh, as the figures and tables used in these mix design processes are based on the materials of their regions (Maiti et al., 2006). Furthermore, the climatic conditions of Bangladesh are different from that of other countries. So aggregate gradations like ASTM C33 or BS 882 is difficult to achieve through these standard methodologies. Again the aggregate characteristics of this region also vary from other regions. Islam (2010) observed that concrete made with locally available PCC cement brands and following ACI method of concrete mix design was unable to achieve target strength within 28 days. In addition to that if locally available materials can be used to produce concrete, then it will reduce the total production cost significantly. Now a days, combined aggregate gradation is gaining popularity all over the world because it performs better in terms of workability, shrinkage, pumpability and some other properties of concrete (Shilstone, 1990). Ashraf (2012) observed that contemporary band gradations of aggregates result in better strength and workability compared to conventional gradations (ASTM C33, BS 882) and developed two band aggregate gradations- ‗5-10-14-18' and ‗5-10-18-22'. Ashraf (2012) proposed a guideline for concrete mix design using locally available aggregates of Bangladesh but durability parameter of the mixes was not incorporated in that work. Durability is a major concern for concrete structures. Chloride ion attack, carbonation and sulfate attack are the three major types of chemical attack that affect the durability of concrete structures. Rumman (2018) developed a mix design process considering both strength and durability parameters using Rice Husk Ash (RHA) as supplementary cementing materials. RHA performs well in terms of durability and it is available in Bangladesh as Bangladesh is a rice producing country. But commercial viability of using RHA as supplementary cementing material has not been assessed yet. On the other hand, fly ash and blast furnace slags are widely used SCM all over the world. In this research, a mix design guideline incorporating durability criteria is proposed for Bangladesh considering fly ash and blast furnace slag as SCM.

1.3 Objectives with Specific Aims

a) To propose a mix design guideline for durable concrete using fly ash and slag as supplementary cementing material

b) To use locally available graded aggregate in the proposed mix design which will reduce construction cost

1.4 Outline of Methodology

Ashraf (2012) proposed two distinct combined aggregate bands 5-10-14-18 and 5-10-18-22 which have been found to give better concrete properties compared to other aggregate gradation methodologies in terms of concrete workability and compressive strength only. Rumman (2018) developed that mix design by incorporating durability parameter and using locally available aggregates and Rice Husk Ash as Supplementary Cementing Material (SCM). But Rumman (2018) did not consider other widely used SCM such as fly ash, blast furnace slag etc.

In this research fly ash and slag have been used as partial replacement of cement in order to increase durability and to reduce the cost of cement production. Durability and strength properties of Green Cement that contains 90 percent slag were also evaluated. Locally produced Ordinary Portland Cement was used to make concrete mixes.

Total one hundred and eight mixes of concrete specimens were produced. Thirty six mixes were prepared using fly ash as cement replacement. The fly ash replacement levels were 20% and 35%. Fifty four mixes were prepared using blast furnace slag as cement replacement. The slag replacement levels were 20%, 65% and 90%. Eighteen control mixes (containing 100% OPC Cement) were also prepared. Half of the total one hundred and eight mixes were prepared using aggregates from band 5-10-14-18 and the rest of them from band 5-10-18-22. Three different water cement ratios (0.4, 0.5 and 0.6) were used for these mix designs. Density test were conducted on fresh concrete along with workability test. Compressive strength test and durability tests (chloride permeability) were performed on hardened concrete.

1.5 Organisation of the Thesis

The total research work is described in various chapters of this book. Following section briefly explains the content of the chapters –

Chapter 2 describes literature review about various existing concrete mix design methods, concrete and its components, types of cement and aggregates, properties and compositions of cement which affect concrete properties, aggregate gradation and other properties which have effect on concrete properties, properties and suitability of fly ash and slag.

Chapter 3 describes different existing concrete mix design methods used by civil engineers in Bangladesh and around the world. The philosophy of proposing a new mix design is also described in this chapter

Chapter 4 presents the methodology of the mix design. In this chapter, different materials used in the mix design process are described. The results of various laboratory tests on aggregate and concrete are also presented.

Chapter 5 lists the information required for designing the mixes and describes the mix design steps.

Chapter 6 presents some worked out examples of the proposed new mix design. Laboratory experiments and their results for the verification of the process are also presented in the chapter.

Chapter 7 describes the significant outcomes of the research and recommendations for future work.

Chapter 2

LITERATURE REVIEW

2.1 General

Concrete is a composite construction material, consisting mainly of cement, water and aggregate. It may also include supplementary materials such as fly ash, slag and chemical admixtures. When these materials are mixed together, they form a workable paste which gradually hardens over time through a chemical process known as hydration. The characteristics of concrete such as strength and durability are determined by the aggregate or cement used, or by the method that is used to produce it.

The word concrete comes from the Latin word “concretus” (meaning compact or condensed), the perfect passive participle of “concresco”, from “com” (together) and “cresco” (to grow). It was not until the 19th century that the noun “concrete”, and its related adjective, began to be used for the building material composed of cementing material and sand, gravel, or similar materials (Merriam-Webster's online dictionary, 2017).

The process of selecting suitable ingredients of concrete and determining their relative amounts with the objective of producing a concrete of the required, strength, durability, and workability as economically as possible, is termed the concrete mix design.

The following sections discuss the major elements of concrete and their effects on concrete properties.

2.2 Cement

Cement is a binder, a substance that sets and hardens independently, and can bind other materials together. It is a finely grounded powder that, when mixed with water, set to a hard mass. The most common type of cement is Portland cement. It is a fine powder produced by grinding Portland cement clinker (more than 90%), a limited amount of calcium sulfate (which controls the set time) and up to 5% minor constituents as allowed by various standards such as the European Standard EN 197-1. ASTM C150 defines Portland cement as “hydraulic cement (cement that not only hardens by reacting with water but also forms a water-resistant product) produced by pulverizing clinkers consisting essentially of hydraulic calcium silicates, usually containing one or more of the forms of calcium sulfate as an inter ground addition.”

Cement is the most active component of concrete and usually has the greatest unit cost, hence, its selection and proper use are important in obtaining most economically the balance of properties desired for any particular concrete mixture.

ASTM C150 and AASHTO M85 have specified certain physical requirements of cement. These properties include 1) fineness, 2) soundness, 3) consistency, 4) setting time, 5) compressive strength, 6) heat of hydration, 7) specific gravity, and 8) loss on ignition.

2.2.1 Constituents

The constituents of Portland cement are described in the following sections:

2.2.1.1 Portland cement clinker

Portland cement clinker is a hydraulic material which shall consist of at least two-thirds by mass of calcium silicates ($3\,CaO{\cdot}SiO_2$ and $2\,CaO{\cdot}SiO_2$), the remainder consisting of aluminum- and iron-containing clinker phases and other compounds. It is made by heating, in a kiln, a homogeneous mixture of raw materials to a sintering temperature, which is about 1450 °C for modern cements. The aluminum oxide and iron oxide are present as a flux and contribute little to the strength.

Portland cement clinker consists essentially of compounds of lime (calcium oxide, CaO) mixed with silica (silicon dioxide, SiO_2) and alumina (aluminum oxide, Al_2O_3). The lime is obtained from a calcareous (lime-containing) raw material, and the other oxides are derived from an argillaceous (clayey) material. Additional raw materials such as silica sand, iron oxide (Fe_2O_3), and bauxite—containing hydrated aluminum, $Al(OH)_3$—may be used in smaller quantities to get the desired composition. The major raw material for the clinker-making is usually limestone ($CaCO_3$) mixed with a second material containing clay as source of alumino-silicate. Normally, an impure limestone which contains clay or SiO_2 is used. The $CaCO_3$ content of these limestones can be as low as 80%. Second raw materials (materials in the raw mix other than limestone) depend on the purity of the limestone. Some of the second raw materials used are clay, shale, sand, iron ore, bauxite, fly ash and slag.

2.2.1.2 Pozzolanic materials

Pozzolanic materials are natural substances of siliceous or silico-aluminous composition or a combination of both. Pozzolanic materials do not harden in themselves when mixed with water but, when finely ground and in the presence of water, they react at normal ambient temperature with dissolved calcium hydroxide ($Ca(OH)_2$) to form strength-developing calcium silicate and calcium aluminate compounds.

Artificial pozzolans are the by-products of various thermal treatments, such as, fly ash, slag, burnt shale, silica fume etc.

2.2.1.3 Limestone

Limestone, a sedimentary rock, consists mainly of calcium carbonate; the most stable form is calcite. Limestone often contains Mg, Al and Fe combined as carbonates and silicates. It is stated in TS EN 197-1 that in order to use limestone as a constituent in cement, calcium oxide content should be at least 75% by mass. Moreover, limestone is divided into two groups in TS EN 197-1 according to its Total Organic Carbon (TOC) content. If TOC value does not exceed 0.20 % by mass, the limestone is demonstrated with LL. If TOC value does not exceed 0.50 % by mass, then the limestone is demonstrated with L (TS EN 197-1). The requirement of limestone is as follows:

a) The calcium carbonate ($CaCO_3$) content calculated from the calcium oxide content shall be at least 75 % by mass.
b) The clay content, determined in accordance with EN 933-9, shall not exceed 1.20 g/100 g.

2.2.1.4 Burnt shale

Burnt shale is another cementitious constituent used in cement production. It mainly contains dicalcium silicate and monocalcium aluminate. It also contains larger proportions of pozzolanically reacting oxides, especially silicon dioxide along with small amounts of free calcium oxide and calcium sulfate. Burnt shale is produced by burning of oil shale in fluidized bed furnace at temperatures between 600 and 800°C. It shows hydraulic properties like Portland cement and in addition pozzolanic properties in a finely ground state.

2.2.2 Types

According to EN 197, the various types of cements are grouped into five main types as illustrated in Table 2.1.

2.2.3 Effect of cement on concrete properties

Composition and type of cement have significant effects on concrete strength, workability, durability etc. These effects are discussed in the following sections

2.2.3.1 Composition

Cement composition controls the rate of hydration and thus effect the permeability of concrete. The coarse cement produces concrete with higher porosity than that produced by finer cement (Powers et al. 1954). Fineness of cement affects workability, placeability and water content of a concrete mixture. Cement composition has minor effect on freeze-thaw resistance. The C_3A and sulfur trioxide (SO_3) content of the cement largely influence the paste, mortar, and concrete rheological behavior (Alonso and Puertas 2015). By reducing the C_3A content of the cements, the fresh state, rheological, and consistency retention properties of the mixtures improves, although the strength of the mixtures at early ages decrease (Mardani-Aghabaglou et al., 2017).

Table 2.1: Classification of Cement

Main types	Notation of the 27 products (types of common cement)		Composition (percentage by mass [a])										
			Main constituents										Minor additional constituents
			Clinker	Blast-furnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone		
						natural	natural calcined	siliceous	calca-reous				
			K	S	D [b]	P	Q	V	W	T	L	LL	
CEM I	Portland cement	CEM I	95-100	–	–	–	–	–	–	–	–	–	0-5
CEM II	Portland-slag cement	CEM II/A-S	80-94	6-20	–	–	–	–	–	–	–	–	0-5
		CEM II/B-S	65-79	21-35	–	–	–	–	–	–	–	–	0-5
	Portland-silica fume cement	CEM II/A-D	90-94	–	6-10	–	–	–	–	–	–	–	0-5
	Portland-pozzolana cement	CEM II/A-P	80-94	–	–	6-20	–	–	–	–	–	–	0-5
		CEM II/B-P	65-79	–	–	21-35	–	–	–	–	–	–	0-5
		CEM II/A-Q	80-94	–	–	–	6-20	–	–	–	–	–	0-5
		CEM II/B-Q	65-79	–	–	–	21-35	–	–	–	–	–	0-5
	Portland-fly ash cement	CEM II/A-V	80-94	–	–	–	–	6-20	–	–	–	–	0-5
		CEM II/B-V	65-79	–	–	–	–	21-35	–	–	–	–	0-5
		CEM II/A-W	80-94	–	–	–	–	–	6-20	–	–	–	0-5
		CEM II/B-W	65-79	–	–	–	–	–	21-35	–	–	–	0-5
	Portland-burnt shale cement	CEM II/A-T	80-94	–	–	–	–	–	–	6-20	–	–	0-5
		CEM II/B-T	65-79	–	–	–	–	–	–	21-35	–	–	0-5
	Portland-limestone cement	CEM II/A-L	80-94	–	–	–	–	–	–	–	6-20	–	0-5
		CEM II/B-L	65-79	–	–	–	–	–	–	–	21-35	–	0-5
		CEM II/A-LL	80-94	–	–	–	–	–	–	–	–	6-20	0-5
		CEM II/B-LL	65-79	–	–	–	–	–	–	–	–	21-35	0-5
	Portland-composite cement [c]	CEM II/A-M	80-94	<------------------ 6-20 ------------------>									0-5
		CEM II/B-M	65-79	<------------------ 21-35 ------------------>									0-5
CEM III	Blastfurnace cement	CEM III/A	35-64	36-65	–	–	–	–	–	–	–	–	0-5
		CEM III/B	20-34	66-80	–	–	–	–	–	–	–	–	0-5
		CEM III/C	5-19	81-95	–	–	–	–	–	–	–	–	0-5
CEM IV	Pozzolanic cement [c]	CEM IV/A	65-89	–	<---------- 11-35 ---------->					–	–	–	0-5
		CEM IV/B	45-64	–	<---------- 36-55 ---------->					–	–	–	0-5
CEM V	Composite cement [c]	CEM V/A	40-64	18-30	–	<------ 18-30 ------>			–	–	–	–	0-5
		CEM V/B	20-38	31-50	–	<------ 31-50 ------>			–	–	–	–	0-5

2.2.3.2 Type

The rate of strength development and ultimate compressive strength of concrete is influenced by the chemical reactivity of the cement. C_3S has a much faster hydration rate, and contributes to higher early-strength gain. On the other hand, C_2S reacts slowly and contributes to long-term strength gain. Therefore, cement with a higher proportion of C_3S tend to have a higher early strength. High alumina cement provides strength in lesser time as compared to OPC cement, PCC cement has tendency to provide strength at later days of curing. Moreover PCC cement has the tendency to convert calcium hydroxide to calcium silicate hydrate gel which provides more strength and better resistance to environment attacks owing to concentration of less permeable voids. Figure 2.1 shows the strength gain of cement mortars for different types of cements conforming to the ASTM classification.

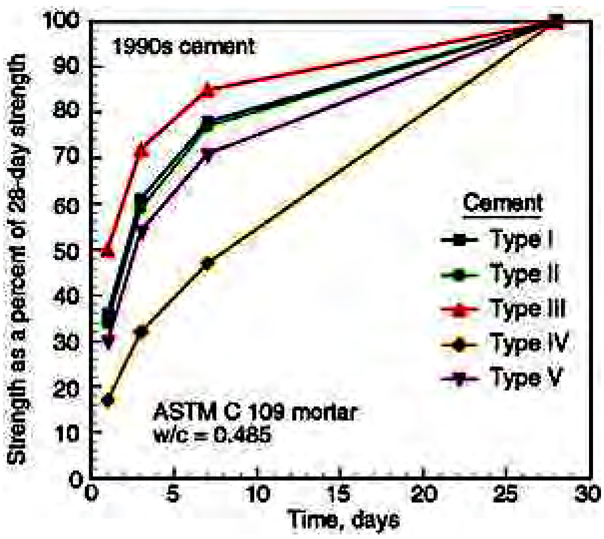


Figure 2.1: Strength Gain of Various Types of Cements (ASTM Classification)

Ilica et al., 2008 found that blast furnace slag cement gives highest resistance against chloride penetration, while the pure Portland cement gives the lowest resistance. Ilica et al., 2008 also found that sulfate resisting cement has a low resistance against chloride penetration. Concrete produced using the sulfate resisting cement has substantially higher capillary sorption compared to other mixtures. Concrete slump also varies depending on cement type. Studies conducted by PP, 2018 found that workability of concrete decreases as fines content increases. Again at the same level of fines content, workability increases when the W/C ratio increases. Concrete slumps for various types of cements as per EN 197 classification is shown in Figure 2.2.

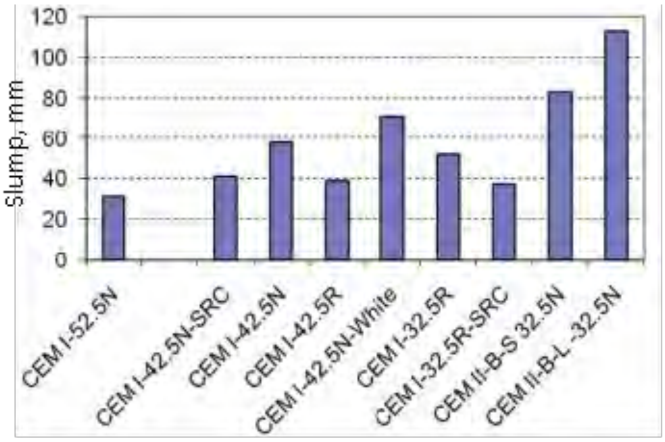


Figure 2.2: Slump Variations for Various Types of Cements (EN 197 Classification)

From the figure, it can be seen that highest slump range was observed for CEM II cements. This can be correlated to lower level of clinker in CEM II cement.

2.2.4 Cement production

Portland cement clinker is made by heating a homogeneous mixture of raw materials at a temperature of about 1450 °C in a kiln. The major raw material for the clinker-making is usually limestone ($CaCO_3$) mixed with a second material containing clay as source of alumino-silicate. Normally, an impure limestone which contains clay or SiO_2 is used. The aluminum oxide and iron oxide are present as a flux and contribute little to the strength. For special cements, such as Low Heat (LH) and Sulfate Resistant (SR) types, it is necessary to limit the amount of tricalcium aluminate ($3\ CaO{\cdot}Al_2O_3$) formed. The $CaCO_3$ content of these limestones can be as low as 80%. Second raw materials (materials in the raw mix other than limestone) depend on the purity of the limestone. Some of the second raw materials used are: clay, shale, sand, iron ore, bauxite, fly ash and slag. When a cement kiln is fired by coal, the ash of the coal acts as a secondary raw material.

Cement production consumes huge energy and causes about 7% of total greenhouse gas emission in the world (Malhotra, 2002). Therefore the suitability of supplementary cementing materials such as blast furnace slag, fly ash and silica fume as partial replacement of cement are being studied to produce durable and sustainable concrete which will also provide comparable strength.

2.3 Supplementary Cementing Materials

Supplementary cementing materials (SCMs) are added to concrete to make it economical, increase strength, reduce permeability or influence other concrete properties. Fly ash, blast-furnace slag, silica fume etc. are some examples of supplementary cementing materials. These materials contribute to the properties of hardened concrete through hydraulic or pozzolanic activities. The following sections describe different types of supplementary cementing materials.

2.3.1 Fly ash

Fly ash is a by-product of the combustion of pulverised coal and is a pozzolanic material. Fly ash is used widely in the construction industry as a binder replacement due to its pozzolanic activity, low water demand, reduced bleeding, and less heat evolution.

2.3.1.1 Production

Fly ash, a finely divided residue is obtained from the combustion of pulverized coal and is carried from the combustion chamber of the furnace by exhaust gases. It is obtained by mechanical or electrostatic precipitation of dust-like particles from the flue gases of furnaces fired with pulverized coal.

2.3.1.2 Property

The spherical particles of fly ash produce the ball bearing effect, thus fly ash concrete has a better particle packing and dense paste (Ahmaruzzaman, 2010). Class F fly ash contains a small quantity of lime. Thus, compressive strength is reduced with the increment of fly ash content in concrete. However, due to the pozzolanic activity of fly ash, the compressive strength increased in later stages of curing (Sumer, 2012). The amorphous silica present in fly ash undergoes a chemical reaction with the calcium hydroxide and generates calcium silicate hydrate (Nonavinakere and Reed, 1995). Due to the pozzolanic reaction, the strength increment continues for a longer period of time comparing to the conventional concrete (Saha and Sarker, 2017). In addition, fly ash reduces the concrete bleeding and improves its workability (Yao et al., 2015).

2.3.1.3 Replacement level

ACI Committee recommends fly ash replacement level of 15 - 25% for high strength concrete (ACI Committee 211 2008), On the other hand, it can be used as more than 50% of total binder for normal strength concrete (Carette et al., 1993).

Historically, fly ash has been used in concrete at levels ranging from 15% to 25% by mass of the cementitious material component. The actual amount used varies widely depending on the application, the properties of the fly ash, specification limits, and the geographic location and climate. Higher levels (30% to 50%) have been used in massive structures (for example, foundations and dams) to control temperature rise. In recent decades, research has demonstrated that high dosage levels (40% to 60%) can be used in structural applications, producing concrete with good mechanical properties and durability (Marceau, 2002). Naik et al. (1994) tested concretes with up to 70% Class C fly ash and obtained reduced air and water permeability of fly ash concretes at 91 days.

2.3.1.4 Effect of fly ash addition on concrete properties

Strength

Studies conducted by Nath and Sarker, 2011 indicate that incorporation of fly ash in concrete decreased strength at the earlier age as compared to the control concrete. However, they either gained more strength or reached very close to control concrete‘s strength at a later age as shown in Figure 2.3. Concretes with 30% fly ash showed higher strength gain than those with 40% fly ash. However, fly ash concretes achieved over 80% of control concrete‘s strength at 28 days. They reached 92% and 96% of control concrete‘s strength at 56 days, for 40% and 30% fly ash content respectively. Also high strength concrete with 28-day compressive strength of 60 MPa could be obtained with w/b ratio of 0.31 and with 40% fly ash replacement (Nath & Sarker, 2011).

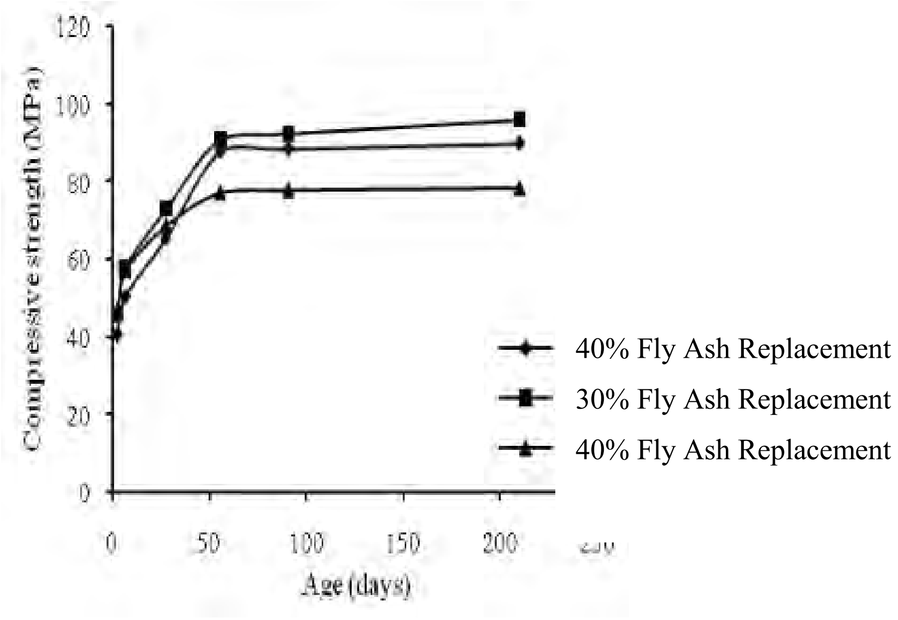


Figure 2.3: Compressive Strength Development of Concrete Containing Different Percentages of Fly Ash (Nath & Sarker, 2011)

Camões et al. (2003) found that adding 60% fly ash produces considerably weaker concrete in terms of compressive strength, compared to control concrete although both its workability and the durability improve when compared to the control concrete mix.

Durability

Nath and Sarker, 2011 studied the effect of fly ash on the durability properties of high strength concrete using concrete mixtures with fly ash replacement level of 30% and 40% of total binder and found that the fly ash concrete showed less drying shrinkage than the control concrete samples when designed for the same 28-day compressive strength of the control concrete. Inclusion of fly ash also reduced sorptivity and chloride ion permeation significantly at 28 days which reduced further at 6 months. In general, incorporation of fly ash as partial replacement of cement improved the durability properties of concrete.

Cao et al. (1996) found that fly ash concretes produced better result in chloride diffusion and sulphate attack than OPC concrete. Langley et al., 1989 and Mathotra, 1990 found that concrete having high volume of Class F fly ash exhibited excellent durability properties such as low permeability to chloride ions and other aggressive agents.

Papadakis (1999) observed increased porosity when Class F fly ash replaced cement and decreased porosity when fly ash replaced aggregate in mortar.

Tasdemir (2003) found higher sorptivity coefficient for fly ash incorporated concrete as compared to normal concrete at early age adding fly class C ash as 10% of cement and using water to binder (w/b) ratio of 0.60. However, Camoes et al. (2003) obtained reduced sorptivity coefficient by using w/b ratio in the range of 0.25-0.40 and Class F fly ash content of as high as 60% of the total binder.

Rapid Chloride Permeability Test (RCPT) performed by Nath and Sarker, 2011 indicated that fly ash concretes showed better resistance to chloride ion penetration at both 28 days and 180 days. Penetrability of Cl- reduced with the increase of fly ash in the mixtures. At 28 days of age, fly ash concretes achieved ‗Low' level of Cl- penetration in contrast to the ‗Moderate' level of the corresponding control concretes. At 180 days, the Cl- penetration level decreased to ‗Very Low' for the fly ash concretes.

Fly ash has a positive impact on shrinkage mitigation. Atis, 2003 found that the application of high volume fly ash in concrete, particularly 50% replacement of cement by fly ash led to the shrinkage reduction by 30% compared to the conventional concrete.

Supit and Shaikh (2015) showed that inclusion of fly ash in concrete reduces the volume of the permeable void by 6-11% compared to the conventional concrete. Furthermore, the authors observed the effects of the different fly ash content in concretes on permeable voids and found that at 40% replacement level of fly ash, the permeable void of concrete decreased, however, 60% substitution level exhibited higher permeable void comparing to control specimens. On the other hand, Mardani-Aghabaglou et al. (2013) reported that fly ash concrete showed higher permeable voids corresponding to the control samples and the void content increased with the increment of the fly ash content. Wang et al. (2008) concluded that class F fly ash was the most efficient in the reduction of the chloride permeability of concrete among all types.

Studies conducted by Aggarwal et al. (2010) showed that icncrease of fly ash content from 30% to 45% increased the durability of concrete without loss of compressive and flexural strength

Slump

Huang et al. (2013) performed workability test using fly ash replacement level up to 80 % and found that concrete containing fly ash up to 80% can have adequate workability using a suitable admixture. Madhavi et al. (2014) found that addition of fly ash increased workability when compared with conventional concrete having the same water content.

Setting Time

The effect of fly ash on the setting behavior of concrete depends on the composition and quantity of fly ash used, type and amount of cement, the water/cement ratio, type and amount of chemical admixtures, and concrete temperature. Because of low cement content and slow reaction of fly ash, the setting time of fly ash concrete is more than that of conventional concrete. Dinakar et al. (2009) reported that Class F fly ash, especially with high loss on ignition (LOI), increases the setting time, while Class C fly ash sometimes exhibits the opposite behavior of reducing the setting time. Huang et al. (2013) found that setting time of the fly ash concrete increased with increase in fly ash content. The setting times were 1.25 h to 11 h longer than those for the control concrete.

2.3.1.5 Advantage

Use of fly ash as supplementary cementing material has the following advantages:

i. Environmental: The more fly ash being utilized in concrete, the less will be the demand for Portland cement, and therefore the less will be Portland cement production, and therefore the lower CO_2 emissions;
ii. Economical: Fly ash is less expensive than Portland cement. Therefore, the cost to produce concrete decreases as the replacement level of fly ash increases;
iii. Durability Improvement: Concretes with high volume of fly ash is more durable than concrete produced with ordinary Portland Cement.

2.3.2 Blast furnace slag

Ground Granulated Blast furnace Slag (GGBS) is a byproduct from the blast furnaces used to make iron. It is a glassy, granular material formed when molten, iron blast-furnace slag is rapidly chilled and then ground to the fineness of cement. Although normally designated as ‗GGBS', it can also be referred to as ‗Slag cement'. Being a by-product and also a waste product, its effective use can serve as a step for a greener environment.

2.3.2.1 Production

GGBS is formed by rapid cooling of the liquid slag, which is produced during smelting of the iron ore in the blast furnace. After grinding, it forms a fine powder. These operate at a temperature of about 1500 degrees centigrade and are fed with a carefully controlled mixture of iron ore, coke and limestone. The slag is, therefore, the waste material from the production of the iron. According to Neville, 2012, there is about 300 kg of the slag produced together with 1000 kg of the pig iron.

2.3.2.2 Composition

Table 2.2: Requirements for the Ground Granulated Blast-Furnace Slag according to EN 15167-1

Property	Test method	Requirement
Content of magnesium oxide, mass %	EN 196-2	≤ 18
Content of sulphides, mass %	EN 196-2	≤ 2.0
Content of sulphates, mass %	EN 196-2	≤ 2.5
Loss on ignition, corrected for oxidation of sulfide, mass %	EN 196-2	≤ 3.0
Content of chlorides, mass %	EN 196-2	≤ 0.10
Content of moisture, mass %	EN 15167-1 App. A	≤ 1.0
Fineness, m^2/kg	EN 196-6	≥ 275
Initial setting time	EN 196-3	for combination (by mass) of 50 % of GGBS with 50 % of test cement shall not be more than twice as long as that of the test cement on its own
Activity index	EN 196-3	after 7 days ≥ 45 % at 28 days ≥ 70 %

The minimum requirements for the ground granulated blast-furnace slag according to European Standard EN 15167- 1 are given in Table 2.2.

2.3.2.3 Property

According to European Standard EN 197-1, the blast-furnace slag is an important constituent of Portland-composite cements CEM II, blast furnace cements CEM III, slag-pozzolan cements CEM V and composite cements CEM VI.

Concrete made with GGBS cement sets more slowly than concrete made with ordinary Portland cement, depending on the amount of GGBS in the cementitious material, but also continues to gain strength over a longer period in production conditions. This results in lower heat of hydration and lower temperature rises, and makes avoiding cold joints easier, but may also affect construction schedules where quick setting is required (Suresh & Nagaraju, 2015).

2.3.2.4 Replacement level

GGBS is used as a direct replacement for Portland cement. Replacement levels for GGBS vary from 30% to up to 85%. Typically 40 to 50% is used in most instances. For on the ground concrete structures with higher early-age strength requirement, the replacement ratio would usually be 20 to 30%. For underground concrete structures with average strength requirement, the replacement ratio would usually be 30 to 50%. For mass concrete or concrete structures with strict temperature rise requirement, the replacement ratio would usually be 50 to 65%. For the special concrete structures with higher requirement on durability i.e., corrosion resistance for marine structures, sewerage treatment plants etc., the replacement ratio would usually be 50 to 70% (Suresh & Nagaraju, 2015). The authors also mentioned the following ranges of GGBS to be used for various purposes:

- 66 to 80% GGBS may be best for high sulphate resistance or for high resistance to chloride ingress.
- 50 to 70% GGBS may be best to reduce heat of hydration and control early-age cracking.
- 25 to 40% GGBS may be best to avoid extended finishing times for applications such as power-floated floors.
- 20 to 40% GGBS may be best to ensure high early strength.
- 80 to 95% GGBS may be best to achieve very low early-strength gain in applications such as secant piles.

- 30 to 45% GGBS may be best to avoid excessive retardation in cold weather.

2.3.2.5 Effect of slag addition on concrete properties

Strength

Lukowski and Salih (2015) have found that the strength development of the composites with GGBS is slower as can be seen from the Figure 2.4.

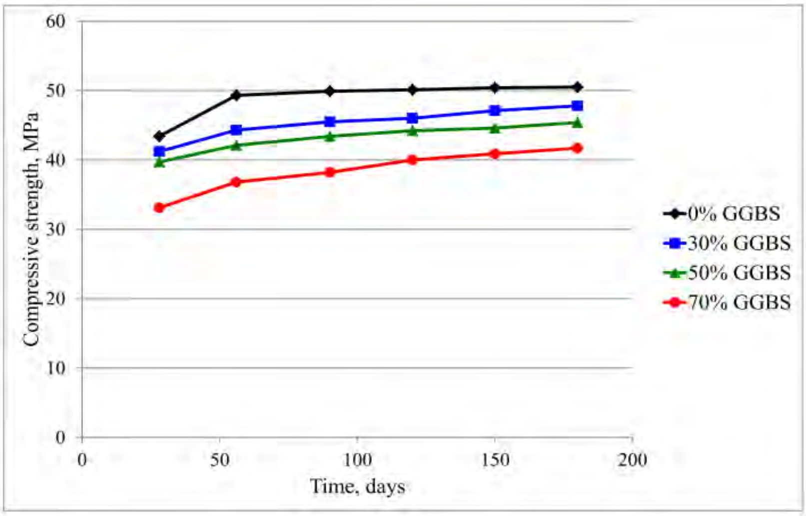


Figure 2.4: Development of Compressive Strength of the Mortars with Various Content of GGBS (Lukowski & Salih, 2015)

Suresh and Nagaraju (2015) found that with the same content of cementitious material (the total weight of Portland cement plus GGBS), similar 28 day strengths to Portland cement will normally be achieved when using up to 50% GGBS. But at higher GGBS percentages the cementitious content may need to be increased to achieve equivalent 28 day strength. Typically a Portland cement concrete will achieve about 75% of its 28 day strength at seven days, with a small increase of 5 to 10% between 28 and 90 days. By comparison, a 50% GGBS concrete will typically achieve about 45 to 55% of its 28 day strength at seven days, with a gain of between 10 and 20% from 28 to 90 days. At 70% GGBS, the seven day strength would be typically around 40 to 50% of the 28 day strength, with a continued strength gain of 15 to 30% from 28 to 90 days. Under normal circumstances, the striking times for concretes containing up to 50% GGBS, do not increase sufficiently to significantly affect the construction program. However, concretes with higher levels of GGBS will not always achieve sufficient strength after one day to allow removal of vertical formwork, particularly at lower temperatures, lower cementitious contents and in thinner sections (Suresh & Nagaraju, 2015).

Durability

Łukowski and Salih, 2015 found that, after storing in the aggressive environment, the losses in the strength and mass as well as linear changes of composites containing GGBS are lesser than for those containing only Portland cement. This can be seen in Figure 2.5. The addition of GGBS makes the structure of the hardened cement paste more compacted, diminishing the porosity and improving the tightness.(Łukowski & Salih, 2015)

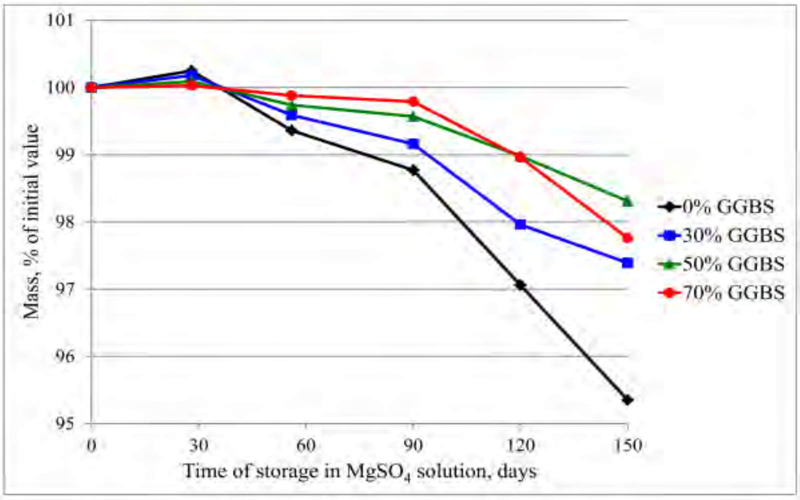


Figure 2.5: Changes of Mass of the Mortars with Various Content of GGBS Stored in Sulphate Solution (Łukowski & Salih, 2015)

Suresh and Nagaraju (2015) found that in the production of ready mixed concrete, GGBS replaces a substantial portion of the normal Portland cement concrete, generally about 50%, but sometimes up to 70%. The higher the portion, the better is the durability.

When Portland cement reacts with water, the insoluble hydration products (mainly calcium silica hydrates) form close to the cement particle. The more soluble product of hydration (Calcium hydroxide) migrates through the pore solution and precipitates as discrete crystals, surrounded by large pores. When GGBS particles are also present, both the GGBS and Portland cement hydrate to form calcium silicate hydrates. Additionally, the GGBS react with the excess of calcium hydroxide to form a finely dispersed gel, which fills the larger pores. The result is a hardened cement paste, which contains far fewer calcium hydroxide crystals and therefore has fewer large capillary pores. The reduction in free calcium hydroxide makes concrete chemically more stable, and the finer pore structure limits the ability of aggressive chemicals to diffuse through the concrete which in turn results in higher durability (Suresh & Nagaraju, 2015). The authors also found that use of 50% GGBS typically gives high resistance to chloride and use of 70% GGBS gives very high resistance.

Setting Time

Suresh and Nagaraju (2015) found that with increasing proportion of GGBS, setting time increases as can be seen from Figure 2.6

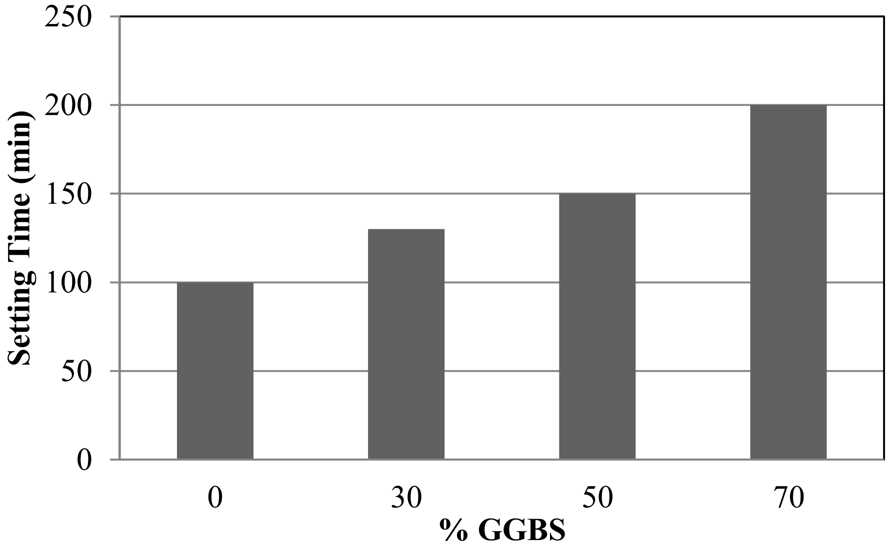


Figure 2.6: Effect of GGBS on Setting time (Suresh & Nagaraju, 2015)

Slump

Fresh concrete containing GGBS tends to require less energy for movement. This makes it easier to place and compact, especially when pumping or using mechanical vibration. In addition, it will retain its workability for longer (Suresh & Nagaraju, 2015).

2.3.2.6 Advantage

Suresh and Nagaraju (2015) mentioned following advantages of GGBS:

- Better workability, making placing and compaction easier;
- Lower early age temperature rise, reducing the risk of thermal cracking in large pours;
- Elimination of the risk of damaging internal reactions;
- High resistance to chloride ingress, reducing the risk of reinforcement corrosion;
- High resistance to attack by sulphate and other chemicals;
- Considerable sustainability benefits.

2.3.3 Silica fume

Silica fume is a finely divided residue resulting from the production of elemental silicon or ferro-silicon alloys that is carried from the furnace by the exhaust gases. It originates from the reduction of high purity quartz with coal in electric arc furnaces in the production of silicon and ferrosilicon alloys. Silica fume is often used to make high strength concrete along with other SCMs. It consists of very fine spherical particles containing at least 85 % by mass of amorphous silicon dioxide.

2.4 Aggregate

Aggregate is one of the main constituents of concrete. It takes about 60 to 80% of the total volume of concrete. Aggregates affect the workability and the hardened properties of concrete. Using more aggregate reduces the cost of producing concrete as cement is more expensive than aggregate. Moreover, most of the durability problems, e.g. shrinkage, freezing and thawing of hardened concrete are caused by cement. Generally, concrete shrinkage increases with increase in cement content. Aggregates, on the other hand, reduce shrinkage and provide more volume stability.

2.4.1 Classification

Aggregate is mainly divided into two types- coarse aggregate and fine aggregate. Coarse aggregates consist of gravels or crushed stones with particles predominantly larger than 5 mm and generally between 9.5 mm and 37.5 mm. Fine aggregates generally consist of natural sand or crushed stone with most particles smaller than 5 mm. This classification of aggregate according to particle size is summarized in Table 2.3.

Table 2.3: Classification of Aggregates Based on Particle Size

Aggregate Fraction	Size Range
Coarse	Retained in No. 4
Fine	Passing No. 4 – Retained in No. 200
Microfines	Passing No. 200

2.4.2 Effects of aggregate characteristics on concrete properties

Aggregate characteristics have a significant effect on the behavior of both fresh and hardened concrete. The main characteristics that effect concrete properties are size, shape, texture, grading, specific gravity, soundness, absorption etc. Some of the effects are discussed in the following sections.

2.4.2.1 Size

Maximum size of aggregates (MSA) influences workability, strength, shrinkage, and permeability. Washa, 1998 found that mixtures with large maximum size of coarse aggregate tend to produce concrete with better workability because of the decrease in specific surface area. Again, there is an optimal maximum size of coarse aggregate that produces the highest strength for a given consistency and cement content (Popovics, 1998; Washa, 1998). Joshaghani et al. (2014) observed that if maximum size of the coarse aggregate increases, the strength decreases but the permeability and porosity increases. Increasing the size of the aggregate also affects the tensile strength of concrete. An increase in the maximum grain size to 120–180 mm reduces the tensile strength up to 30–50% as compared with concretes with maximum aggregate size 20 mm.

2.4.2.2 Shape

The shape of the aggregate particles influences paste demand, placement characteristics such as workability and pumpability, strength and cost. (O'Flynn, 2000). Rough-textured, angular and elongated particles require more water to produce workable concrete than smooth, rounded, compact aggregates. Therefore, angular aggregates require more cement to maintain the same water cement ratio. Angular aggregates can also be more difficult to pump. The bond between cement paste and a given aggregate generally increases as particles change from smooth and rounded to rough and angular. Round or nearly cubical shaped aggregates are desirable due to the ease in which they move in the mixing and handling process.

The shape of an aggregate influences the workability of the mixture as well as the void content and packing density. For the same amount of paste, a mixture with round shaped aggregate will have better workability than a mixture with flaky and elongated aggregates. Moreover, for the same mass of aggregates, round and cubical aggregates produce mixtures with higher packing, which results in a lower void content. Concrete made with flat and elongated aggregate particles require an increase in mixing water and thus may affect the strength of concrete, if the water-cement ratio is not adjusted. So flat or elongated particles should be avoided as much as possible.

2.4.2.3 Surface texture

The surface texture of aggregate influences the workability, quantity of cement and bond between particles and the cement paste. Natural aggregates have a smooth surface. Increase in surface roughness improves the bond. Rough-textured angular grains bond better with the cement paste to generate higher tensile strengths (O'Flynn, 2000). Although rougher textures lead to better bond between paste and aggregate, they also lead to harsher mixtures. As texture roughness increases, the internal friction increases between the aggregates, and therefore more paste is needed to achieve a given workability.

2.4.3 Aggregate gradation

Aggregate gradation affects concrete density, void content, workability, segregation, pumpability, economy, porosity, shrinkage, and durability. Particle size distribution of fine aggregate plays a very important role on workability, segregation, and pumpability of fresh concrete. Grading is the particle-size distribution of an aggregate as determined by a sieve analysis.

Variations in grading can affect the uniformity of concrete. Very coarse sands and coarse aggregate can produce harsh, unworkable mixtures. On the other hand, very fine sands are often uneconomical. The scarcity or excess of any size fraction in aggregate could result in poor workability and poor durability of concrete (Shilstone, 1990). Excess sand requires more cementitious materials, produces sticky mixtures, makes pumping difficult, and increases bleeding and permeability. On the other hand, insufficient sand causes different types of finishing problems. In general, aggregates that do not have a large deficiency or excess of any size and give a smooth grading curve will produce the most satisfactory results. Uniformly distributed mixtures generally lead to higher packing resulting in concrete with higher density and less permeability (Golterman, 1997). They also require less paste, thus decreasing bleeding, creep, and shrinkage (Washa, 1998; Shilstone, 1999). Both coarse aggregate and fine aggregate should be uniformly graded. Uniformly distributed mixtures produce better workability than gap-graded mixtures (Golterman, 1997), although higher slumps can be achieved with gap-graded mixtures. Grading should also be changed depending on the construction procedures. For example, pumpable concrete requires a high fine aggregate content.

Studies performed by Cramer, 1995 showed that increases strength can be achieved using well graded aggregate. Well graded mixtures also produce more durable concrete. In reducing permeability, it is desirable to have the highest aggregate content possible.

2.4.3.1 Fineness modulus

Fineness Modulus (FM) is an index of the fineness of an aggregate. The higher the FM, the coarser is the aggregate. FM of aggregate is calculated by adding the cumulative percentages by mass retained on each of a specified series of sieves and dividing the sum by 100 (ASTM C125). The specified sieves for determining FM are: 150 µm (No. 100), 300 µm (No. 50), 600 µm (No. 30), 1.18 mm (No. 16), 2.36 mm (No. 8), 4.75 mm (No. 4), 9.5 mm (3⁄8 in.), 19.0 mm (3⁄4 in.), 37.5 mm (1½ in.), 75 mm (3 in.) and, 150 mm (6 in.). Effect of FM on concrete properties is not totally clear because for any single FM, there could be numerous gradations of various aggregate contents.

2.4.3.2 0.45 Power chart

The Power Chart is a plot of the percent passing each sieve size and the sieve size in microns to the 0.45 power. A well graded, tight packing aggregate that produces a maximum density will approximately plot along a straight line. This straight line is the Power Chart line and may be plotted using the following equation.

$$\%\,Passing = \left(\frac{d}{D}\right)^{0.45} \qquad \textit{Power Chart Line}$$

Where,

d = Square opening of the sieve size being considered.

D = Square opening of the nominal Maximum Sieve size.

2.4.3.3 Gradation curve

In gradation curve the percent passing of aggregate is plotted against sieve opening sizes. This curve is used to define good-graded, gap-graded and poorly-graded mix. Figure 2.7 shows the gradation curve of well graded, gap graded and uniformly graded aggregate sample.

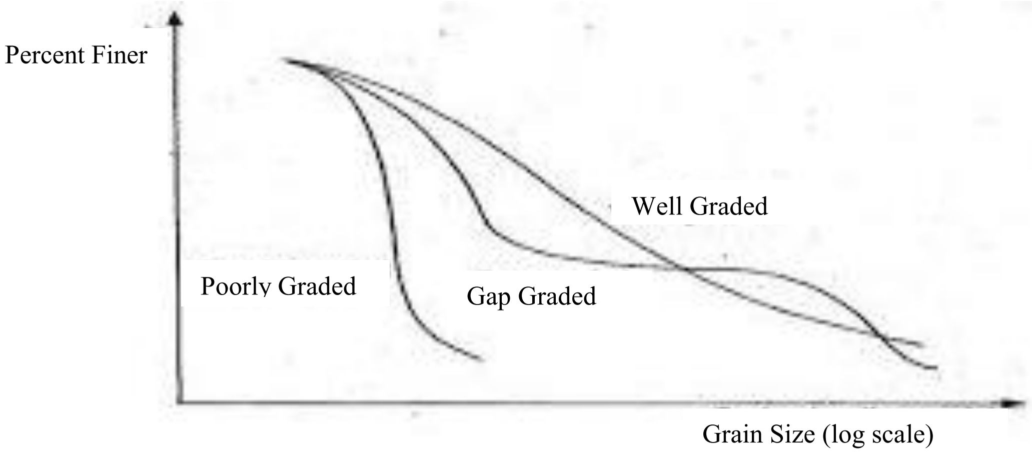


Figure 2.7: Typical Gradation Curve of Well Graded, Gap Graded and Uniformly Graded Aggregate Sample

2.4.3.4 Individual percent retained curve and aggregate band gradation

Individual percent retained (IPR) vs. sieve sizes is another method of representing the particle size distribution of an aggregate sample. Shilstone (1990) promoted the use of IPR curve, since it is very easy to determine which sizes are excessive or deficient.

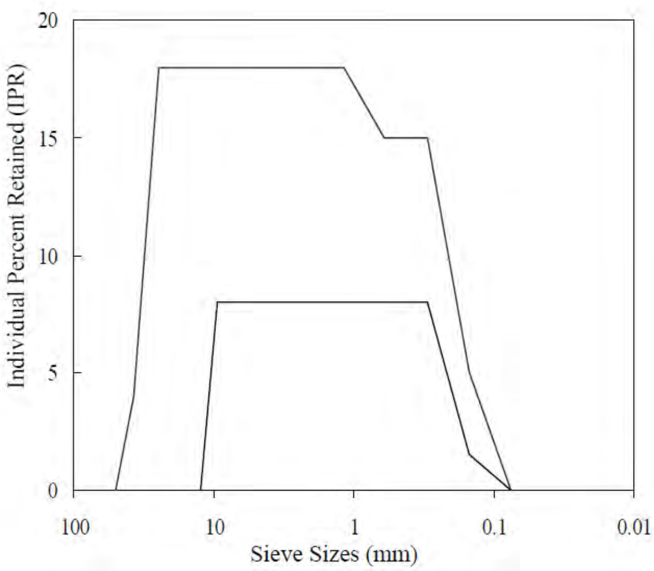


Figure 2.8: IPR Requirements for ―8-18" Band Gradation

Different aggregate band gradations have been proposed by different authors. Holland (1990) proposed ‗8-18' band gradation. The requirement of this gradation is that the total percentage of fine and coarse aggregate retained on any one sieve to be in between 8 and 18 percent (Figure 2.8). It reduces shrinkage by reducing water demand through optimized gradation (Harrison, 2004).

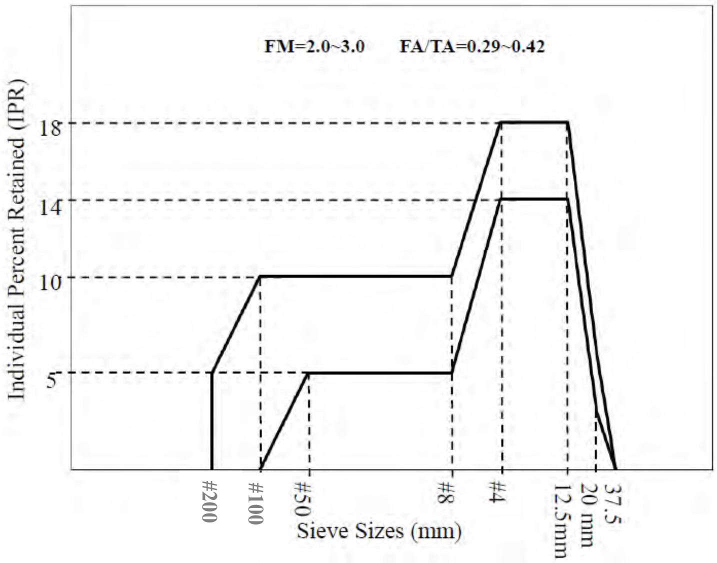


Figure 2.9: IPR Requirements for 5-10-14-18 Band Gradation (Ashraf and Noor, 2012)

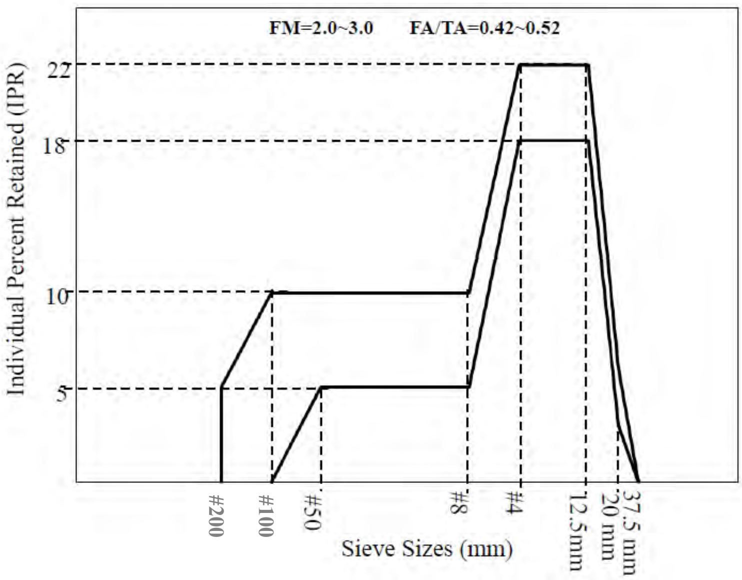


Figure 2.10: IPR Requirements for 5-10-18-22 Band Gradation (Ashraf and Noor, 2012)

An inherent disadvantage of _8-18' band gradation is that, it leads to a wide variation of fineness modulus and it covers a wide range of combined aggregate gradation. To overcome the drawbacks of _8-18' band gradation, two new band gradations, 5-10-14-18 and 5-10-18-22 were developed by Ashraf and Noor (2012). Aggregate properties such as FM and fa/ta fall into a narrow range in these two gradations. IPR requirements for these gradations are shown in Figures 2.9 and 2.10.

Ashraf and Noor (2012) concluded that, any aggregate gradation that falls within 5-10-14-18 band will have FM between 2 and 3.5, fa/ta between 0.28 and 0.43. For 5-10-18-22 band gradation, FM and fa/ta are 2 to 3.5 and 0.4 to 0.55, respectively.

2.5 Green Cement

The present rate of release of this greenhouse gas into the atmosphere is a serious threat to or current and future generation. Authorities in various countries have introduced laws and incentives such as CO_2 tax, quarrying and extraction tax, etc. in order to regulate and reduce the emission of CO_2. But they are finding difficulties to implement these regulations because of population growth and industrialization.

Cement industries face a number of challenges that include depleting fossil fuel reserves, scarcity of raw materials, increasing demand for cements and concretes, growing environmental concerns linked to climate change and an ailing world economy. Every tonne of Ordinary Portland Cement (OPC) that is produced releases on average a similar amount of CO_2 into the atmosphere, or in total roughly 6% of all man-made carbon emissions (Imbabi et al., 2012). For contributing to effective emission reduction, the cement industries need to rely on OPC blends incorporating waste materials, develop clinker substitutions using other low carbon cementitious materials and formulate new low carbon cement production process.

Ground granulated blast furnace slag is one of the greenest construction materials. Manufacturing of GGBS utilizes all of the slag and produces no significant waste. As well as the environmental benefit of utilizing a byproduct, GGBS replaces cement which is produce by a highly energy intensive process. Comparing with Portland cement, manufacturing of GGBS requires less than a fifth the energy and produces less than a fifteenth of the carbon dioxide emissions (Suresh & Nagaraju, 2015). Further green benefits are that manufacture of GGBS does not require the quarrying of virgin materials, and if the slag was not used as cement it might have to be disposed as waste.

Using a high dosage of GGBS in concrete is an effective approach to control the heat release rate, reduce the material cost and enhance the durability which will help to produce greener environment. However, high dosage of GGBS often exhibits low compressive strength at an early stage, which limits the material to non-structural or semi-structural applications.

Use of ultrahigh-volume fly ash (UHVFA) concrete can be a step towards green concrete. Yu, et al., 2017 studied the properties of concrete using 20%, 40%, 60%, 80% and 98% fly ash replacement and found that, the proposed green structural concrete showed a reduction in CO_2 emission of around 70%, a reduction in embodied energy of more than 60% and a reduction in material cost of 15% compared to commercial Grade 45 concrete. Yu, et al., 2017 also concluded that, with a suitable mix proportion, even with 80% of the binder replaced by fly ash, the compressive strength of the mortar and concrete can reach over 40 MPa at 7-day age and over 60 MPa at 28-day age.

2.6 Concrete Mix Design

Concrete mix design is the process of selecting suitable ingredients of concrete and determining the relative proportions of the ingredients of concrete with a view to produce concrete of specified minimum strength, durability and workability as economically as possible. The proportioning of ingredient of concrete is governed by the required performance of concrete in two states, namely the plastic and the hardened states.

The various factors that affect concrete mix design are described below:

Compressive Strength

Compressive strength is one of the most important properties of concrete. It influences many other properties of the hardened concrete. Usually 28 day compressive strength determines the nominal water-cement ratio of the mix. The other factor affecting the strength of concrete at a given age and cured at a prescribed temperature is the degree of compaction. The strength of fully compacted concrete is inversely proportional to the water-cement ratio.

Workability

The degree of workability required depends on the size of the section to be concreted, the amount of reinforcement, and the method of compaction to be used. A desired workability is required for proper compaction and placement of concrete. Higher workability is desired for ready- mix concrete and where it needs to be pumped. For the narrow and complicated section with numerous corners or inaccessible parts, the concrete must have a high workability so that full compaction can be achieved with a reasonable amount of effort.

Durability

The durability of concrete is its resistance to the aggressive environmental conditions. High strength concrete is generally more durable than low strength concrete. In the situations when the high strength is not necessary but the conditions of exposure are such that high durability is vital, the durability requirement will determine the water-cement ratio to be used.

Maximum Nominal Size and Grading of Aggregate

In general, larger the maximum size of aggregate, smaller is the cement requirement for a particular water-cement ratio, because the workability of concrete increases with increase in maximum size of the aggregate. However, the compressive strength tends to increase with the decrease in size of aggregate.

The grading of aggregate influences the mix proportions for a specified workability and water-cement ratio. Coarser the grading leaner will be mix which can be used. Very lean mix is not desirable since it does not contain enough finer material to make the concrete cohesive. The type of aggregate influences strongly the aggregate-cement ratio for the desired workability and stipulated water cement ratio. An important feature of a satisfactory aggregate is the uniformity of the grading which can be achieved by mixing different size fractions.

2.6.1 Requirements of concrete mix design

The requirements which form the basis of selection and proportioning of mix ingredients are:

a) The minimum compressive strength required from structural consideration

b) The adequate workability necessary for full compaction with the compacting equipment available.
c) Maximum water-cement ratio and/or maximum cement content to give adequate durability for the particular site conditions
d) Maximum cement content to avoid shrinkage cracking due to temperature cycle in mass concrete.

2.6.2 Existing concrete mix design methods

Concrete mix design is a well-established practice around the world. There are many methods of concrete mix design. These methods are based on empirical relations, charts, graphs, and tables developed as outcomes of extensive experiments and investigations of locally available materials. A particular mix design method will not be applicable for all countries because of the use of region specific climatic conditions and concrete ingredients. Some of the widely used mix design methods are ACI Mix Design, USBR Mix Design, British Mix Design, ISI Recommended guidelines etc.

2.6.2.1 American Concrete Institute (ACI) mix design

This mix design method was first published in 1944 by ACI committee 613. The method was revised to include the use of entrained air in 1954. In ACI mix design, proportioning of concrete ingredients can be done by two methods. One method is based on the estimated weight of the concrete per unit volume. The other method is based on absolute volume occupied by concrete ingredients. The ACI methods take into consideration the requirements for workability, consistency, strength and durability. The procedure of mix proportioning is described below:

(i) From the minimum strength specified, the average design strength is estimated.

(ii) The water-cement ratio is calculated from the strength as well as durability considerations.

(iii) Maximum size of aggregate to be used is determined based on the economical availability and dimensions of the structure.

(iv) Workability is decided in terms of slump depending on placing condition.

(v) The total water in kg/m^3 of concrete is read from table, entering the table with selected slump and selected maximum size of aggregates.

(vi) Cement content is computed by dividing the total water content by the water-cement ratio.

(vii) From the table, the bulk volume of dry rodded coarse aggregates per unit volume of concrete is selected for the particular maximum size of coarse aggregate and fineness modulus of fine aggregate.

(viii) The weight of coarse aggregate per cubic meter of concrete is calculated by multiplying the bulk volume with bulk density.

(ix) The solid volume of coarse aggregate in one m^3 of concrete is calculated by knowing the specific gravity of coarse aggregate.

(x) Similarly the solid volume of cement, water and volume of air is calculated in on cubic meter of concrete

(xi) The solid volume of fine aggregate is computed by subtracting from the total volume of concrete, the solid volume of cement, coarse aggregate, water and entrapped air

(xii) Weight of fine aggregate is calculated by multiplying the solid volume of fine aggregates by its specific gravity.

(xiii) Mixing water quantity is adjusted based on the moisture content in the aggregate.

(xiv) The calculated mix proportions are checked by trial batches prepared and tested in accordance with specifications and another trial is made if required.

ACI mix design method has the advantages of simplicity because it uses more or less identical procedures to rounded or angular aggregate, to regular or light weight aggregates and to air entrained or non-air entrained concretes. But this method has some inherent limitations. Wadud and Ahmad (2001) observed that in the ACI method, cement content determination process is not directly related to aggregate gradation. But in reality, the binding action of the hydrated cement paste always takes place on the surface of the aggregate particles. Again, so far as the aggregate surface area is concerned, fine aggregate is the major contributor. Therefore, the quantity of fine aggregate is essential to the determination of the cement content. ACI method fails to rationally predict the proportion of the ingredients when coarse aggregates of higher voids is used in making the concrete. In such cases, the amount of fine aggregate is over estimated. This over estimation leads to a higher surface area to be covered by the same amount of cement, which is determined without any reference to aggregate grading. As a result, the mix fails to attain the design strength.

2.6.2.2 USBR (United States Bureau of Reclamation) mix design

In this method of mix design, the water content of air entrained concrete and the proportions of fine and coarse aggregates are determined for a fixed workability and grade of fine aggregates. This mix design steps are described below:

(i) The water cement ratios for the target mean 28 day compressive strength of concrete is determined from table.

(ii) Approximate air and water contents and the percentages of coarse aggregate per cubic meter concrete are determined from the table, for concrete containing natural fineness of modulus 2.75 and having workability of 75 to 100mm.

(iii) Adjustment of values in water content and percentage of sand or coarse aggregate are made as provided in table for changes in the fineness modulus of sand, slump of concrete, air content, water-cement ratio and sand content.

(iv) The cement content is calculated using the selected water-cement ratio and the final water content of the mix is arrived after adjustments.

(v) Proportions of aggregates are determined by estimating the quality of coarse aggregate from the table or by computing the total solid volume of sand and coarse aggregate in the concrete mix and multiplying the final percentage after adjustment.

2.6.2.3 British mix design

The British method of Concrete mix design popularly referred to as the DOE method is used in the United Kingdom and other parts of the world. This method was first published in 1975 and then revised in 1988. The DOE method utilizes British test data obtained at the Building Research Establishment, the Transport and Road Research Establishment, and the British Cement Association. The aggregates used in the tests conformed to BS 882 and the cements to BS12 or BS 4027.

The DOE method is based on following assumptions:

(i) The strength of a concrete mix depends on the free water/cement ratio, the coarse aggregate type and the cement properties.

(ii) The volume of freshly mixed concrete equals the sum of air content and of the absolute volumes of its constituent materials.

This mix design steps are described below:

(i) Finding the target mean strength from the specified characteristic strength.

(ii) Calculating the water-cement ratio.

(iii) Deciding the water content for the required workability expressed in terms of slump taking into consideration the size of aggregates and its type from table.

(iv) Calculating cement content by dividing the water content by water cement ratio.

(v) Finding the total aggregate content. This requires an estimate of the wet density of the fully compacted concrete. This can be found out for approximate water content and specific gravity of aggregate.

(vi) Determining the proportion of fine aggregate in the total aggregate from workability, maximum size of aggregates and percent of fine aggregates passing through 600μ sieve. Once the proportion of fine aggregate is obtained, the amount aggregate content can be calculated by multiplying the proportion to the weight of total aggregate.

(vii) Calculating the amount of coarse aggregate from total aggregate.

2.6.2.4 ISI recommended guidelines

Indian Standard Recommended Method of Concrete Mix Design is sentenced in IS 10262-1982. This mix design steps are described below:

(i) Calculation of target mean strength.

(ii) Determination of water-cement ratio from a graph showing the relation between strength and water cement ratio.

(iii) Estimation of air content from table for the nominal maximum size of aggregate used.

(iv) Determination of the water content in percent of fines in total aggregate by the maximum size of aggregates.

(v) Calculation of cement content per unit volume of concrete from free water cement ratio and cement content per unit volume.

(vi) Calculation of aggregate by the following two formulas:

$V = [w+(c/Sc) + (1/p)*(1/1000)$

$Ca = [(l-p)/p]* F.agr *(S_{ca} / S_{fa})$

V = absolute volume of fresh concrete, which is equal to gross volume (m^3) - the volume of entrapped air.

W = mass of water (kg) per m^3 of concrete.

C = mass of cement (kg) per m^3 of concrete.

Sc = specific gravity of cement.

P = ratio of FA to total aggregate by absolute volume.

Actual qualities required for mix are calculated by adjusting the proportion for the water content and absorption of aggregates. The calculated mix proportions shall be checked by means of trial batches.

Chapter 3

PHILOSOPHY AND PROPOSAL OF CONCRETE MIX DESIGN

3.1 General

Concrete mix design is a major factor for determining the properties of concrete. The existing well established mix design methods were developed using locally available materials of the concerned countries. The charts, graphs, tables and empirical relationships used in those mix designs are best suited only in those countries. In Bangladesh, concrete is prepared following the standards of these existing concrete mix designs. Therefore, the design strength is difficult to achieve in many cases of actual construction. To overcome this problem, different researchers have proposed different mix design methods exclusive and unique to Bangladesh using locally available materials.

3.2 Mix Design incorporating Band Gradation and Contours

Conventional methods of concrete mix design i.e. ACI 211 and BS 812 are popular in Bangladesh. But subsequent aggregate gradations i.e. ASTM C33, BS 882 may not be achievable through these standard methodologies due to possible variation in aggregate characteristics of this particular geographic region. Ashraf (2012) developed a mix design guideline suitable for Bangladesh using locally available materials using band gradation as an important tool of the mix design procedure.

Ashraf compared different existing methodologies in terms of fresh concrete workability (slump) and 28 days concrete compressive strength to determine the most suitable aggregate gradation method. The test results signify that concrete compressive strength and workability are highly affected by its aggregate gradation. Moreover, concrete compressive strength can be increased more than 50 % just by altering its aggregate gradation. Ashraf also compared effectiveness of different parameters of aggregate gradation namely fineness modulus (FM) of fine aggregate (fa), FM of total aggregate (ta), coarseness factor, workability factor etc. She found that contemporary ‗band gradations‘ of aggregates result in better properties of concrete when compared with conventional gradations (ASTM C33, BS 882). Ashraf proposed two band gradations ‗5-10-14-18‘ and ‗5-10-18-22‘ which give better concrete only if some parameters are maintained within a range. Any aggregate gradation that satisfies the 5-10-14-18 or 5-10-18-22 band requirements results in concrete properties (workability, strength and density) with very little variation. FM and FA/TA fall within a narrow range for aggregates belonging to these bands. Therefore compressive strength and workability of concrete also vary insignificantly within the bands.

Ashraf (2012) also introduced contours in the mix design steps. Application of contours in concrete mix design increases the freedom of user and makes the process more users friendly.

Although the mix design process proposed by Ashraf is innovative, user friendly and specially designed for Bangladesh, it only considered workability and compressive strength as major requirements of the mix design process. With increasing incidences of concrete deterioration, compressive strength alone cannot be considered as the sole criterion for evaluating concrete quality. Durability of concrete is an important parameter that should be included in design.

3.3 Mix Design incorporating Durability Parameter

In continuation to Ashraf�because (2012) research, Rumman (2018) proposed a mix design considering durability parameter. She used 5-10-14-18 and 5-10-18-22 aggregate bands as these bands ensure reasonable workability and strength. For improving durability, Rumman used Rice Husk Ash (RHA) as supplementary cementing material. The RHA replacement levels were 0%, 10% and 20%. She concluded that, replacement of 20% cement by RHA can increase 21.5% compressive strength. Moreover 20% RHA addition resulted in the lowest level of concrete permeability or highest level of concrete durability.

Although RHA performed excellent in terms of durability, it has some inherent disadvantages. Quality of the produced ash depends on type of paddy and burning temperature. Availability of RHA is another issue in non-rice producing countries. Therefore other more common supplementary cementing materials such as fly ash and blast furnace slag should be incorporated in mix design steps.

For determining durability, Rumman (2018) performed Rapid Chloride Permeability Test (RCPT) as per ASTM C1202. She proposed a new classification of durability using 90 day RCPT values on the basis of exposure conditions which is shown in Table 3.1 and 3.2.

Table 3.1: Permeability Classes for Determining Durability of Concrete (Rumman, 2018)

Allowable Permeability Class	Exposure conditions
Negligible	Surface of members in tidal zone; members in direct contact with liquid/solid aggressive chemicals
Very Low	Concrete surfaces exposed to sea water spray, corrosive fumes or severe freezing conditions whilst wet; concrete in contact with or buried under aggressive sub-soil/ground water
Low	Concrete surfaces exposed to severe rain, alternate wetting and drying or occasional freezing whilst wet or severe condensation; concrete completely immersed in sea water; concrete exposed to coastal environment
Moderate	Concrete surface exposed to mild rain; concrete continuously under water
High	Concrete surface sheltered from severe rain; concrete exposed to condensation; concrete in contact or buried under non-aggressive soil/ground water; concrete surfaces sheltered from saturated salt air in coastal area
Very High	Concrete surfaces protected against weather or aggressive conditions, except those situated in coastal areas

Table 3.2: Values of 90 Day Charge Passed (RCPT) for Corresponding Allowable Permeability Classes (Rumman, 2018)

Allowable Permeability Class	90 Day Charge Passed (Coulomb)
Negligible	1000-1800
Very Low	1801-2600
Low	2601-3400
Moderate	3401-4200
High	4201-5000
Very High	>5000

Rumman (2018) proposed the durability classes based on chloride permeability of RHA blended concretes only. The durability classes differ from ASTM C1012 durability classes which are shown in Table 3.3.

Table 3.3: Ratings of RCPT (ASTM C1202)

Total Charge Passed (Coulombs)	**Chloride Ion Permeability**
> 4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

Rumman (2018) did not perform any experiment on the proposed exposure conditions. Validation of the permeability class based on the exposure condition is required.

3.4 Proposed Mix Design Philosophy

The proposed mix design considers durability parameter in addition to compressive strength. Rapid Chloride Permeability Test (RCPT) is performed to assess durability and its 90 day value is specified in the mix design. To limit to short comings on Rice Husk Ash, it was intended to use common and widely available supplementary cementing materials for enhancing durability. For that reason, fly ash and blast furnace slag were used as supplementary cementing materials. The replacement level of fly ash was 0%, 20% and 35% and that of slag was 0%, 20%, 65% and 90%. Ordinary Portland Cement (OPC) was replaced to 90% level by slag which can work as green cement. Use of such high dosage of GGBS in concrete is an effective approach to control the heat release rate, reduce the material cost and enhance the durability which in turn will help to produce greener environment. Moreover a modified durability class is intended to be proposed which does not take into account the exposure conditions.

In the proposed mix design, 5-10-14-18 and 5-10-18-22 aggregate band gradations were used as recommended by Ashraf (2012) and Rumman (2018). These two band gradations provide reasonably durable and workable high strength concrete. Contour diagrams were also used in the mix design steps which make the total process easy and user friendly.

Chapter 4

PREPARATION AND TESTING OF SPECIMENS

4.1 General

Different laboratory tests on cement, coarse aggregate, fine aggregate, blast furnace slag and fly ash have been performed in this research. Total one hundred and eight mixes of concrete specimens were produced. This chapter describes test standards, procedures and results for the source materials that have been used in concrete production. Gradation and other properties of source aggregates and properties of the band gradations are also calculated and are included in this chapter.

4.2 Materials Used

The materials which have been used in this work are as follows

(i) Aggregate

(ii) Cement

(iii) Fly ash

(iv) Ground Granulated Blast-furnace Slag (GGBS)

4.2.1 Aggregates

In this research work, crushed stone chips are used as coarse aggregate. For proposing a new concrete mix design method, various properties of aggregates have been tested. The aggregates of the proposed mix design have been confined to two aggregate bands (5-10-14-18 and 5-10-18-22) since these two bands of aggregates show optimum strength, slump and durability.

4.2.1.1 Sources

List of the source aggregates which have been used in this research purpose are described in the following article.

(i) Coarse aggregate 1 ($^3/_4$ inch downgrade aggregates)
(ii) Coarse aggregate 2 (1/2 inch downgrade aggregates)
(iii) Fine aggregate (Sylhet sand and Local sand Mixed in 1:1 ratio)

(iv) 5-10-14-18 band of combined aggregate

(v) 5-10-18-22 band of combined aggregate

4.2.1.2 Preparation

Source Aggregate

The aggregate which are commonly known as ¾ inch downgrade, ½ inch downgrade and fine aggregate should satisfy the limiting range of aggregate gradation according to BS 882. To satisfy this, the value obtained in each standard size sieve should be within limit. Upper and lower limits of aggregates according to BS 882 are given below in the following tables.

Table 4.1: Grading Limits for Coarse Aggregate (British Standard, 1992)

Sieve Size (mm)	Single Sized Aggregate	
	20mm	10mm
50	-	-
37.5	100	-
20	85-100	-
14	-	100
10	0-25	85-100
5	0-5	0-25
2.36	-	0-5
0.3		
0.15		

In order to prepare the single sized aggregates according to the limits of British Standard, all the aggregate have been sieved and separated as different sizes. Then they are mixed according to BS limits. Following figures show the separated aggregates according to various sizes.

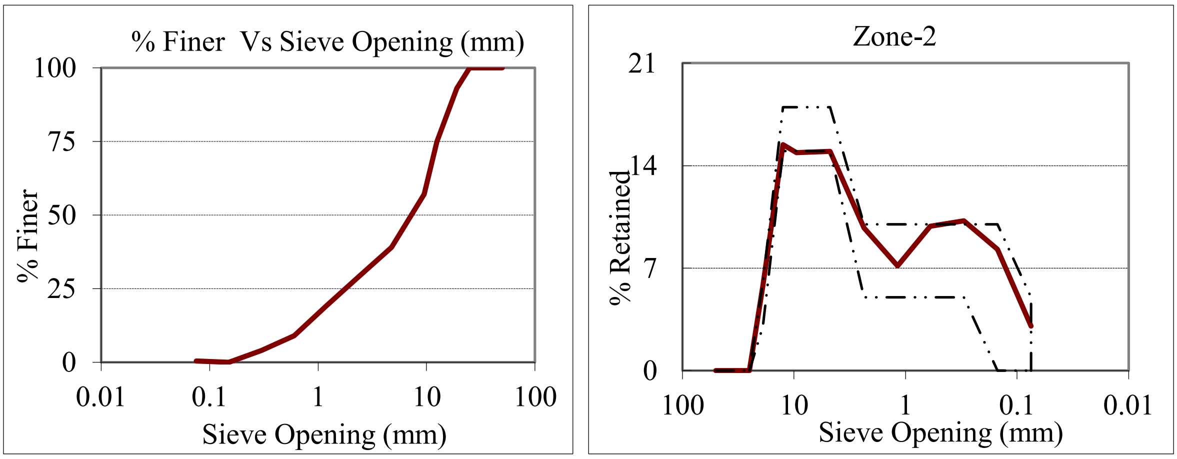
Table 4.2: Grading Limits for Fine Aggregate (British Standard, 1992)

Sieve Size (mm)	Fine Aggregate
10	100
5	89-100
2.36	60-100
1.18	30-100
.6	15-100
.3	5-70
.15	0-15

Figure 4.1: Various Sizes of Aggregates separated

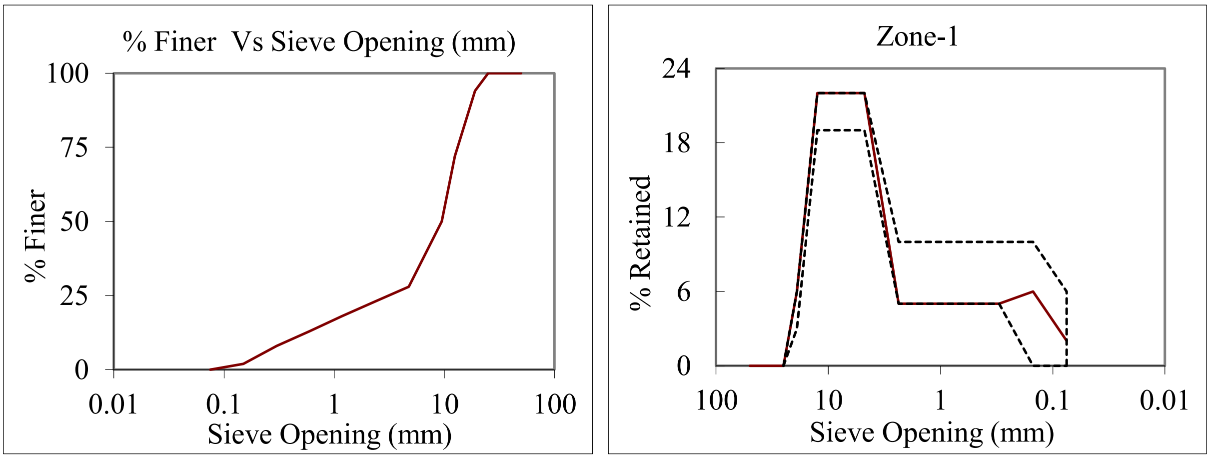
Combined Aggregate Bands

Two band gradations have been used for carrying out the experiments. These bands are 5-10-14-18 and 5-10-18-22. Since variations of concrete properties (compressive strength and slump) due to various possible aggregate gradations within the particular band have been found to follow some specific patterns (Ashraf, 2012), only one combined aggregate mix has been taken from each one of the two bands. Following figures show the gradation curve and IPR (Individual Percent Retained) curves for the aggregate mixes that have been used in this research.



IPR Curve Gradation Curve

Figure 4.2: Gradation Curves for Aggregate Mix from Gradation Band 5-10-14-18



IPR Curve Gradation Curve

Figure 4.3: Gradation Curves for Aggregate Mix from Gradation Band 5-10-18-22

From Figure 4.2, the individual percent retained curve can explain the name of the band "5-10-14-18". It requires that individual percent retained on #50 to #8 sieves should vary between 5% and 10% and individual percent retained on #4 to 12.5 mm sieve should vary between 14% and 18%. Similarly for 5-10-18-22 band, Figure 4.3 shows that the percent retained requirement on sieves #50 to #8 is varied between 5% and 10% and on #4 to 12.5 mm sieve, the requirement is 18% to 22%. Thus, the 5-10-18-22 band requires greater percentage of larger sized aggregates than 5-10-14-18. According to the values of individual percentages retained on each sieve, aggregate mixes have been prepared. Figures 4.4 and 4.5 show the two types of aggregate mixes.

Figure 4.4: Aggregate Mix from 5-10-14-18 Band

Figure 4.5: Aggregate Mix from 5-10-18-22 Band

4.2.1.3 Tests

Following section describes briefly the tests which have been conducted for aggregate samples.

(i) Specific gravity and absorption capacity of fine aggregate.

(ii) Specific gravity and absorption capacity of coarse aggregate.

(iii) Unit weight and voids in aggregate.

(iv) Sieve analysis of fine and coarse aggregate.

Specific Gravity and Absorption Capacity of Fine Aggregate

Specific gravity of aggregate has significant effects on both concrete mix proportioning and theoretical yield of concrete. Bulk specific gravity is defined as the ratio of the weight of the aggregate (oven-dry or saturated-surface dry) to the weight of water occupying a volume equal to that of the solid including permeable pores. Absorption capacity is important in determining the net water cement ratio in the concrete mix. Specific gravity and absorption capacity tests have been done as per the standard ASTM C128.

Specific Gravity and Absorption Capacity of Coarse Aggregate

Specific gravity and absorption capacity of coarse aggregates have been done according to the specifications of ASTM C127.

Specific Gravity of Combined Aggregate

Specific gravity of coarse and fine aggregates has been determined by ASTM C127 and ASTM C128 respectively. Specific gravity of the aggregate mixture has been calculated by use of the following formula.

$$G = \frac{P1 + P2 + P3 + \ldots}{\frac{P1}{G1} + \frac{P2}{G2} + \frac{P3}{G3} + \ldots}$$

Where: G = Specific gravity of the combined aggregate.

P1,P2,P3, etc. = Percentage by weight of aggregates No. 1,2,3, etc. in the mixture. G1,G2,G3, etc. = Specific gravity (Bulk-Saturated Surface Dry) of aggregates No. 1,2,3, etc.

Unit Weight and Voids in Aggregate

Unit weight of aggregate plays an important role in selecting concrete mix proportions and also required for mass - volume conversion relation. Void content of aggregate measured here does not include the permeable or impermeable voids within the aggregate particles. Void contents act as indications of the amount of cement paste required for concrete mixture. This test method conforms to the standard ASTM C29. As per the standard there are three procedures available for measuring the unit weight of aggregate. These are- i) shoveling procedure (provides loose unit weight), ii) rodding procedure (applicable for aggregates having a nominal maximum size of 1.5 inch or less), iii) jigging procedure (applicable for aggregates having a nominal maximum size greater than 1.5 inch). In this research the nominal maximum size of aggregates used has been 0.75 inch, thus for all aggregate samples the unit weight have been measured by rodding procedure. Figure 4.6 shows the unit weight and void content test of coarse aggregates using rodding procedure.

Figure 4.6: Unit Weight and Void Content Test of Coarse Aggregates using Rodding Procedure

Sieve Analysis of Fine and Coarse Aggregate

The term sieve analysis is given to the simple operation of dividing a sample of aggregates into fraction each consisting of particles between specific limits. This test results plays a substantial role in concrete mix design. These tests also provide the Fineness Modulus of any aggregate samples, which is a significant parameter in concrete mix design. Moreover, it indicates the relative fineness or coarseness of aggregate samples when compared. These tests have been done as per the standard ASTM C136.

4.2.1.4 Test results

Properties of source aggregates (single sized ¾ and ½ inch downgrade) and combined aggregates are shown in the tables 4.3 and 4.4. Figures 4.7-4.9 show the gradation curves for source aggregates and Figures 4.10 and 4.11 show the gradation curves for the combined mixes.

Table 4.3: Properties of Source Aggregates

	ID	Type	Absorption Capacity, %	FM	Specific Gravity (SSD)
Fine Aggregate	FA-1	Sylhet Sand	1.69	2.69	2.7
	FA-2	Local Sand	1.20	1.16	2.69
	FA	Sylhet Sand:Local Sand=1:1	1.8	1.95	2.67
Coarse Aggregate	CS-1	¾ inch down Grade	0.7	7.21	2.69
	CS-2	½ inch down Grade	0.8	6.06	2.68

Table 4.4: Properties of Combined Aggregates

	ID	Type	Absorption Capacity, %	FM	Specific Gravity (SSD)
Combined Aggregate	G1	5-10-14-18	0.7	5.32	2.64
	G2	5-10-18-22	0.7	5.92	2.65

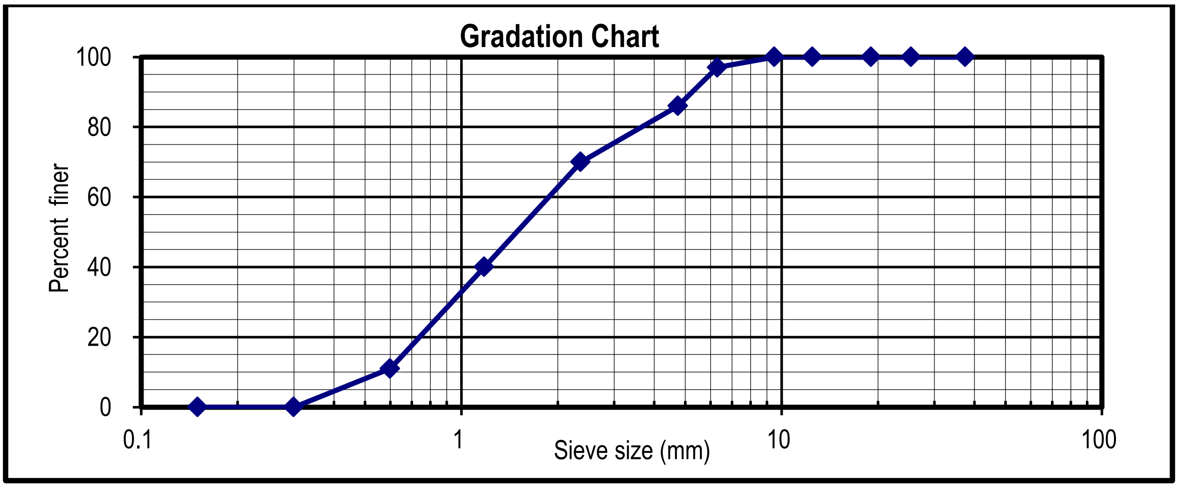


Figure 4.7: Gradation Curve for Source Aggregate (CA1)

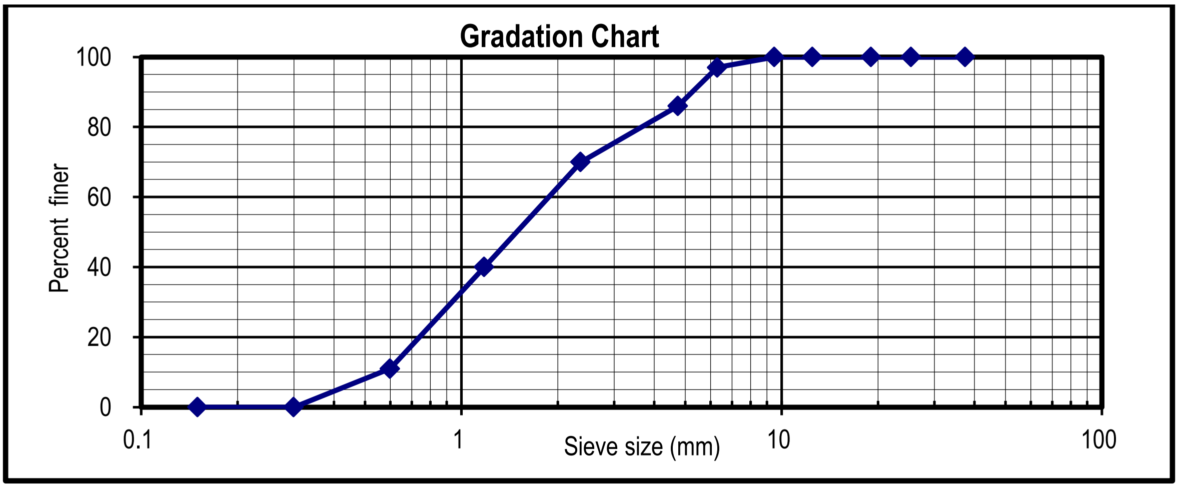


Figure 4.8: Gradation Curve for Source Aggregate (CA2)

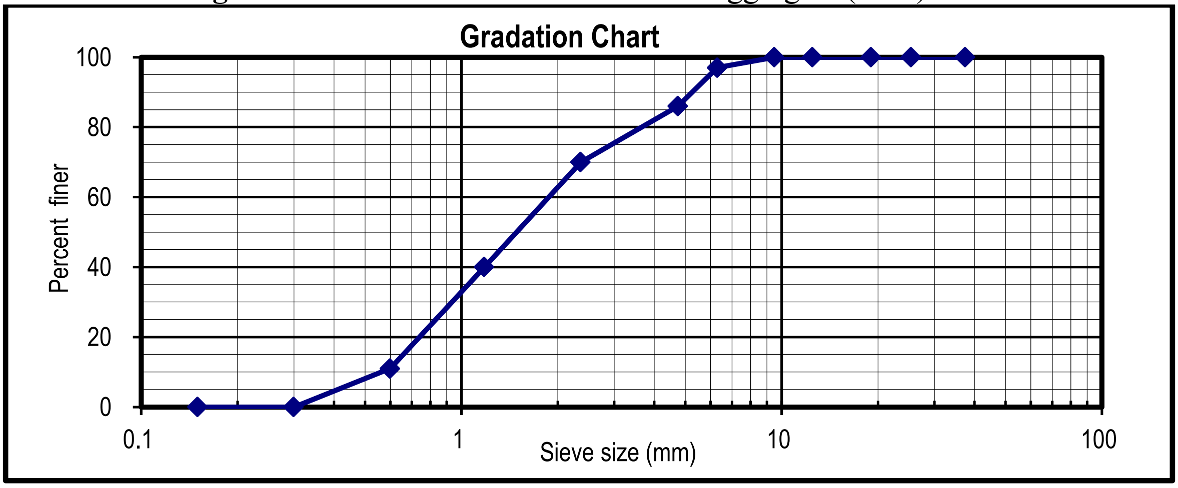


Figure 4.9: Gradation Curve for Source Aggregate (FA)

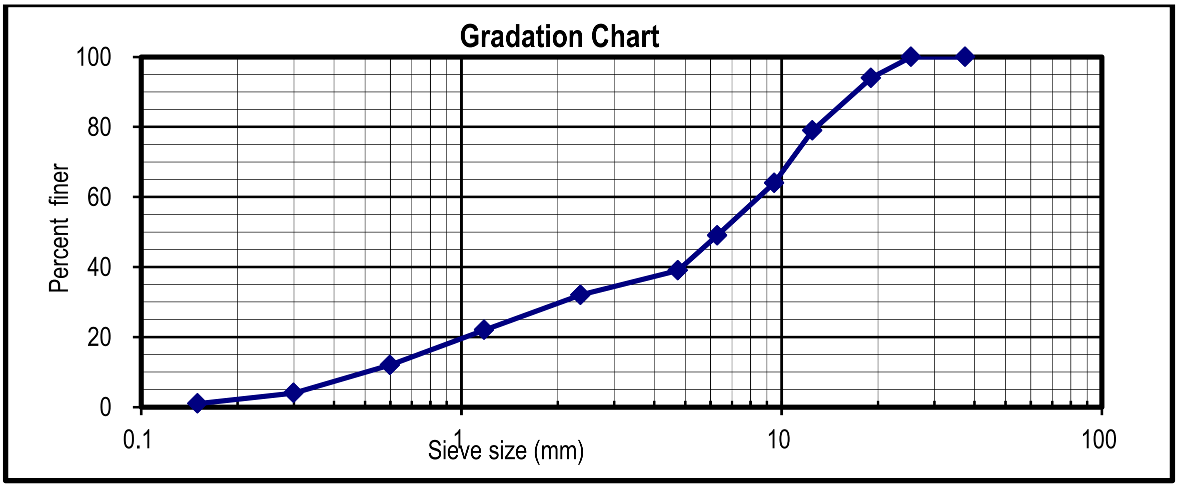


Figure 4.10: Gradation Curve for Combined Aggregate from Band 5-10-14-18

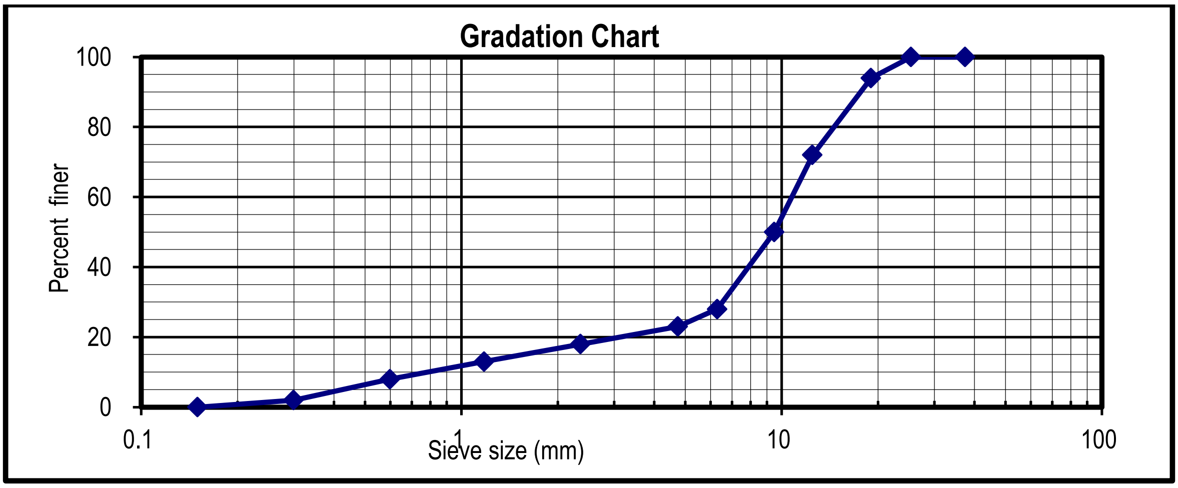


Figure 4.11: Gradation Curve for Combined Aggregate from Band 5-10-18-22

4.2.2 Cement

Locally available CEM I cement has been used in this research. In CEM I cements, the main constituents are Portland clinker (95-100%) and minor constituents only up to 5%.

4.2.2.1 Tests

Fineness, compressive strength, initial setting time and final setting time, and consistency of cement have been tested.

Fineness Test

Fineness test has been performed according to the specification of ASTM C204. This test method covers determination of the fineness of hydraulic cement, using the Blaine air-permeability apparatus, in terms of the specific surface expressed as total surface area in square centimeters per gram, or square meters per kilogram, of cement.

Compressive Strength Test

Compressive strength test of cements has been conducted as per the standard ASTM C150 for cement samples. 2 inch x 2 inch cement mortar cube specimens have been prepared and tested at 7, 28 and 90 days.

Setting Time Test

Setting times of cement have been tested as per the standard ASTM C109. Both of initial and final setting time of cement play important role in determining the workability loss of concrete mixture due to time delay between mixing and casting of concrete.

Normal Consistency Test

The amount of water content that brings the cement paste to a standard condition of wetness is called “normal consistency”. Normal consistency of cement has significant effects on setting time of cements and the workability of concrete. Normal consistencies of cements have been tested as per the standard ASTM C 187.

4.2.2.2 Test results

Table 4.5 shows the test results for cement which have been used in this research.

Table 4.5: Test Results for Cement used in this Research

Cement Type		Fineness (m^2/kg)	Normal consistency %	Initial setting time (Minute)	Final setting time (Minute)	Compressive strength (psi)		
						7 days	28 days	28 – days
CEM - I	Test results	442	26	129	332	3975	6880	7200

4.2.3 Fly ash

In this research, fly ash has been provided by Bashundhara Cement Company. It was collected from India. Figure 4.12 shows the fly ash used.

Figure 4.12: Fly Ash used in this Research

4.2.3.1 Tests

Fineness, compressive strength, normal consistency, setting time and chemical composition test of fly ash has been performed.

Fineness Test

Fineness test of fly ash has been conducted using Blaine's Air Permeability apparatus which is used to determine fineness of cement in ASTM standard.

Compressive Strength test

Cement mortars have been prepared using 0%, 20% and 35% replacement with fly ash and compressive strength has been determined using ASTM C150. 2 inch x 2 inch cement mortar cube specimens have been prepared and tested at 7, 28 and 91 days. Three samples have been tested at each case.

Normal Consistency and Setting Time Tests

Normal consistency and setting time tests have been performed on cement mortars with fly ash replacements of 20% and 35% and compared with control mortar. These tests have been conducted according to the specifications of ASTM C187 and ASTM C109.

4.2.3.2 Test results

Fineness Test

Fineness of fly ash using Blaine‘s Air permeability Apparatus has been observed to be 256 m^2/kg.

Compressive Strength Test

Cement has been replaced by fly ash to 20% and 35% by weight. Their strength test results along with the control mortar cube have been shown in Table 4.6. Figure 4.13 shows the comparison of the strength results.

Table 4.6: Compressive Strength Test Results of Cement Mortar with Different Levels of Fly Ash Replacement

Sample ID	Fly Ash Replacement (%)	7 day Compressive Strength (psi)	28 day Compressive Strength (psi)	90 day compressive strength
FA-1	0	3975	6880	7200
FA-2	20	3450	5820	6940
FA-3	35	2590	4110	6145

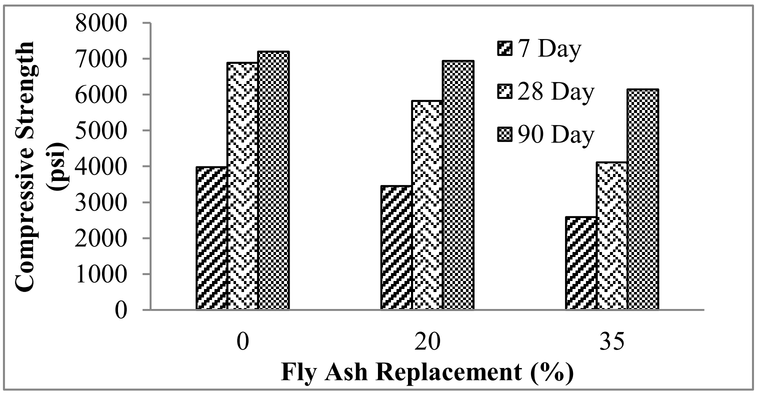


Figure 4.13: Comparison of Compressive Strength of Cement Mortars for Various Fly Ash Replacement Levels

Normal Consistency Test

Water content at normal consistency of cement with different levels of fly ash replacement has been determined according to the specifications of ASTM C187. The results have been shown in Table 4.7.

Table 4.7: Water Content at Normal Consistency (%) of Mortar at Various Percentages of Fly Ash Replacements

Fly Ash Replacement (%)	Water Content at Normal Consistency (%)
0	26.5
20	35.2
35	41.3

Setting Time Test

Both the initial and final setting time of cement mortars with fly ash replacements have been determined according to the specifications of ASTM C109. Table 4.8 shows the initial and final setting time values and their variations for different fly ash replacement levels respectively.

Table 4.8: Setting Time of Mortar at Various Percentages of Fly Ash Replacements

Fly Ash Replacement (%)	Initial Setting Time (minutes)	Final Setting Time (minutes)
0	106	260
20	135	280
35	165	318

Chemical Composition Test

The result of chemical composition test of fly ash is shown Table 4.9.

Table 4.9: Chemical Composition of Fly Ash

Sl. No.	Element	Test Result (%)
1	Calcium Oxide (CaO)	1.99
2	Silicon di-Oxide (SiO_2)	56.60
3	Aluminium Oxide (Al_2O_3)	26.80
4	Iron Oxide (Fe_2O_3)	5.27
5	Magnesium Oxide (MgO)	0.853
6	Sulphuric Anhydride (SO_3)	0.370

4.2.4 Ground Granulated Blast-furnace Slag (GGBS)

In this research, slag has also been provided by Bashundhara Cement Company. It was collected from Vietnam. Figure 4.14 shows the slag used.

Figure 4.14: Slag used in this Research

4.2.4.1 Tests

Fineness, compressive strength, normal consistency, setting time and chemical composition test of slag has been performed.

Fineness Test

Fineness test of slag has been conducted using Blaine's Air Permeability apparatus.

Compressive Strength Test

Cement mortars have been prepared using 0%, 20%, 65% and 90% replacement with fly ash and compressive strength has been determined using ASTM C150. 2 inch x 2 inch cement mortar cube specimens have been prepared and tested at 7, 28 and 91 days. Three samples have been tested at each case.

Normal Consistency and Setting Time Tests

Normal consistency and setting time tests have been performed on cement mortars with slag replacements of 20%, 65% and 90% and compared with control mortar. These tests have been conducted according to the specifications of ASTM C187 and ASTM C109.

4.2.4.2 Test results

Fineness Test

Fineness of slag using Blaine's Air permeability Apparatus has been observed to be 548 m^2/kg.

Compressive Strength Test

Cement has been replaced by slag to 20%, 65% and 90% by weight. Their strength test results along with the control mortar cube have been shown in Table 4.10. Figure 4.15 shows the comparison of the strength results.

Table 4.10: Compressive Strength Test Results of Cement Mortar with Different Levels of Slag Replacement

Sample ID	Fly Ash Replacement (%)	7 day Compressive Strength (psi)	28 day Compressive Strength (psi)	90 day compressive strength
SL-1	0	3980	6880	7200
SL-2	20	3990	7220	7540
SL-3	65	3770	7095	7290
SL-4	90	1650	2580	2960

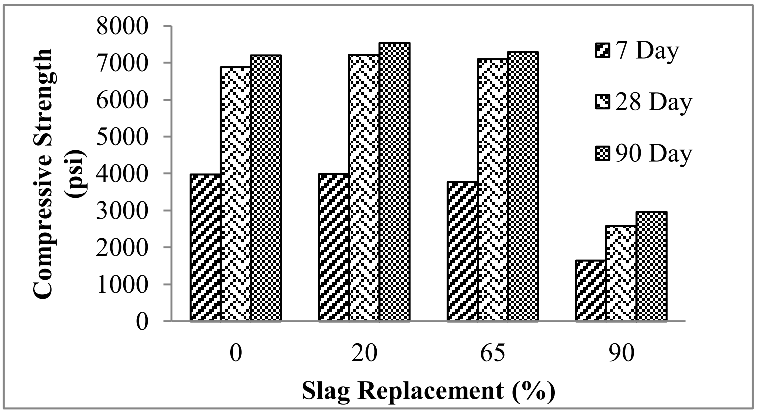


Figure 4.15: Comparison of Compressive Strength of Cement Mortars for Various Slag Replacement Levels

Normal Consistency Test

Water content at normal consistency of cement with different levels of slag replacement has been determined according to the specifications of ASTM C 187. The results have been shown in Table 4.11.

Table 4.11: Water Content at Normal Consistency (%) of Mortar at Various Percentages of Slag Replacements

Slag Replacement (%)	Water Content at Normal Consistency (%)
0	26.5
20	29.6
65	36.4
90	44.2

Setting Time Test

Both the initial and final setting time of cement mortars with slag replacements have been determined according to the specifications of ASTM C109. Table 4.12 shows the initial and final setting time values and their variations for different slag replacement levels respectively.

Table 4.12: Setting Time of Mortar at Various Percentages of Slag Replacements

Slag Replacement (%)	Initial Setting Time (minutes)	Final Setting Time (minutes)
0	106	260
20	124	285
65	156	353
90	195	386

Chemical Composition Test

The result of chemical composition test of slag is shown Table 4.13.

Table 4.13: Chemical Composition of Slag

Sl. No.	Element	Test Result (%)
1	Sulphur Trioxide (SO_3)	0
2	Calcium Oxide (CaO)	40.10
3	Iron Oxide (Fe_2O_3)	1.50
4	Alluminium Oxide (Al_2O_3)	14.30
5	Silicon Dioxide (SiO_2)	33.80
6	Magnesium Oxide (MgO)	4.81

4.3 Experiments on Concrete Specimens

Density and slump tests have been performed on fresh concrete and compressive strength and RCPT tests have been performed on hardened concrete specimens.

4.3.1 Preparation of concrete specimens

Total one hundred and eight mix designs have been prepared for this research work. Thirty six mixes were prepared using fly ash as cement replacement and fifty four mixes were prepared using blast furnace slag as cement replacement. Eighteen control mixes were also prepared for comparison. Since the mix design procedure only includes two aggregates bands (5-10-14-18 and 5-10-18-22), all the mixes have been prepared using aggregate gradations complying with these bands.

(a)Aggregate Gradations

The two aggregate band gradations, 5-10-14-18 and 5-10-18-22 used in this research are not readily available in markets. Thus, locally available coarse aggregates have been first segregated in to particular sieve sizes and then again combined by weight to achieve the particular aggregate gradation. For fine aggregate samples this procedure has not been possible because of large number of sieves. So Sylhet and Local sand have been mixed in order to achieve the required fine aggregate gradation.

(b) Mix Proportions

Mix proportions have been designed mainly for performing various laboratory experiments for concrete mix design. Total one hundred and eight mix designs have been prepared for collecting the required information for concrete mix design method. Thirty six mixes were prepared using fly ash replacement levels of 20% and 35%. Fifty four mixes were prepared using slag replacement levels of 20%, 65% and 90%. The rest of the mixes were control mix containing 100% OPC cement. Two aggregate gradations from each of the proposed bands have been taken. Same mixes have been prepared for both of the aggregate gradations.

Tables 4.14 and 4.15 show the mix proportions containing 100% OPC cement at SSD condition of aggregates for 5-10-14-18 and 5-10-18-22 bands respectively.

Table 4.14: Mix Proportions containing 100% OPC Cement for Aggregate Band 5-10-14-18

Mix ID	Cement Content (kg/m^3)	Water Content (kg/m^3)	Aggregate Content (kg/m^3)	a/c Ratio	w/c Ratio
C-1	350	140	1862	5.32	0.4
C-2	425	170	1785	4.2	0.4
C-3	500	200	1645	3.29	0.4
C-4	350	175	1862	5.32	0.5
C-5	425	213	1785	4.2	0.5
C-6	500	250	1645	3.29	0.5
C-7	350	210	1862	5.32	0.6
C-8	425	255	1785	4.2	0.6
C-9	500	300	1645	3.29	0.6

Table 4.15: Mix Proportions containing 100% OPC Cement for Aggregate Band 5-10-14-18

Mix ID	Cement Content (kg/m^3)	Water Content (kg/m^3)	Aggregate Content (kg/m^3)	a/c Ratio	w/c Ratio
C-10	350	140	1862	5.32	0.4
C-11	425	170	1785	4.2	0.4
C-12	500	200	1645	3.29	0.4
C-13	350	175	1862	5.32	0.5
C-14	425	213	1785	4.2	0.5
C-15	500	250	1645	3.29	0.5
C-16	350	210	1862	5.32	0.6
C-17	425	255	1785	4.2	0.6
C-18	500	300	1645	3.29	0.6

Tables 4.16 and 4.17 show the mix proportions containing fly ash at SSD condition of aggregates for 5-10-14-18 and 5-10-18-22 bands respectively.

Table 4.16: Mix Proportions containing Fly Ash for Aggregate Band 5-10-14-18

Mix ID	Cement Content (kg/m^3)	Water Content (kg/m^3)	Cement Content Replaced by Fly Ash (kg/m^3)	Aggregate Content (kg/m^3)	a/c Ratio	w/c Ratio
F-1	350	140	70	1862	5.32	0.4
F-2	350	140	123	1862	5.32	0.4
F-3	425	170	85	1785	4.2	0.4
F-4	425	170	149	1785	4.2	0.4
F-5	500	200	100	1645	3.29	0.4
F-6	500	200	175	1645	3.29	0.4
F-7	350	175	70	1862	5.32	0.5
F-8	350	175	123	1862	5.32	0.5
F-9	425	213	85	1785	4.2	0.5
F-10	425	213	149	1785	4.2	0.5
F-11	500	250	100	1645	3.29	0.5
F-12	500	250	175	1645	3.29	0.5
F-13	350	210	70	1862	5.32	0.6
F-14	350	210	123	1862	5.32	0.6
F-15	425	255	85	1785	4.2	0.6
F-16	425	255	149	1785	4.2	0.6
F-17	500	300	100	1645	3.29	0.6
F-18	500	300	175	1645	3.29	0.6

Table 4.17: Mix Proportions containing Fly Ash for Aggregate Band 5-10-14-18

Mix ID	Cement Content (kg/m^3)	Water Content (kg/m^3)	Cement Content Replaced by Fly Ash (kg/m^3)	Aggregate Content (kg/m^3)	a/c Ratio	w/c Ratio
F-19	350	140	70	1862	5.32	0.4
F-20	350	140	123	1862	5.32	0.4
F-21	425	170	85	1785	4.2	0.4
F-22	425	170	149	1785	4.2	0.4
F-23	500	200	100	1645	3.29	0.4
F-24	500	200	175	1645	3.29	0.4
F-25	350	175	70	1862	5.32	0.5
F-26	350	175	123	1862	5.32	0.5
F-27	425	213	85	1785	4.2	0.5
F-28	425	213	149	1785	4.2	0.5
F-29	500	250	100	1645	3.29	0.5
F-30	500	250	175	1645	3.29	0.5
F-31	350	210	70	1862	5.32	0.6
F-32	350	210	123	1862	5.32	0.6
F-33	425	255	85	1785	4.2	0.6
F-34	425	255	149	1785	4.2	0.6
F-35	500	300	100	1645	3.29	0.6
F-36	500	300	175	1645	3.29	0.6

Tables 4.18 and 4.19 show the mix proportions containing blast furnace slag at SSD condition of aggregates for 5-10-14-18 and 5-10-18-22 bands respectively.

Table 4.18: Mix Proportions containing Slag for Aggregate Band 5-10-14-18

Mix ID	Cement Content (kg/m^3)	Water Content (kg/m^3)	Cement Content Replaced by Slag (kg/m^3)	Aggregate Content (kg/m^3)	a/c Ratio	w/c Ratio
S-1	350	140	70	1862	5.32	0.4
S-2	350	140	228	1862	5.32	0.4
S-3	350	140	315	1862	5.32	0.4
S-4	425	170	85	1785	4.2	0.4
S-5	425	170	277	1785	4.2	0.4
S-6	425	170	383	1785	4.2	0.4
S-7	500	200	100	1645	3.29	0.4
S-8	500	200	325	1645	3.29	0.4
S-9	500	200	450	1645	3.29	0.4
S-10	350	175	70	1862	5.32	0.5
S-11	350	175	228	1862	5.32	0.5
S-12	350	175	315	1862	5.32	0.5
S-13	425	213	85	1785	4.2	0.5
S-14	425	213	277	1785	4.2	0.5
S-15	425	213	383	1785	4.2	0.5
S-16	500	250	100	1645	3.29	0.5
S-17	500	250	325	1645	3.29	0.5
S-18	500	250	450	1645	3.29	0.5
S-19	350	210	70	1862	5.32	0.6
S-20	350	210	228	1862	5.32	0.6
S-21	350	210	315	1862	5.32	0.6
S-22	425	255	85	1785	4.2	0.6
S-23	425	255	277	1785	4.2	0.6
S-24	425	255	383	1785	4.2	0.6
S-25	500	300	100	1645	3.29	0.6
S-26	500	300	325	1645	3.29	0.6
S-27	500	300	450	1645	3.29	0.6

Table 4.19: Mix Proportions containing Slag for Aggregate Band 5-10-14-18

Mix ID	Cement Content (kg/m^3)	Water Content (kg/m^3)	Cement Content Replaced by Slag (kg/m^3)	Aggregate Content (kg/m^3)	a/c Ratio	w/c Ratio
S-28	350	140	70	1862	5.32	0.4
S-29	350	140	228	1862	5.32	0.4
S-30	350	140	315	1862	5.32	0.4
S-31	425	170	85	1785	4.2	0.4
S-32	425	170	277	1785	4.2	0.4
S-33	425	170	383	1785	4.2	0.4
S-34	500	200	100	1645	3.29	0.4
S-35	500	200	325	1645	3.29	0.4
S-36	500	200	450	1645	3.29	0.4
S-37	350	175	70	1862	5.32	0.5
S-38	350	175	228	1862	5.32	0.5
S-39	350	175	315	1862	5.32	0.5
S-40	425	213	85	1785	4.2	0.5
S-41	425	213	277	1785	4.2	0.5
S-42	425	213	383	1785	4.2	0.5
S-43	500	250	100	1645	3.29	0.5
S-44	500	250	325	1645	3.29	0.5
S-45	500	250	450	1645	3.29	0.5
S-46	350	210	70	1862	5.32	0.6
S-47	350	210	228	1862	5.32	0.6
S-48	350	210	315	1862	5.32	0.6
S-49	425	255	85	1785	4.2	0.6
S-50	425	255	277	1785	4.2	0.6
S-51	425	255	383	1785	4.2	0.6
S-52	500	300	100	1645	3.29	0.6
S-53	500	300	325	1645	3.29	0.6
S-54	500	300	450	1645	3.29	0.6

Figure 4.16 shows some of the concrete cylinders that have been prepared for the experiments.

Figure 4.16: Concrete Cylinders Prepared for Experiments

4.3.2 Tests of concrete

Tests on concrete can be divided into two groups

(i) Tests on Fresh Concrete

(ii) Tests on Hardened Concrete

4.3.2.1 Tests on fresh concrete

Slump Test

Workability of each mix has been determined by measuring the slump of the mix as per the standard ASTM C143. Figure 4.17 illustrates different types of slump of fresh concrete mix and Figures 4.18 shows a slump measurement of this research.

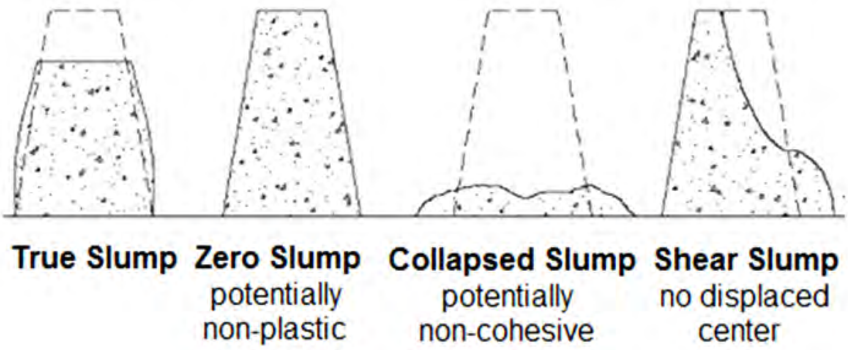


Figure 4.17: Types of Concrete Slump

Figure 4.18: Slump Test of Concrete Sample

Density Test of Fresh Concrete

This test method conforms to the standard ASTM C138. As per the standard, minimum size of the measure for aggregates having nominal maximum size lower than 1 inch is 0.2 m^3 and for ¾ inch nominal maximum size of aggregate the minimum measure size is 0.05 m^3. In this research, a measure having a capacity of 0.05 m^3 has been used for density measurement. Figure 4.19 illustrates the density measurement procedure of fresh concrete mix.

Figure 4.19: Fresh Concrete Density Test

4.3.2.2 Tests on hardened concrete

Concrete Compressive Strength Test

Concrete compressive strengths have been tested as per the standard ASTM C39. In this research three 4 inch x 8 inch (100 mm x 200 mm) cylinder samples have been prepared for each day testing.

Rapid Chloride Permeability Test

This test method covers the determination of the electrical conductance of concrete to provide a rapid indication of its resistance to the penetration of chloride ions. The entire test setup is installed according to the specifications of ASTM C1202.

After curing for a specific time, concrete cylinder has been taken out of the curing pond and a 2 inch slice has been cut out parallel to the top of the core with a concrete cutter saw. This 2 inch thick specimen has been allowed to surface dry for an hour and the side surfaces of the specimen has been painted with rapid setting coating of paint. After the paint has been dried and no longer sticky to touch, the specimen has been put into the desiccator of the vacuum saturation apparatus. The desiccator being completely sealed, the vacuum pump has been started and pressure has been decreased to around 1 mm Hg. This vacuum pressure has been maintained for 3 hours. With the vacuum pump still running sufficient de-aerated water has been drained into the container from the separatory funnel to completely cover the specimen inside. Vacuum pump has then been run for an additional hour. Then the pump has been turned off and the specimen has been soaked under water for 18 hours. The specimen has been removed from water and after blotting off excess water, the sample has been inserted between the two halves of the test cell. The cell containing the top surface of the specimen has been filled with 3% NaCl while the other one has been filled with 0.3N NaOH solution. A voltage source of 60 V has been connected with lead wires whose positive end has been connected to the NaOH end. The current reading has been recorded every 30 minutes for 6 hours and the total charge passed has been calculated. During the test it has been strictly maintained that the temperature of the solutions has not been allowed to exceed 90° C. A thermometer has been used to check the temperature of the solution every 30 minute in this regard. Figure 4.21 and Figure 4.22 show the Rapid Chloride Permeability Test (RCPT) setup.

Figure 4.20: Vacuum Saturation Apparatus

Figure 4.21: Current Measurement

4.3.3 Test results

Two levels (20% and 35%) of fly ash and three levels (20%, 65% and 90%) of blast furnace slag replacement have been taken to observe concrete properties with respect to control concrete. The aggregates have been graded to follow the requirements of ‗5-10-14-18' and ‗5-10-18-22' band gradations. The effect of water cement ratio, cement content and water content on concrete workability, strength and durability have been observed through various experiments. Tables 4.20-42.24 show the test results.

Table 4.20: Test Results of Concrete Prepared with 5-10-14-18 Band Gradation using Fly Ash as Supplementary Cementing Material

Cement Content (kg/m^3)	Water Content (kg/m^3)	w/c	Fly Ash Replacement (%)	Slump (cm)	28 Day Compressive Strength (psi)	90 Day Charge Passed (coulomb)
350	140	0.4	0	7.6	4680	3903
425	170			12.4	5375	3888
500	200			15.3	5750	3580
350	175	0.5		15.6	4130	4131
425	212.5			16.5	4200	3994
500	250			21	4580	3810
350	210	0.6		16.5	2790	4995
425	255			20.4	3000	4806
500	300			23.6	3210	4609
350	140	0.4	20	0	4090	1917
425	170			1.8	4940	1899
500	200			12.4	5310	1678
350	175	0.5		6.3	3440	2754
425	212.5			15.3	3770	2654
500	250			19.4	3990	1742
350	210	0.6		16.3	2280	3398
425	255			20.2	2350	3282
500	300			22.8	2550	3123
350	140	0.4	35	0	3790	1548
425	170			1.5	4610	1476
500	200			10.3	4880	648
350	175	0.5		4.3	3150	2343
425	212.5			13	3340	2291
500	250			17	3670	1315
350	210	0.6		14.9	2090	2802
425	255			18.8	2180	2635
500	300			20.9	2310	2478

Table 4.21: Test Results of Concrete Prepared with 5-10-18-22 Band Gradation using Fly Ash as Supplementary Cementing Material

Cement Content (kg/m^3)	Water Content (kg/m^3)	w/c	Fly Ash Replacement (%)	Slump (cm)	28 Day Compressive Strength (psi)	90 Day Charge Passed (coulomb)
350	140	0.4	0%	6.2	4220	4128
425	170			11.2	4810	3933
500	200			14.3	4930	3609
350	175	0.5		14.8	3470	4190
425	212.5			16.3	3680	4073
500	250			19.7	4020	4061
350	210	0.6		16.5	2670	5090
425	255			20.3	2740	4922
500	300			22.9	3050	4889
350	140	0.4	20%	0	3820	2327
425	170			1	4610	2300
500	200			10.8	4700	2024
350	175	0.5		5	3180	2838
425	212.5			14	3470	2701
500	250			18	3740	2139
350	210	0.6		16	2050	3663
425	255			19.9	2310	3373
500	300			22.3	2480	3204
350	140	0.4	35%	0	3540	1857
425	170			0.5	4070	1732
500	200			9	4230	864
350	175	0.5		4	2970	2498
425	212.5			12.2	3170	2444
500	250			15.5	3500	1452
350	210	0.6		13.9	1710	2843
425	255			18	2130	2715
500	300			18.8	2350	2556

Table 4.22: Test Results of Concrete Prepared with 5-10-14-18 Band Gradation using Slag as Supplementary Cementing Material

Cement Content (kg/m3)	Water Content (kg/m3)	w/c	Slag Replacement (%)	Slump (cm)	28 Day Compressive Strength (psi)	90 Day Charge Passed (coulomb)
350	140	0.4	0%	7.6	4680	3903
425	170			12.4	5380	3888
500	200			15.3	5750	3580
350	175	0.5		15.6	4130	4131
425	212.5			16.5	4200	3994
500	250			21.0	4580	3810
350	210	0.6		16.5	2790	4995
425	255			20.4	3000	4806
500	300			23.6	3210	4609
350	140	0.4	20%	1.3	5970	1101
425	170			2.2	6410	976
500	200			14.8	6740	648
350	175	0.5		6.9	4460	1564
425	212.5			14.0	4940	1345
500	250			20.6	4930	819
350	210	0.6		16.2	3840	2879
425	255			20.2	3890	1774
500	300			23.3	4080	1455
350	140	0.4	65%	1.0	5800	487
425	170			1.5	6220	432
500	200			13.5	6620	432
350	175	0.5		5.6	4360	648
425	212.5			13.3	4390	549
500	250			20.0	4460	523
350	210	0.6		15.0	2810	1055
425	255			20.0	2900	864
500	300			23.0	3060	846
350	140	0.4	90%	0.0	3190	216
425	170			0.5	3520	216
500	200			11.9	4520	216
350	175	0.5		5.0	2590	261
425	212.5			12.3	3190	216
500	250			17.5	3210	216
350	210	0.6		13.8	2160	632
425	255			19.5	2200	419
500	300			22.3	2230	432

Table 4.23: Test Results of Concrete Prepared with 5-10-18-22 Band Gradation using Slag as Supplementary Cementing Material

Cement Content (kg/m3)	Water Content (kg/m3)	w/c	Slag Replacement (%)	Slump (cm)	28 Day Compressive Strength (psi)	90 Day Charge Passed (coulomb)
350	140	0.4	0%	6.2	4220	4128
425	170			11.2	4810	3933
500	200			14.3	4930	3609
350	175	0.5		14.8	3470	4190
425	212.5			16.3	3680	4073
500	250			20.7	4030	4061
350	210	0.6		16.5	2670	5090
425	255			20.3	2740	4922
500	300			22.9	3050	4889
350	140	0.4	20%	1.0	5080	1116
425	170			2.0	5950	990
500	200			13.8	6060	665
350	175	0.5		6.3	3560	1769
425	212.5			13.3	4550	1683
500	250			19.5	4630	1116
350	210	0.6		15.5	3000	3457
425	255			19.2	3010	1863
500	300			22.5	3110	1499
350	140	0.4	65%	0.0	4810	544
425	170			1.0	4820	495
500	200			12.8	4880	461
350	175	0.5		5.0	3410	819
425	212.5			12.5	3820	801
500	250			19.2	3990	735
350	210	0.6		14.8	2340	1170
425	255			18.8	2680	905
500	300			22.0	2910	934
350	140	0.4	90%	0.0	3140	216
425	170			0.5	3500	216
500	200			10.5	3590	216
350	175	0.5		3.5	2230	287
425	212.5			10.8	3020	216
500	250			16.8	3000	216
350	210	0.6		13.0	1580	754
425	255			18.0	1590	464
500	300			21.8	1690	216

4.3.3.1 Durability

Figures 4.22(a), 4.22(b) and 4.22(c) illustrate the variation of RCPT values with fly ash replacement for w/c ratio of 0.4, 0.5 and 0.6 respectively and Figures 4.22(d), 4.22(e) and 4.22(f) illustrate the variation for various percentages of slag replacement. From the figures, it is evident that concrete with gradation band 5-10-14-18 show lower permeability than 5-10-18-22 (up to 25% lower for fly ash and to 31% lower for slag. Concrete containing 35% fly ash prepared using 5-10-14-18 band, 350 kg/m^3 cement content and w/c ratio 0.4 reached RCPT value of 1890 coulomb which lies in the low permeability range according to ASTM C1202 whereas the same concrete prepared using 5-10-18-22 band reached RCPT value of 4143.5 coulomb which lies in the high permeability range. The difference between these two bands is that 5-10-14-18 band contains 14% to 18% particles on #4 to 12.5 mm sieve whereas 5-10-18-22 band has 18% to 22%. Therefore, 5-10-14-18 has greater proportion of finer particles resulting in denser concrete and hence higher durability. It is also found from the figures that durability increases gradually with increase of both fly ash and slag percentages. Concrete made with 425 kg/m^3 cement content, 0.5 w/c ratio and 5-10-14-18 band gradation achieved high, moderate and low permeability for 0%, 20% and 35% fly ash replacement respectively. Again in case of slag, concrete prepared with 350 kg/m^3 cement content, 0.6 w/c ratio and 5-10-14-18 band gradation reached high, moderate, low and very low permeability for 0%, 20%, 65% and 90% replacement respectively. These SCMs decrease the permeability of concrete by their micro filling property at early age and at later age, they reduce pore interconnectivity due to hydration of $Ca(OH)_2$.

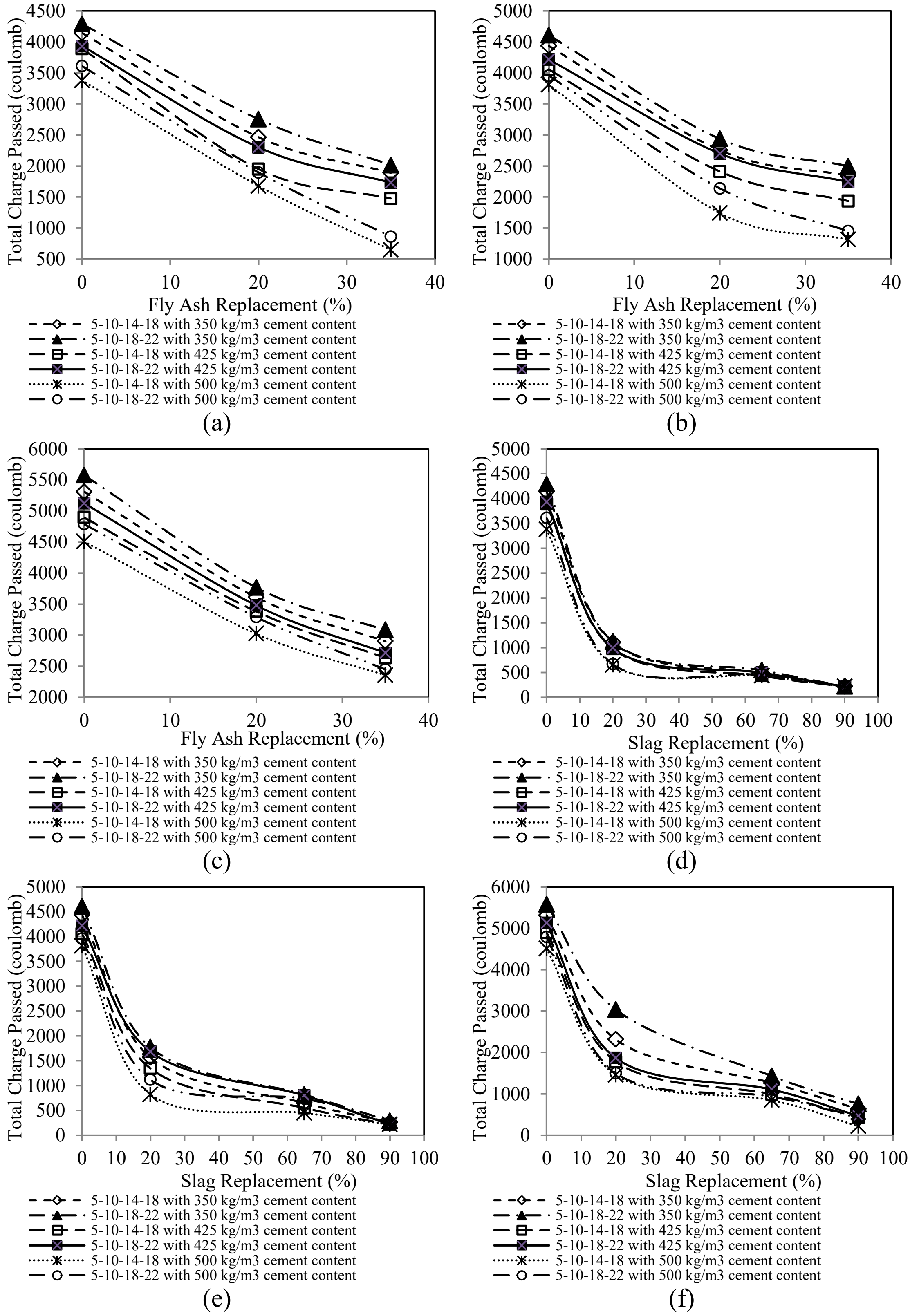


Figure 4.22: Variation of 90 Day RCPT Values with SCM Replacement for (a) w/c 0.4 with Fly Ash, (b) w/c 0.5 with Fly Ash (c) w/c 0.6 with Fly Ash, (d) w/c 0.4 with Slag, (e) w/c 0.5 with Slag and (f) w/c 0.6 with Slag

4.3.3.2 Compressive Strength

Figures 4.23(a), 4.23(b) and 4.23(c) show the variation of compressive strength with fly ash replacement for w/c ratio of 0.4, 0.5 and 0.6 respectively. From the figures, it is observed that 28 day compressive strength decreases with increased percentages of fly ash which agrees with the result obtained by Basha et al. (2014). It is also evident that concrete made with 5-10-14-18 band gradation exhibited greater 28-day compressive strength than 5-10-18-22 band concrete because the former resulted in denser concrete as it has more fine particles.

Figures 4.23(d), 4.23(e) and 4.23(f) illustrate the variation of strength for different percentages of slag replacement. It can be seen from the figures that initially, compressive strength increases with slag replacement and reaches the highest strength at 20% replacement for all water-cement ratios. After that, strength decreases gradually up to 90% replacement. For cement content of 500 kg/m^3, w/c ratio 0.5 and 5-10-14-18 band gradation, compressive strength of concrete made with 20% slag replacement was found to be 5000 psi which is 9% higher than the strength of control concrete. For 65% slag replacement, strength was almost equal to the strength of control concrete (0.87% higher). Strength of green concrete made with 90% slag replacement was 3390 psi which is 26% lower than the strength of control concrete.

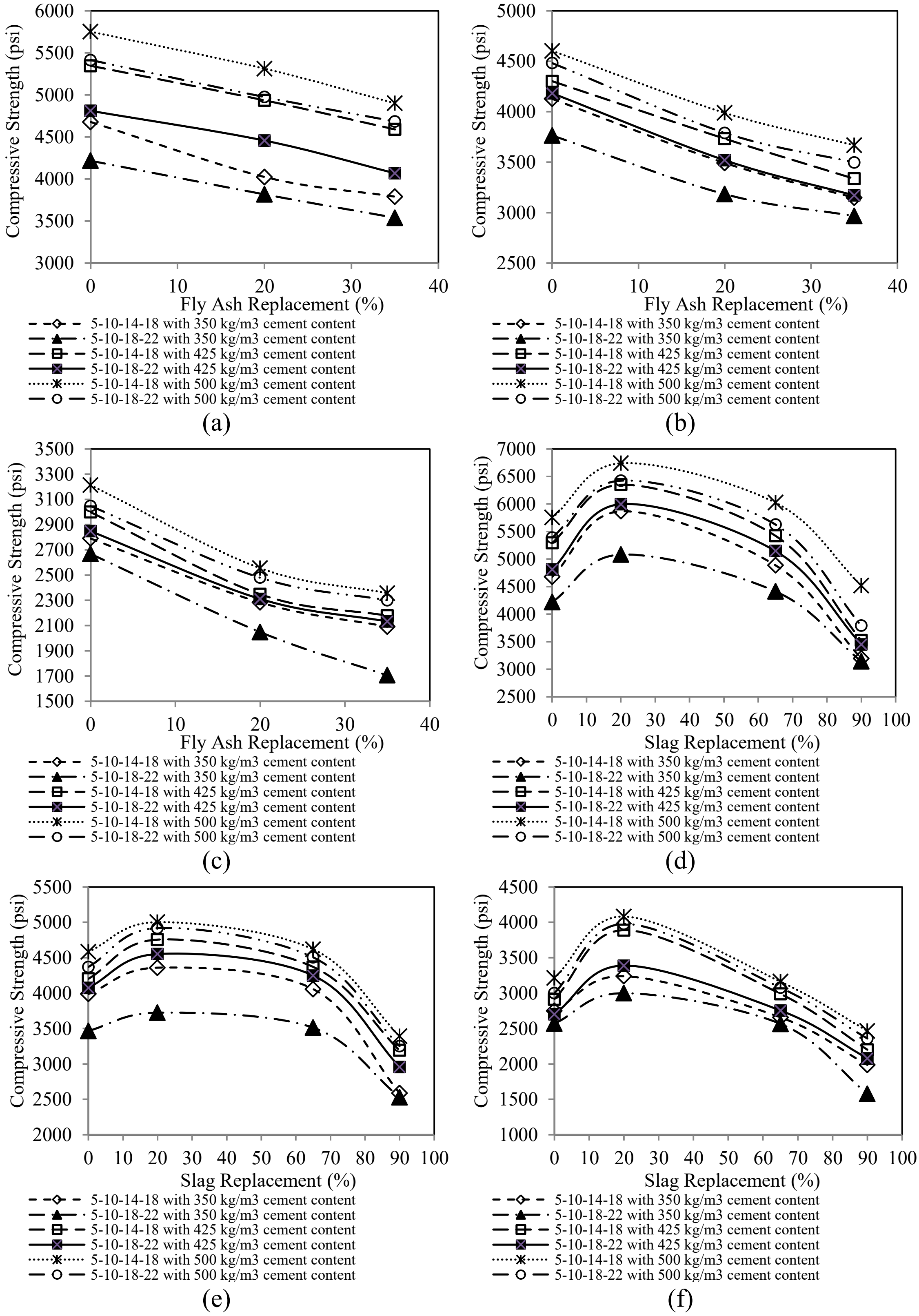


Figure 4.23: Variation of compressive strength with SCM replacement for (a) w/c 0.4 with fly ash, (b) w/c 0.5 with fly ash (c) w/c 0.6 with fly ash, (d) w/c 0.4 with slag, (e) w/c 0.5 with slag and (f) w/c 0.6 with slag

Chapter 5

DEVELOPMENT OF MIX DESIGN METHOD

5.1 General

In this chapter, an innovative method of concrete mix design has been proposed which is based on the locally available aggregates in Bangladesh and includes fly ash and blast furnace slag as supplementary cementing materials. The proposed mix design method incorporates durability in addition to strength and slump.

5.2 Information Required for Concrete Mix Design

i. Compressive Strength

The first required parameter for the proposed mix design is compressive strength. The concrete mix has to be designed for a target mean strength which is higher than the characteristic strength depending upon the level of quality control available at the site.

ii. Workability

Choice of a workability of the concrete at the time of placement depends on the difficulty of the structure to be executed. It includes minimum section of the structure and its shape, amount of reinforcement and quality of the man-power. Table 5.1 represents the concrete workability requirement for different types of concrete works according to IS 456-2000.

iii. Durability

Total charge passed in coulomb as per Rapid Chloride Permeability Test (RCPT) signifies the permeability of the sample concrete. Lower the charge passed, higher is the durability of the sample. Total charge passed value in coulomb needs to be selected in the mix design process according to ASTM classification which is shown in Table 5.6.

iv. Aggregate Gradation Band

Two types of aggregate gradation bands (5-10-14-18 and 5-10-18-22) have been proposed through this research work. Graphs have been drawn using both of the proposed band graded aggregates. The final band to be used is designed to be chosen in the mix design steps by taking various properties in consideration.

Table 5.1: Recommended Workability of Concrete at the Time of Concrete Placement (IS 456-2000)

Type of concrete work	**Degree of workability**	**Slump (cm)**
Blinding concrete; Shallow sections; Pavements using pavers	Very low	< 2.5
Mass concrete; Lightly reinforced sections in slabs, beams, walls, columns; Floors; Hand placed pavements; Strip footings	Low	2.5-7.5
Heavily reinforced sections in slabs, beams, walls, columns; Canal lining;	Medium	7.5-10.0
Trench fill; In-situ piling	High	10.0 – 15.0
Decks Floors	Very high	> 15.0

v. Type of Cement and Supplementary Cementing Material

This mix design method has been proposed for CEM I cement and some percent variations of fly ash and blast furnace slag as replacement of cement. Fly ash replacement levels were 20% and 35% and slag replacement levels were 20%, 65% and 90%.These supplementary cementing materials improve durability of concrete because of their pozzolanic properties. Use of these SCMs as cement replacement depends on availability and durability and strength requirements concrete.

vi. Maximum Possible Water/Cement Ratio.

The Bangladesh National Building Code (BNBC) has limited the maximum w/c ratio for reinforced concrete at different exposure conditions (Table 5.2) for particularly concrete works at Bangladesh. In these concrete mix design same limiting maximum w/c ratio will be followed.

Table 5.2: Limiting w/c Ratio Based on Exposure Conditions

Exposure Type	Maximum w/c Ratio*
Exposed to normal water	0.6
Exposed to brackish water, sea water or spray form these	0.4
Moderate Sulphate exposure (150 – 1500 ppm)	0.5

*Source: Bangladesh National Building Code (1993), Article: 5.5: Durability of Concrete

i. Degree of Supervision.

Information on degree of supervision is significant in estimating the probable deviation of actual strength from the design strength.

ii. Time Delay between Concrete Mixing and Concrete Placing.

The time delay between concrete mixing and concrete placing results in loss of concrete workability. Therefore information on the time delay is required to modify the concrete proportion properly so as to get the required workability at the time of concrete placement.

5.3 Development of Contour Plots

Various contour plots were developed in this research to show four parameters in one graph instead of conventional plots that makes the mix design process convenient for users. The development of contour plot for 20% fly ash replacement and 5-10-14-18 band graded aggregate that combines slump, compressive strength, water content and cement content together is shown below as an example:

i. Compressive strength is plotted against water content and cement content as shown in Figure 5.1.

To further explain the development process of Figure 5.1, Figure 5.2 has been provided that shows the MATLAB interface. This plot is developed from nine sets of data obtained from test results which is shown in Table 4.20. MATLAB has been used to fit the data sets for water content (x axis), cement content (y axis) and the resulting compressive strength (z axis). Surface fitting tool of MATLAB has been used where these three data sets are fit and a contour is plotted. Figure 5.2(a) shows the plot in 3D format for better understanding and Figure 5.2(b) is the 2D contour plot of the same figure. The 9 black dots shown on each of these figures are the actual data from experimental results.

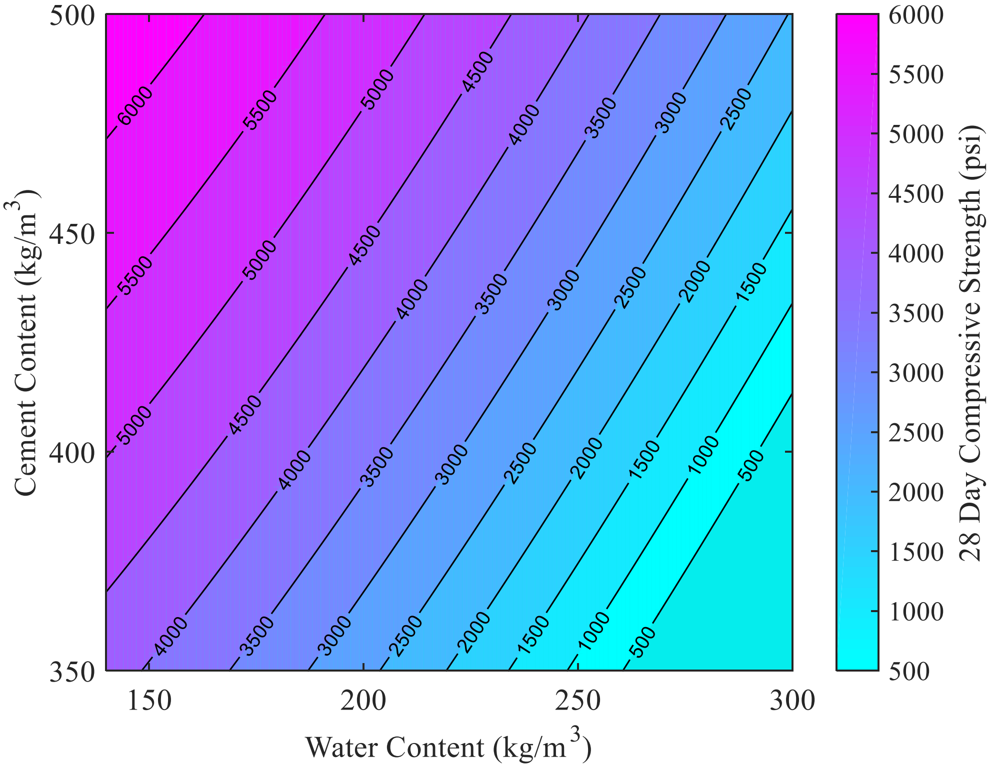
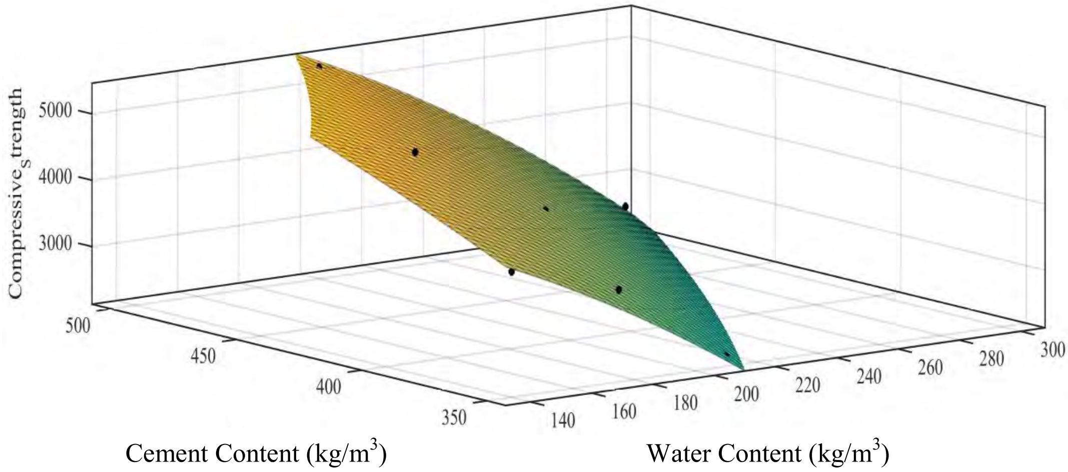
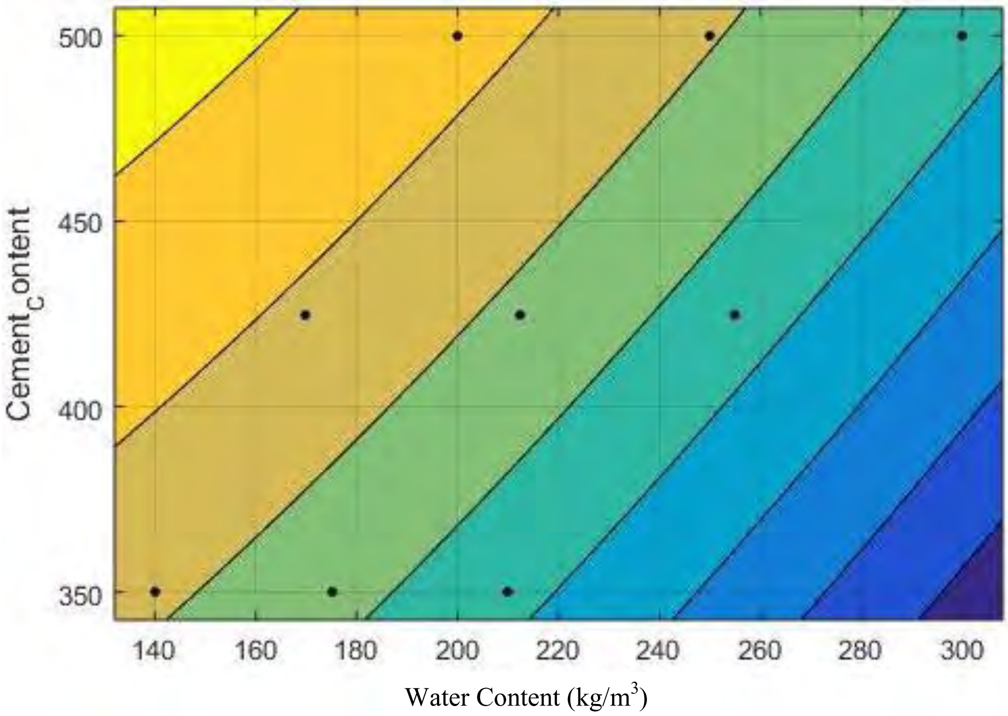


Figure 5.1: Variation of 28 Day Compressive Strength for Concrete Mixes prepared with 5-10-14-18 Band Gradation and 20% Fly Ash Replacement



(a)



(b)

Figure 5.2: Development of Contour Plot

ii. Similarly, slump is plotted against water content and cement content as shown in Figure 5.3.

iii. The contours of slump and strength are superimposed on each other to finally develop a single plot that combines four parameters together (slump, compressive strength, water content and cement content) as shown in Figure 5.4. This plot becomes a part of the mix design steps.

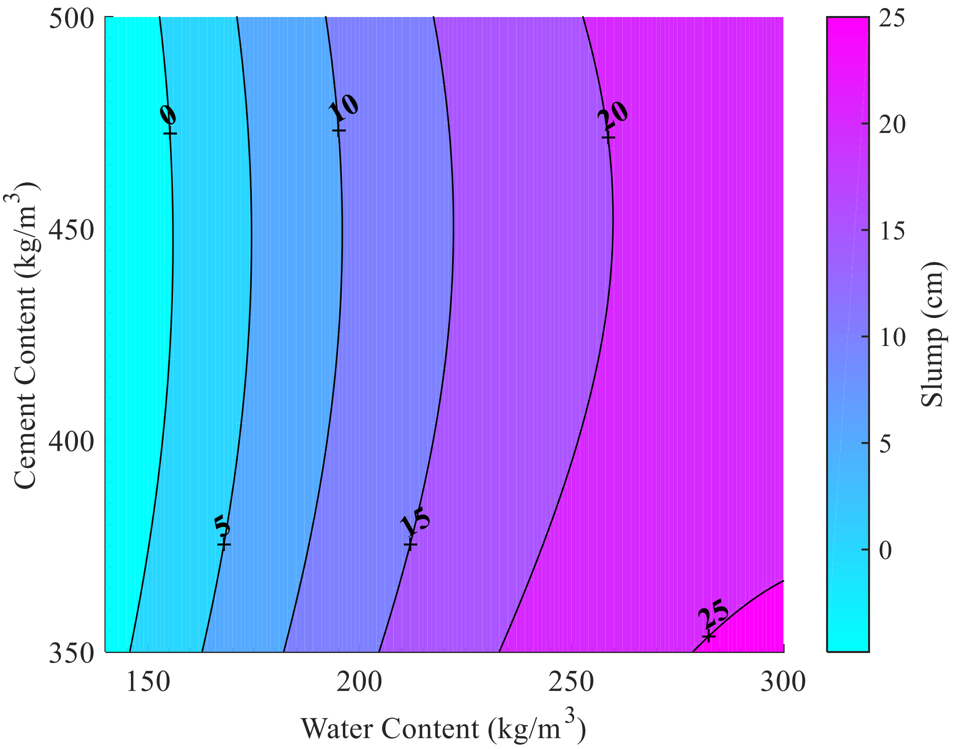


Figure 5.3: Variation of Slump for Concrete Mixes prepared with 5-10-14-18 Band Gradation and 20% Fly Ash Replacement

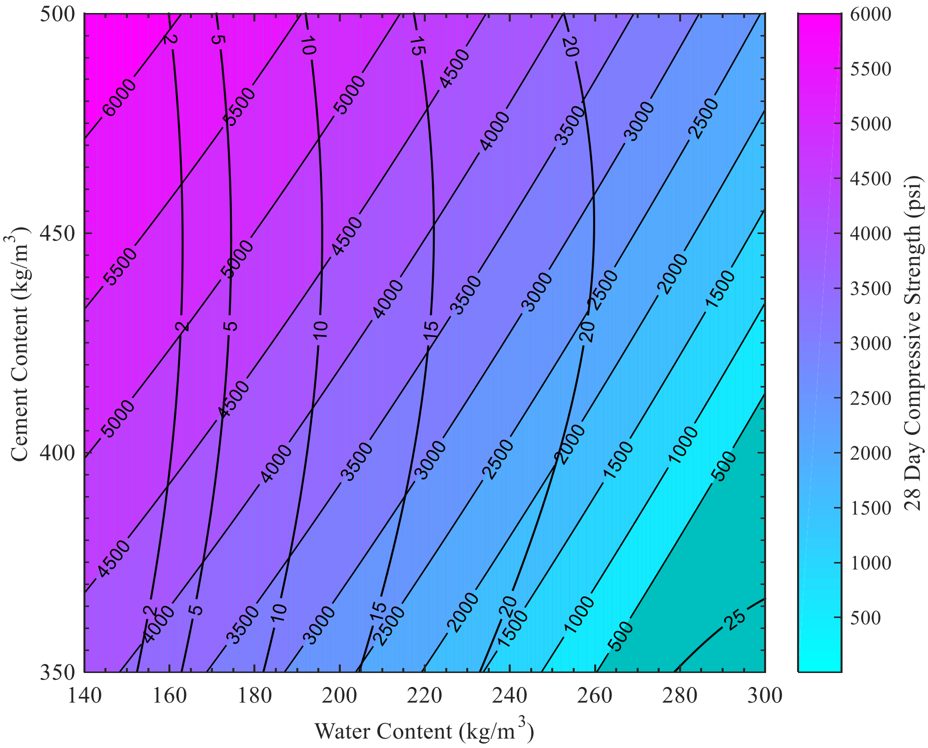


Figure 5.4: 28 Day Compressive Strength and Slump Variations with Various Mix Proportions for Cement with 20% Fly ash Replacement and 5-10-14-18 Band Gradation

Figure 5.5 describes the development of the contour plot shown in Figure 5.4. The text boxes shown in white background show the values derived from contours using MATLAB and the text boxes in green background show the actual values obtained from experiment.

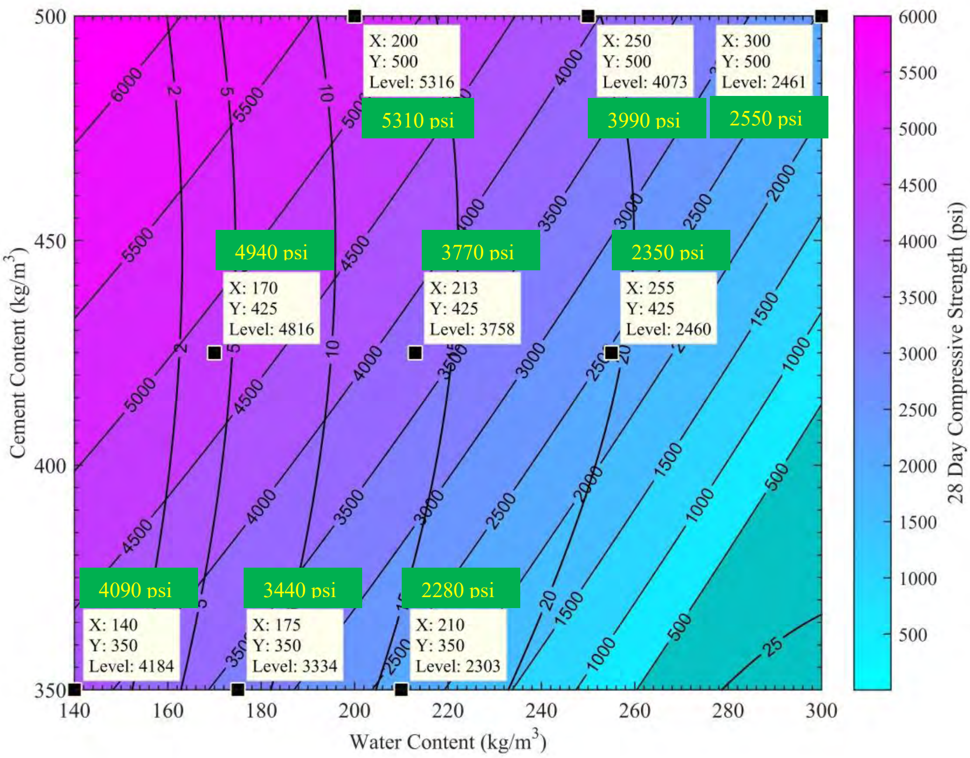


Figure 5.5: Development of Contour Plot showing Experimental Values and MATLAB Contour Values

Similar contour plots have been developed for other percentages of fly ash and slag and also for 5-10-18-22 band gradation. The contours for concrete workability (slump) and compressive strength are illustrated in section 5.3.1 and 5.3.2 respectively.

Contour plots were also developed to establish the relationship among durability, cement content and water content for different fly ash and slag replacements and band gradations. The contour of durability for 20% fly ash replacement and 5-10-14-18 band gradation is shown in Figure 5.6 as an example and the rest are provided in the mix design steps (Figure 5.44-5.49 and Figure 5.60 5.67). Another type of contour was developed to show relationship among durability, slump and SCM percentages. One such plot is shown in Figure 5.7 and the rest are illustrated in mix design steps (Figures 5.36-5.37 and 4.50-5.51)

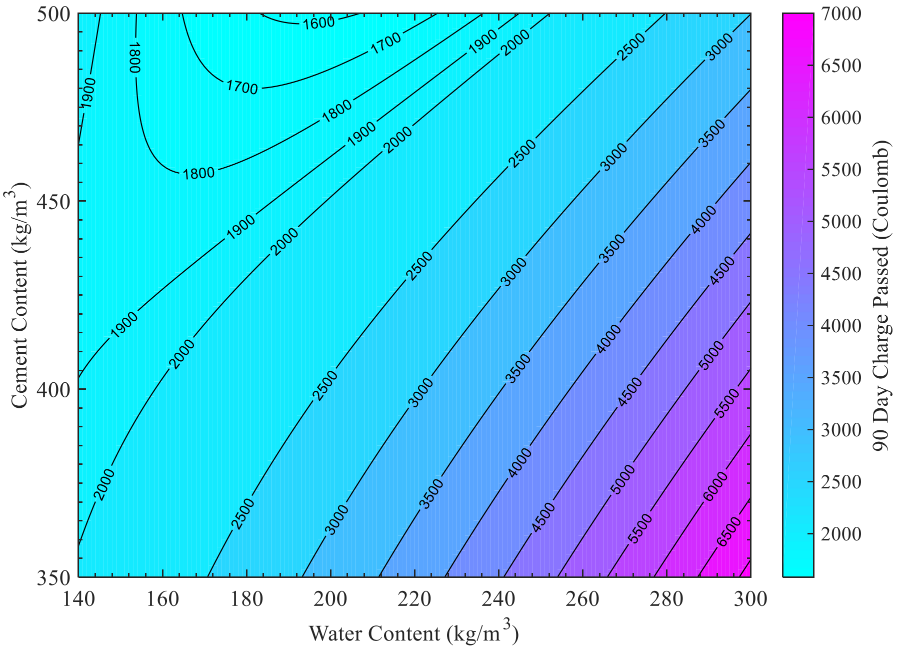


Figure 5.6: Variation of Charge Passed (RCPT) with Various Water and Cement Contents for Cement with 20% Fly Ash Replacement and 5-10-14-18 Band Gradation

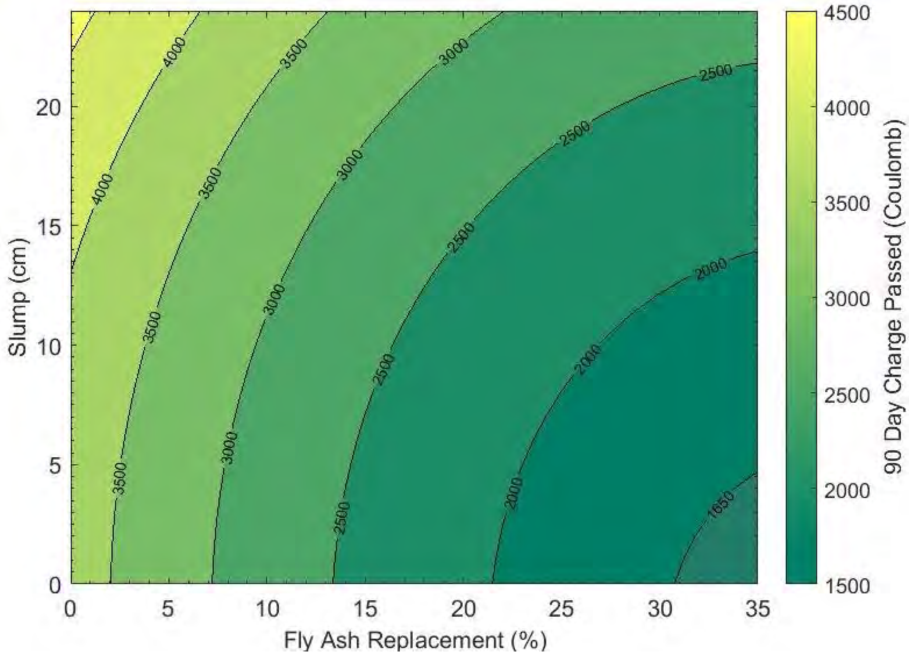


Figure 5.7: Variation of Permeability Classes with Slump and Fly Ash Replacement Percentages for Aggregate Band 5-10-14-18

5.3.1 Concrete workability

In this research, three w/c ratios (0.40, 0.50 and 0.60) have been used and water contents have been varied from 140 kg/m^3 to 300 kg/m^3. Variations of slump (mm) with various mix proportions for different categories of concrete mixes using fly ash are shown in Figure 5.8 to Figure 5.13 and that of slag are shown in Figure 5.14 to 5.21.

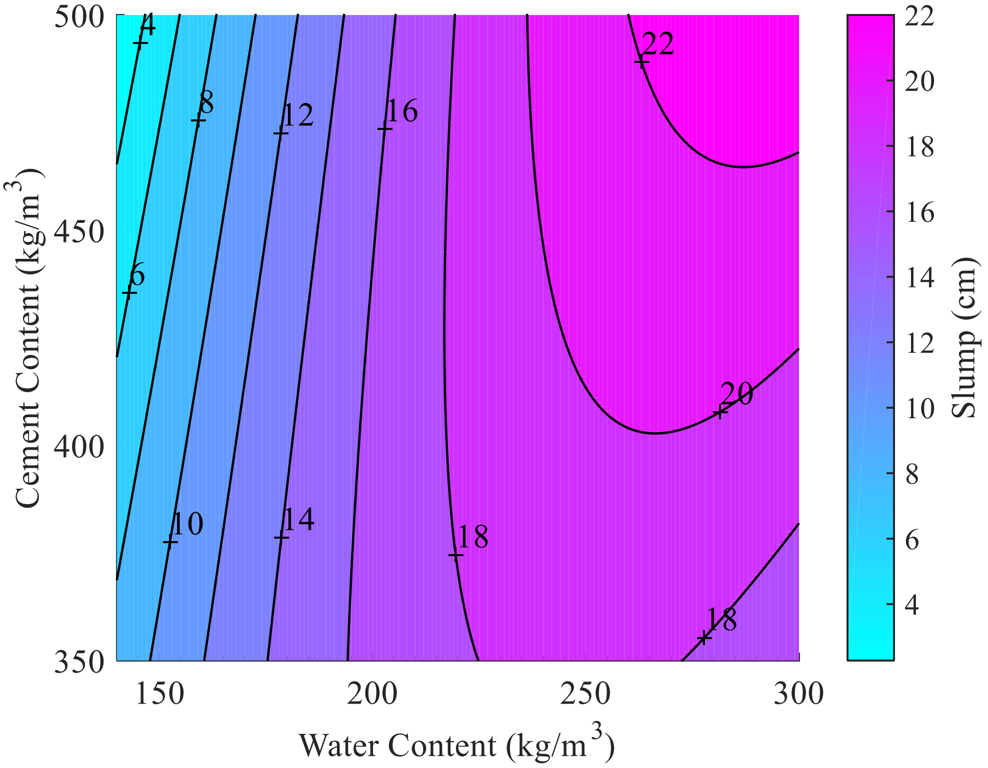


Figure 5.8 Variation of Slump for Concrete Mixes Prepared with 5-10-14-18 Band Gradation and No Fly Ash Replacement

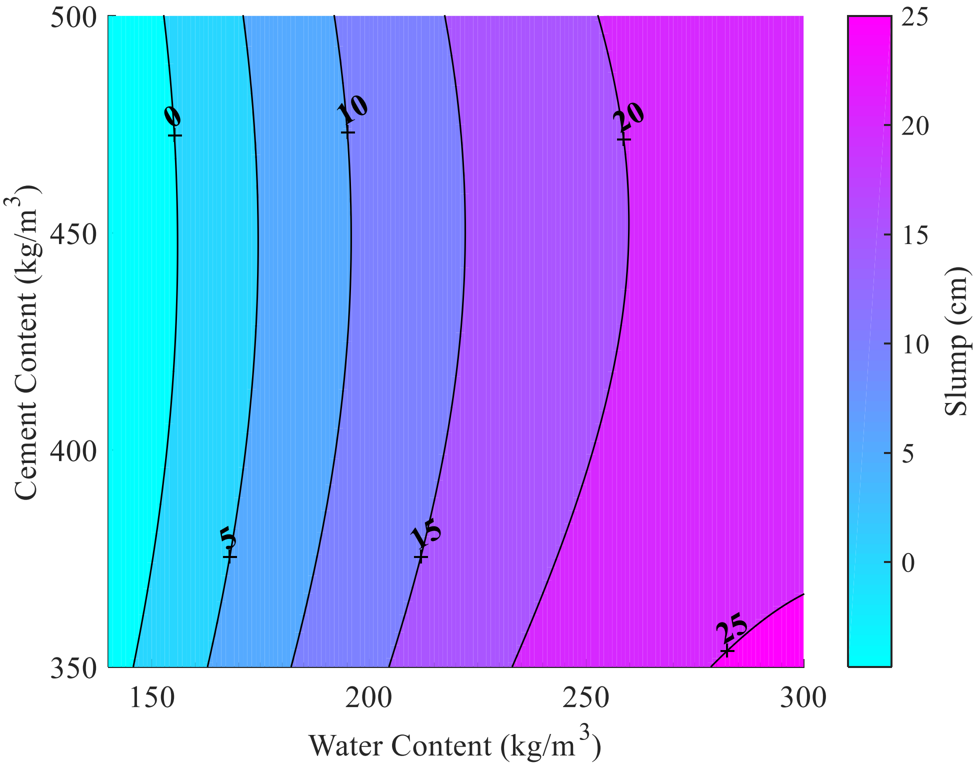


Figure 5.9: Variation of Slump for Concrete Mixes Prepared with 5-10-14-18 Band Gradation and 20% Fly Ash Replacement

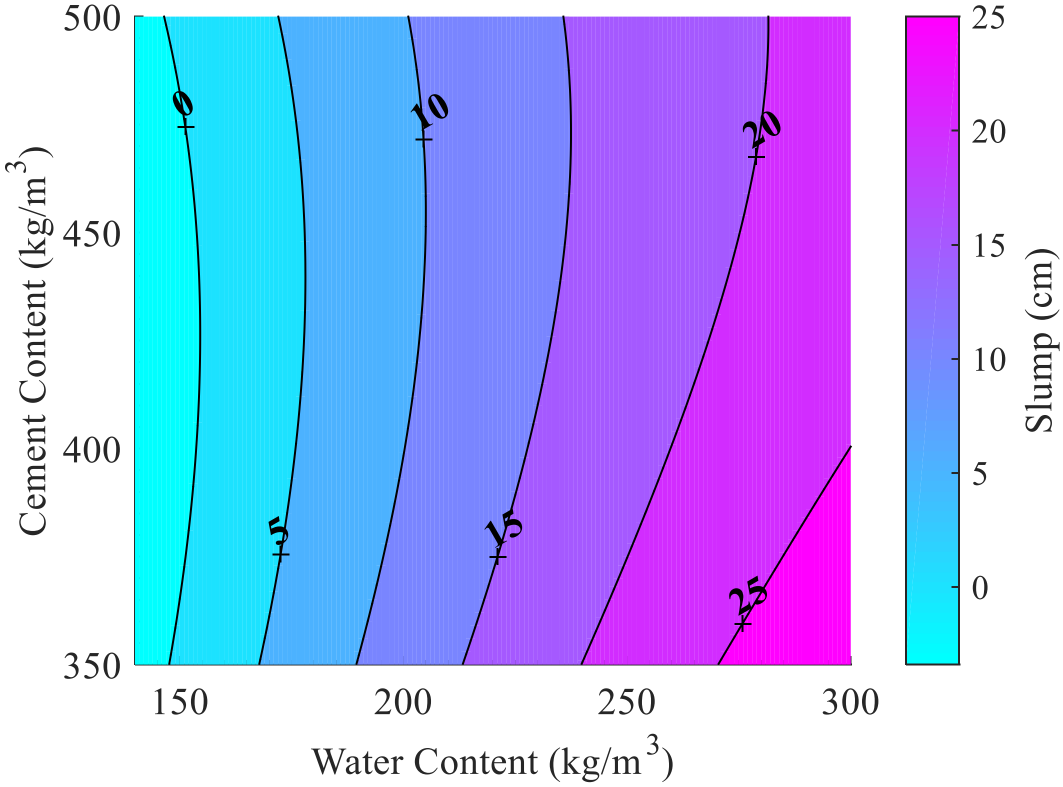


Figure 5.10: Variation of Slump for Concrete Mixes prepared with 5-10-14-18 Band Gradation and 35% Fly Ash Replacement

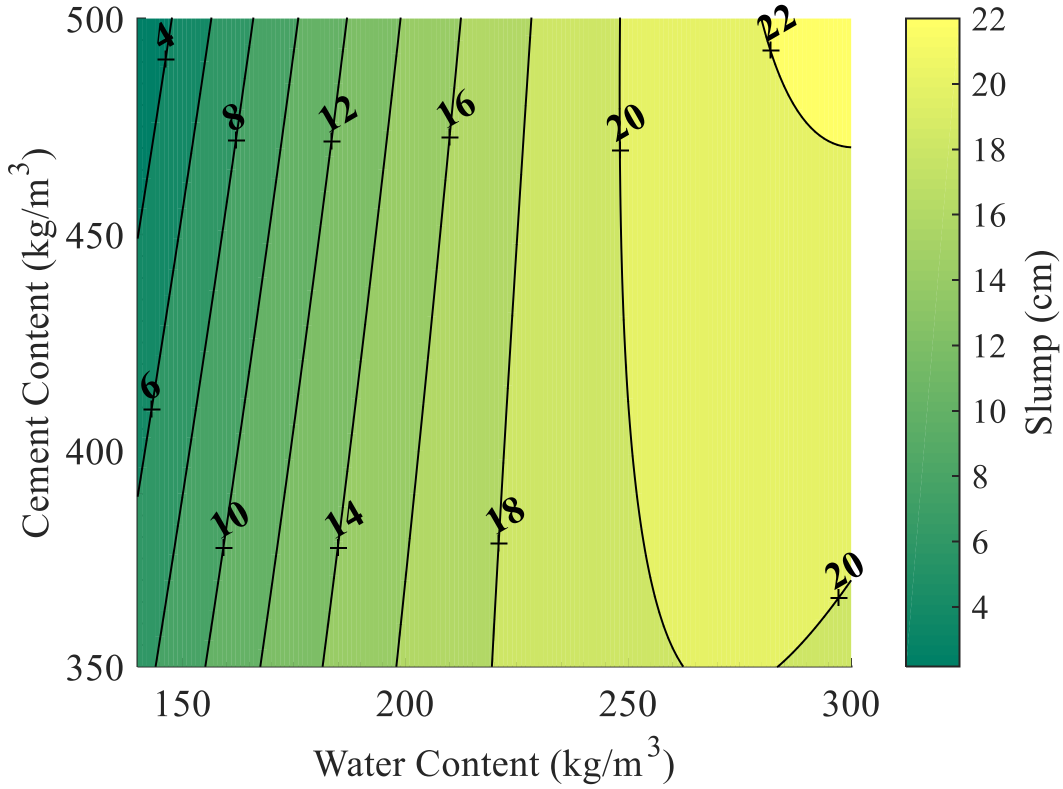


Figure 5.11: Variation of Slump for Concrete Mixes Prepared with 5-10-18-22 Band Gradation and No Fly Ash Replacement

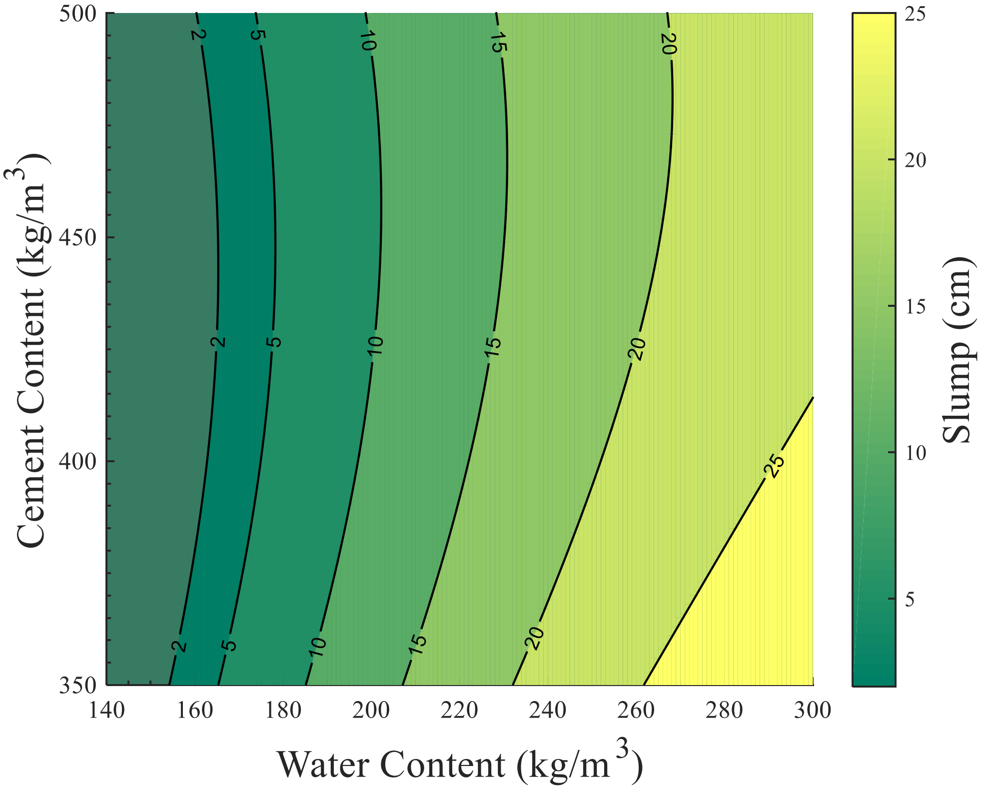


Figure 5.12: Variation of Slump for Concrete Mixes Prepared with 5-10-18-22 Band Gradation and 20% Fly Ash Replacement

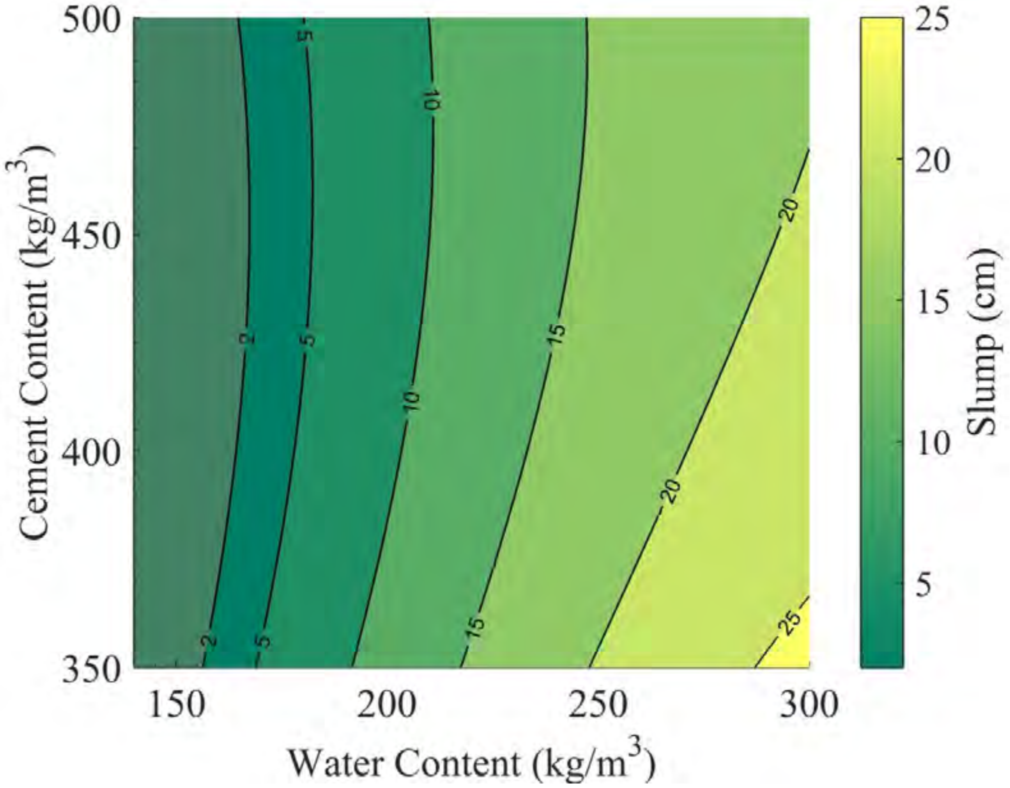


Figure 5.13: Variation of Slump for Concrete Mixes Prepared with 5-10-18-22 Band Gradation and 35% Fly Ash Replacement

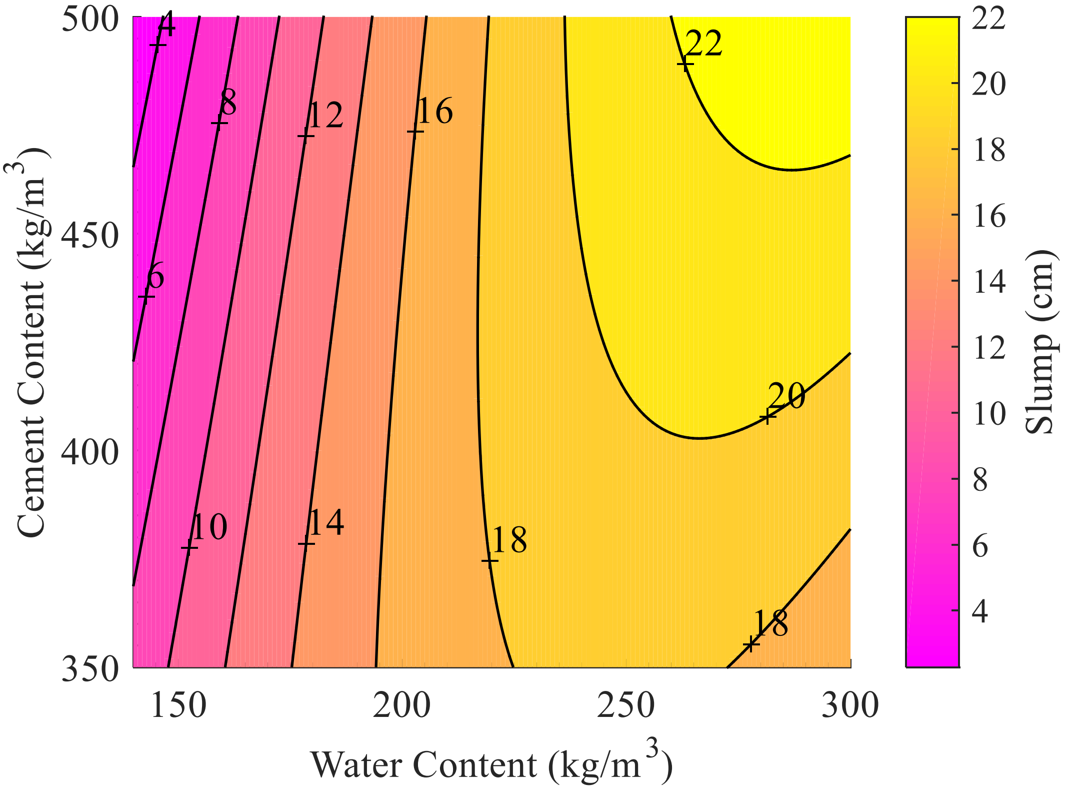


Figure 5.14: Variation of Slump for Concrete Mixes Prepared with 5-10-14-18 Band Gradation and No Slag Replacement

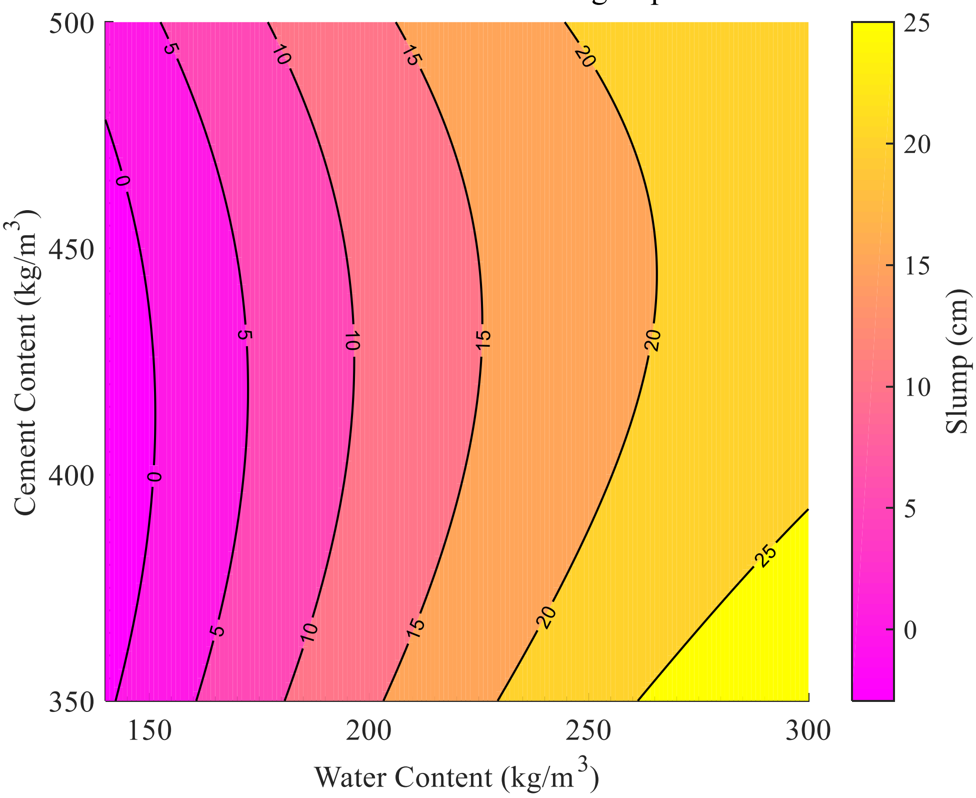


Figure 5.15: Variation of Slump for Concrete Mixes Prepared with 5-10-14-18 Band Gradation and 20% Slag Replacement

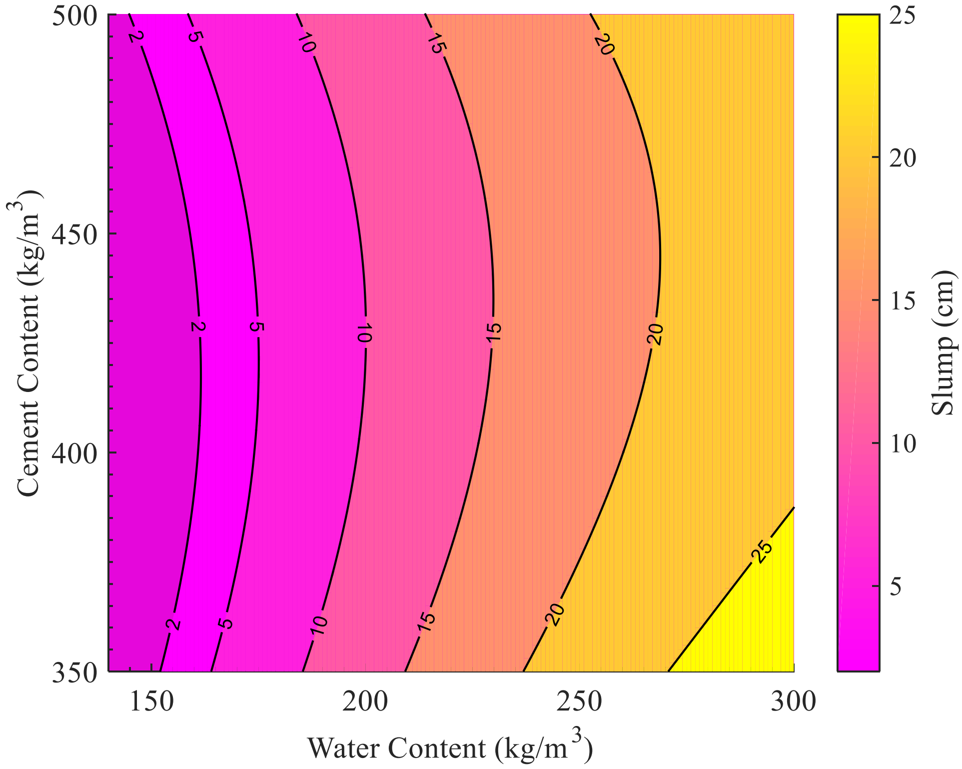


Figure 5.16: Variation of Slump for Concrete Mixes Prepared with 5-10-14-18 Band Gradation and 65% Slag Replacement

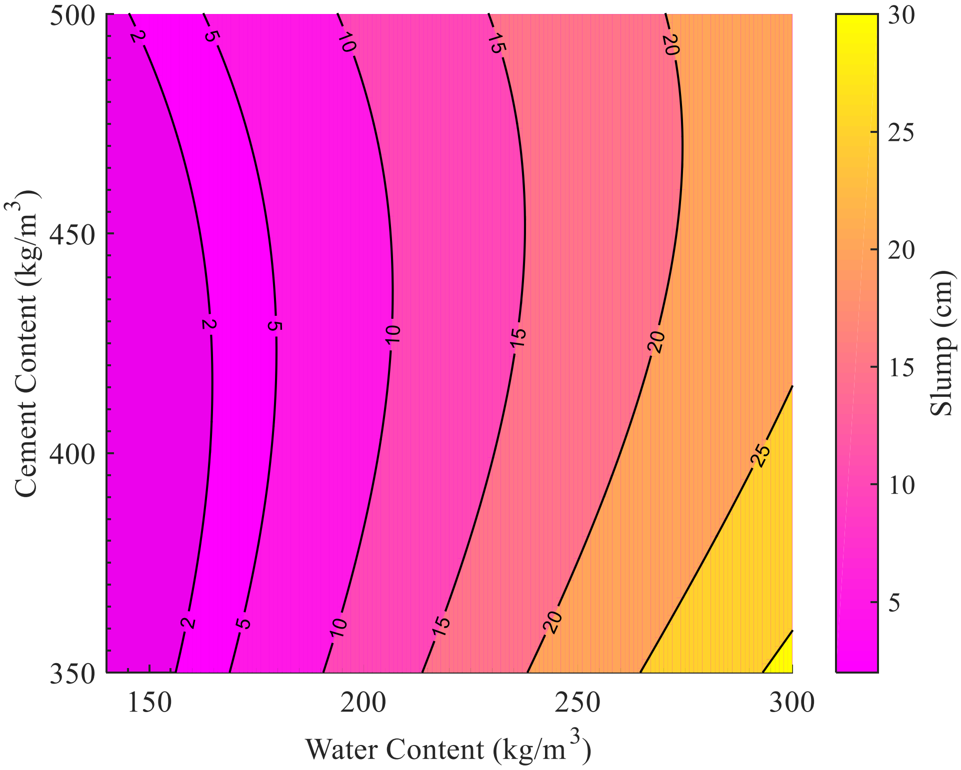


Figure 5.17: Variation of Slump for Concrete Mixes Prepared with 5-10-14-18 Band Gradation and 90% Slag Replacement

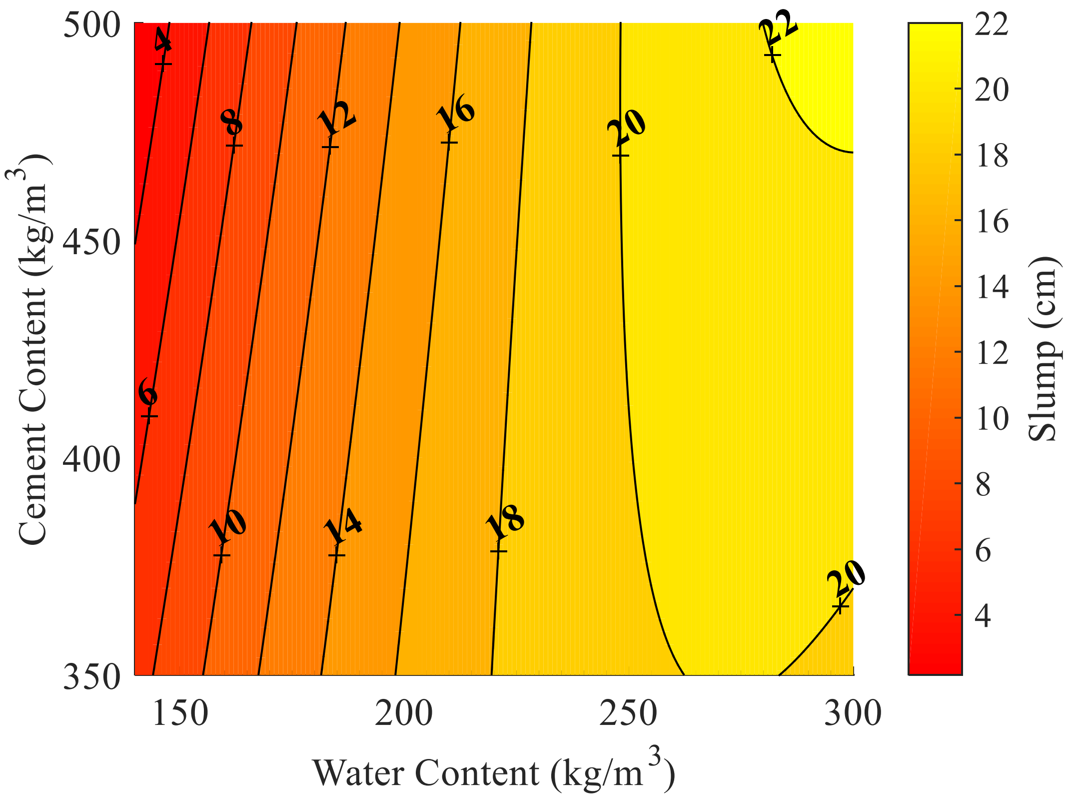


Figure 5.18: Variation of Slump for Concrete Mixes Prepared with 5-10-18-22 Band Gradation and No Slag Replacement

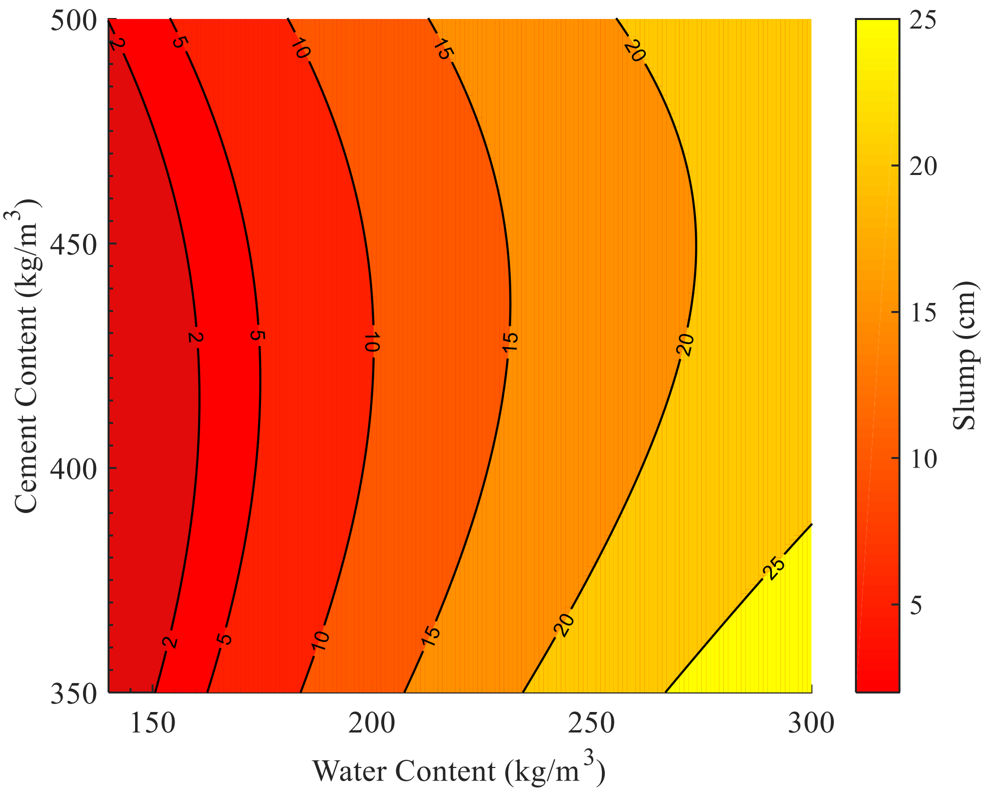


Figure 5.19: Variation of Slump for Concrete Mixes Prepared with 5-10-18-22 Band Gradation and 20% Slag Replacement

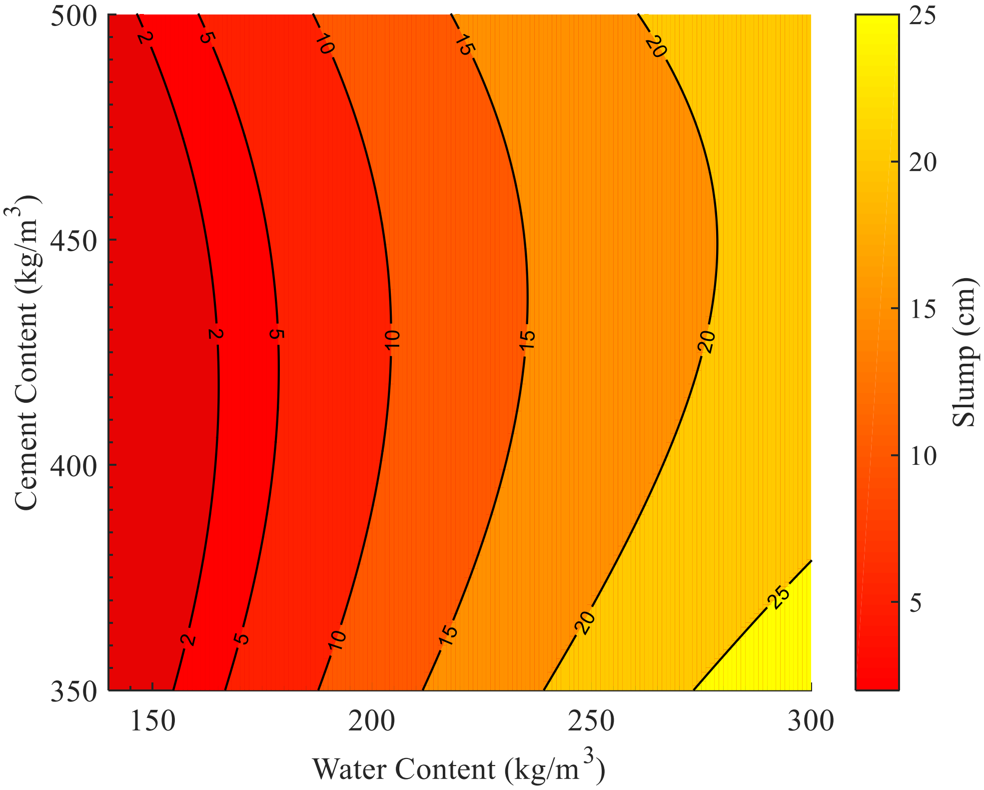


Figure 5.20: Variation of Slump for Concrete Mixes Prepared with 5-10-18-22 Band Gradation and 65% Slag Replacement

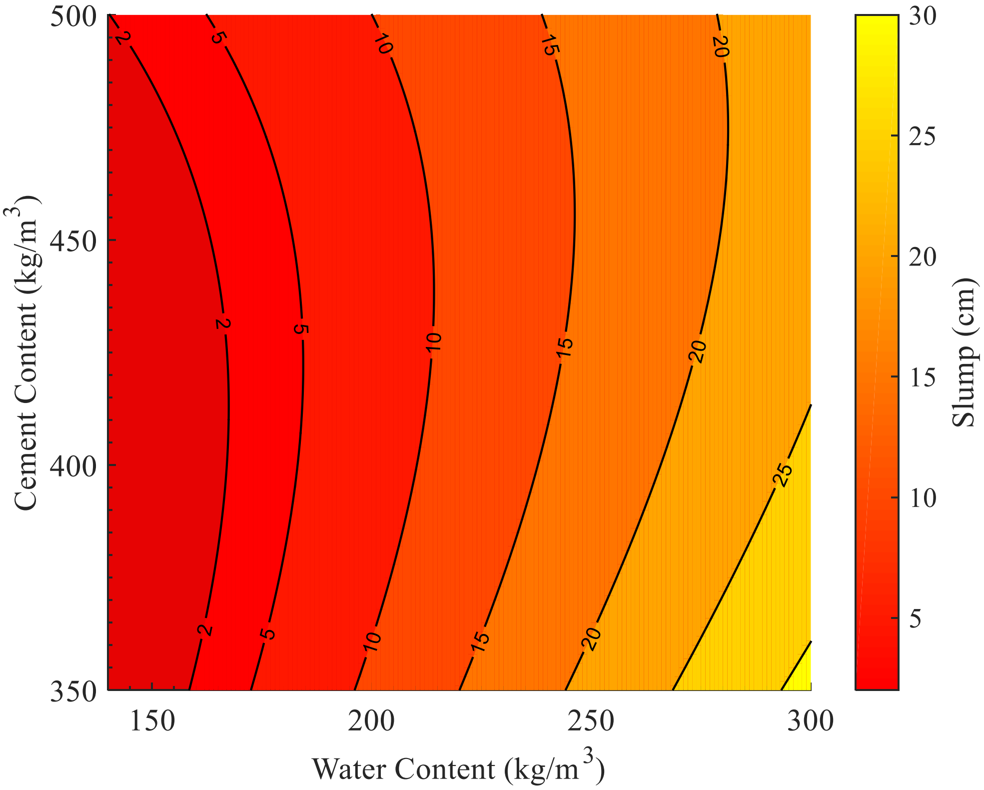


Figure 5.21: Variation of Slump for Concrete Mixes Prepared with 5-10-18-22 Band Gradation and 90% Slag Replacement

5.3.2 Concrete compressive strength

Variations of concrete compressive strength (psi) with mix proportions for different concrete mixes using fly ash have been shown in Figures 5.22 to 5.27 and that using blast furnace slag is shown in Figures 5.28 to 5.35.

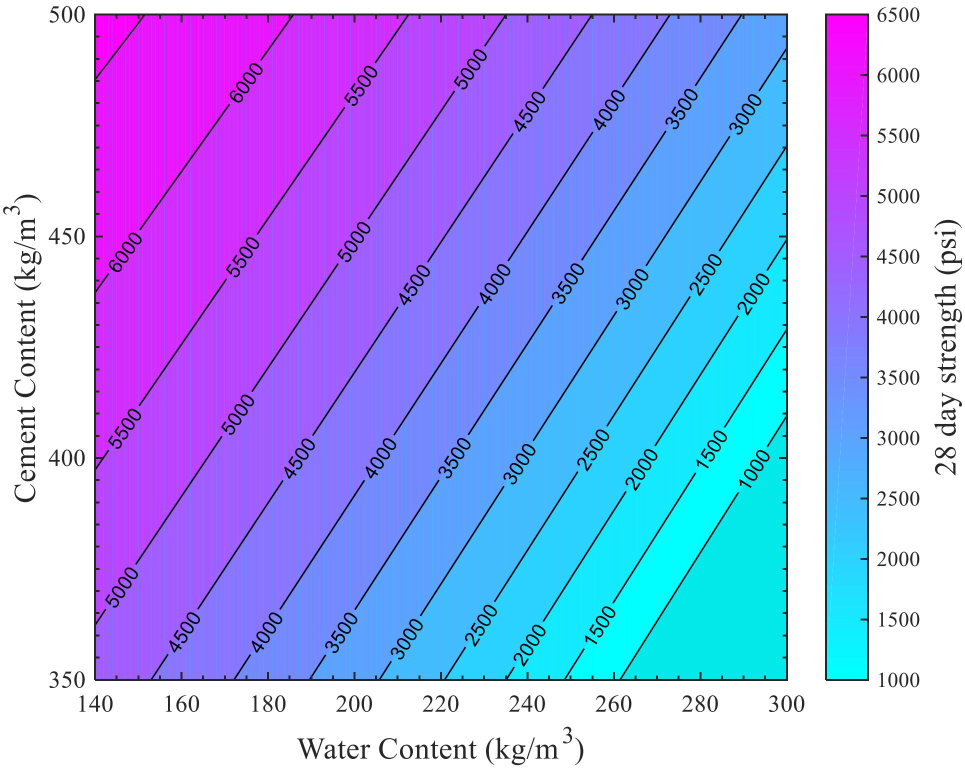


Figure 5.22: Variation of 28 Day Compressive Strength for Concrete Mixes Prepared with 5-10-14-18 Band Gradation and No Fly Ash Replacement

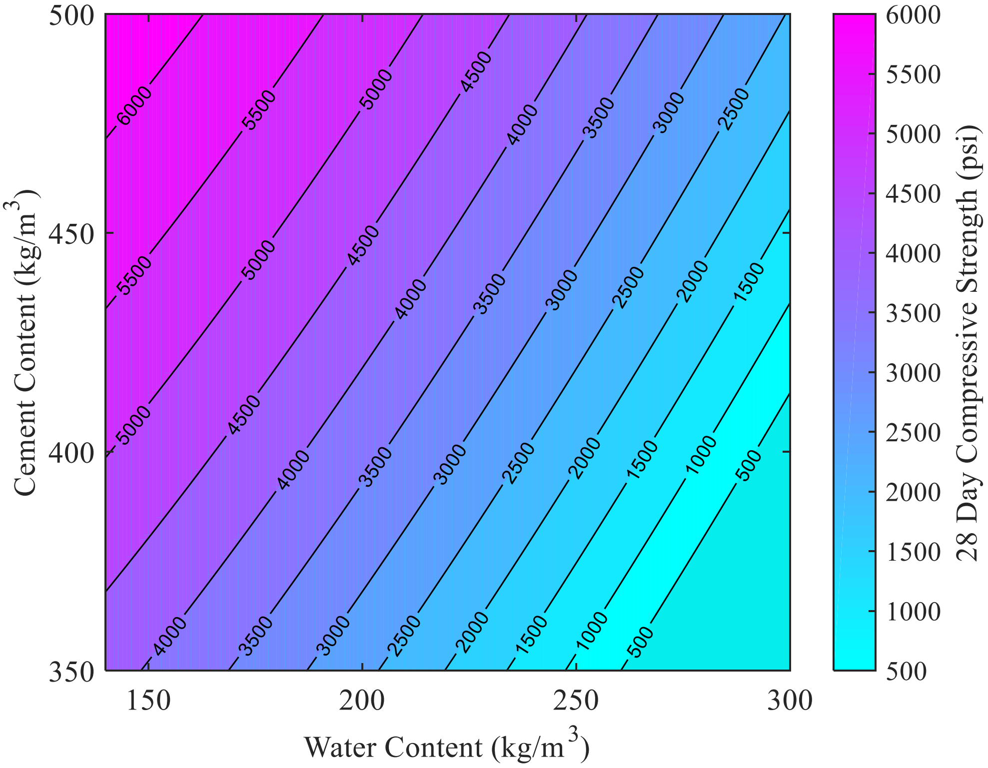


Figure 5.23: Variation of 28 Day Compressive Strength for Concrete Mixes Prepared with 5-10-14-18 Band Gradation and 20% Fly Ash Replacement

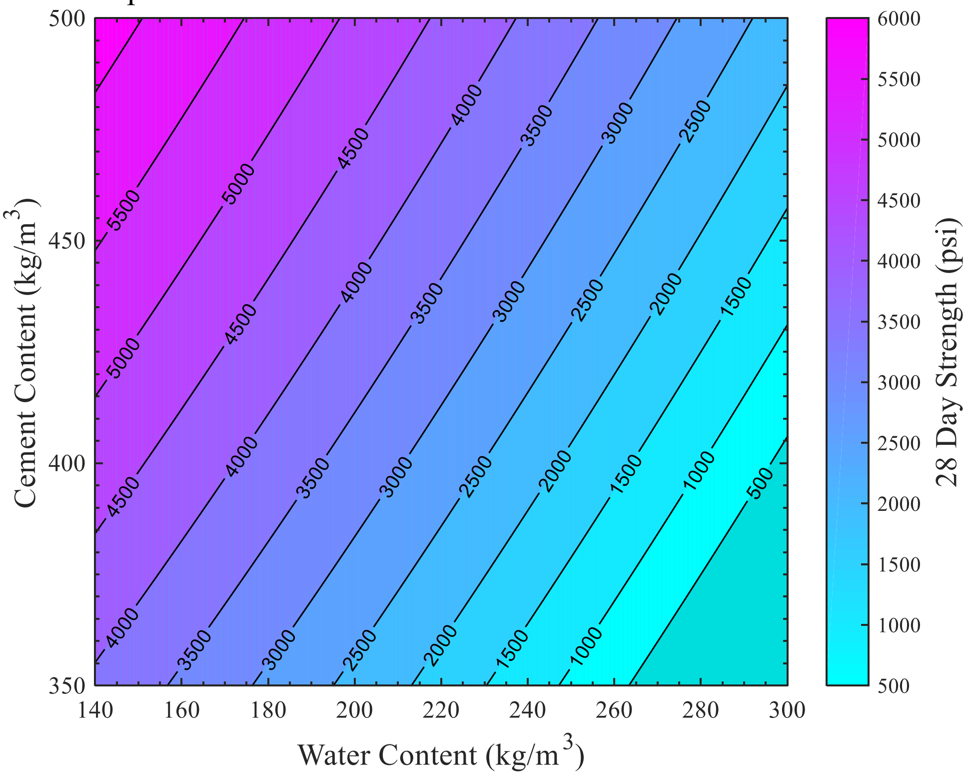


Figure 5.24: Variation of 28 Day Compressive Strength for Concrete Mixes Prepared with 5-10-14-18 Band Gradation and 35% Fly Ash Replacement

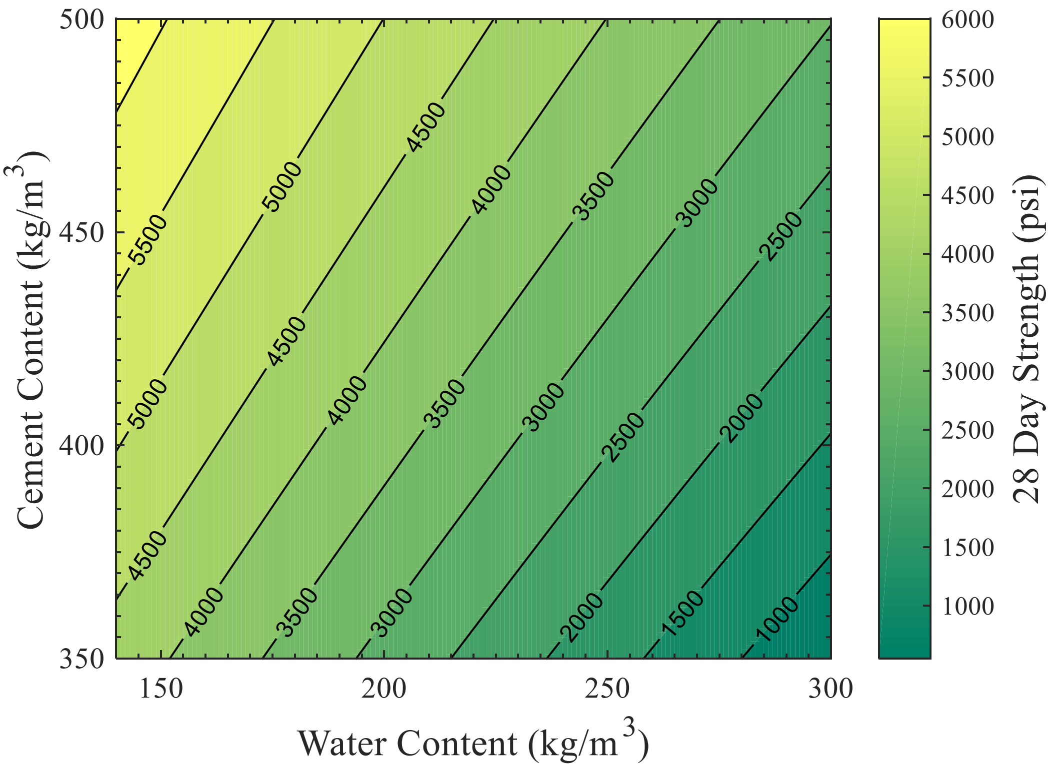


Figure 5.25: Variation of 28 Day Compressive Strength for Concrete Mixes Prepared with 5-10-18-22 Band Gradation and No Fly Ash Replacement

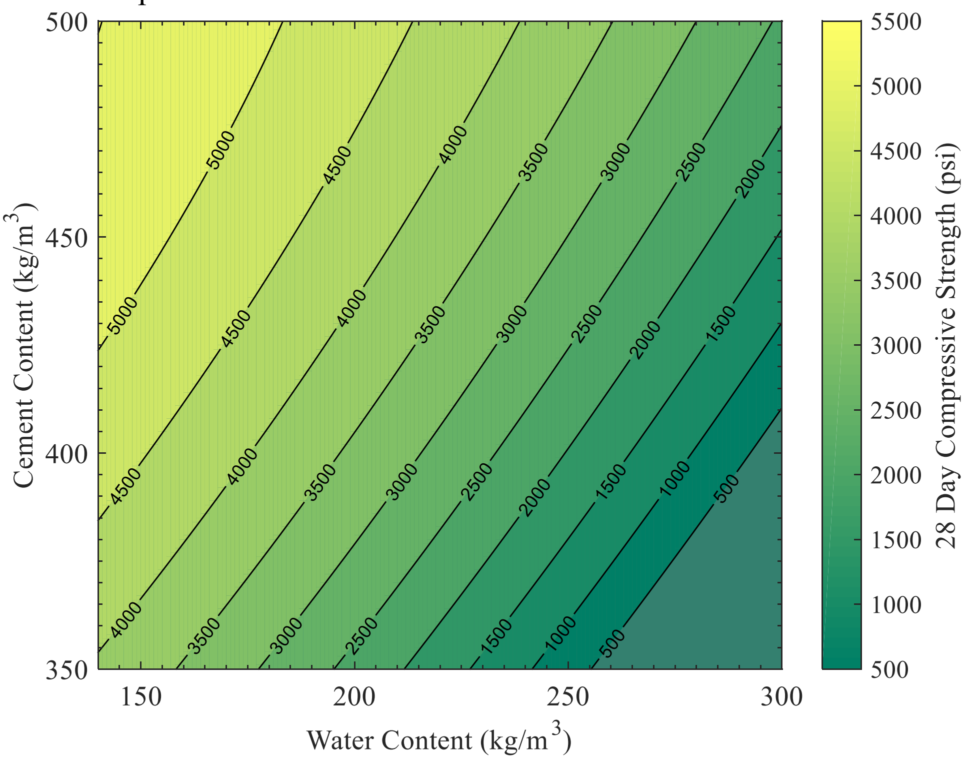


Figure 5.26: Variation of 28 Day Compressive Strength for Concrete Mixes Prepared with 5-10-18-22 Band Gradation and 20% Fly Ash Replacement

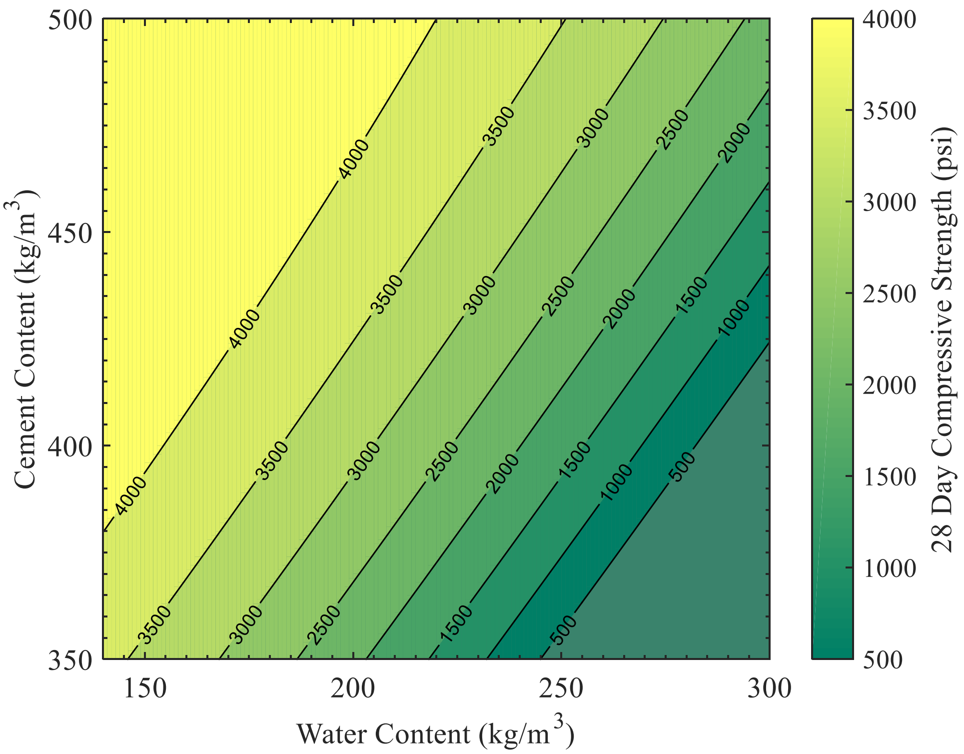


Figure 5.27: Variation of 28 Day Compressive Strength for Concrete Mixes Prepared with 5-10-18-22 Band Gradation and 35% Fly Ash Replacement

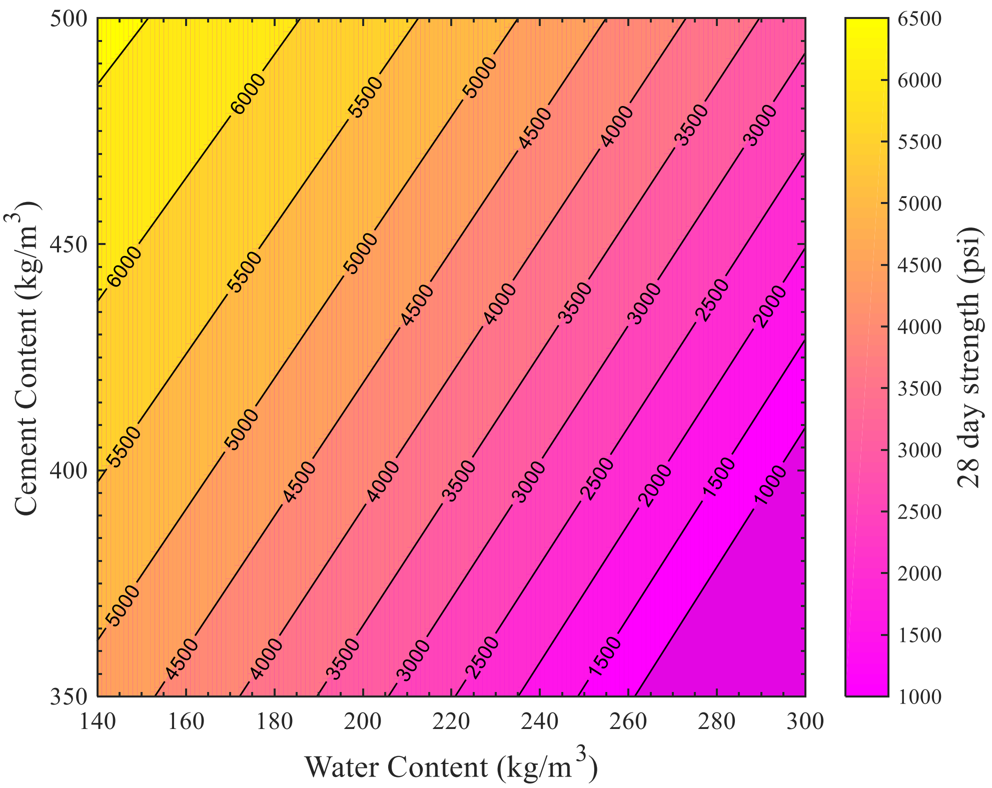


Figure 5.28: Variation of 28 Day Compressive Strength for Concrete Mixes Prepared with 5-10-14-18 Band Gradation and No Slag Replacement

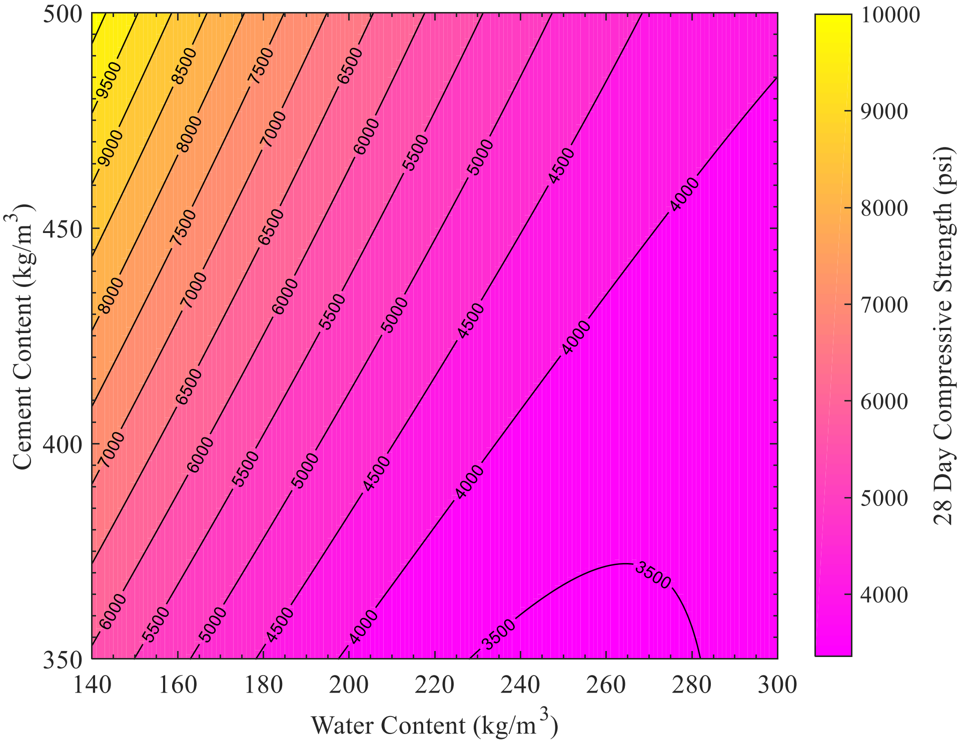


Figure 5.29: Variation of 28 Day Compressive Strength for Concrete Mixes Prepared with 5-10-14-18 Band Gradation and 20% Slag Replacement

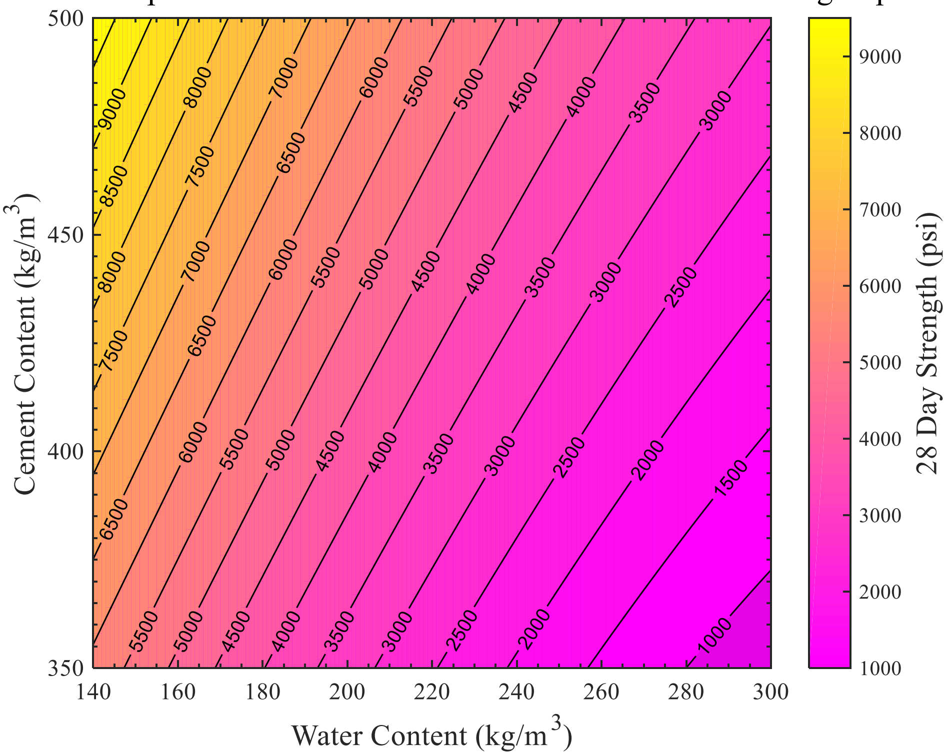


Figure 5.30: Variation of 28 Day Compressive Strength for Concrete Mixes Prepared with 5-10-14-18 Band Gradation and 65% Slag Replacement

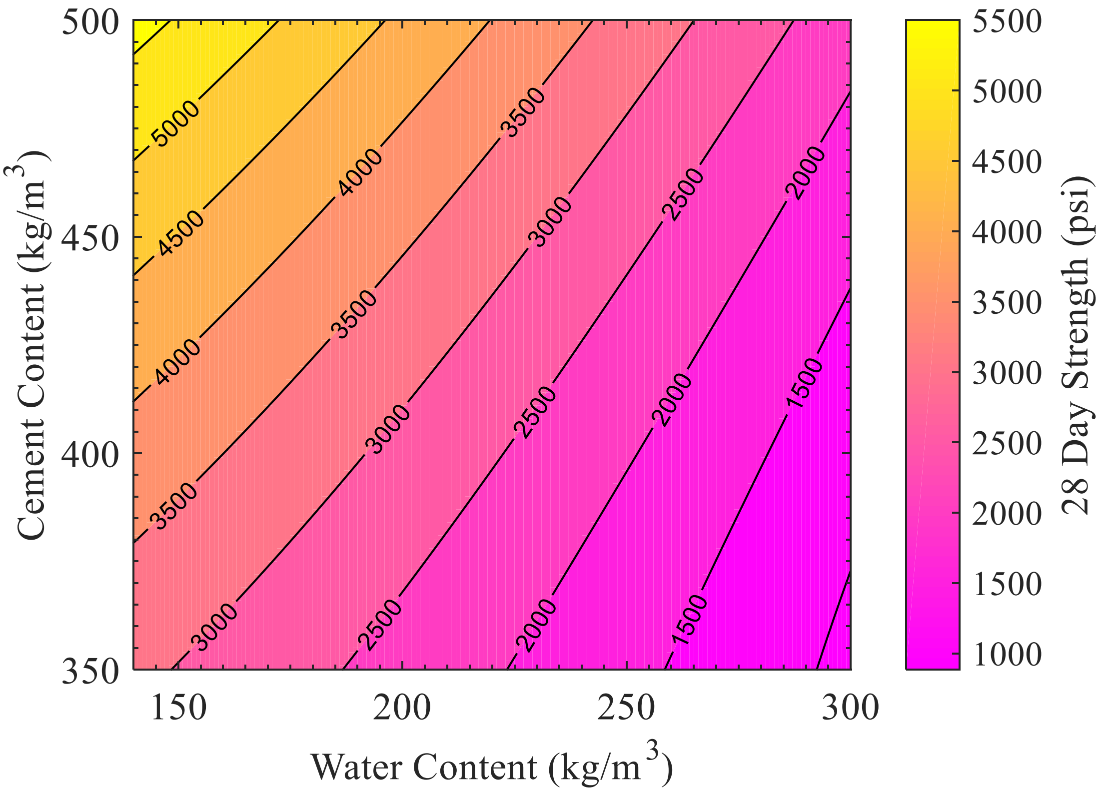


Figure 5.31: Variation of 28 Day Compressive Strength for Concrete Mixes Prepared with 5-10-14-18 Band Gradation and 90% Slag Replacement

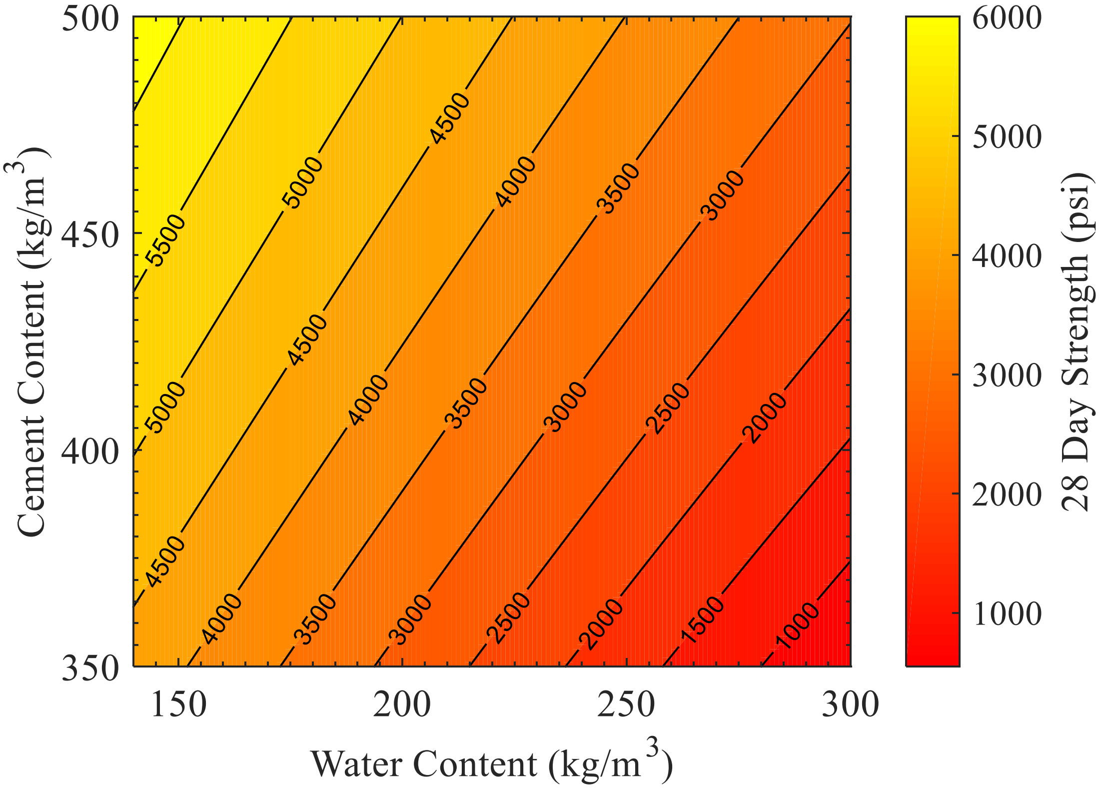


Figure 5.32: Variation of 28 Day Compressive Strength for Concrete Mixes Prepared with 5-10-18-22 Band Gradation and No Slag Replacement

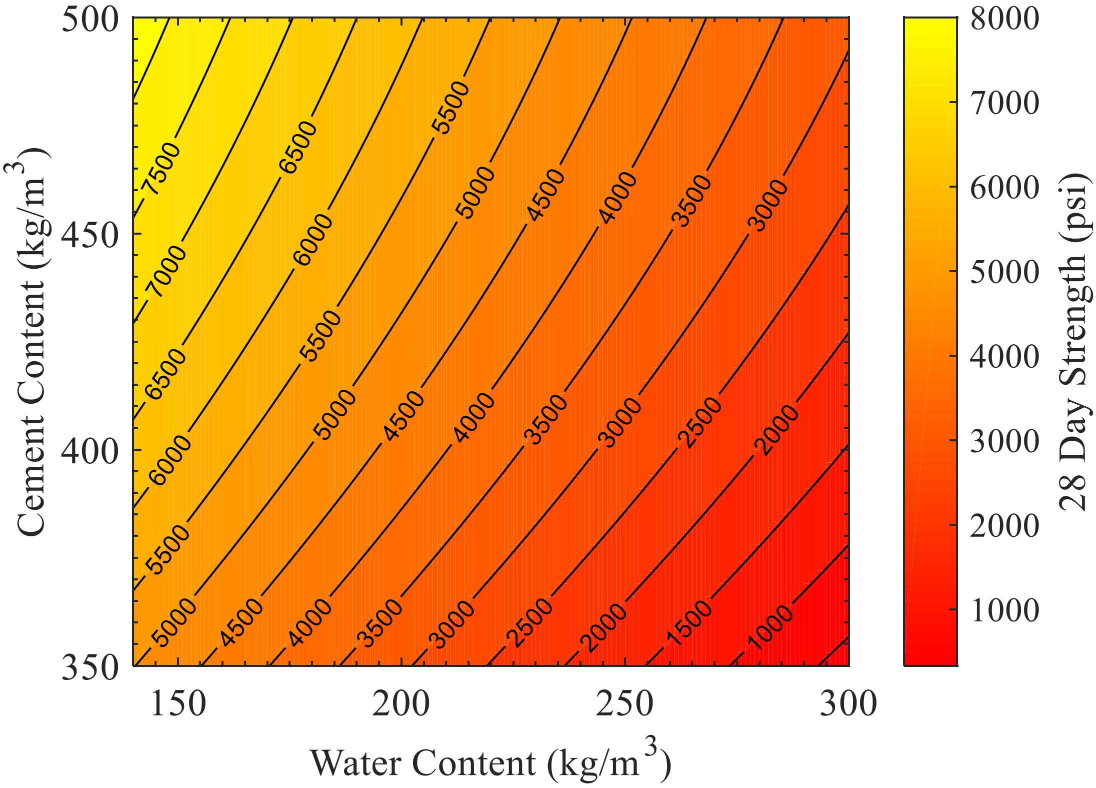


Figure 5.33: Variation of 28 Day Compressive Strength for Concrete Mixes Prepared with 5-10-18-22 Band Gradation and 20% Slag Replacement

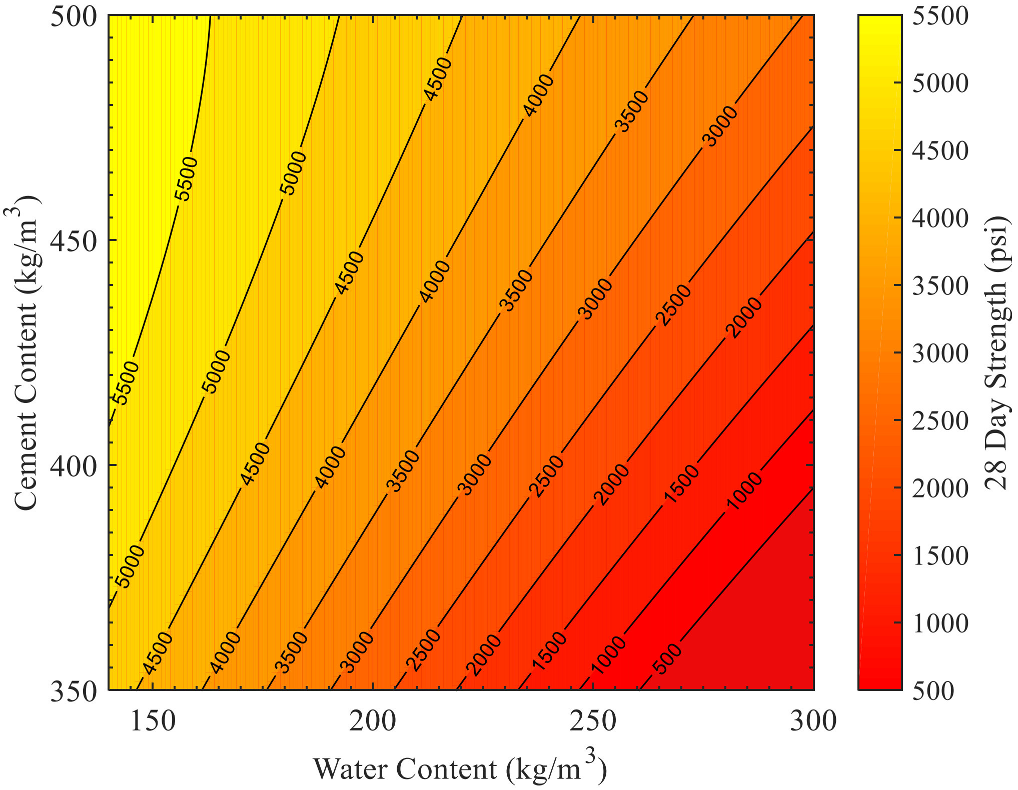


Figure 5.34: Variation of 28 Day Compressive Strength for Concrete Mixes Prepared with 5-10-18-22 Band Gradation and 65% Slag Replacement

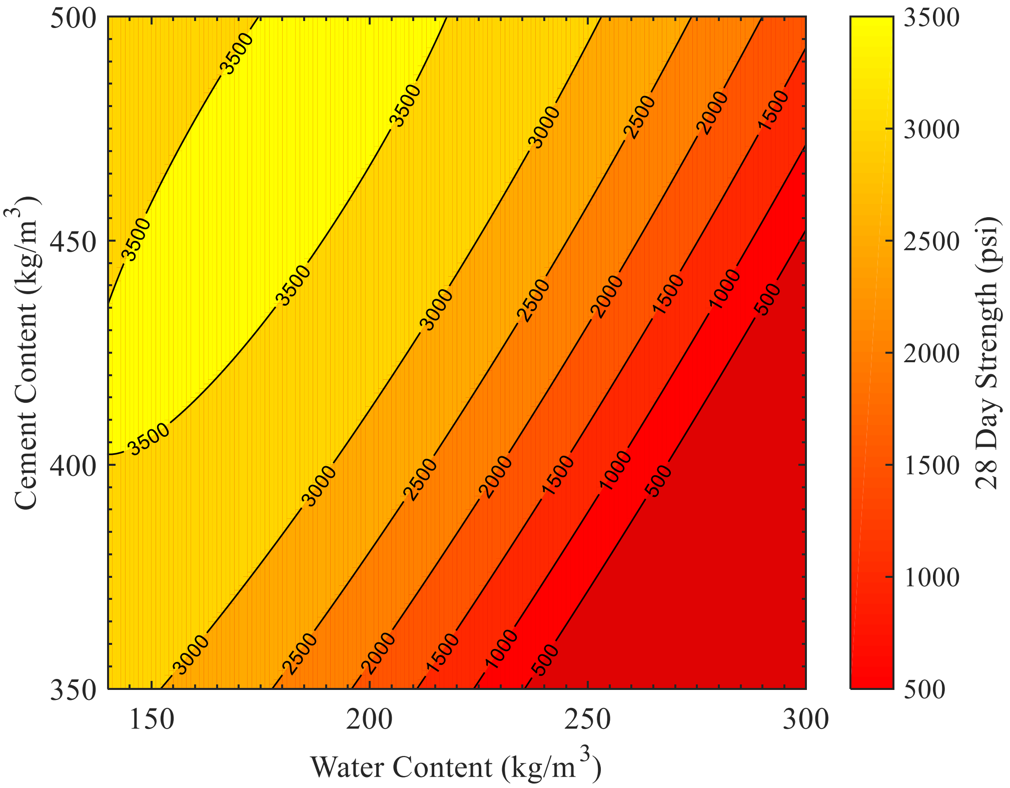


Figure 5.35: Variation of 28 Day Compressive Strength for Concrete Mixes Prepared with 5-10-18-22 Band gradation and 90% Slag Replacement

5.4 Concrete Mix Design Steps using Fly Ash as SCM

<u>Step 1:</u> Determination of Target Strength and Workability

The required target average compressive strength can be calculated using design compressive strength as per the following equation.

$$f_t = f'_c + sk$$

Where,

f_t = target compressive strength (MPa) at 28 days

f'_c = characteristic compressive strength (MPa) at 28 days,

s = standard deviation of compressive strength described in Table 5.3.

k = a statistical factor, depending upon the accepted proportion of low results and the number of tests, in general comes from Himsworth constant (1954) (Table 5.4)

Table 5.3: Typical Values of the Standard Deviation for Different Conditions of Placing and Mixing of Concrete (Ashraf, 2012)

Degree of Quality Control	**Degree of Supervision**	**Description**	**Standard Deviation, *s* (MPa)**
Excellent / Laboratory precision	Continual supervision	Completely accurate aggregate gradation, exact water/cement ratio, controlled temperature environment.	≤ 3
Very good	Continual supervision	Weigh batching of all materials, combination of different aggregate sizes to achieve the recommended aggregate gradation, strict control of aggregate grading, control of water added to allow for moisture content of aggregates.	3 – 4
Good	Frequent supervision	Weigh-batching of all materials, control of aggregate grading, control of water added, periodic check of workability.	4 – 6
Fair	Occasional supervision	Volume batching of all aggregates allowing for bulking of sand, slight deviation of aggregate gradation allowed, water content controlled by inspection of mix.	6 – 8
Poor / uncontrolled	Little or no supervision	Volume batching of all materials.	8 – 10

Table 5.4: Values for the Factor “k” (Himsworth, 1954)

Percentage of results allowed to fail below the minimum	**Value of “k”**
16	1.0
10	1.28
5	1.64
2.5	1.96
1.0	2.33
0.6	2.50
0.1	3.09

Workability of concrete mixture during the time of mixing and during the time of placing may not be always same. After the mixing, the cement starts hydration process and thus concrete starts losing its workability. If there is any considerable time delay between concrete mixing and concrete placing procedure, then this time delay may result significant difference in concrete workability at these two stages.

Workability, measured in terms of slump, at the time of concrete mixing will be higher than that of the time of concrete placing and the difference between these two slumps can be termed as –slump loss”.

Therefore,

$Slump_{loss} = Slump_{mixing} - Slump_{casting}$

Here,

$Slump_{loss}$ = Loss of slump due to time delay between concrete mixing and placing

$Slump_{mixing}$ = Required workability at the time concrete mixing

$Slump_{casting}$ = Required workability at the time concrete Placing

Slump loss depends on number of factors, these are –

- Time delay between concrete mixing and concrete placing – as the time delay increases the slump loss will also increase.
- Temperature – hydration process is faster in higher temperature, thus slump loss will also be higher for higher temperature.
- Type of chemical admixture – water reducers and superplasticzers reduce the w/c ratio at a given slump and thus increases slump loss. Again for accelerator the slump loss will be higher and for retarder this loss will be lower.

The slump loss being taken into account, the required slump *($Slump_{mixing}$)* for concrete mix design at the time of concrete mixing can be calculated using the following equation:

$$Slump_{mixing} = Slump_{loss} + Slump_{casting}$$

Table 5.5 shows the slump loss (mm) for variable time delays according to findings of Ashraf (2012).

Table 5.5: Slump (mm) Losses for Time Delay between Mixing and Placing of Concrete (Ashraf, 2012)

Time Delay (minute)	Slump Loss (mm)
10 to 20	up to 35 mm
25 to 40	25 to 50 mm
40 to 60	30 to 70 mm
60 to 80	up to 110 mm

<u>Step-2</u> Determination of Required Durability

The required durability of concrete based on concrete permeability will be specified by the client. ASTM C1202 provides a classification of concrete permeability according to RCPT values which is shown in Table 5.6. Total charge passed value in coulomb needs to be selected according to this classification.

Table 5.6: Classification of Concrete Permeability according to RCPT Values (ASTM C1202)

Total Charge Passed (Coulombs)	Chloride Ion Permeability
> 4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

Step 3: Incorporation of Fly Ash in Concrete Mix Design

Incorporating supplementary cementing materials such as fly ash or slag in concrete mix as replacement of cement up to a certain percentage has positive effects on concrete durability. Use of these SCMS depends on their availability. In this step, percentage of fly ash is chosen from workability and durability requirements. Figure 5.36 and 5.37 show the workability (slump) and durability changes for replacement of cement with fly ash for gradation bands 5-10-14-18 and 5-10-18-22 respectively.

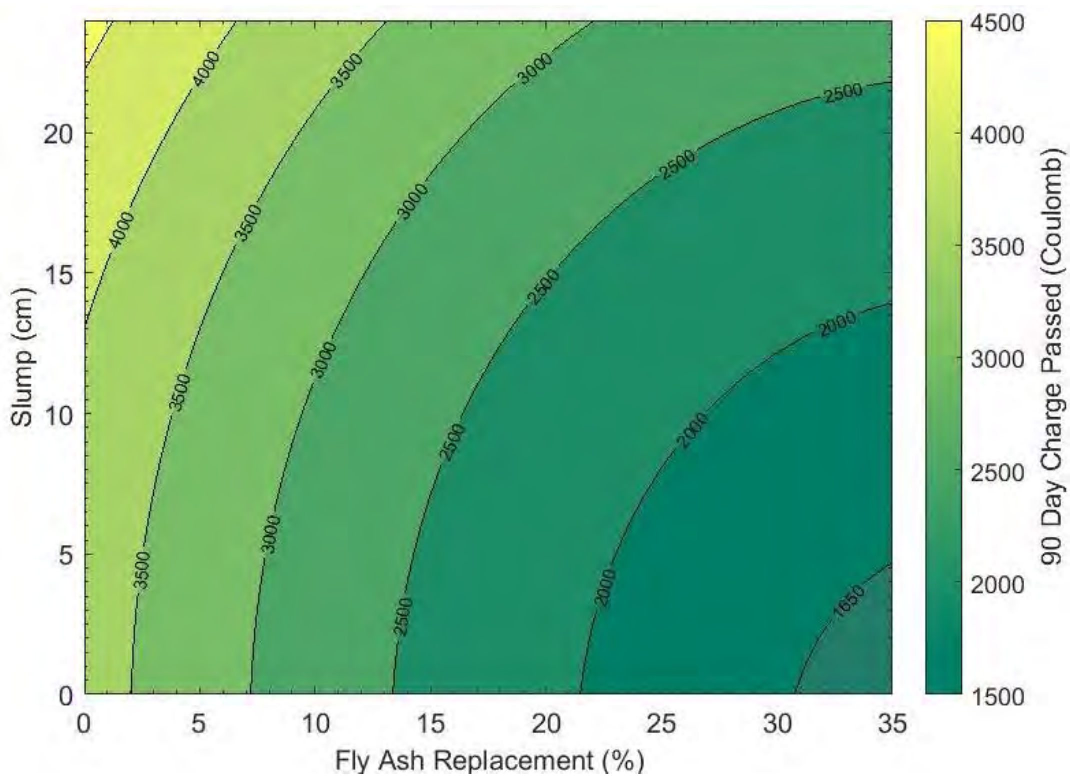


Figure 5.36: Variation of Permeability Classes with Slump and Fly Ash Replacement Percentages for Aggregate Band 5-10-14-18

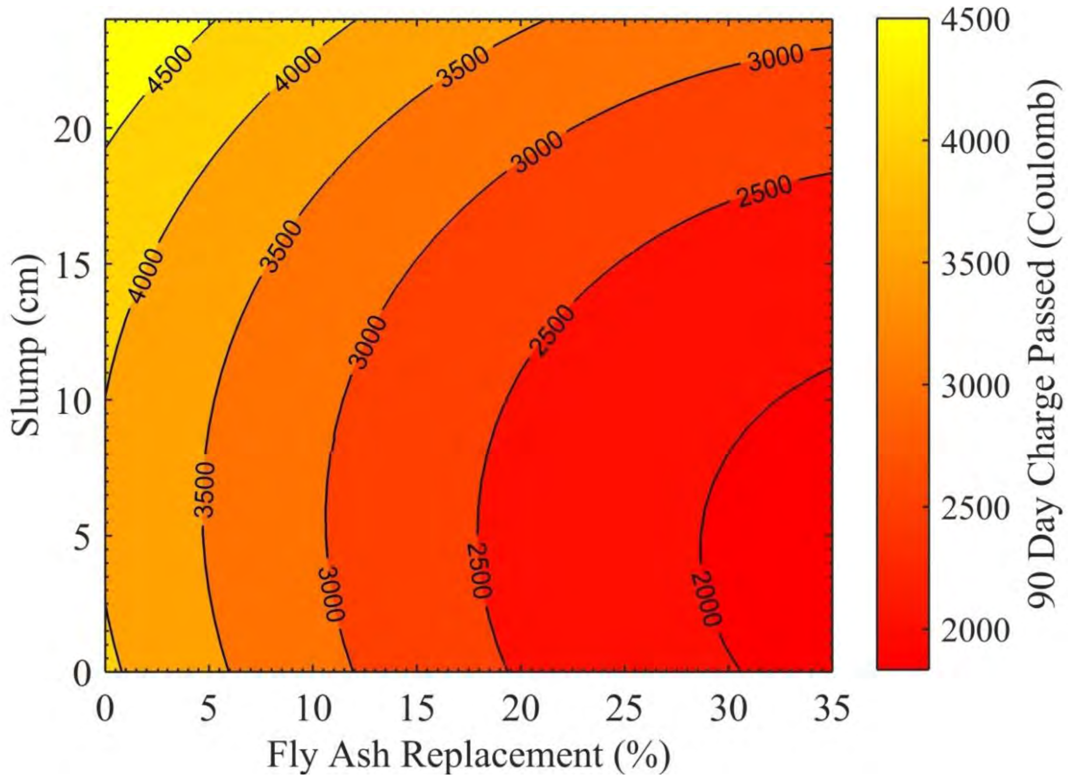


Figure 5.37: Variation of Permeability Classes with Slump and Fly Ash Replacement Percentages for Aggregate Band 5-10-18-22

Step 4: Determination of Cement Content, Water Content and Gradation Band from Workability and Strength Requirements

Now, if the target concrete compressive strength at 28 days and required workability are known, mix proportions such as water and cement content can be determined from Figures 5.38 to 5.43. These figures are for 5-10-14-18 and 5-10-18-22 band gradations. The range of fa/ta- ratio of 5-10-14-18 and 5-10-18-22 band gradations are 0.4-0.5 and 0.3-0.4 respectively.

Using the percentage of fly ash chosen in step 3, the relevant plot is selected or interpolated. The intersecting point of the required slump and compressive strength values is found out. Then horizontal and vertical lines connecting the two axes are drawn. The intersecting point with horizontal gives the water content and the intersecting point with vertical axis gives the cement content. From the two band gradations, two sets of water and cement content values can be found. The band which gives lower cement content is selected as this ensures more economical mix. From the final values of water and cement content, w/c ratio can be calculated.

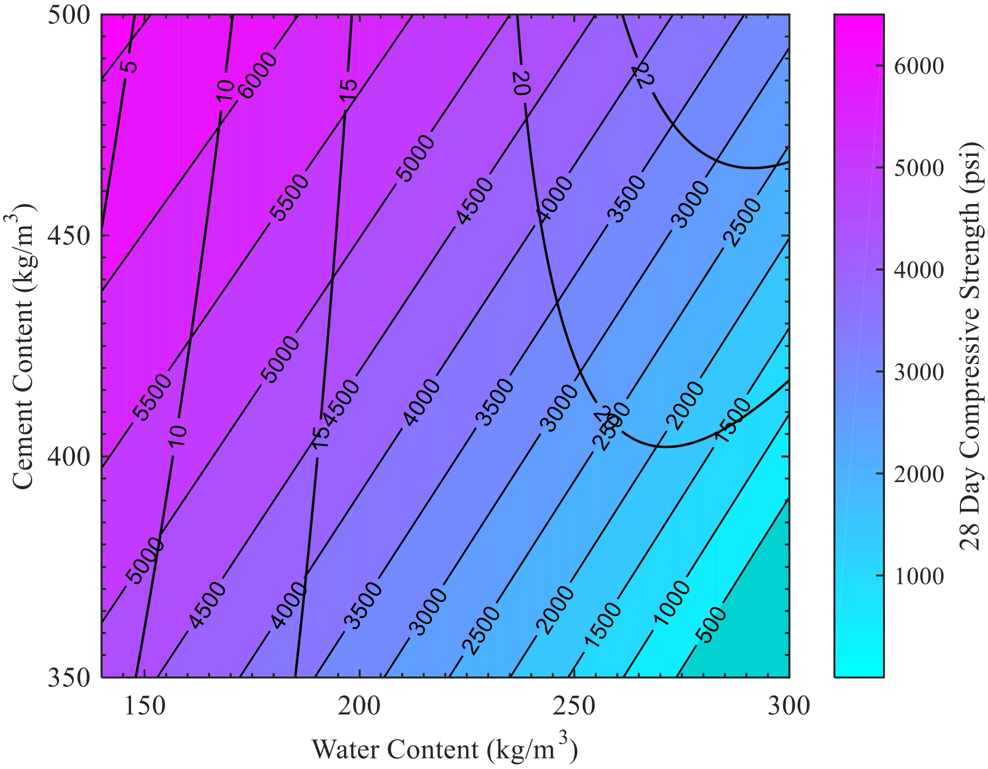


Figure 5.38: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with No Fly Ash Replacement and 5-10-14-18 Band Gradation

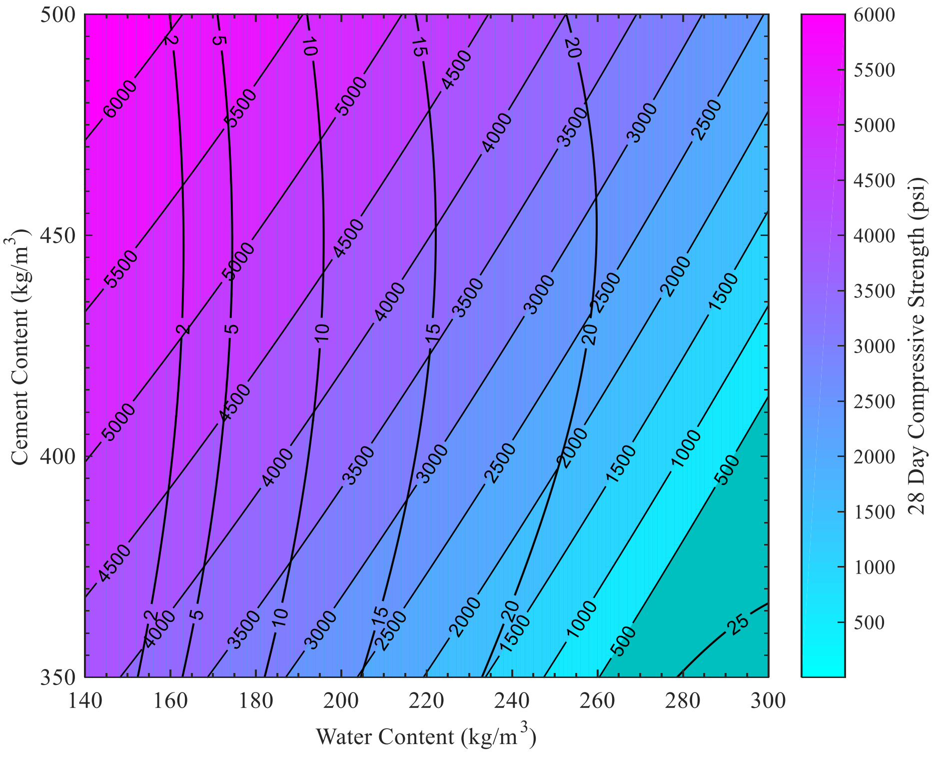


Figure 5.39: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with 20% Fly Ash Replacement and 5-10-14-18 Band Gradation

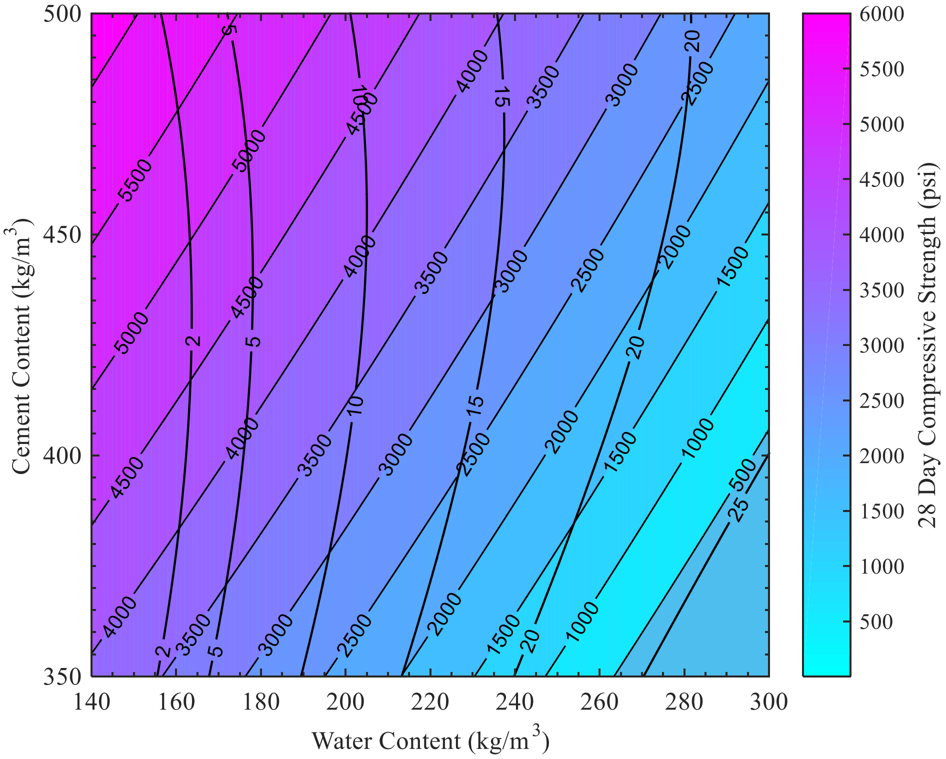


Figure 5.40: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with 35% Fly Ash Replacement and 5-10-14-18 Band Gradation

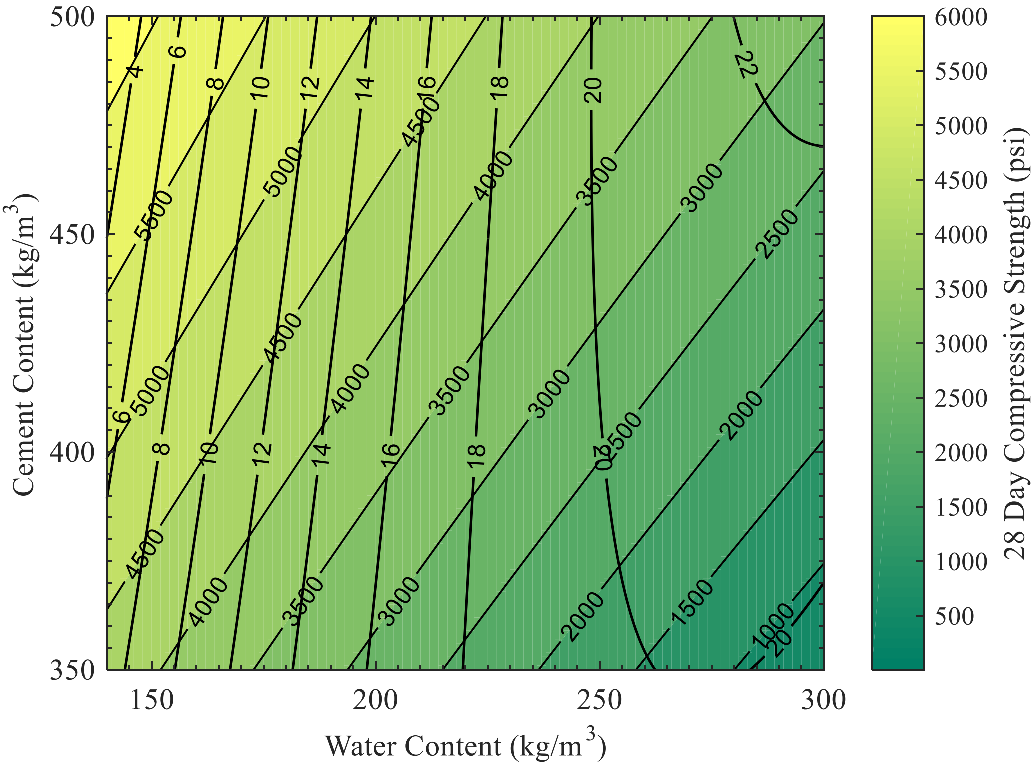


Figure 5.41: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with no Fly Ash Replacement and 5-10-18-22 Band Gradation

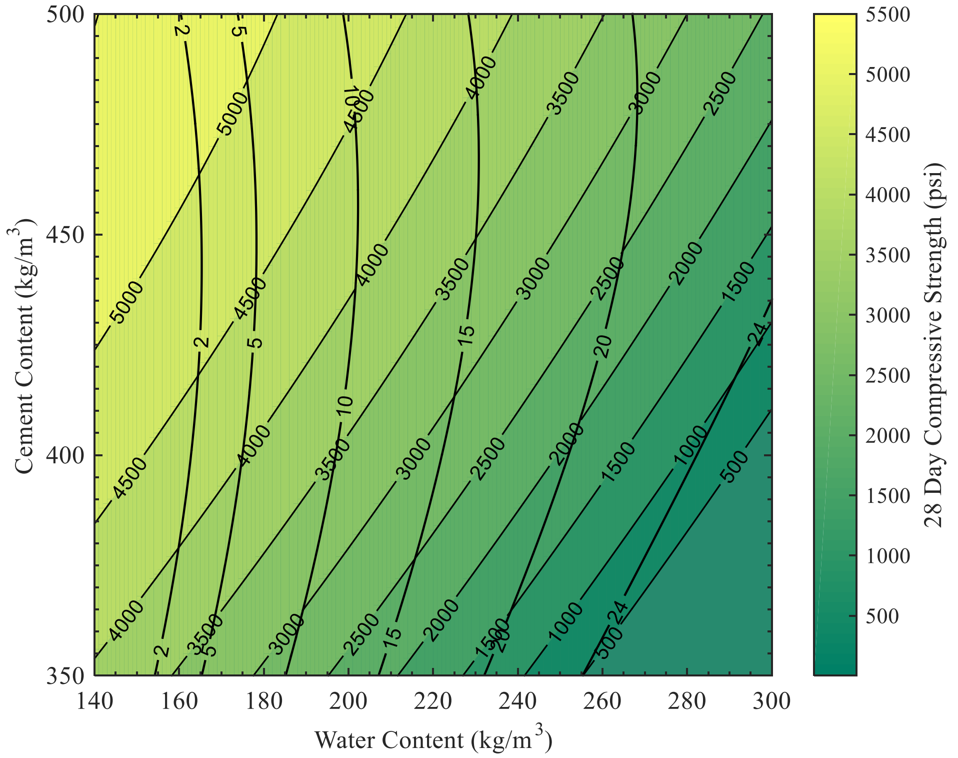


Figure 5.42: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with 20% Fly Ash Replacement and 5-10-18-22 Band Gradation

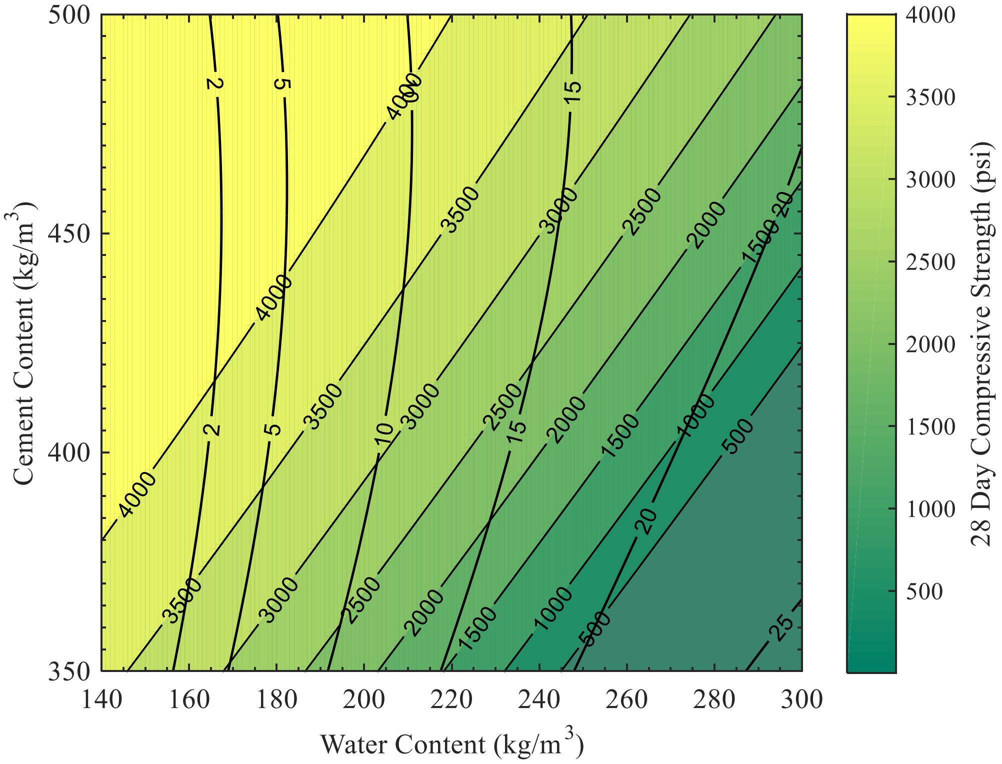


Figure 5.43: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with 35% Fly Ash Replacement and 5-10-18-22 Band Gradation

<u>Step 5:</u> Modification of Water Content considering Durability Parameter

Using the cement content chosen in step 4, the contours of Figures 5.44 to 5.49 are used to determine the modified water content. First it needs to be checked from the contours if the chosen water and cement content in step 4 produce the required concrete permeability. If not, then some modification in water content will be required to reach the required permeability value. For example, if the chosen water and cement contents result in a permeability value higher than the required range, water content needs to be lowered and vice versa. The modified water cement ratio is calculated then.

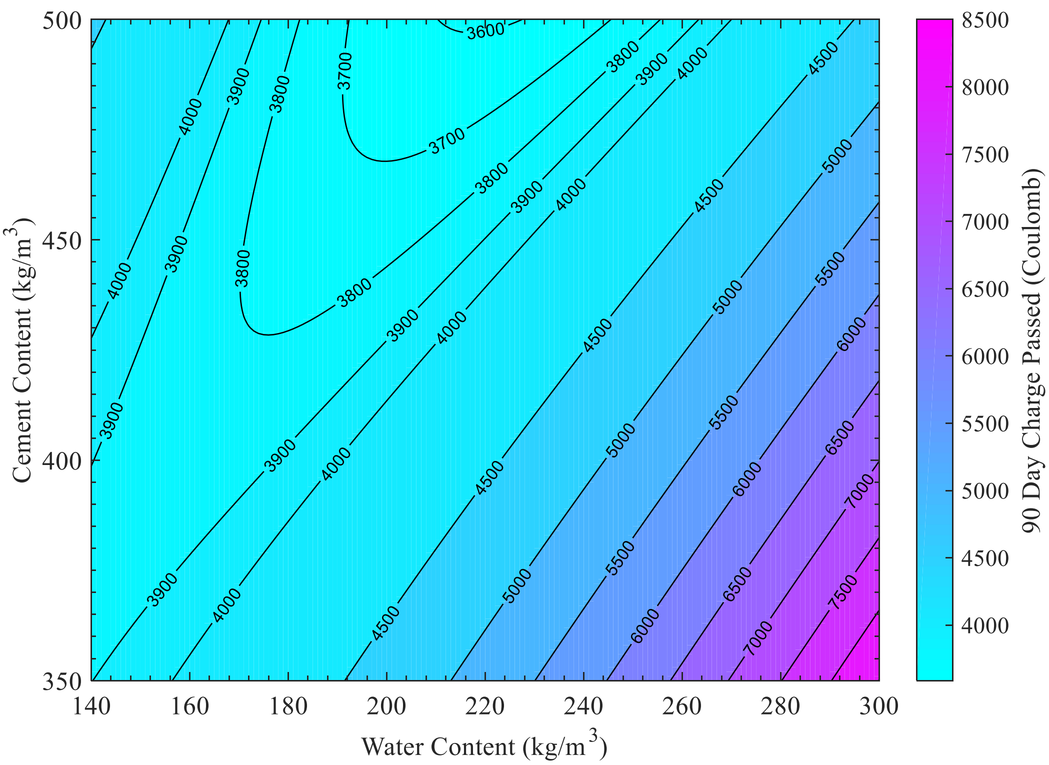


Figure 5.44: Variation of Concrete Permeability with Various Water and Cement Contents for Cement with No Fly Ash Replacement and 5-10-14-18 Band Gradation

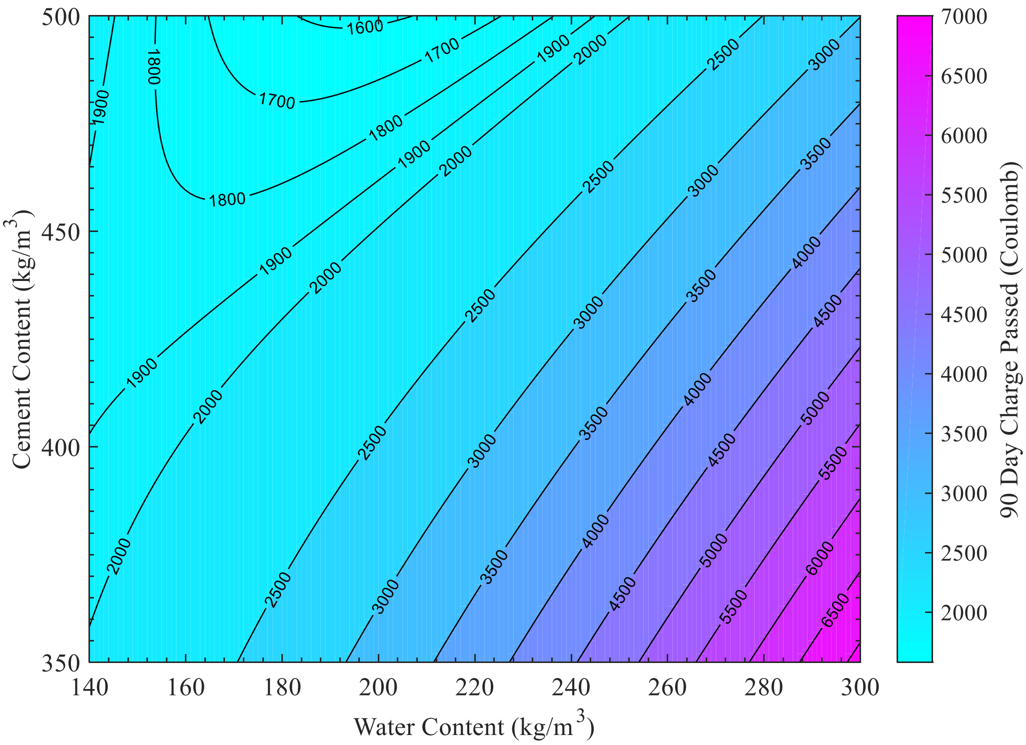


Figure 5.45: Variation of Charge passed (RCPT) with Various Water and Cement Contents for Cement with 20% Fly Ash Replacement and 5-10-14-18 Band Gradation

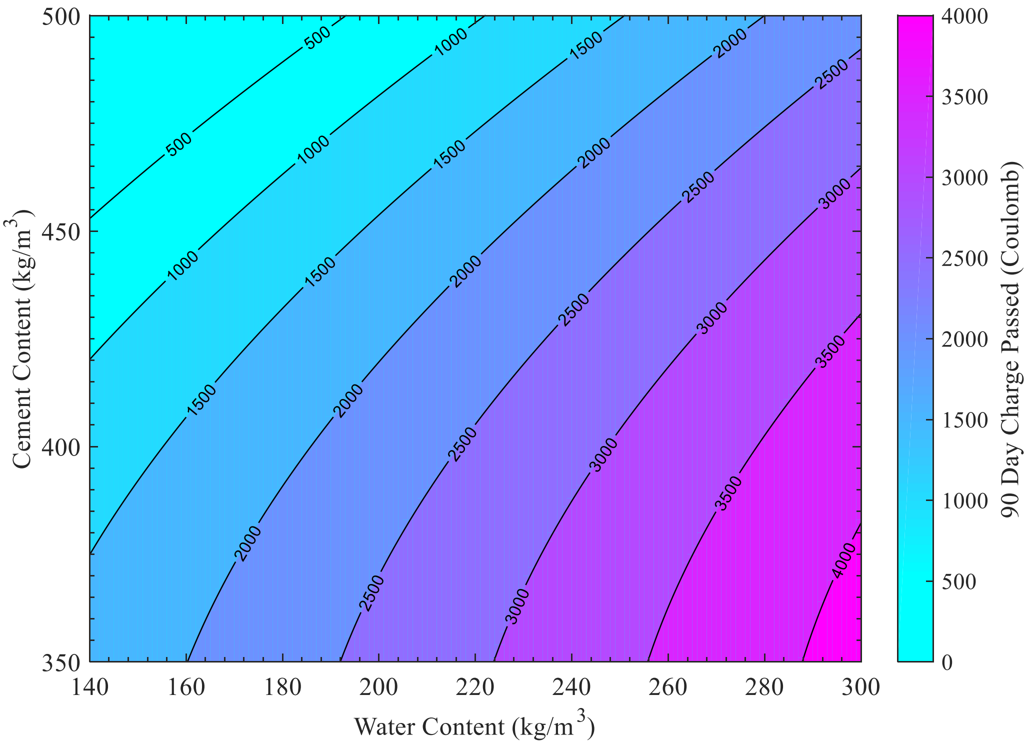


Figure 5.46: Variation of Charge passed (RCPT) with Various Water and Cement Contents for Cement with 35% Fly Ash Replacement and 5-10-14-18 Band Gradation

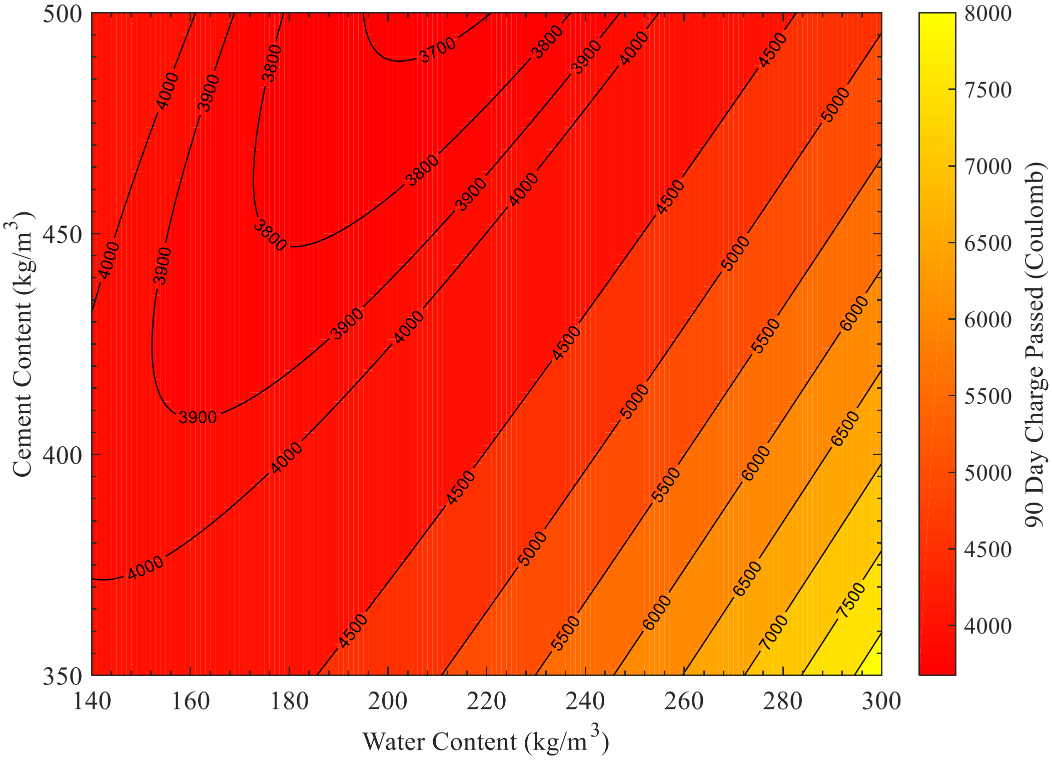


Figure 5.47: Variation of Charge passed (RCPT) with Various Water and Cement Contents for Cement with No Fly Ash Replacement and 5-10-18-22 Band Gradation

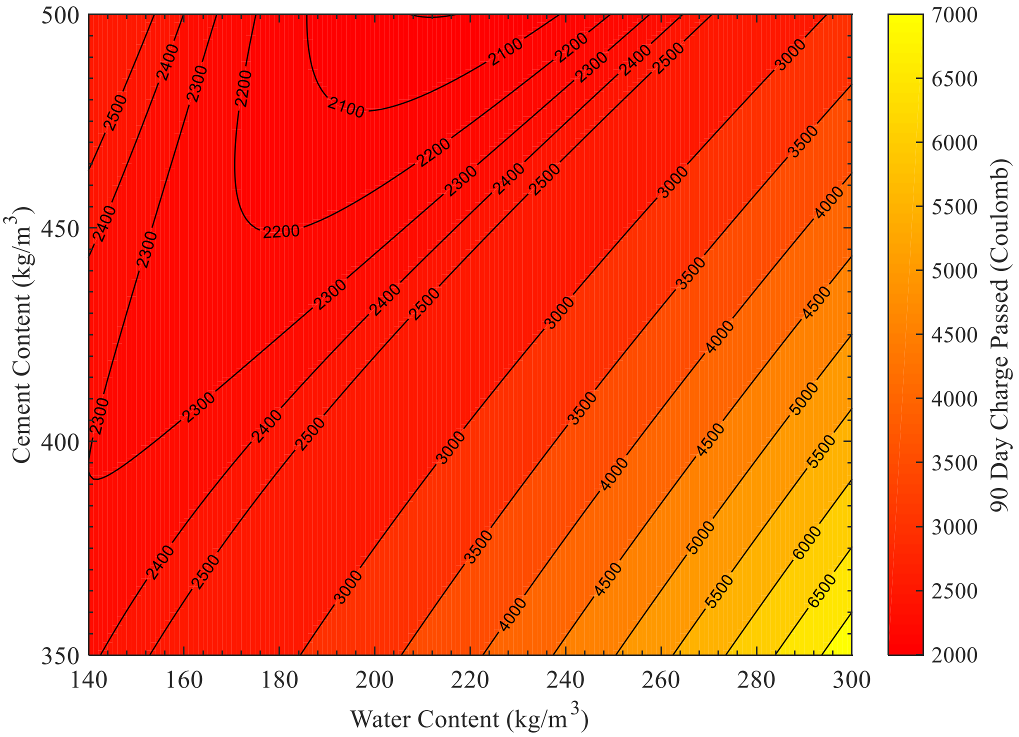


Figure 5.48: Variation of Charge passed (RCPT) with Various Water and Cement Contents for Cement with 20% Fly Ash Replacement and 5-10-18-22 Band Gradation

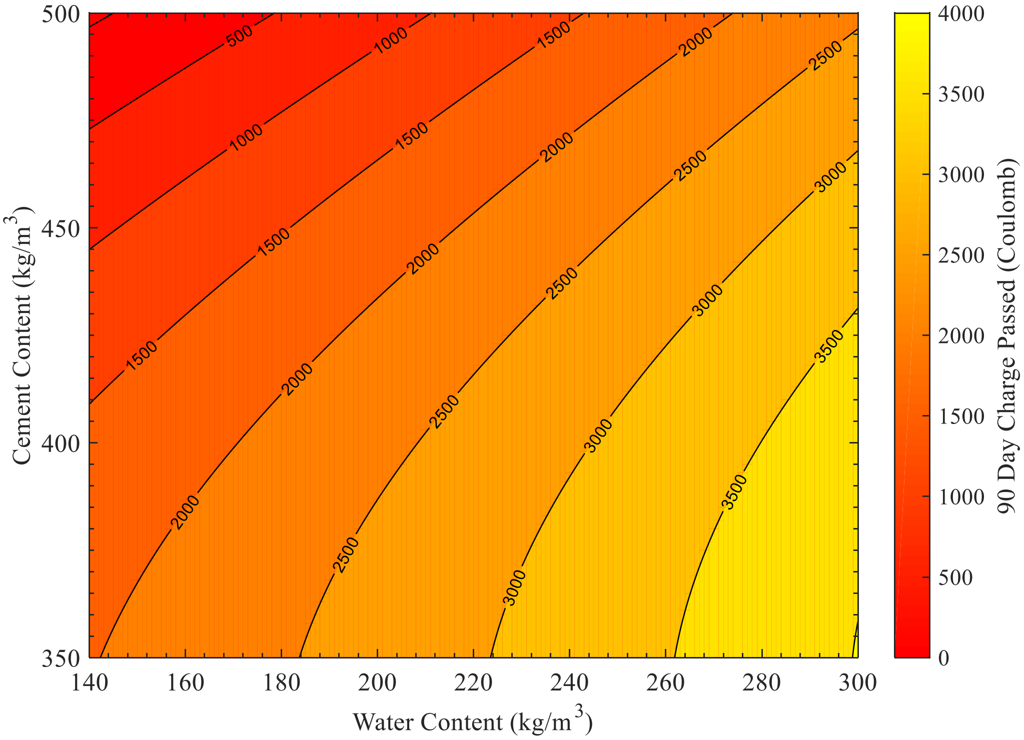


Figure 5.49: Variation of Charge passed (RCPT) with Various Water and Cement Contents for Cement with 35% Fly Ash Replacement and 5-10-18-22 Band Gradation

Step 6: Calculation of Cement Content

After determining both w/c ratio and water content, required cement content can be calculated using following equation-

Cement Content (kg/m³) = Water content (kg/m³) / w/c ratio

Step 7: Calculation of Total Aggregate Content

Total aggregate content can be determined by absolute volume method. For unit volume of concrete, the portion fulfilled by cement and water is determined first. The rest of the volume must be occupied by the aggregates.

For unit volume of concrete, ($1m^3$),

- *Cement volume, m^3 = Cement Content (kg) / (sp. Gravity of cement x unit weight of water (kg/m^3)*
- *Water volume, m^3 = Water Content (kg) / unit weight of water (kg/m^3)*
- *Aggregate Volume, m^3 = 1 - Cement volume, m^3 - Water volume, m^3*

5.4 Concrete Mix Design Steps using Slag as SCM

Step 1 and Step 2 is same as the steps shown in mix design steps using fly ash.

<u>Step 3:</u> Incorporation of Slag in Concrete Mix Design

In this step, percentage of slag replacement is chosen from workability and durability requirements. Figure 5.50 and 5.51 show the workability (slump) and durability changes for replacement of cement with slag for gradation bands 5-10-14-18 and 5-10-18-22 respectively.

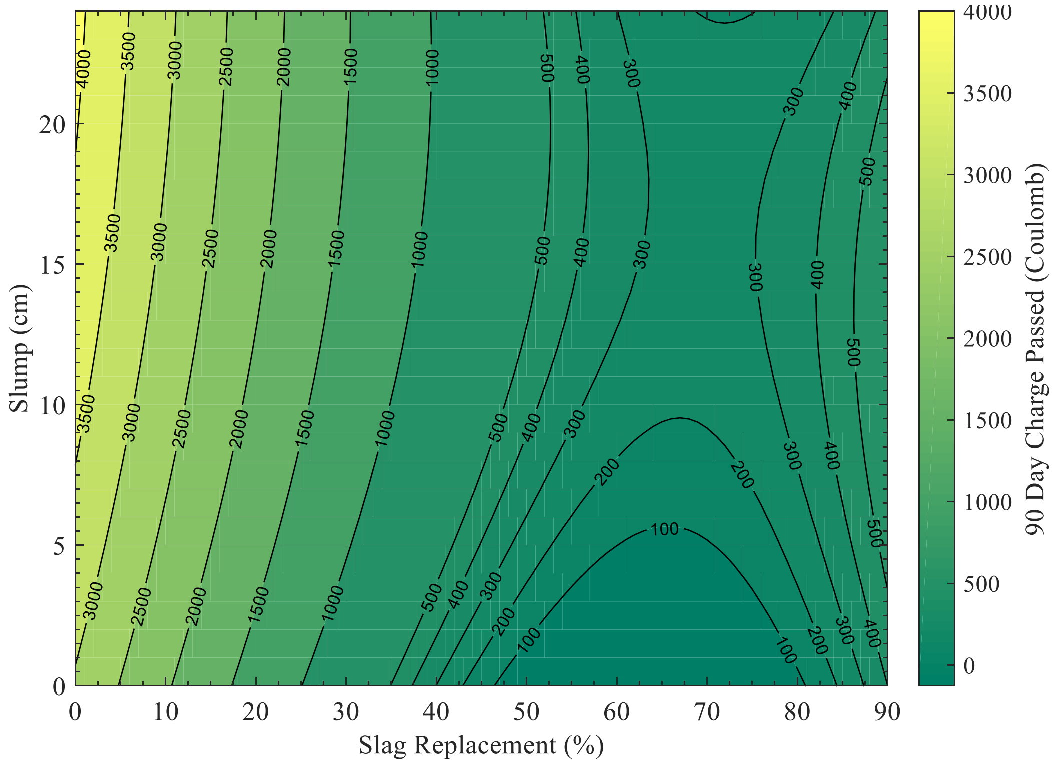


Figure 5.50: Variation of Permeability Classes with Slump and Slag Replacement Percentages for Aggregate Band 5-10-14-18

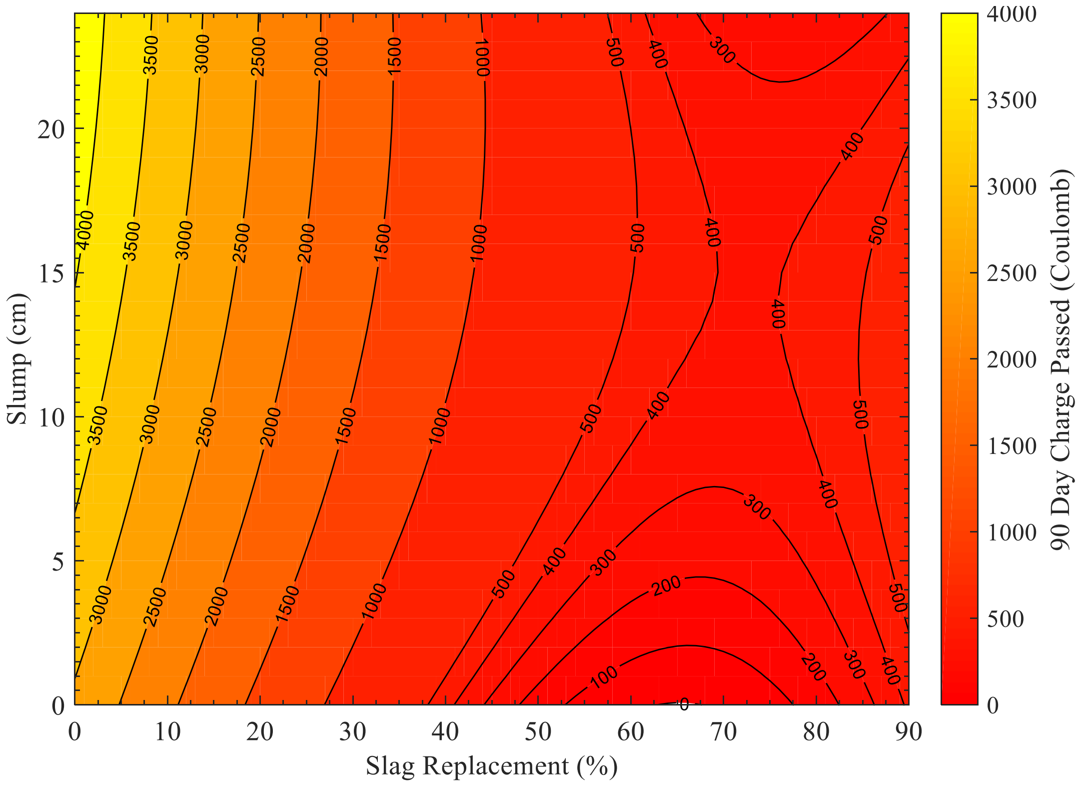


Figure 5.51: Variation of Permeability Classes with Slump and Slag Replacement Percentages for Aggregate Band 5-10-18-22

<u>Step 4:</u> Determination of Cement Content, Water Content and Gradation Band from Workability and Strength Requirements

Now, if the target concrete compressive strength at 28 days and required workability are known, mix proportions such as water and cement content can be determined from Figures 5.52 to 5.59. These figures are for 5-10-14-18 and 5-10-18-22 band gradations. The range of fa/ta- ratio of 5-10-14-18 and 5-10-18-22 band gradations are 0.4-0.5 and 0.3-0.4 respectively.

Using the percentage of slag chosen in step 3, the relevant plot is selected or interpolated. The intersecting point of the required slump and compressive strength values is found out. Then horizontal and vertical lines connecting the two axes are drawn. The intersecting point with horizontal gives the water content and the intersecting point with vertical axis gives the cement content. From the two band gradations, two sets of water and cement content values can be found. The band which gives lower cement content is selected as this ensures more economical mix. From the final values of water and cement content, w/c ratio can be calculated.

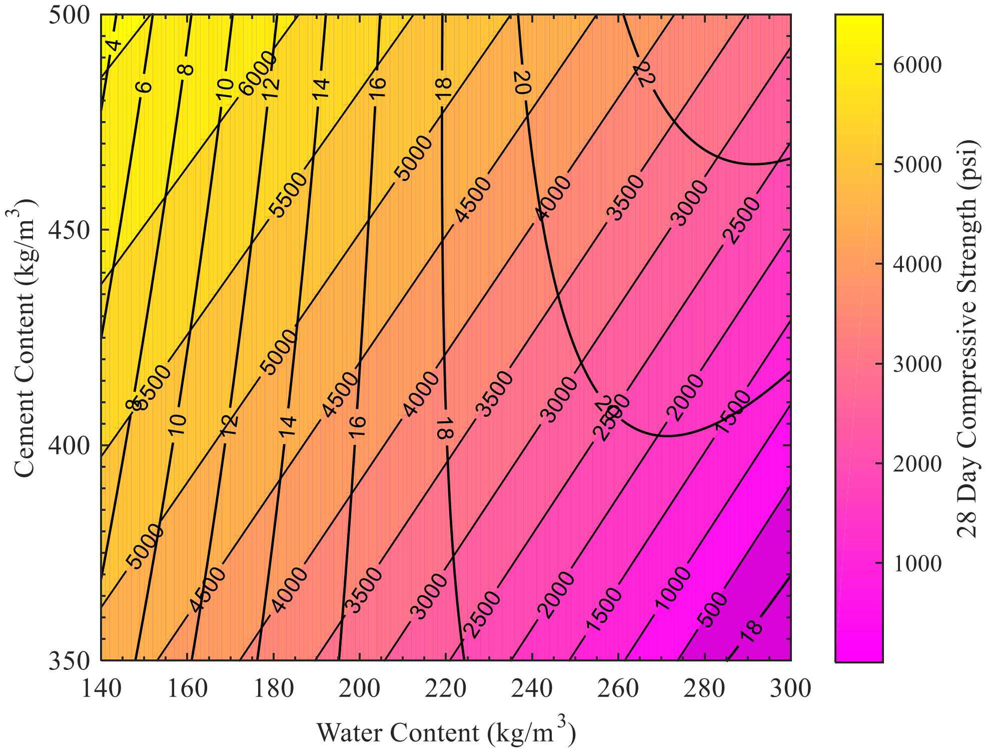


Figure 5.52: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with no Slag Replacement and 5-10-14-18 Band Gradation

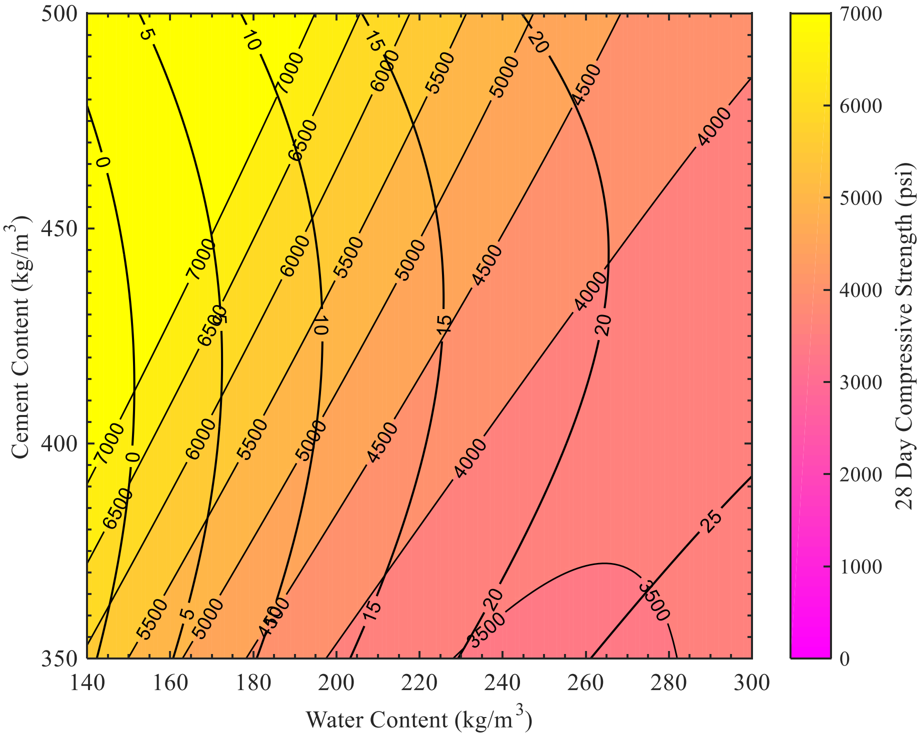


Figure 5.53: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with 20% Slag Replacement and 5-10-14-18 Band Gradation

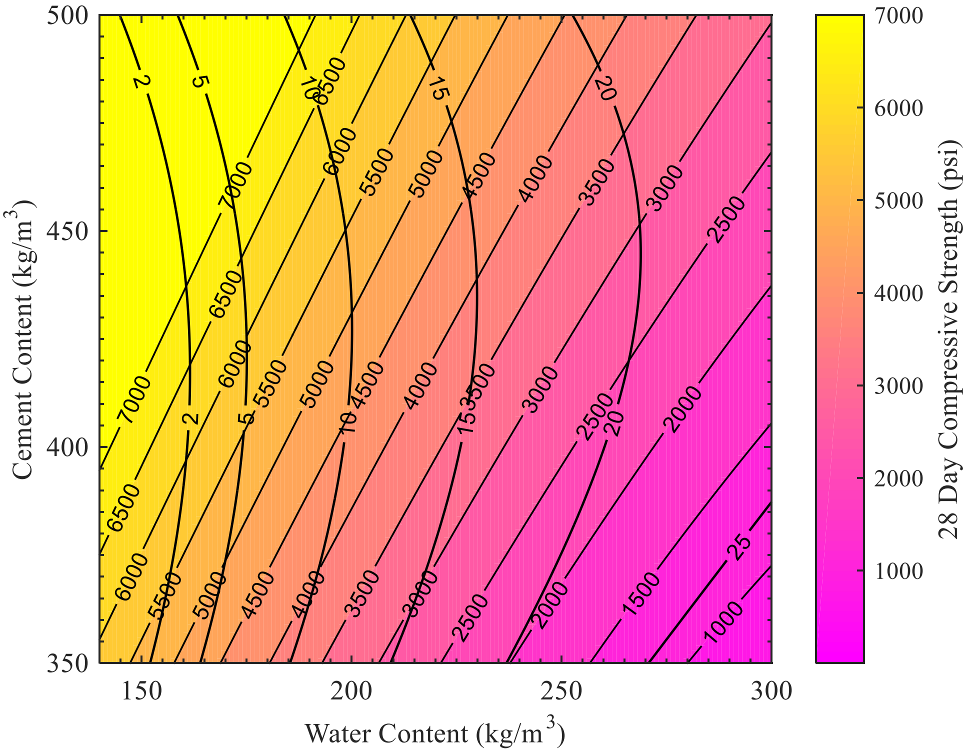


Figure 5.54: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with 65% Slag Replacement and 5-10-14-18 Band Gradation

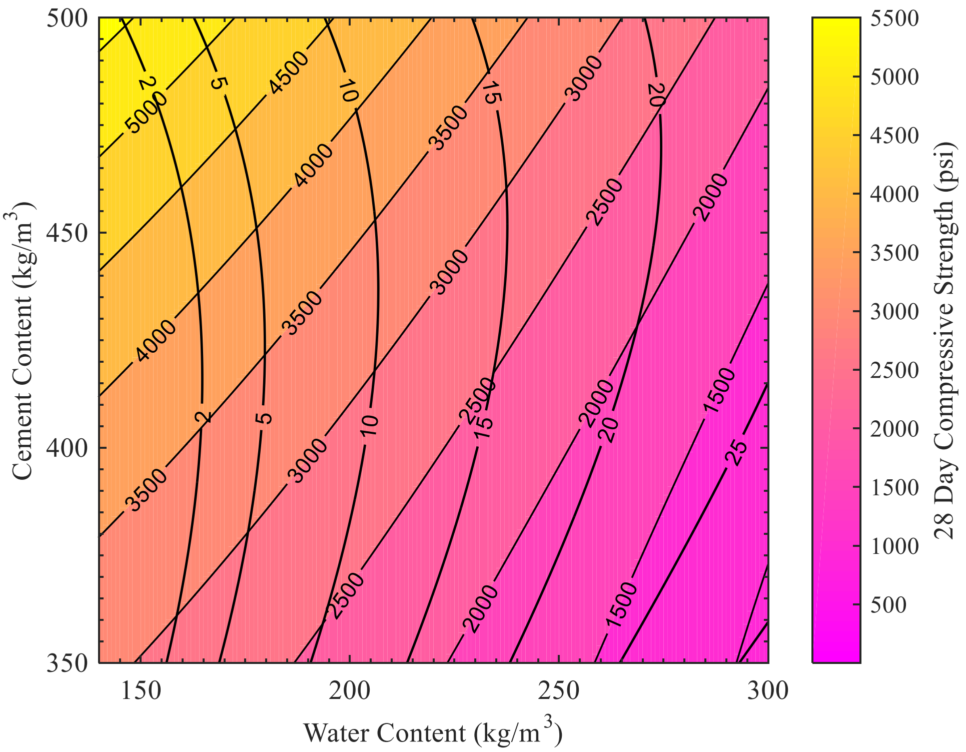


Figure 5.55: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with 90% Slag Replacement and 5-10-14-18 Band Gradation

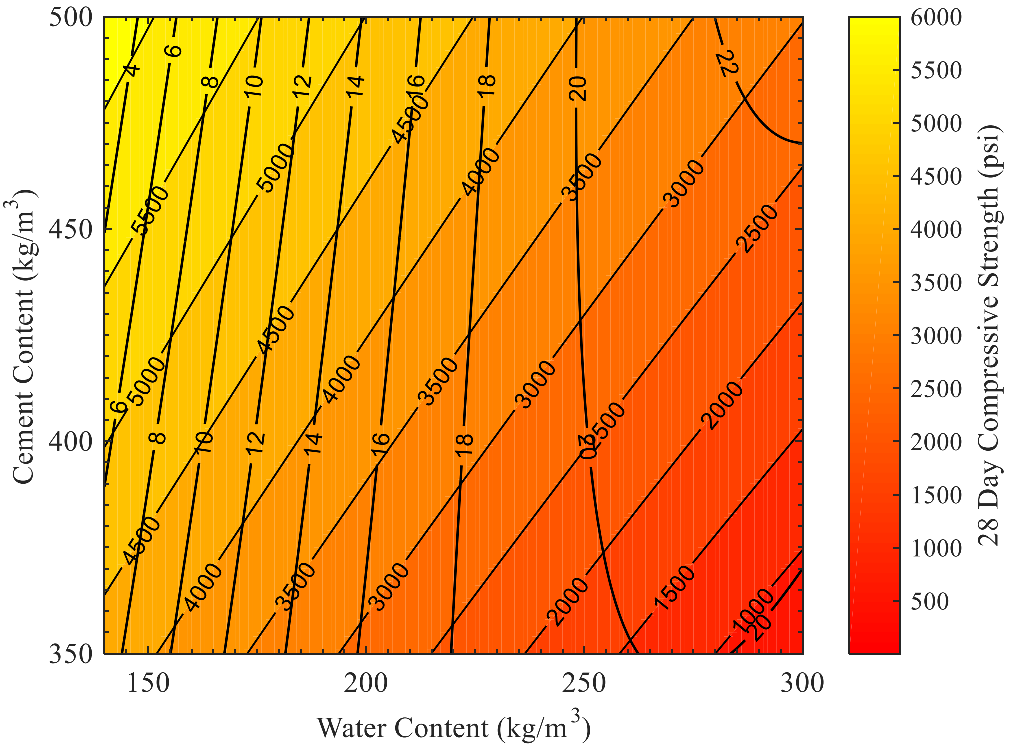


Figure 5.56: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with No Slag Replacement and 5-10-18-22 Band Gradation

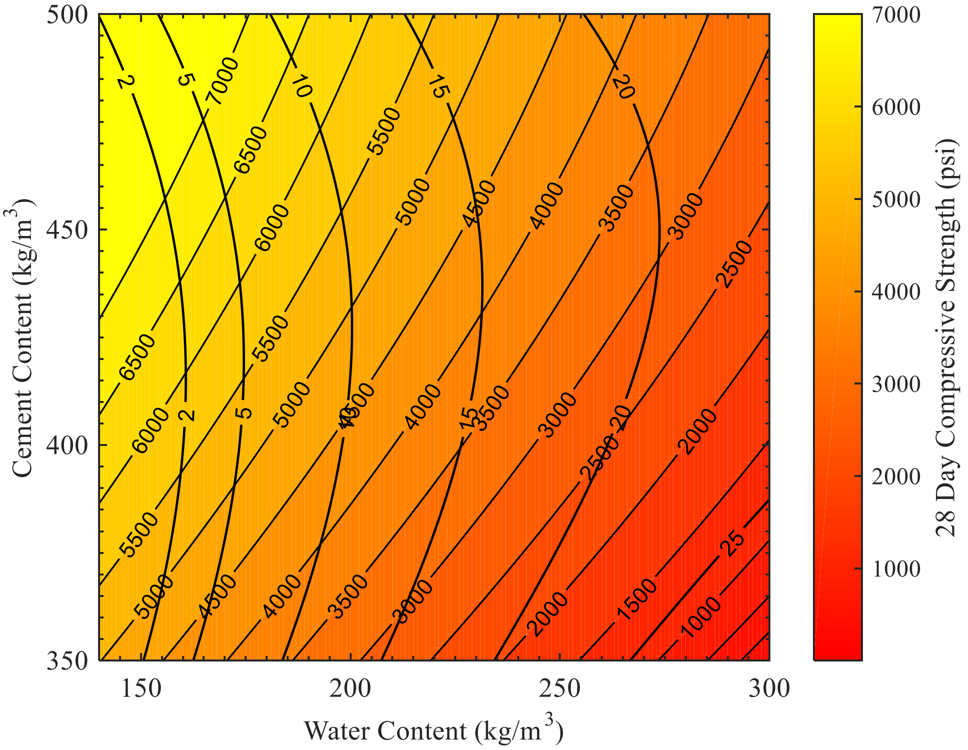


Figure 5.57: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with 20% Slag Replacement and 5-10-18-22 Band Gradation

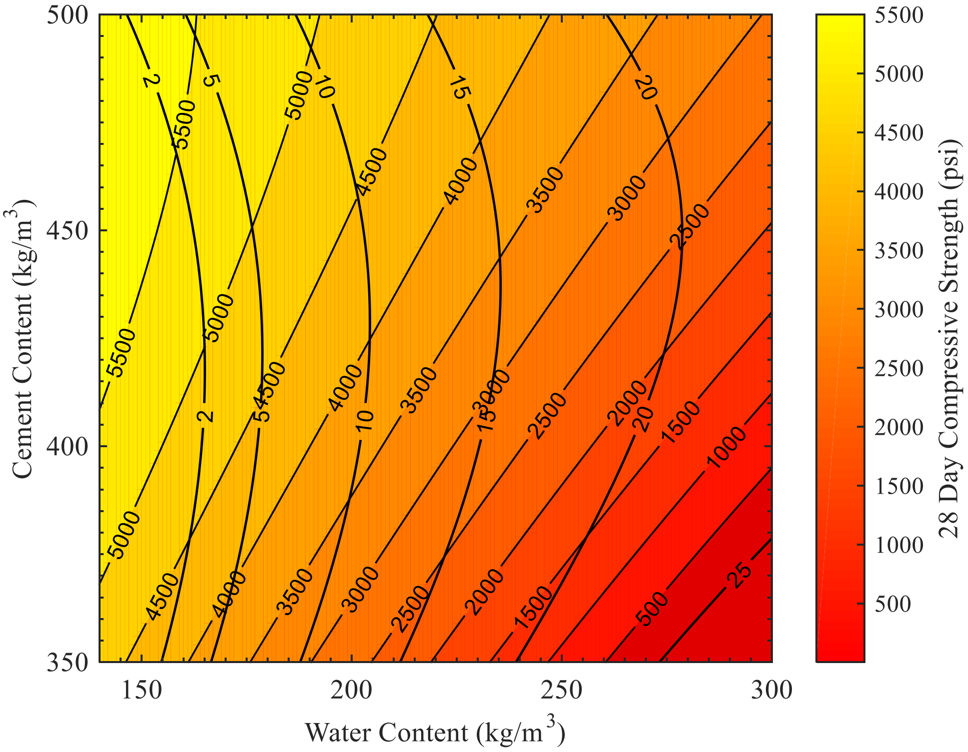


Figure 5.58: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with 65% Slag Replacement and 5-10-18-22 Band Gradation

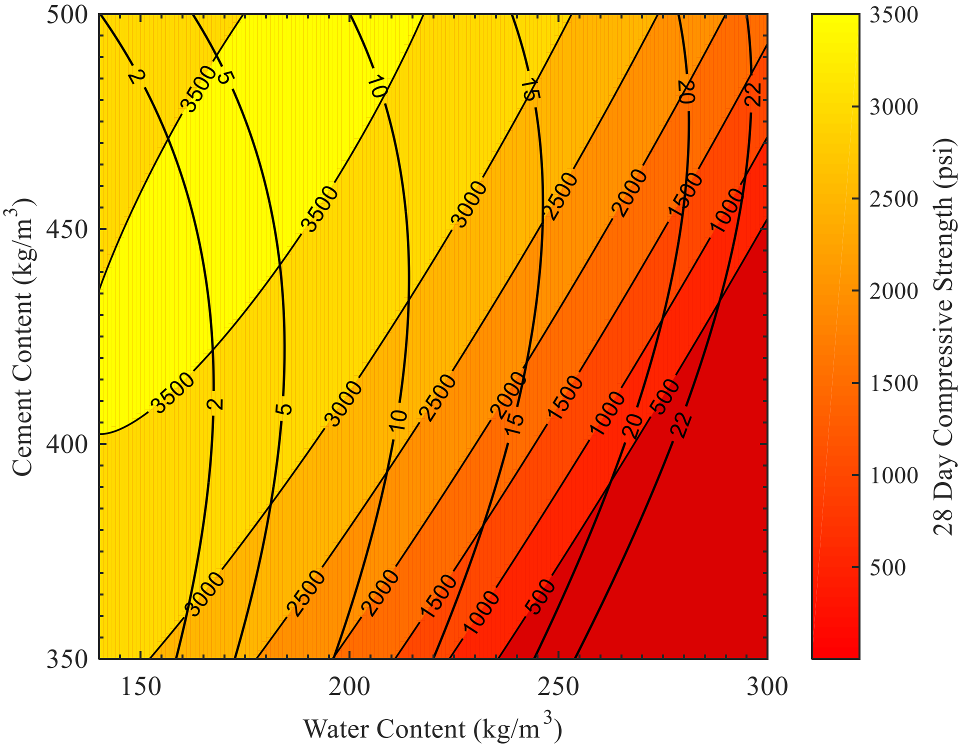


Figure 5.59: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with 90% Slag Replacement and 5-10-18-22 Band Gradation

Step 5: Modification of Water Content considering Durability Parameter

Using the cement content chosen in step 4, the contours of Figures 5.60 to 5.67 are used to determine the modified water content. First it needs to be checked from the contours if the chosen water and cement content in step 4 produce the required concrete permeability. If not, then some modification in water content will be required to reach the required permeability value. For example, if the chosen water and cement contents result in a permeability value higher than the required range, water content needs to be lowered and vice versa. The modified water cement ratio is calculated then.

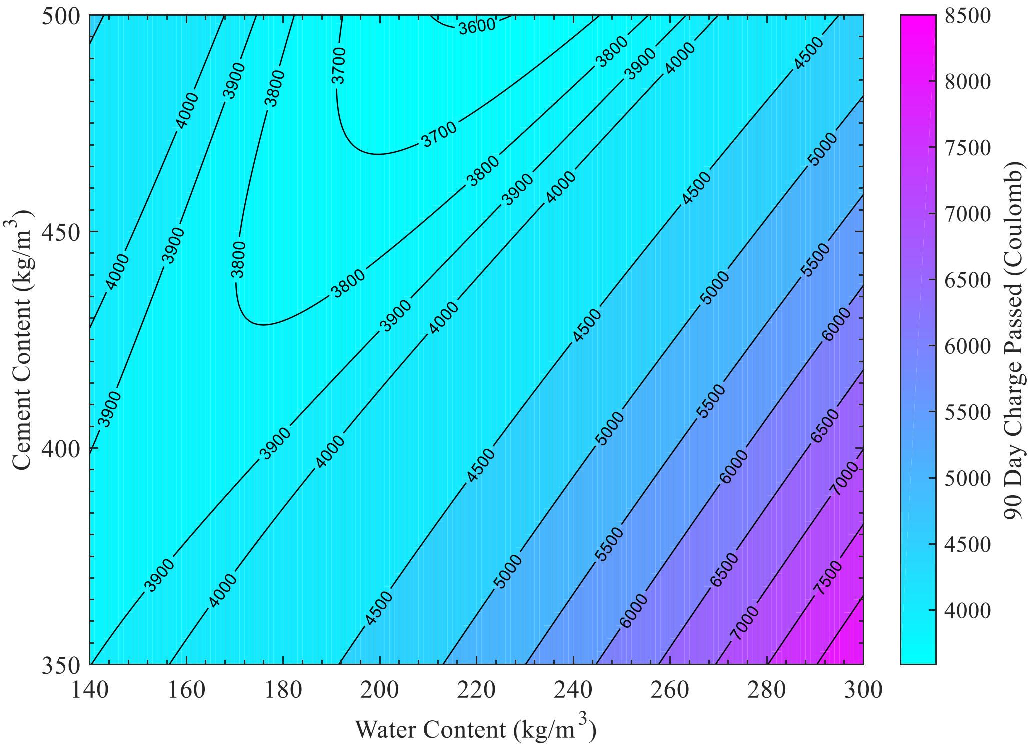


Figure 5.60: Variation of Charge Passed (RCPT) with Various Water and Cement Contents for Cement with No Slag Replacement and 5-10-14-18 Band Gradation

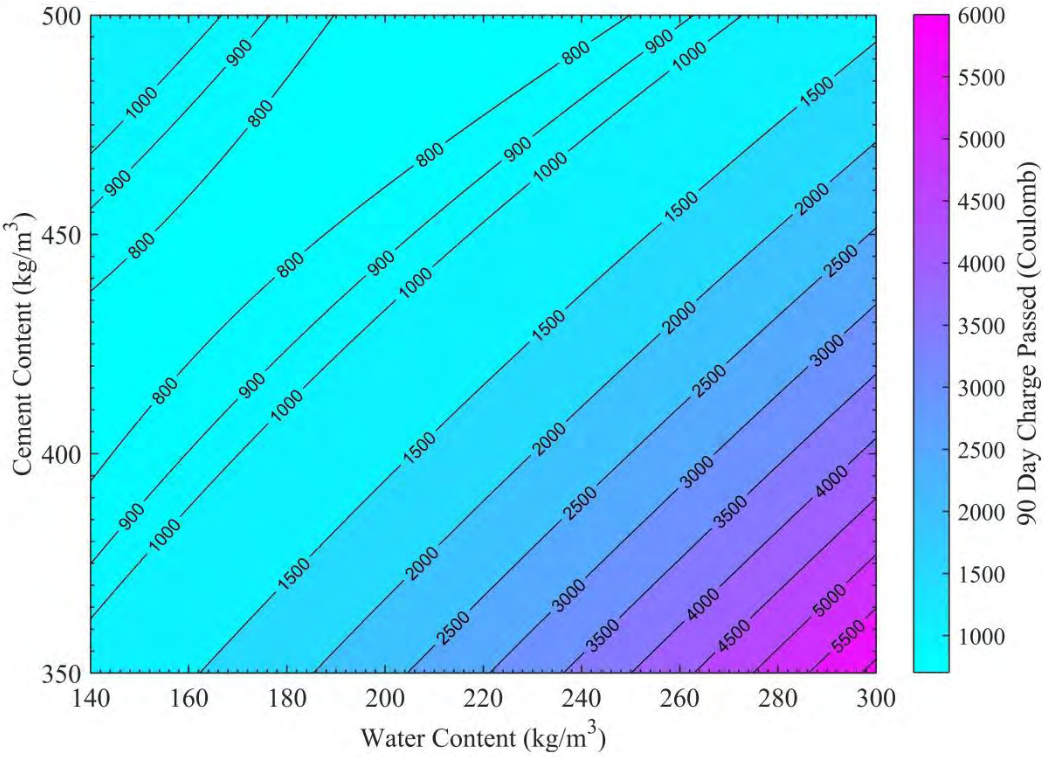


Figure 5.61: Variation of Charge Passed (RCPT) with Various Water and Cement Contents for Cement with 20% Slag Replacement and 5-10-14-18 Band Gradation

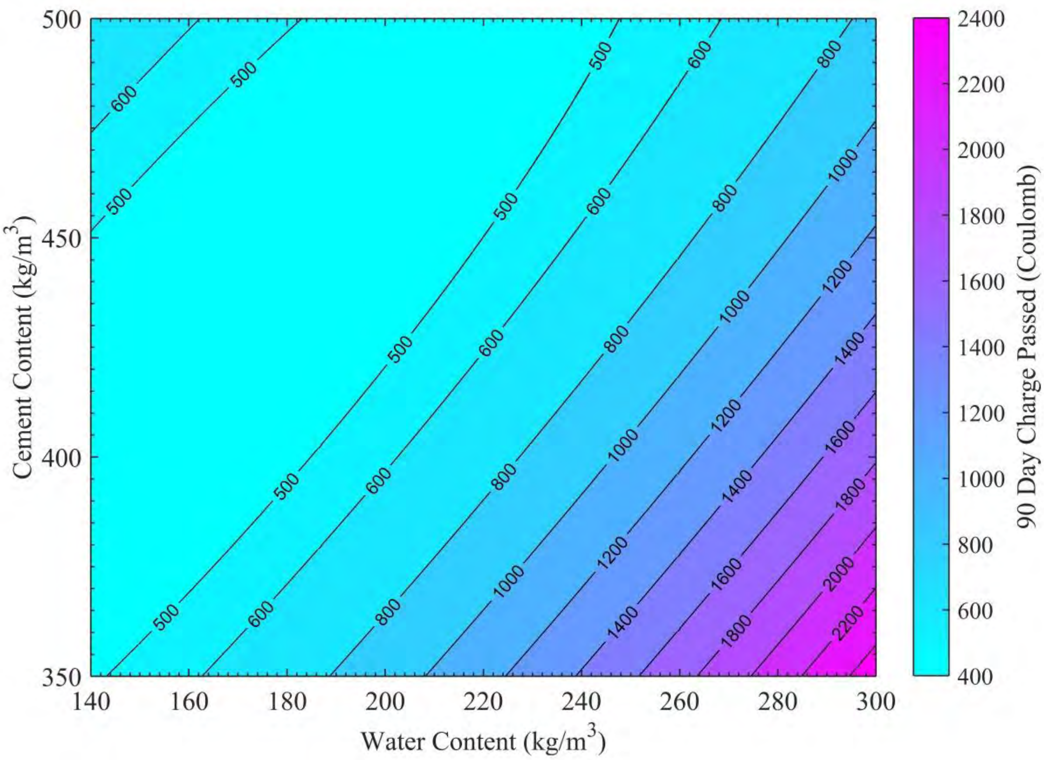


Figure 5.62: Variation of Charge Passed (RCPT) with Various Water and Cement Contents for Cement with 65% Slag Replacement and 5-10-14-18 Band Gradation

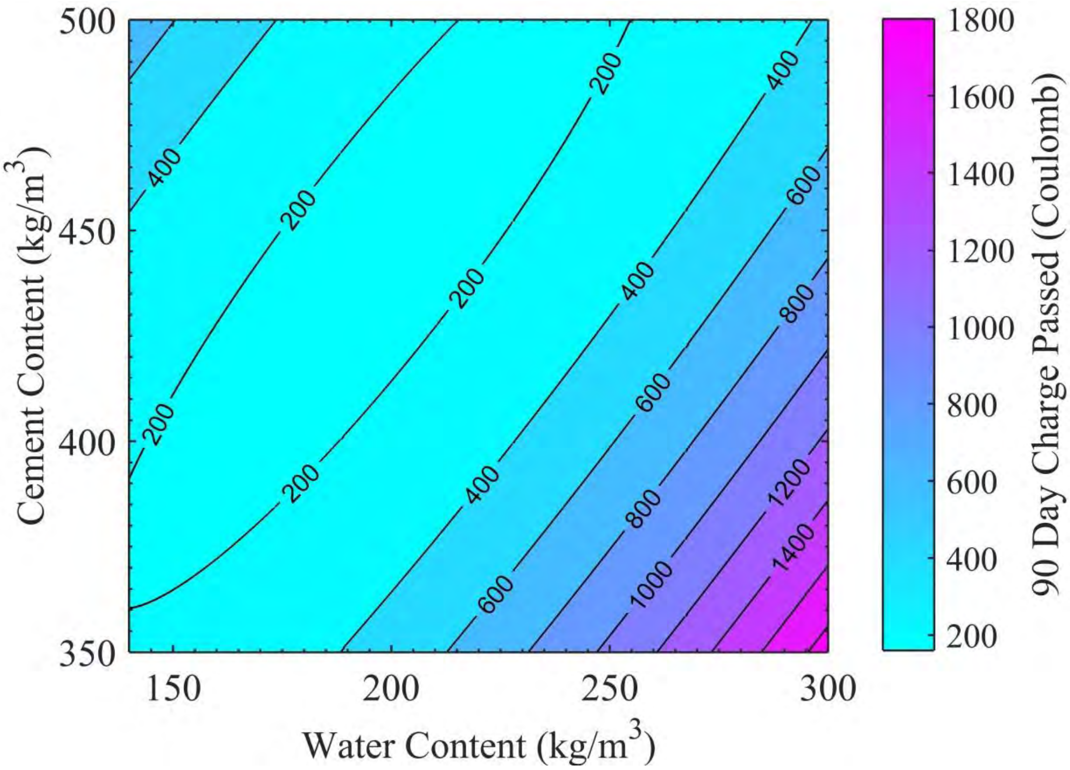


Figure 5.63: Variation of Charge Passed (RCPT) with Various Water and Cement Contents for Cement with 90% Slag Replacement and 5-10-14-18 Band Gradation

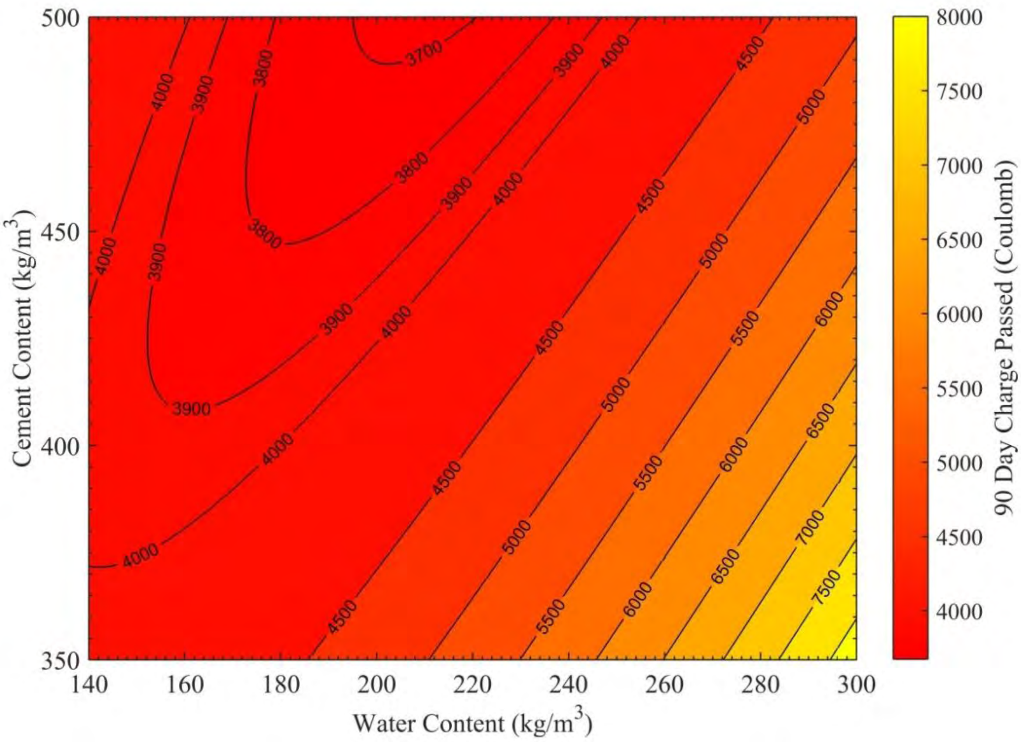


Figure 5.64: Variation of Charge Passed (RCPT) with Various Water and Cement Contents for Cement with No Slag Replacement and 5-10-18-22 Band Gradation

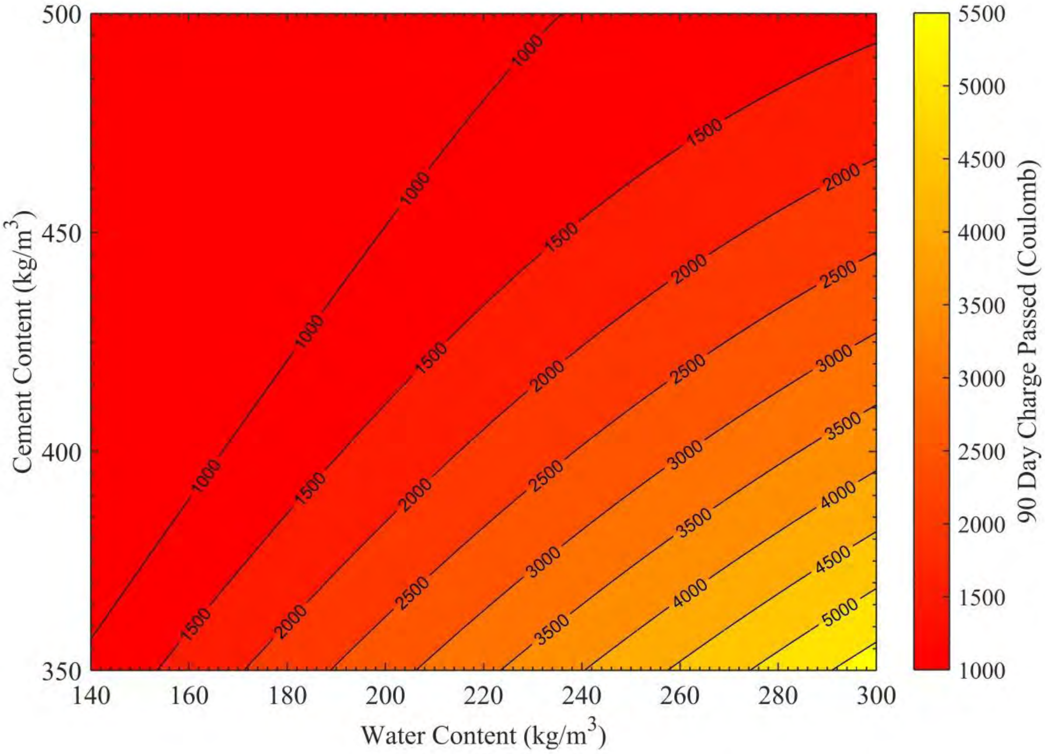


Figure 5.65: Variation of Charge Passed (RCPT) with Various Water and Cement Contents for Cement with 20% Slag Replacement and 5-10-18-22 Band Gradation

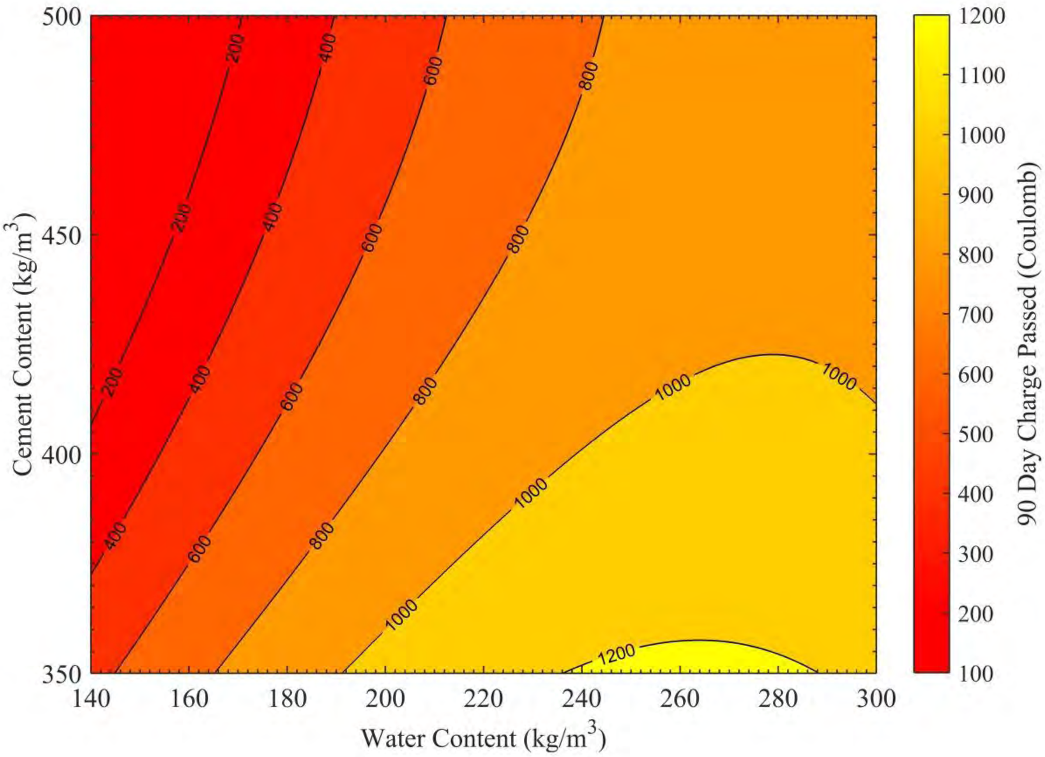


Figure 5.66: Variation of Charge Passed (RCPT) with Various Water and Cement Contents for Cement with 65% Replacement and 5-10-18-22 Band Gradation

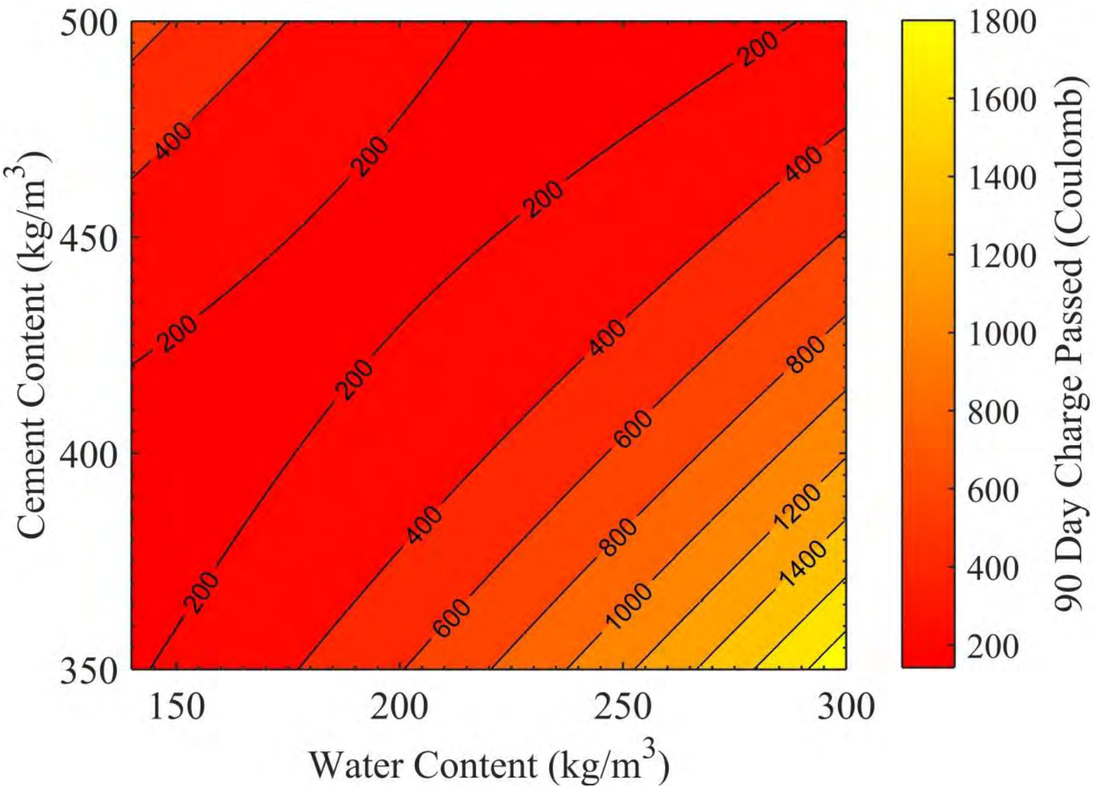


Figure 5.67: Variation of Charge Passed (RCPT) with Various Water and Cement Contents for Cement with 90% Replacement and 5-10-18-22 Band Gradation

Step 6: Calculation of Cement Content

After determining both w/c ratio and water content, required cement content can be calculated using following equation-

Cement Content (kg/m^3) = Water content (kg/m^3) / w/c ratio

Step 7: Calculation of Total Aggregate Content

Total aggregate content can be determined by absolute volume method. For unit volume of concrete, the portion fulfilled by cement and water is determined first. The rest of the volume must be occupied by the aggregates.

For unit volume of concrete, (*1m^3*),

- *Cement volume, m^3 = Cement Content (kg) / (sp. Gravity of cement x unit weight of water (kg/m^3)*
- *Water volume, m^3 = Water Content (kg) / unit weight of water (kg/m^3)*
- *Aggregate Volume, m^3= 1 - Cement volume, m^3 - Water volume, m^3*

Chapter 6

EXAMPLE AND VALIDATION OF PROPOSED MIX DESIGN

6.1 General

This chapter consists of two examples of the proposed concrete mix design explained in chapter 5. One example is shown using fly ash as supplementary cementing material and the other is shown using slag as SCM. Four mix designs have been carried out according to the proposed mix design method. They have been tested for workability, slump and durability. The test results are shown at the end of this chapter in order to validate the proposed mix design method with real experimental data set.

6.2 Proposed Concrete Mix Design Example using Fly Ash

Example - 1: Design the concrete mix whose target compressive strength at 28 days is 27.6 MPa (4000 psi), slump is 12 cm (4.72 inch) at the time of concrete mixing and has durability of moderate permeability range (total charge passed between 2000 to 4000 coulomb). Available Cement type is CEM I, supplementary cementing material is fly ash and aggregate is locally available.

Solution:

<u>Step 1:</u> Determination of Target Strength and Workability

Since the target 28 days compressive strength and required slump at the time of concrete mixing have been given, it is not needed to consider standard deviation and workability loss.

<u>Step 2:</u> Determination of required Durability

As the required permeability class has already been mentioned here, mix design can be continued using that permeability range.

<u>Step-3</u> Incorporation of Fly Ash in Concrete Mix

If 5-10-14-18 band gradation is used along with fly ash as SCM, then from figure 6.1, fly ash replacement is found to be 20%. And if 5-10-18-22 band gradation is used along with fly ash as SCM, then from figure 6.2, fly ash replacement is also found to be 20%.

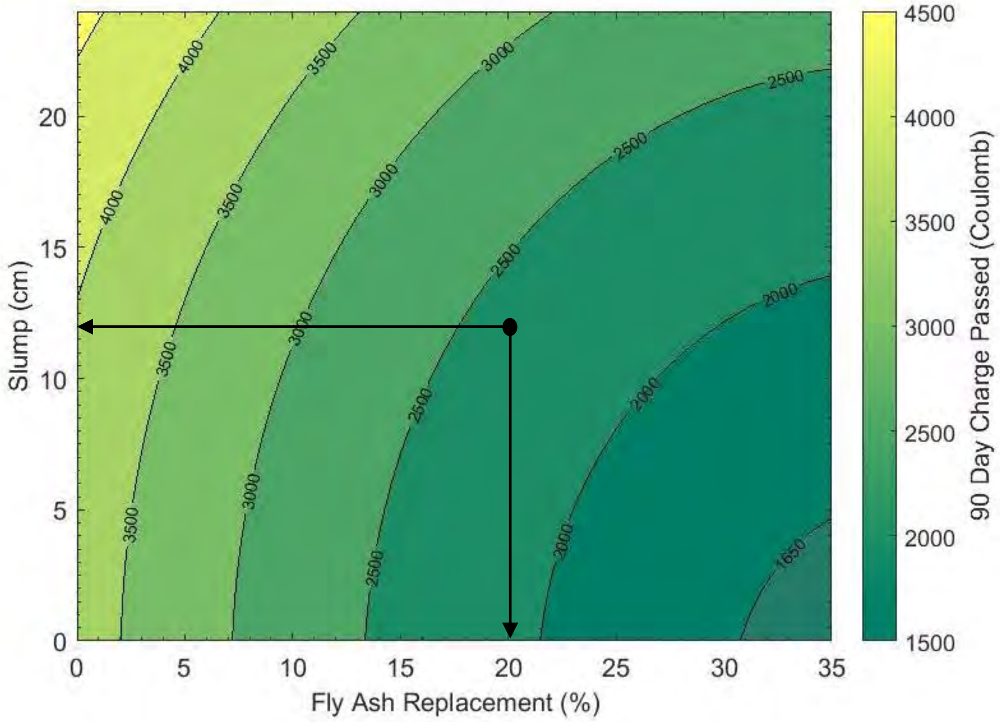


Figure 6.1: Variation of Permeability Classes with Slump and Fly Ash Replacement Percentages for Aggregate Band 5-10-14-18 (Example)

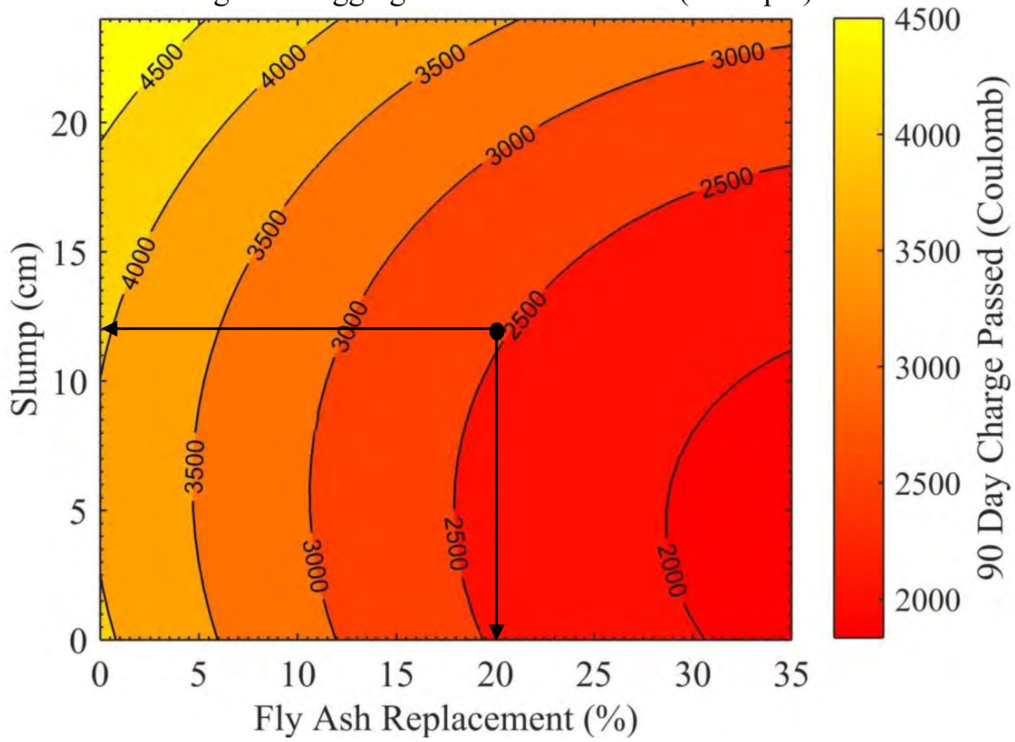


Figure 6.2: Variation of Permeability Classes with Slump and Fly Ash Replacement Percentages for Aggregate Band 5-10-18-22 (Example)

<u>Step 4</u> Determination of Cement Content and Gradation Band from Workability and Strength Requirements

For 5-10-14-18 Band

Since 20 % fly ash replacement is required, Figure 6.3 needs to be used for determining the required water and cement contents. For required 28 day compressive strength of 27.6 MPa (4000 psi) and 12 cm slump, let the point A be selected on Figure 6.3.

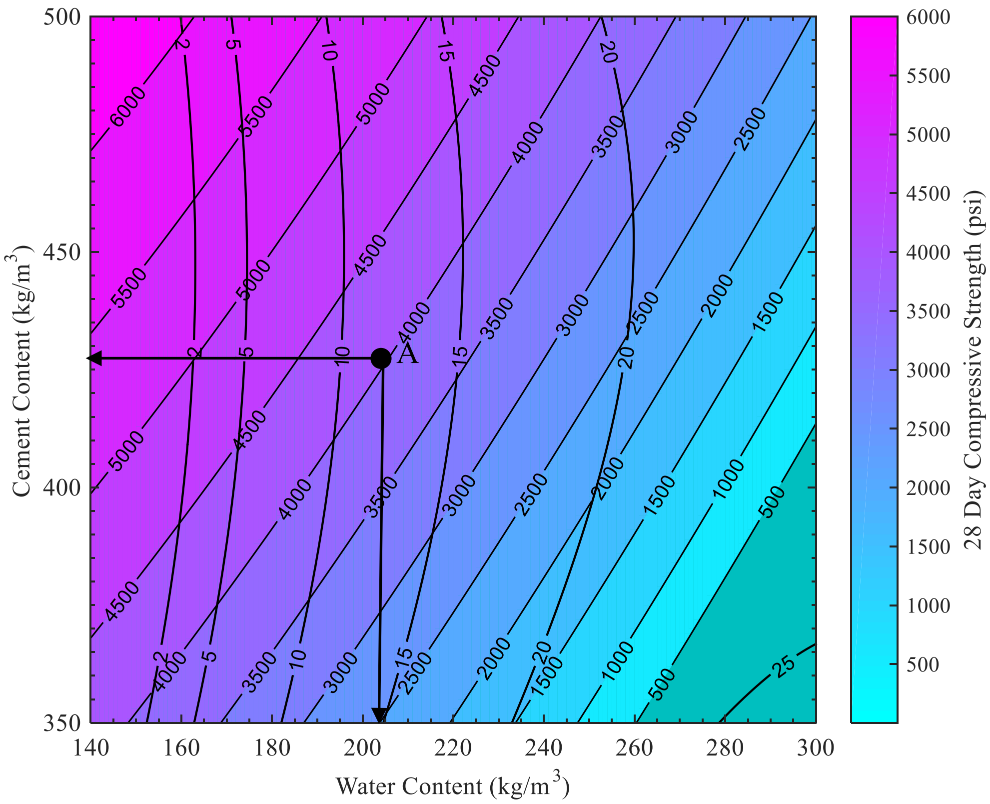


Figure 6.3: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with 20% Fly Ash Replacement and 5-10-14-18 Band Gradation (Example)

Thus from preliminary selection,

Band gradation 5-10-14-18 gives,

Water content = 204 kg/m^3

Cement Content = 427 kg/m^3

w/c ratio = 0.47

For 5-10-18-22 Band

Since 20% fly ash replacement is required, Figure 6.4 needs to be used for determining the required water and cement contents. For required 28 day compressive strength of 27.6 MPa (4000 psi) and 12 cm slump, let the point B be selected on Figure 6.4.

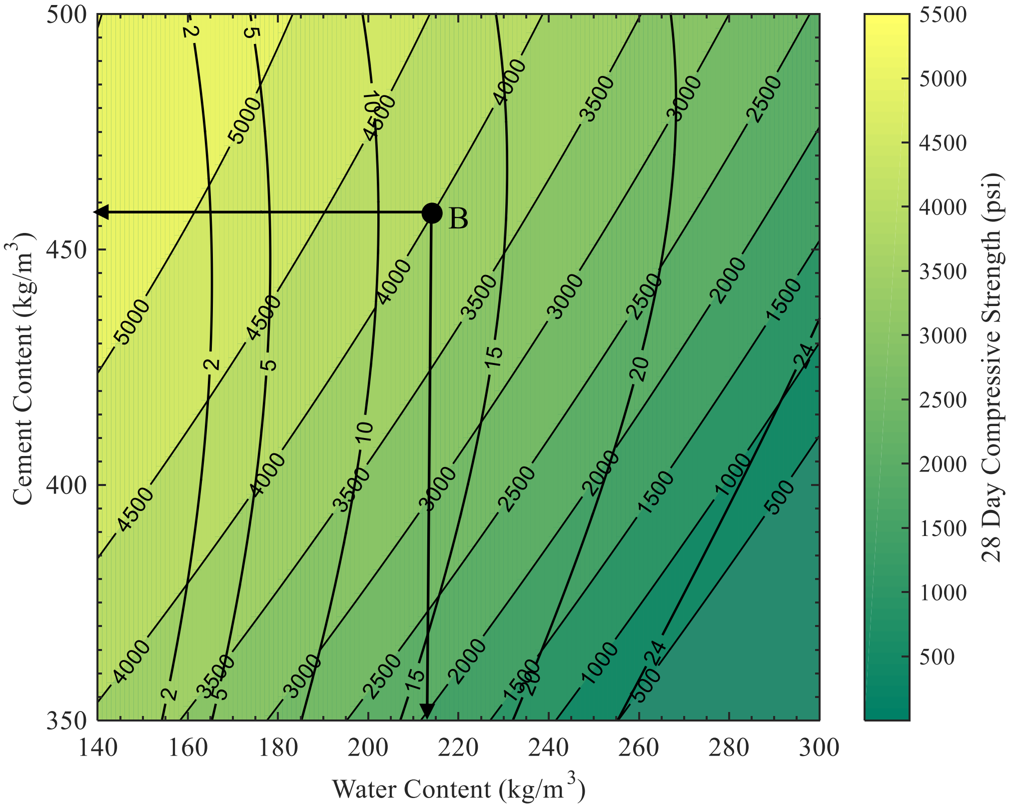


Figure 6.4: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with 20% Fly Ash Replacement and 5-10-18-22 Band Gradation (Example)

Thus from preliminary selection,

Band gradation 5-10-18-22 gives,

Water content = 213 kg/m^3

Cement Content = 458 kg/m^3

w/c ratio = 0.465

Though the water cement ratio for aggregate gradation band 5-10-18-22 is slightly less than that for 5-10-14-18, cement content required for the latter one is much higher than that for the former. Hence, gradation band 5-10-14-18 is chosen.

Step 5: Modification of Water Content considering Durability Parameter

The cement content and water content chosen from step 4 are 427 kg/m^3 and 204 kg/m^3 respectively (5-10-14-18 band gradation). As the fly ash replacement level is 20%, so durability is checked using Figure 6.5

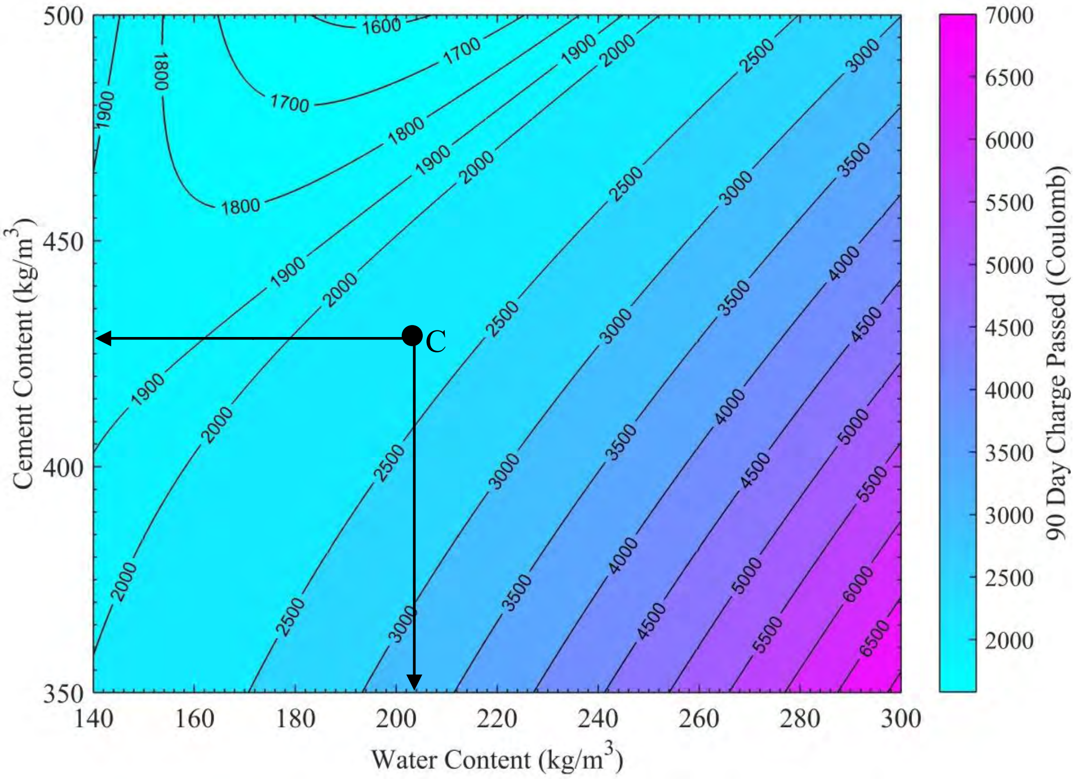


Figure 6.5: Variation of Charge passed (RCPT) with Various Water and Cement Contents for Cement with 20% Fly Ash Replacement and 5-10-14-18 Band Gradation (Example)

From the cement content and water content selected in the previous step, point C on Figure 6.5 shows that permeability is 2350 coulomb which is in moderate permeability range. **So no modification in cement and water content is required considering durability parameter.**

Step 6: Calculation of Cement Content

As no medication of cement and water content was required in step 5, so cement content is 427 kg/m^3.

<u>Step 7:</u> Calculation of Total Aggregate Content

Knowing the cement content and water content, aggregate content is determined by absolute volume method.

For unit volume of concrete, (*1m*^{3}),

- *Cement volume, m*^{3} *= Cement Content (kg) / (sp. Gravity of cement X unit weight of water (kg/m*^{3}*) = 427/(3.15*1000) = 0.136 m*^{3}
- *Water volume, m*^{3} *= Water Content (kg) / unit weight of water (kg/m*^{3}*) = 204/1000 = 0.204 m*^{3}
- *Aggregate Volume, m*^{3}*= 1 - Cement volume, m*^{3} *- Water volume, m = 1-0.136-0.204 = 0.66 m*^{3}

6.3 Proposed Concrete Mix Design Example using Blast Furnace Slag

In this section, the example given in the previous section is continued using slag as supplementary cementing material.

Example - 2: Design the concrete mix whose target compressive strength at 28 days is 27.6 MPa (4000 psi), slump is between 11 cm to 16 cm (4.40 inch to 6.40 inch) at the time of concrete mixing and has durability of moderate permeability range (total charge passed between 2000 to 4000 coulomb). Available Cement type is CEM I, supplementary cementing material is blast furnace slag and aggregate is locally available.

Solution:

<u>Step 1:</u> Determination of Target Strength and Workability

Since the target 28 days compressive strength and required slump at the time of concrete mixing have been given, it is not needed to consider standard deviation and workability loss.

<u>Step 2:</u> Determination of required Durability

As the required permeability class has already been mentioned here, mix design can be continued using that permeability range.

<u>Step-3</u> Incorporation of Slag in Concrete Mix

If 5-10-14-18 band gradation is used along with slag as SCM, then from figure 6.6, slag replacement is found to be 10%. And if 5-10-18-22 band gradation is used along with slag as SCM, then from Figure 6.7, slag replacement is also found to be 10%.

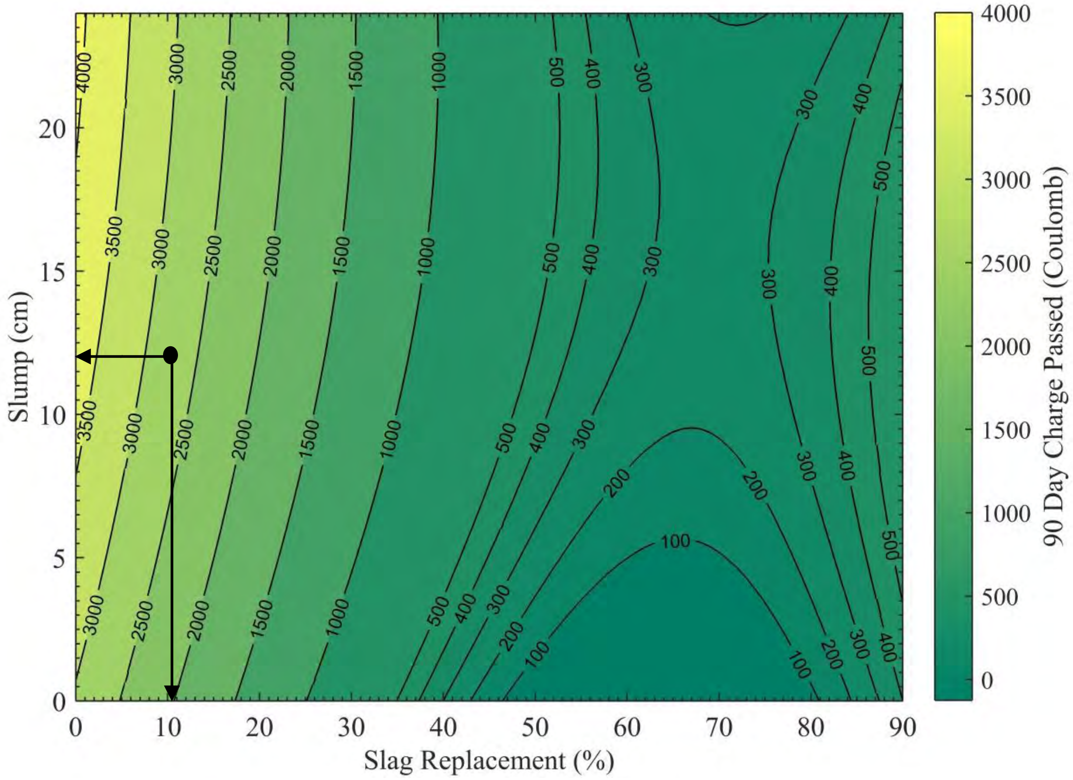


Figure 6.6: Variation of Permeability Classes with Slump and Slag Replacement Percentages for Aggregate Band 5-10-14-18 (Example)

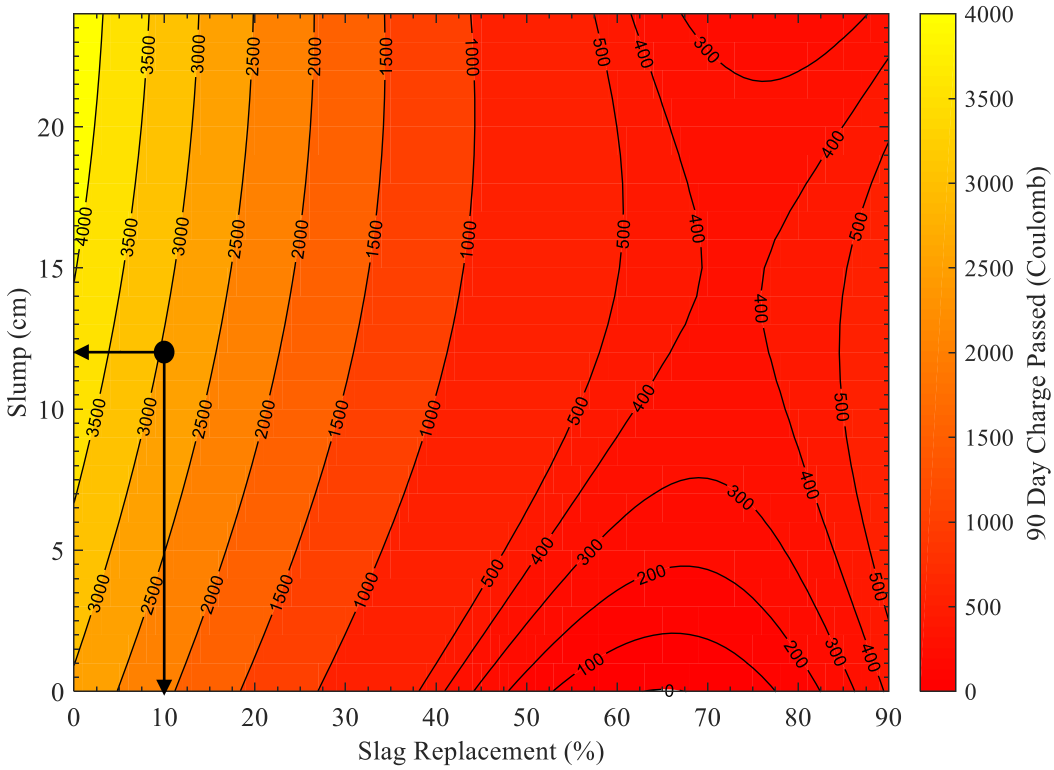


Figure 6.7: Variation of Permeability Classes with Slump and Slag Replacement Percentages for Aggregate Band 5-10-18-22 (Example)

<u>Step 4</u> Determination of Cement Content and Gradation Band from Workability and Strength Requirements

For 5-10-14-18 Band

Since 10% slag replacement is required, required cement content is calculated by interpolating graphs of 0% slag replacement and 20% slag replacement.

From Figure 6.8, for 0% slag replacement, band gradation 5-10-14-18 gives (point A),

Water content = 189 kg/m3

Cement Content = 376 kg/m3

From Figure 6.9, for 20 % slag replacement, band gradation 5-10-14-18 gives (point B),

Water content = 210 kg/m3

Cement Content = 367 kg/m3

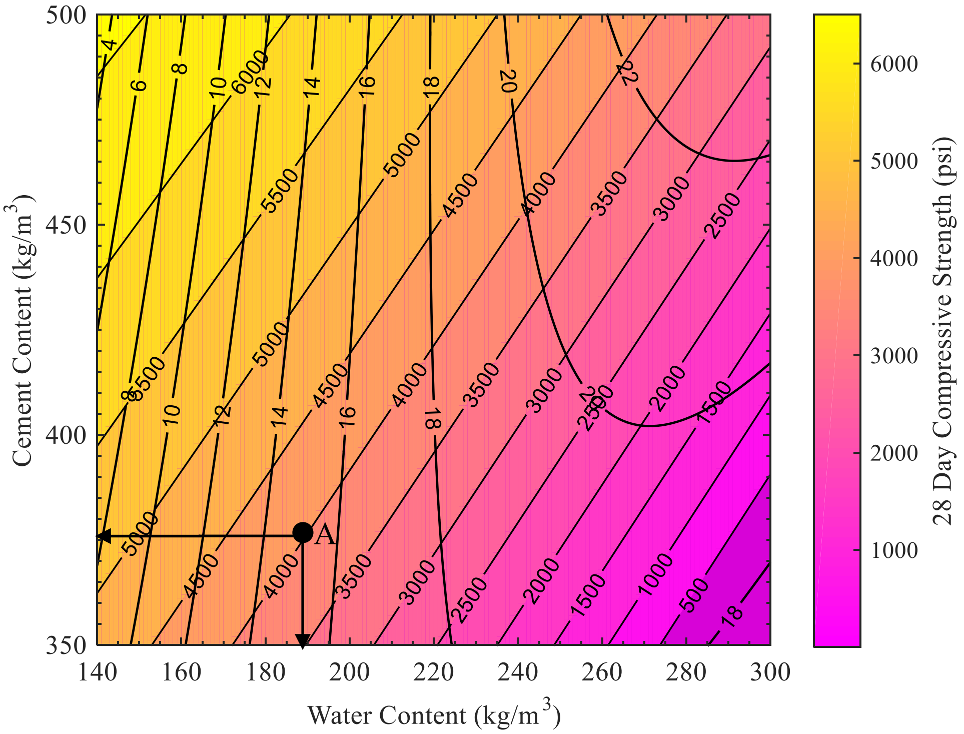


Figure 6.8: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with No Slag Replacement and 5-10-14-18 Band Gradation (Example)

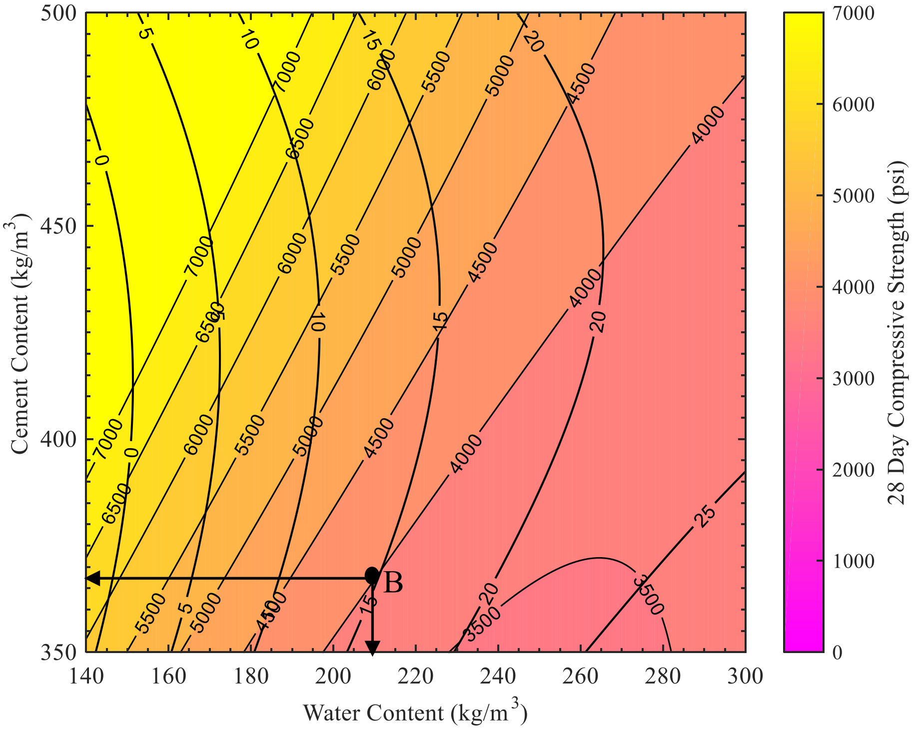


Figure 6.9: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with 20% Slag Replacement and 5-10-14-18 Band Gradation (Example)

So by interpolating, **for 10% slag replacement**,

Water content = 199.5 kg/m^3

Cement Content = 371.5 kg/m^3

w/c = 0.54

For 5-10-18-22 Band

Since 10% slag replacement is required, required cement content is calculated by interpolating graphs of 0% slag replacement and 20% slag replacement.

From Figure 6.10, for 0% slag replacement, band gradation 5-10-18-22 gives (point C),
Water content = 196 kg/m3
Cement Content = 420 kg/m3

From Figure 6.11, for 20% slag replacement, band gradation 5-10-18-22 gives (point D),
Water content = 232 kg/m3
Cement Content = 431 kg/m3

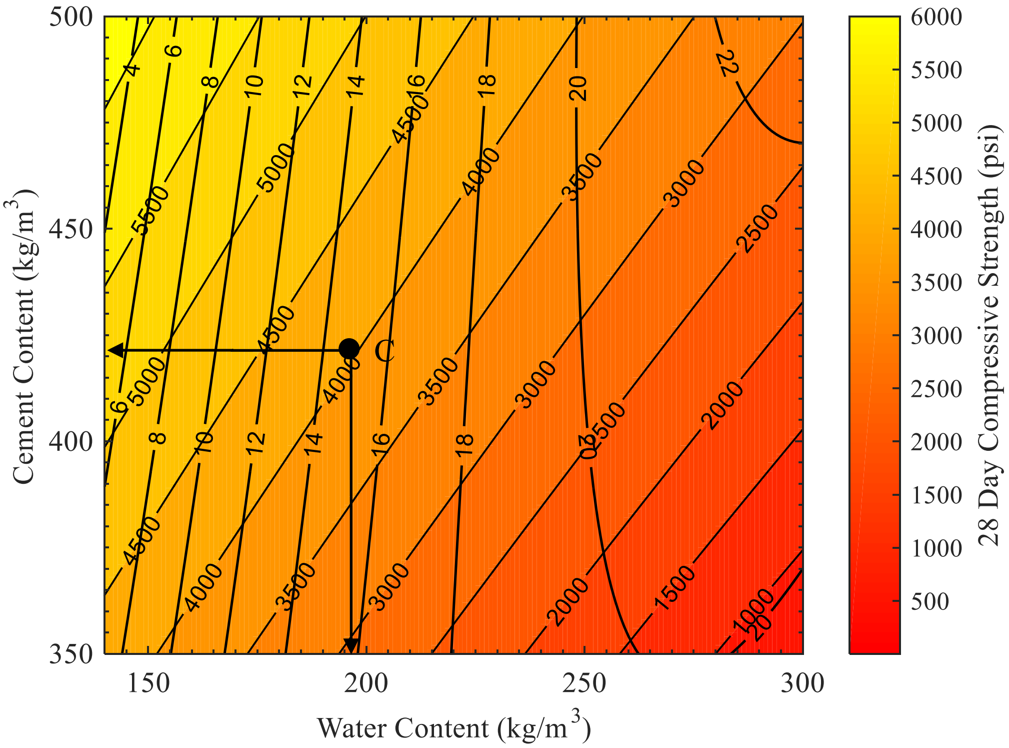


Figure 6.10: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with No Slag Replacement and 5-10-18-22 Band Gradation (Example)

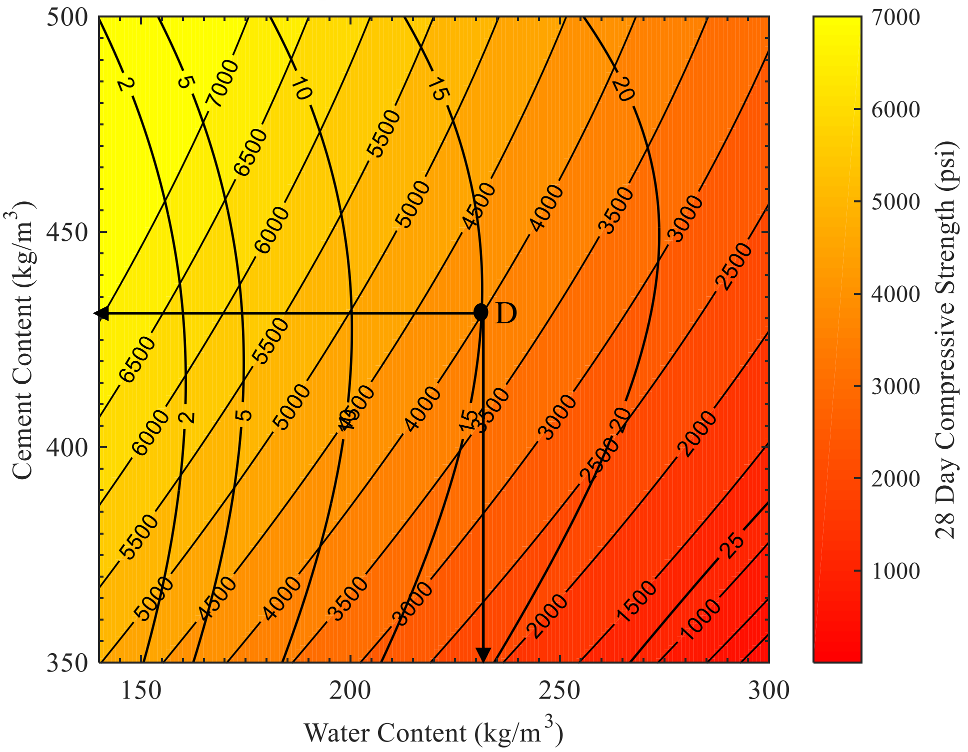


Figure 6.11: 28 Days Compressive Strength and Slump Variations with Various Mix Proportions for Cement with 20% Slag Replacement and 5-10-18-22 Band Gradation (Example)

So by interpolating, **for 10% slag replacement**,

Water content = 214 kg/m^3

Cement Content = 425.5 kg/m^3

w/c = 0.50

Though the water cement ratio for aggregate gradation band 5-10-18-22 is less than that for 5-10-14-18, cement content required for the latter one is much higher than that for the former. Hence, gradation band 5-10-14-18 is chosen.

<u>Step 5:</u> Modification of Water Content considering Durability Parameter

The cement content and water content chosen from step 4 are 371.5 kg/m^3 and 199.5 kg/m^3 respectively (5-10-14-18 band gradation). As the slag replacement level is 10%, so durability is checked by interpolating contours of 0% replacement and 20% replacement.

From Figure 6.12, point E gives charge passed value of 4400 coulomb and from Figure 6.13, point F gives charge passed value of 1850 coulomb.

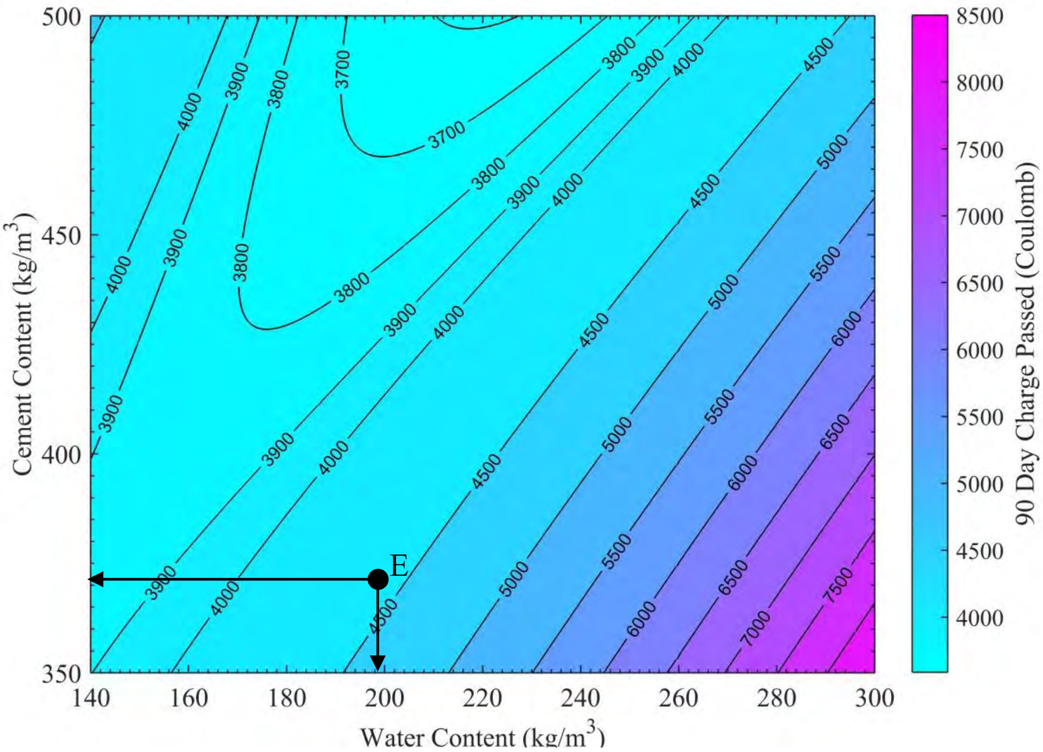


Figure 6.12: Variation of Charge passed (RCPT) with Various Water and Cement Contents for Cement with No Slag Replacement and 5-10-14-18 Band Gradation (Example)

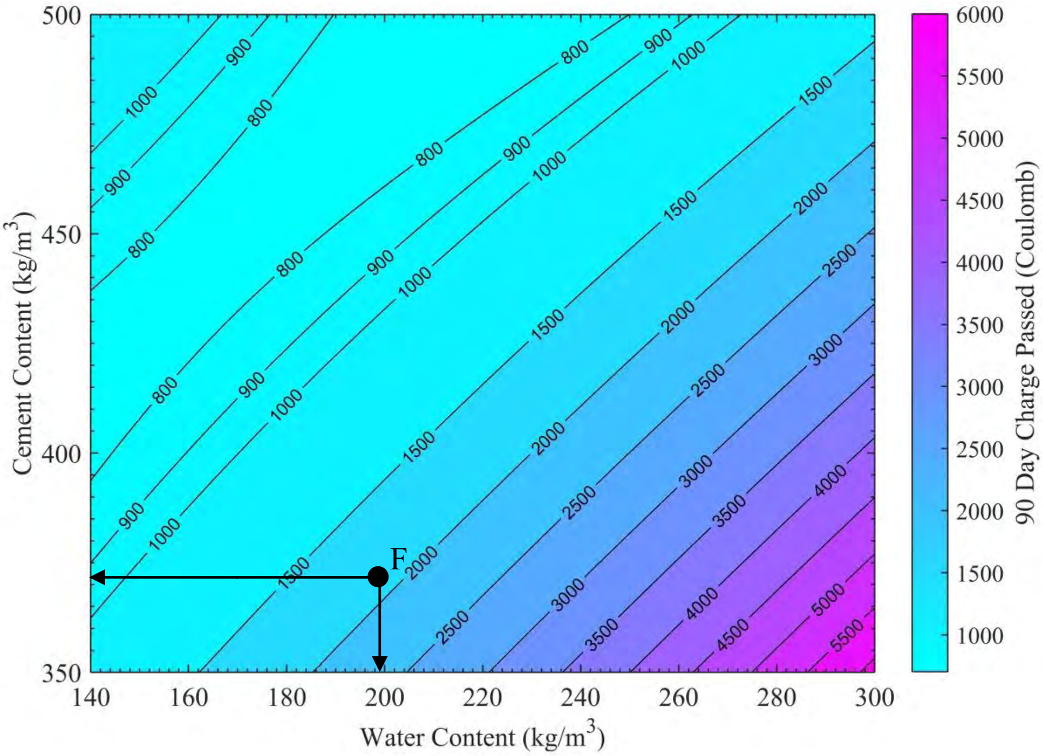


Figure 6.13: Variation of Charge passed (RCPT) with Various Water and Cement Contents for Cement with 20% Slag Replacement and 5-10-14-18 Band Gradation (Example)

So from interpolation, permeability is found to be 3125 coulomb which is in moderate permeability range. **So no modification in cement and water content is required considering durability parameter.**

<u>Step 6:</u> Calculation of Cement Content

As no medication of cement and water content was required in step 5, so cement content is 371.5 kg/m^3.

<u>Step 7:</u> Calculation of Total Aggregate Content

Knowing the cement content and water content, aggregate content is determined by absolute volume method.

For unit volume of concrete, (*1m^3*),

- *Cement volume, m^3 = Cement Content (kg) / (sp. Gravity of cement X unit weight of water (kg/m^3) = 371.5/(3.15*1000) = 0.118 m^3*
- *Water volume, m^3 = Water Content (kg) / unit weight of water (kg/m^3) = 199.5/1000 = 0.1995 m^3*
- *Aggregate Volume, m^3= 1 - Cement volume, m^3 - Water volume, m = 1-0.118-0.1995 = 0.683 m^3*

6.4 Verification of the Proposed Mix Design Method using Laboratory Experiments

Four concrete mixes have been prepared in the laboratory to validate the proposed concrete mix design method. Two mixes have been prepared using fly ash as supplementary cementing material and using 5-10-14-18 and 5-10-18-22 band gradations respectively. Rest of the two mixes have been prepared using slag as supplementary cementing material and using 5-10-14-18 and 5-10-18-22 band gradations respectively.

Table 6.1 shows the target 28 days compressive strength, durability class and slump for these mixes and the mix proportions determined using proposed concrete mix design method.

Table 6.1: Proportions for Laboratory Mix Determined from Proposed Mix Design Method

Mix ID	Target 28 Days Strength (psi)	Target Permeability Class	Target Slump (cm)	SCM Type (%)	SCM Replacement (%)	Gradation Band	Cement Content (kg/m^3)	Water Content (kg/m^3)	w/c Ratio
L-1	5000	Low	4-6	Fly Ash	35	5-10-14-18	470	191	0.41
L-2	4500	Moderate	9-11	Fly Ash	20	5-10-18-22	476	199	0.42
L-3	5500	Very Low	6-8	Slag	42.5	5-10-14-18	424.5	187.5	0.44
L-4	3000	Very Low	11-13	Slag	90 (Green Cement)	5-10-18-22	450	224	0.50

Table 6.2 shows the results of the trial mixes.

Table 6.2: Test Results for Trial Mixes

Mix ID	Slump		Compressive Strength		Durability		
	Target (cm)	Result (cm)	Target (psi)	Result (psi)	Target Permeability Class	Charge Passed (coulomb)	Resulted Permeability Class
L-1	4-6	5	5000	5030	Low	1430	Low
L-2	9-11	11	4500	4550	Moderate	2165	Moderate
L-3	6-8	5	5500	5510	Very Low	432	Very Low
L-4	11-13	9	3000	3160	Very Low	216	Very Low

Table 6.2 shows that the resulted compressive strength for all four mixes are higher than their corresponding target strength. In case of slump, the two mixes prepared using fly ash provided slump values within the target slump. On the other hand, the two mixes prepared with blast furnace slag resulted in slightly lower slump value than the target slump. From Table 6.2, it is also evident that, for all the four trial mixes, the resulted permeability class is same as the target permeability class.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 General

This chapter summarizes the important findings in this research work. This chapter also includes some scopes of further research work for investigating different parameters that affect concrete properties and aggregate gradations. The main objective of this research was to propose a mix design method incorporating durability as a design parameter, fly ash and blast furnace slag as supplementary cementing materials and locally available band graded aggregates as coarse and fine aggregates. The two band gradations used were 5-10-14-18 and 5-10-18-22.

7.2 Conclusions

(i) Contour plots were developed in this research to establish correlations between different parameters i.e. strength, slump, durability, SCM percentage etc. Four parameters can be represented simultaneously in one plot which makes the mix design steps easy and convenient.

(ii) Fly ash and slag were used in the proposed mix design process and it was observed that these two supplementary materials improve concrete durability due to their pozzolanic properties. A designer can use this mix design approach to improve durability of the mix as well as to reduce the cost and detrimental effects of cement production.

(iii) The proposed concrete mix design used combined aggregate band gradations, 5-10-14-18 and 5-10-18-22 that can achieve high durability (90 day RCPT value was as low as 216 coulomb) and compressive strength (28 day compressive strength was achieved up to 6740 psi).

(iv) 5-10-14-18 band resulted in slightly better durability and higher compressive strength than 5-10-18-22 band. This was due to the fact that 5-10-14-18 aggregate band had higher percentage of finer particles that ensured denser packing.

(v) Green cement consisting of 90% slag resulted in the lowest permeability values (216 coulomb) and hence the highest durability. But the compressive strength performance of green cement was not satisfactory.

7.2 Recommendations for Future Work

(i) Further lab mixes can be prepared to compare the proposed concrete mix design method with other conventional methods.

(ii) The research work can be reproduced using different nominal maximum size of aggregates (i.e. 37.5 mm or 40 mm) and using different types of admixtures.

(iii) Further studies can be carried out to improve the compressive strength property of green cement.

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APPENDIX-A

Table A.1: Concrete Test Results for Mixes Prepared with Fly Ash and Water Cement Ratio 0.4

Cement Content kg/m^3	**Water Content kg/m^3**	**Aggregate Band Gradation**	**Fly Ash Replacement (%)**	**Slump (cm)**	**28 Day Strength (psi)**	**28 Day Charge Passed (coulomb)**	**90 Day Charge Passed (coulomb)**
350	140	5-10-14-18	0	7.62	4680	7388	3902.5
			20	0	4020	4981.5	1917
			35	0	3790	2617.25	1548
		5-10-18-22	0	6.23	4220	7416.5	4127.9
			20	0	3820	5011	2327
			35	0	3540	2686	1856.5
425	170	5-10-14-18	0	12.36	5370	6581.25	3888.4
			20	1.8	4940	4702.5	1899.3
			35	1.5	4610	2602.5	1476
		5-10-18-22	0	11.23	4810	6621.5	3932.7
			20	1	4610	4780	2299.5
			35	0.5	4070	2670.5	1732
500	200	5-10-14-18	0	15.27	5750	6457	3579.5
			20	12.4	5310	4095	1678
			35	10.25	4880	2430	648
		5-10-18-22	0	14.29	4930	6487.5	3609
			20	10.8	4700	4646.5	2023.5
			35	9	4230	2515.25	864

Table A.2: Concrete Test Results for Mixes Prepared with Fly Ash and Water Cement Ratio 0.5

Cement Content kg/m^3	Water Content kg/m^3	Aggregate Band Gradation	Fly Ash Replacement (%)	Slump (cm)	28 Day Strength (psi)	28 Day Charge Passed (coulomb)	90 Day Charge Passed (coulomb)
350	175	5-10-14-18	0	15.55	4130	7747	4131
			20	6.25	3520	5142	2754
			35	4.25	3150	2714	2343
		5-10-18-22	0	14.81	3470	7810.5	4189.5
			20	5	3180	5187.25	2837.5
			35	4	2970	2742	2498
425	212.5	5-10-14-18	0	16.51	4200	7674.5	3993.6
			20	15.25	3770	5089	2654
			35	13	3340	2674	2290.5
		5-10-18-22	0	16.33	3680	7712	4072.5
			20	14	3470	5141	2701
			35	12.185	3170	2702	2443.5
500	250	5-10-14-18	0	20.955	4580	7398	3809.8
			20	19.4	3990	4988	1742
			35	17	3670	2644	1315
		5-10-18-22	0	19.69	4020	7478	4060.5
			20	18	3740	5021.25	2139
			35	15.5	3500	2712	1451.5

Table A.3: Concrete Test Results for Mixes Prepared with Fly Ash and Water Cement Ratio 0.6

Cement Content kg/m^3	Water Content kg/m^3	Aggregate Band Gradation	Fly Ash Replacement (%)	Slump (cm)	28 Day Strength (psi)	28 Day Charge Passed (coulomb)	90 Day Charge Passed (coulomb)
350	210	5-10-14-18	0	16.51	2790	7898	4995
350	210	5-10-14-18	20	16.25	2280	5744.5	3397.5
350	210	5-10-14-18	35	14.875	2090	3318	2801.5
350	210	5-10-18-22	0	16.51	2670	8145.25	5089.5
350	210	5-10-18-22	20	16	2050	5985	3663
350	210	5-10-18-22	35	13.85	1710	3519	2843
425	255	5-10-14-18	0	20.35	2300	7805	4806
425	255	5-10-14-18	20	20.2	2350	5547.5	3282
425	255	5-10-14-18	35	18.8	2180	3278	2635
425	255	5-10-18-22	0	20.32	2740	7868.5	4921.5
425	255	5-10-18-22	20	19.875	2310	5643	3372.5
425	255	5-10-18-22	35	17.95	2130	3410.5	2715
500	300	5-10-14-18	0	23.55	3210	7790.25	4609
500	300	5-10-14-18	20	22.75	2550	5389	3123
500	300	5-10-14-18	35	20.9	2310	3121	2478
500	300	5-10-18-22	0	22.86	3050	7825	4889.3
500	300	5-10-18-22	20	22.25	2480	5601	3204
500	300	5-10-18-22	35	18.75	2350	3388	2556

APPENDIX-B

Table B.1: Concrete Test Results for Mixes Prepared with Slag and Water Cement Ratio 0.4

Cement Content kg/m^3	Water Content kg/m^3	Aggregate Band Gradation	Slag Replacement (%)	Slump (cm)	28 Day Strength (psi)	28 Day Charge Passed (coulomb)	90 Day Charge Passed (coulomb)
350	140	5-10-14-18	0	7.62	4680	7380.9	3902.5
			20	1.25	5970	2380	1101
			65	1	5800	1017	487
			90	0	3190	432	216
		5-10-18-22	0	6.23	4220	7416.5	4127.9
			20	1	5080	2445	1116
			65	0	4810	1048.25	543.5
			90	0	3140	445	216
425	170	5-10-14-18	0	12.36	5370	6581.25	3888.4
			20	2.2	6410	1867	976
			65	1.5	6220	684	432
			90	0.5	3520	387	216
		5-10-18-22	0	11.23	4810	6621.5	3932.7
			20	2	5950	1917	990
			65	1	4820	705	495
			90	0.5	3500	405	216
500	200	5-10-14-18	0	15.27	5750	6457	3579.5
			20	14.75	6740	1485	648
			65	13.5	6620	432	432
			90	11.85	4520	216	216
		5-10-18-22	0	14.29	4930	6487.5	3609
			20	13.75	6060	1665	665
			65	12.8	4880	648	461
			90	10.5	3590	216	216

Table B.2: Concrete Test Results for Mixes Prepared with Slag and Water Cement Ratio 0.5

Cement Content kg/m^3	Water content kg/m^3	Aggregate Band Gradation	Slag replacement (%)	Slump (cm)	28 Day Strength (psi)	28 Day Charge Passed (coulomb)	90 Day Charge Passed (coulomb)
350	175	5-10-14-18	0	15.55	4130	7747	4131
350	175	5-10-14-18	20	6.875	4460	3730.5	1563.5
350	175	5-10-14-18	65	5.625	4360	1687.5	648
350	175	5-10-14-18	90	5	2590	535	261
350	175	5-10-18-22	0	14.81	3470	7810.5	4189.5
350	175	5-10-18-22	20	6.25	3560	3765.5	1768.5
350	175	5-10-18-22	65	5	3410	1738	819
350	175	5-10-18-22	90	3.5	2530	645	287
425	212.5	5-10-14-18	0	16.51	4200	7674.5	3993.6
425	212.5	5-10-14-18	20	14	4940	2767.5	1345
425	212.5	5-10-14-18	65	13.25	4370	1444.5	549
425	212.5	5-10-14-18	90	12.3	3190	458	216
425	212.5	5-10-18-22	0	16.33	3680	7712	4072.5
425	212.5	5-10-18-22	20	13.25	4550	2794.5	1683
425	212.5	5-10-18-22	65	12.5	3820	1539	801
425	212.5	5-10-18-22	90	10.75	3020	480	216
500	250	5-10-14-18	0	20.955	4580	7398	3809.8
500	250	5-10-14-18	20	20.6	4930	2549	819
500	250	5-10-14-18	65	20	4460	1059	523
500	250	5-10-14-18	90	17.5	3210	216	216
500	250	5-10-18-22	0	19.69	4020	7478	4060.5
500	250	5-10-18-22	20	19.5	4630	2646	1116
500	250	5-10-18-22	65	19.15	3990	1121	845
500	250	5-10-18-22	90	16.75	3000	216	216

Table B.3: Concrete Test Results for Mixes Prepared with Slag and Water Cement Ratio 0.6

Cement Content kg/m^3	Water content kg/m^3	Aggregate Band Gradation	Slag replacement (%)	Slump (cm)	28 Day Strength (psi)	28 Day Charge Passed (coulomb)	90 Day Charge Passed (coulomb)
350	210	5-10-14-18	0	16.51	2790	7898	4995
			20	16.2	3840	5484	2878.5
			65	15	2810	1897	1055
			90	13.75	2160	1097	632
		5-10-18-22	0	16.51	2670	8145.25	5089.5
			20	15.5	3000	5796	3456.5
			65	14.75	2340	1945	1170
			90	13	1580	1116	754
425	255	5-10-14-18	0	20.35	3000	7805	4806
			20	20.2	3890	5139	1774
			65	20	2900	1728	864
			90	19.5	2200	901	418.5
		5-10-18-22	0	20.32	2740	7868.5	4921.5
			20	19.2	3010	5210	1863
			65	18.75	2680	1874	905
			90	18	1590	1057	464
500	300	5-10-14-18	0	23.55	3212	7790.25	4609
			20	23.25	4080	4768.25	1455
			65	23	3060	1708.5	846
			90	22.25	2230	846	432
		5-10-18-22	0	22.86	3050	7825	4889.3
			20	22.5	3110	4948.5	1498.5
			65	22	2910	1804.5	934
			90	21.8	1690	887	216

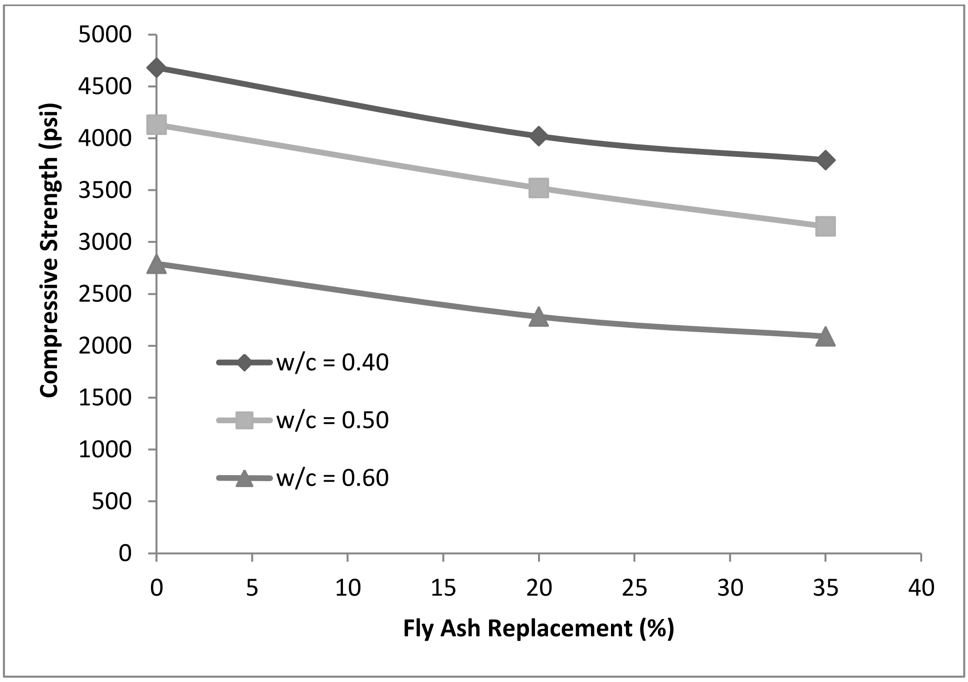

Figure C.1: Variation of Compressive Strength with Fly Ash Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 350 kg/m^3

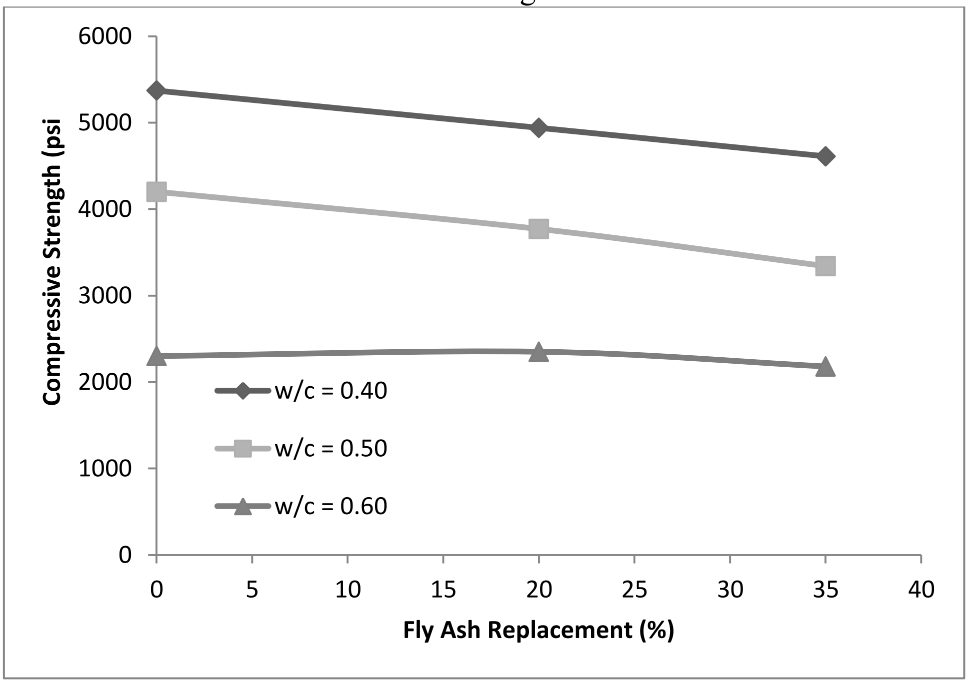

Figure C.2: Variation of Compressive Strength with Fly Ash Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 425 kg/m^3

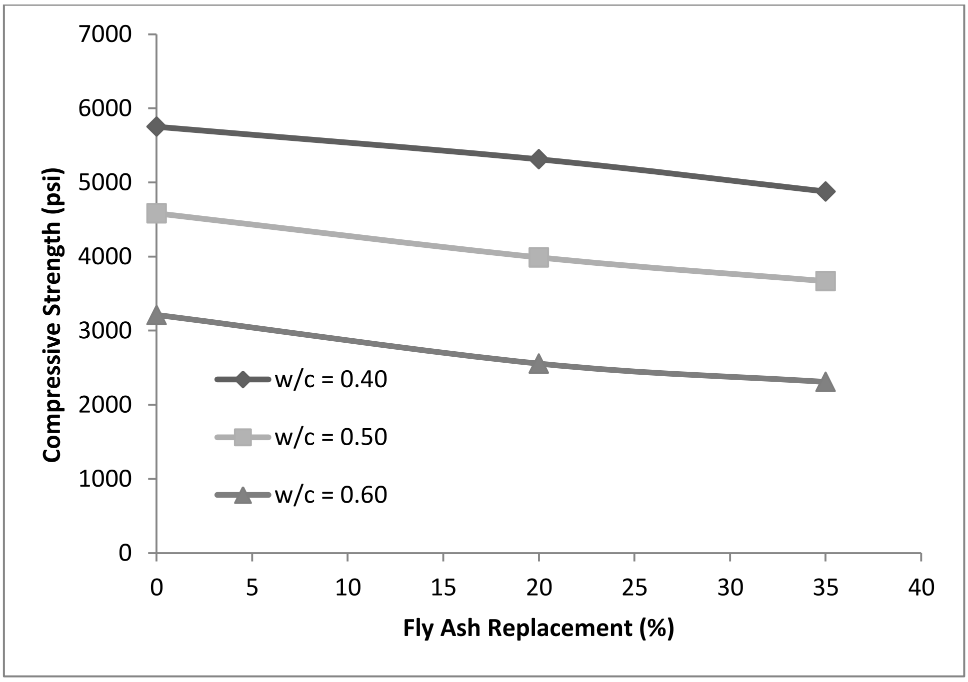

Figure C.3: Variation of Compressive Strength with Fly Ash Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 500 kg/m^3

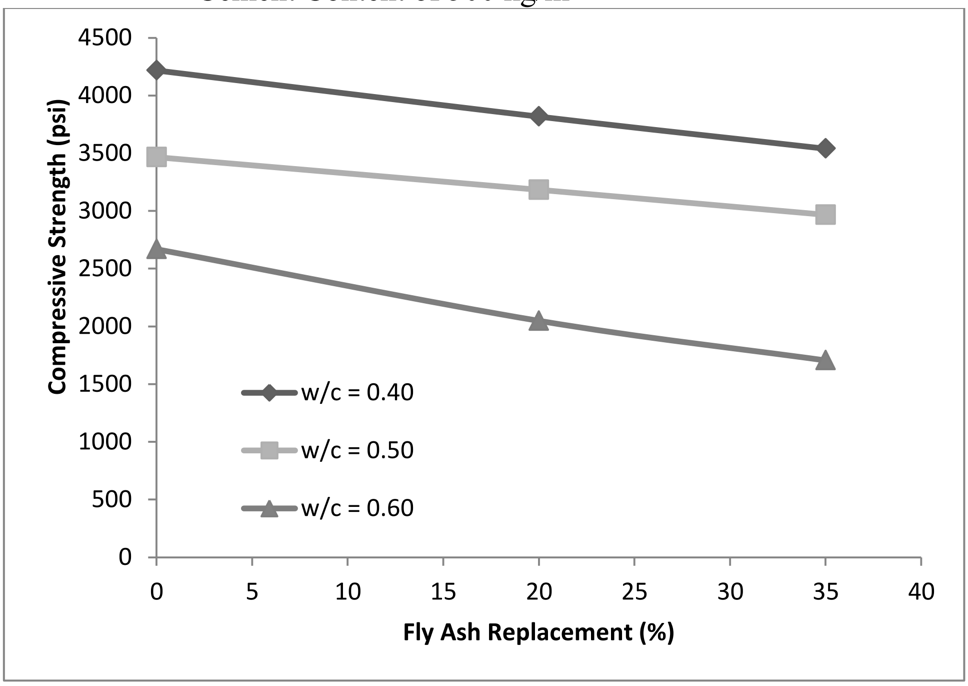

Figure C.4: Variation of Compressive Strength with Fly Ash Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 350 kg/m^3

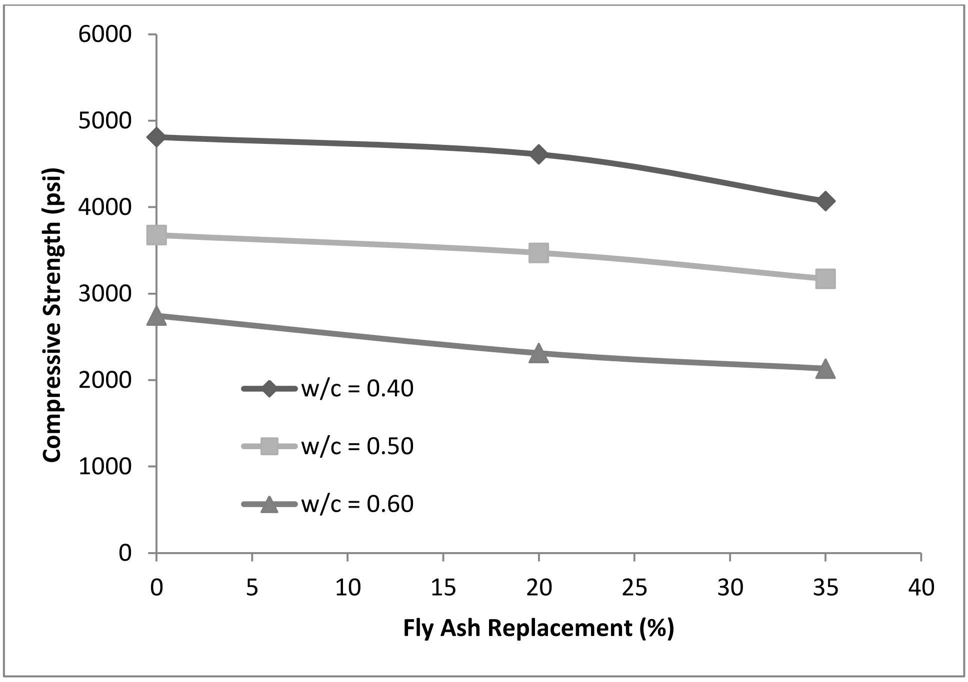

Figure C.5: Variation of Compressive Strength with Fly Ash Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 425 kg/m^3

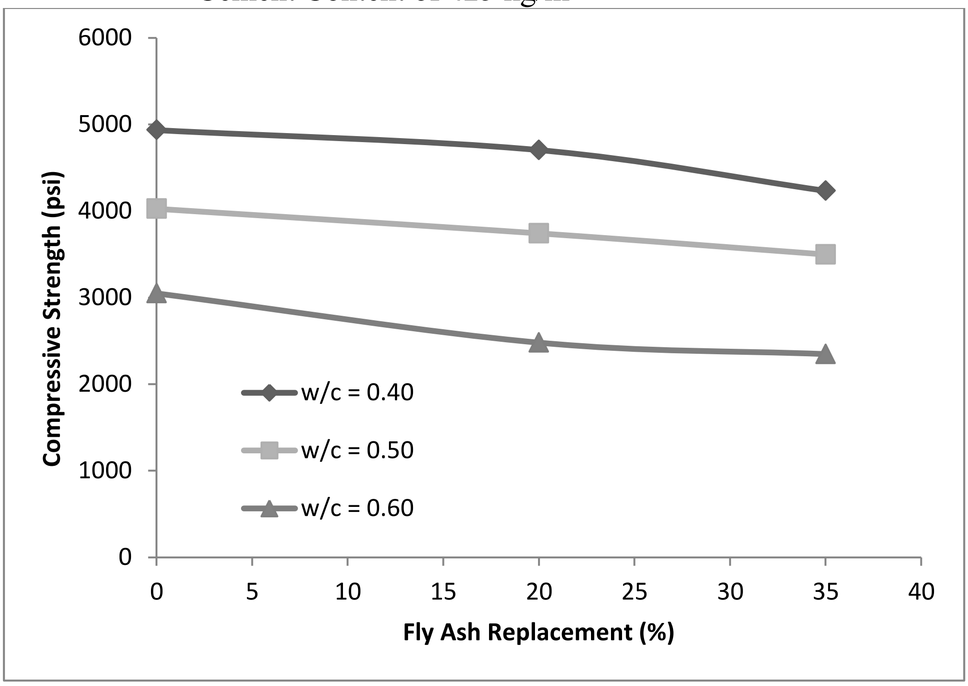

Figure C.6: Variation of Compressive Strength with Fly Ash Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 500 kg/m^3

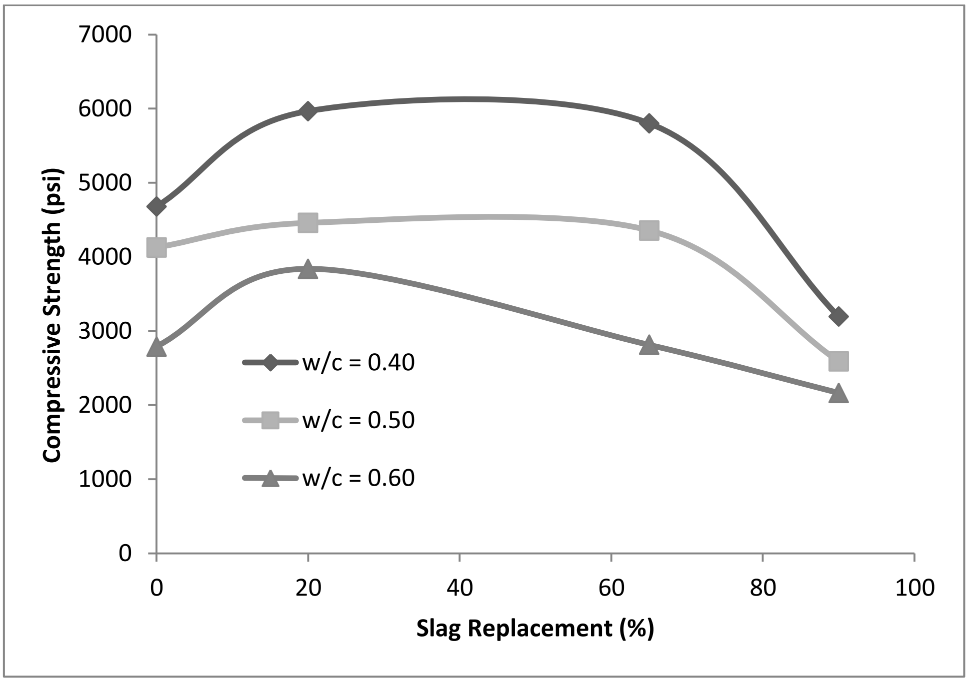

Figure D.1: Variation of Compressive Strength with Slag Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 350 kg/m^3

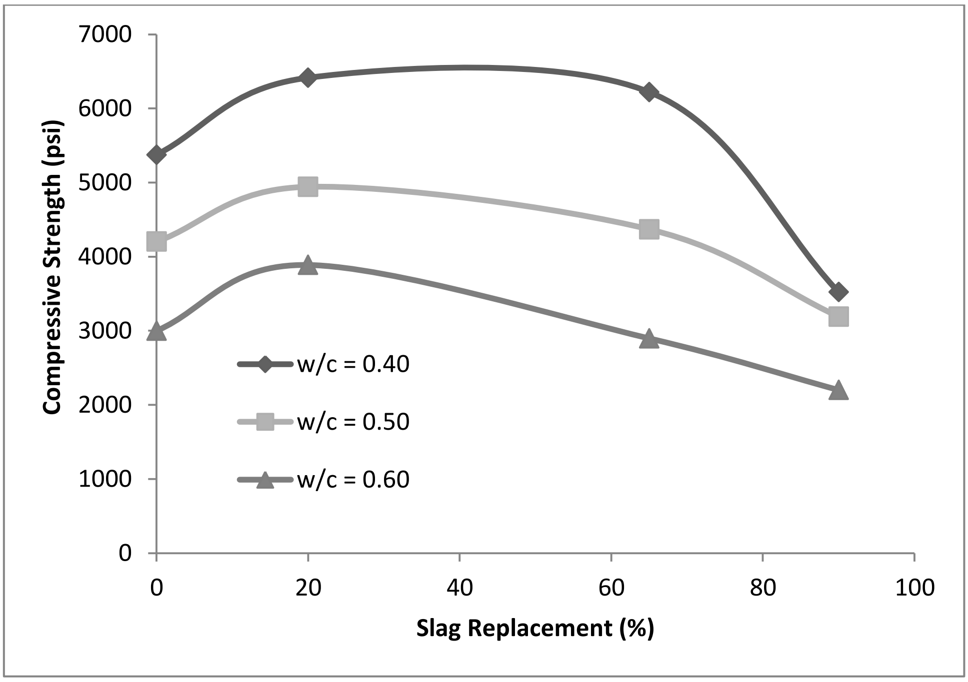

Figure D.2: Variation of Compressive Strength with Slag Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 425 kg/m^3

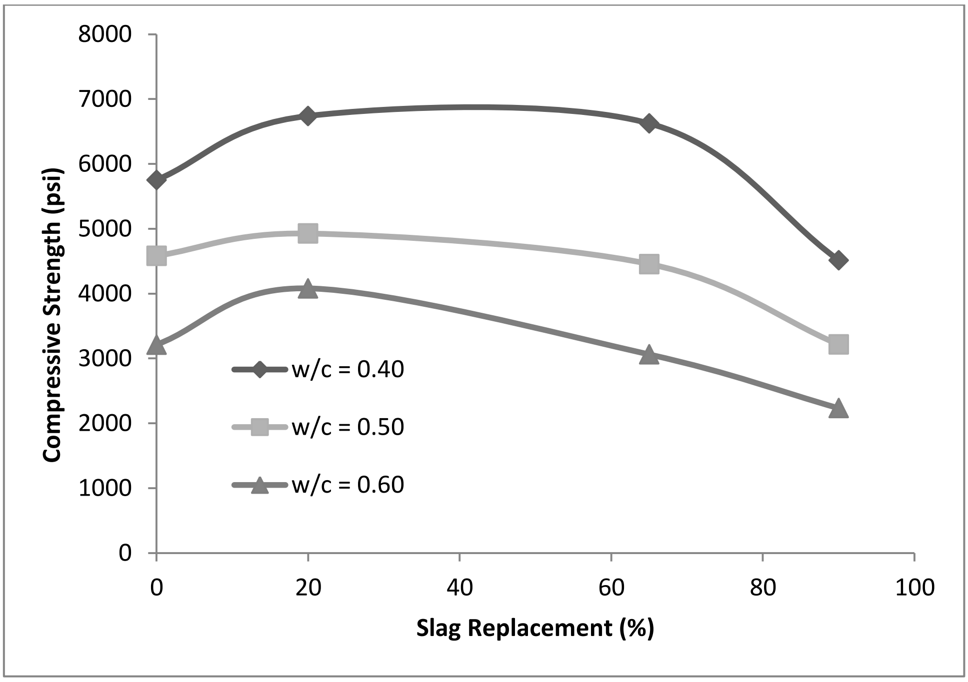

Figure D.3: Variation of Compressive Strength with Slag Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 500 kg/m^3

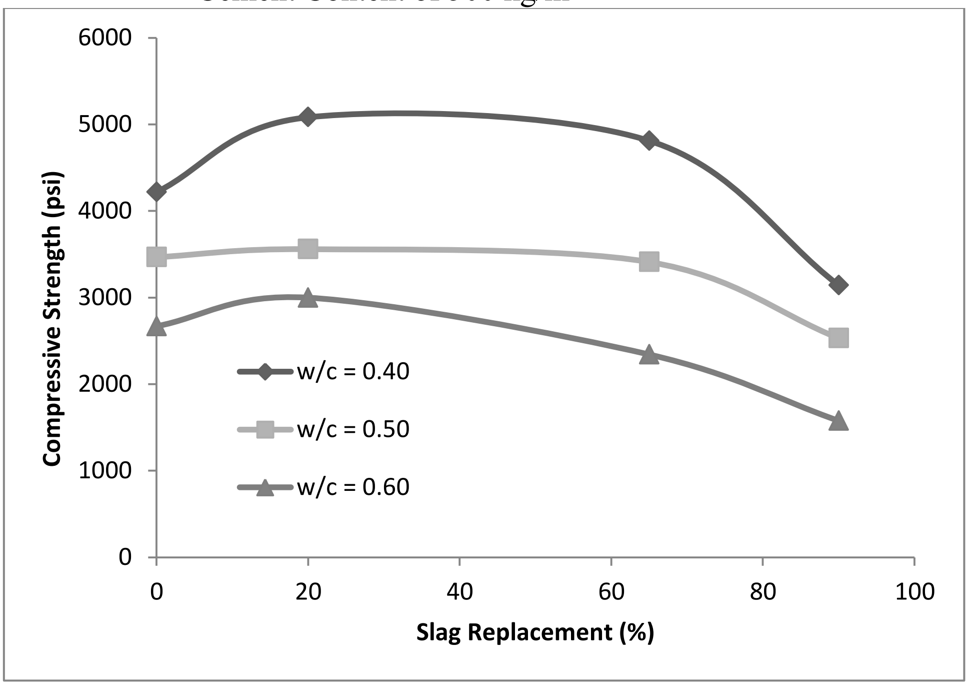

Figure D.4: Variation of Compressive Strength with Slag Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 350 kg/m^3

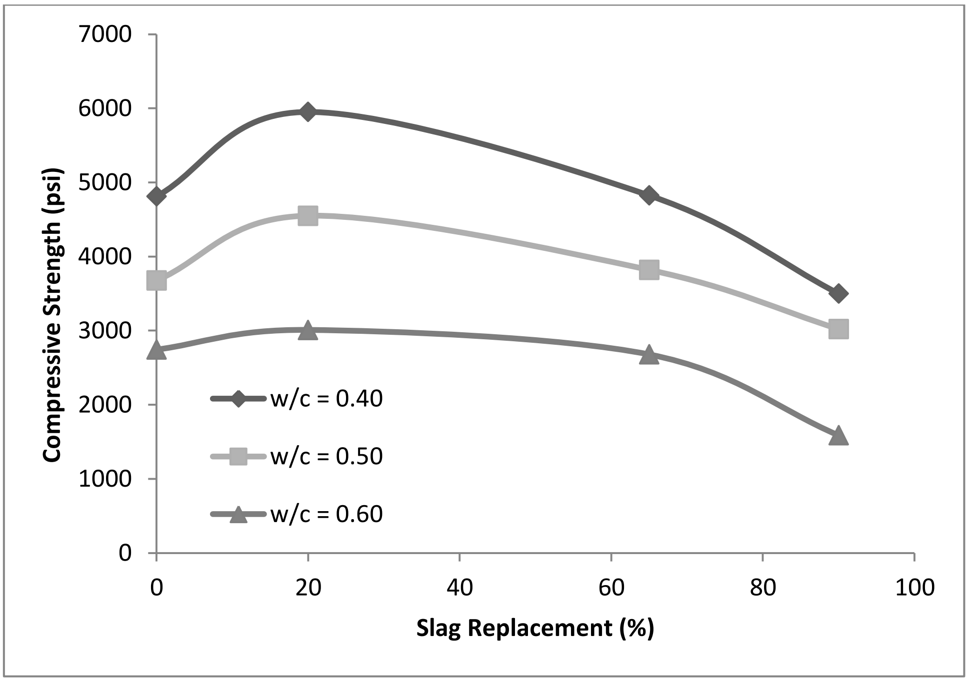

Figure D.5: Variation of Compressive Strength with Slag Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 425 kg/m^3

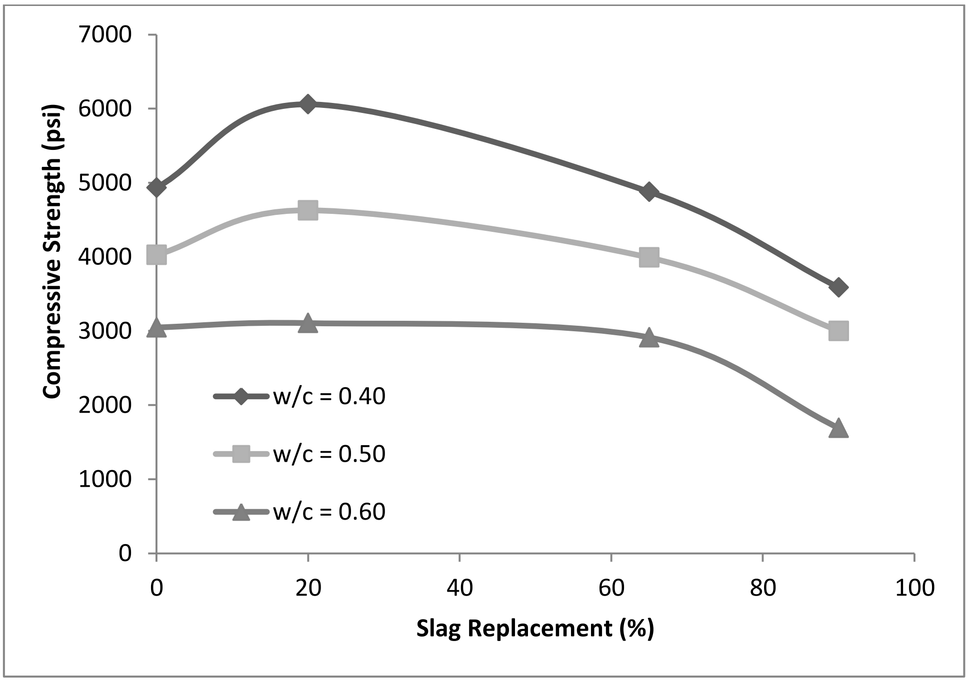

Figure D.6: Variation of Compressive Strength with Slag Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 500 kg/m^3

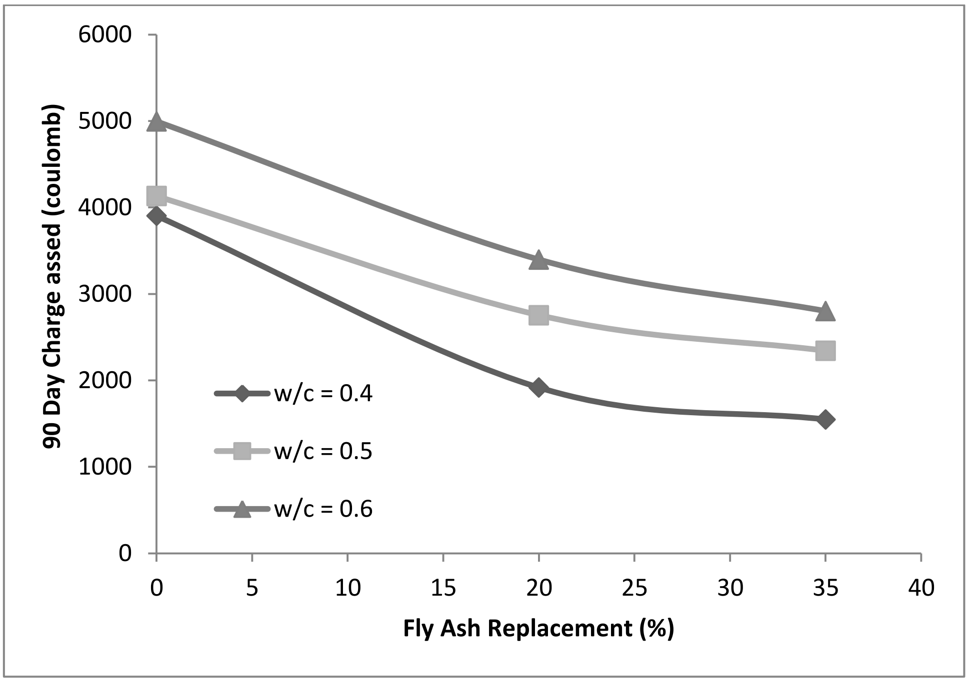

Figure E.1: Variation of 90 Day Charge Passed with Fly Ash Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 350 kg/m^3

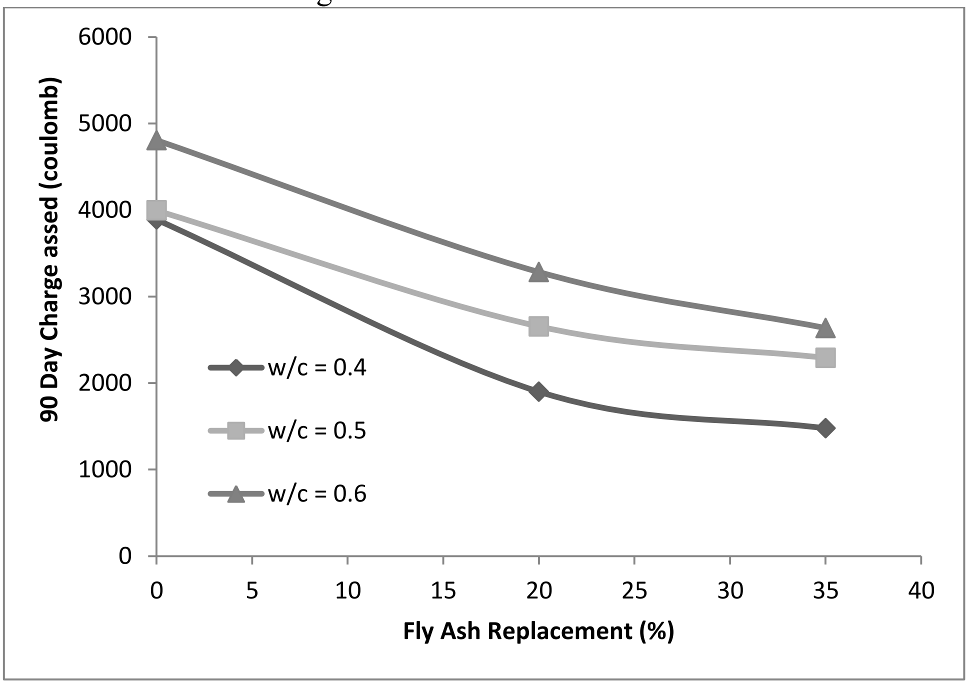

Figure E.2: Variation of 90 Day Charge Passed with Fly Ash Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 425 kg/m^3

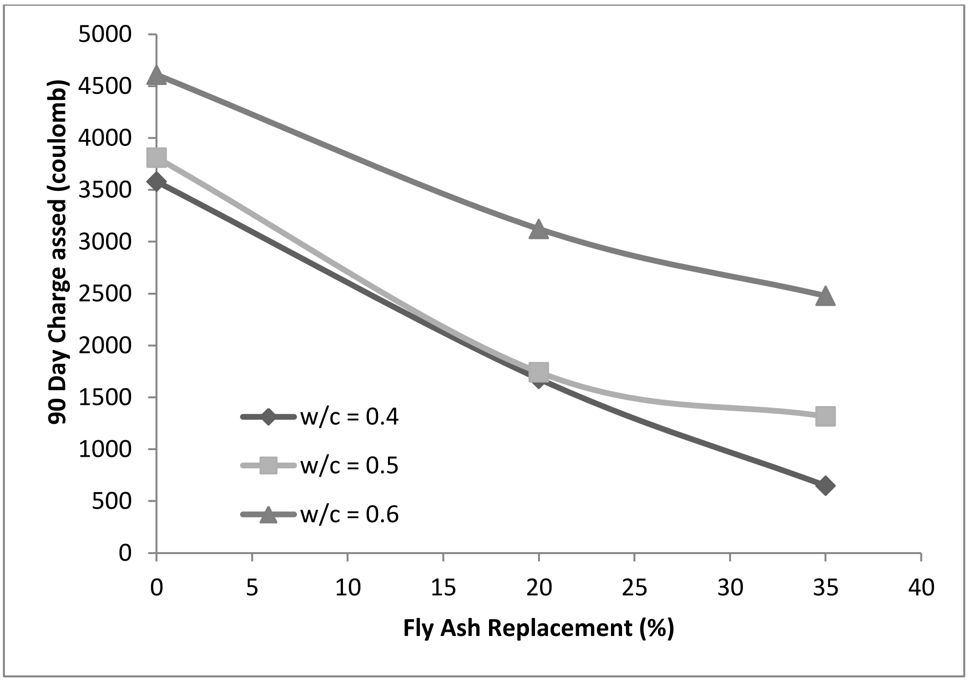

Figure E.3: Variation of 90 Day Charge Passed with Fly Ash Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 500 kg/m^3

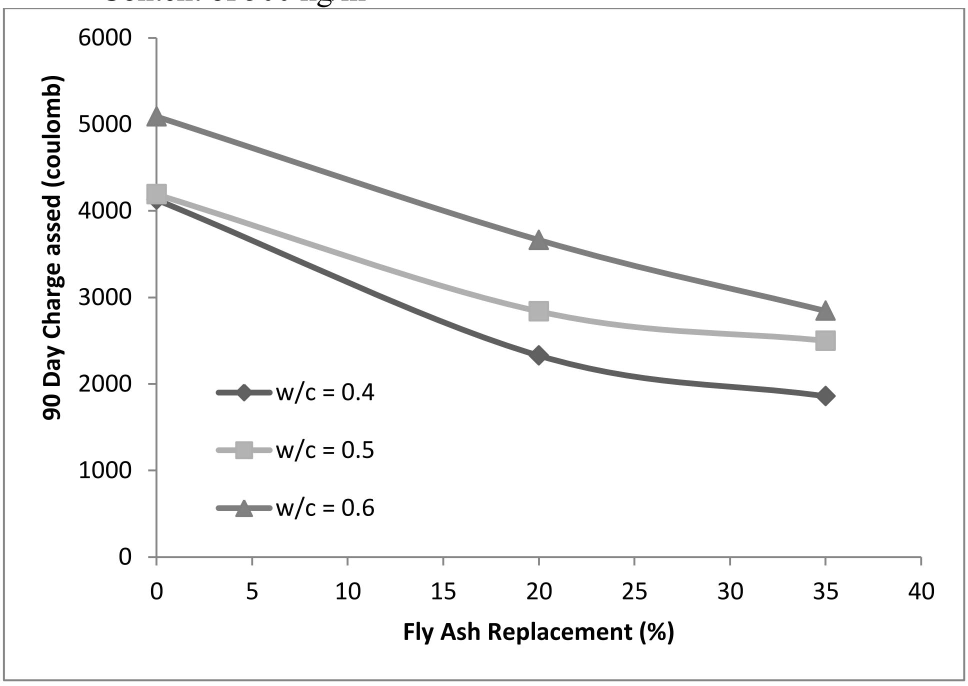

Figure E.4: Variation of 90 Day Charge Passed with Fly Ash Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 350 kg/m^3

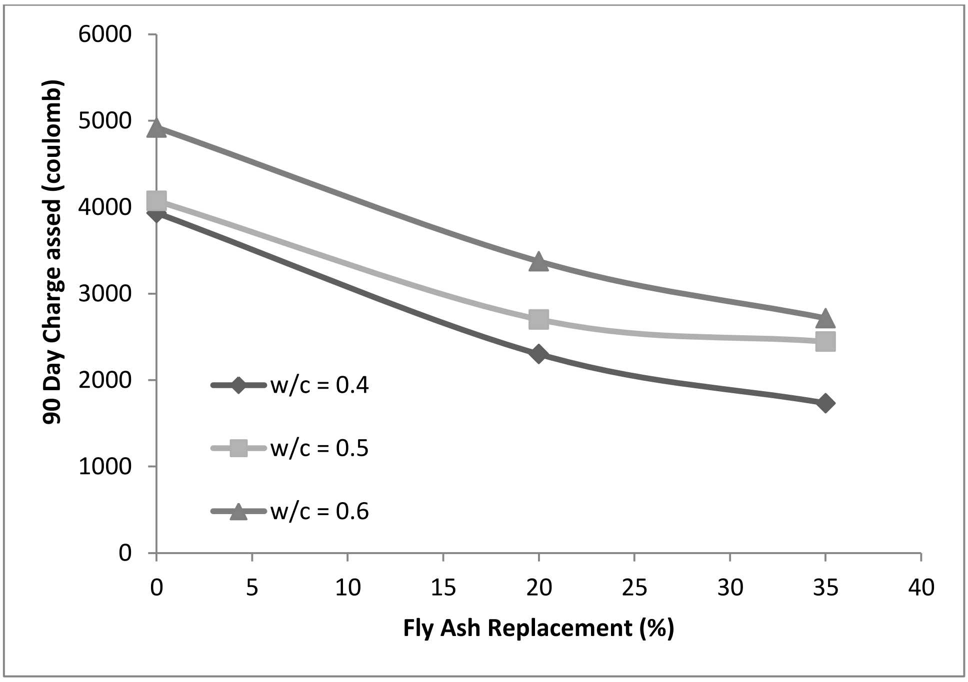

Figure E.5: Variation of 90 Day Charge Passed with Fly Ash Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 425 kg/m^3

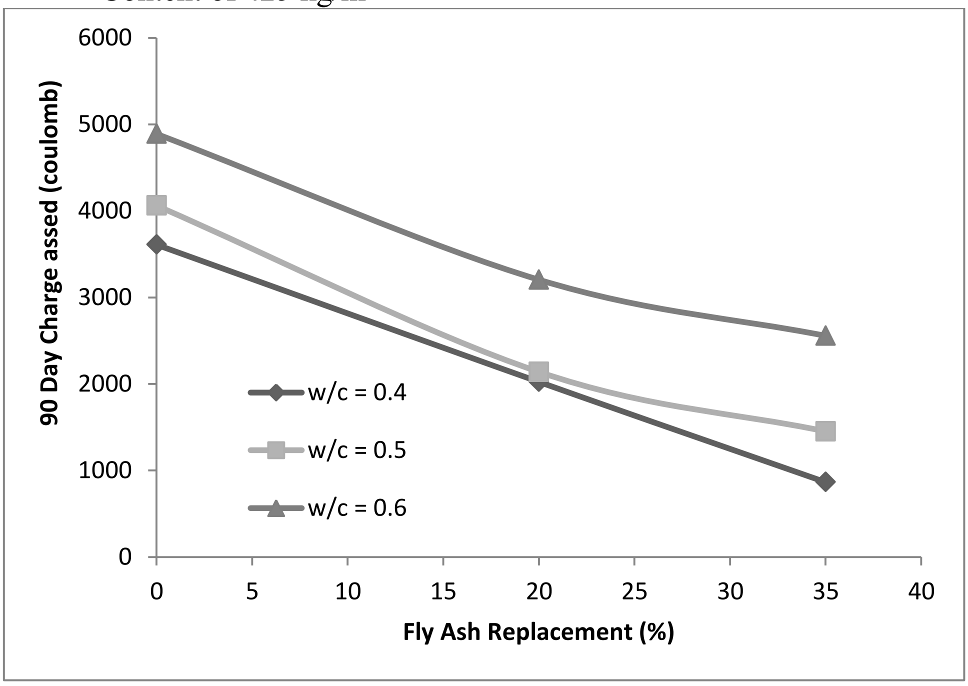

Figure E.6: Variation of 90 Day Charge Passed with Fly Ash Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 500 kg/m^3

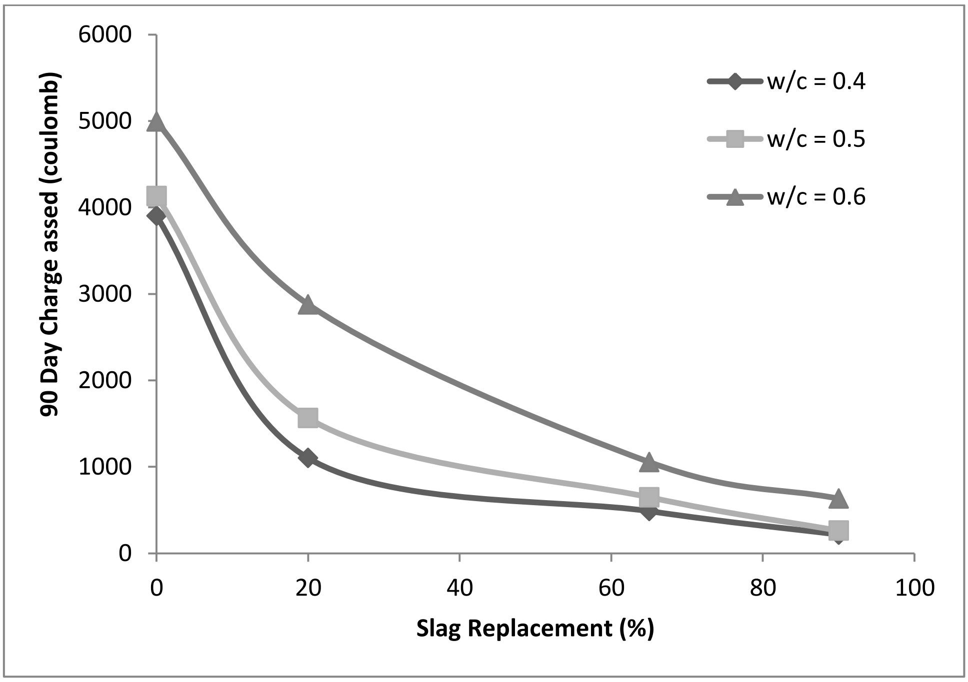

Figure F.1: Variation of 90 Day Charge Passed with Slag Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 350 kg/m^3

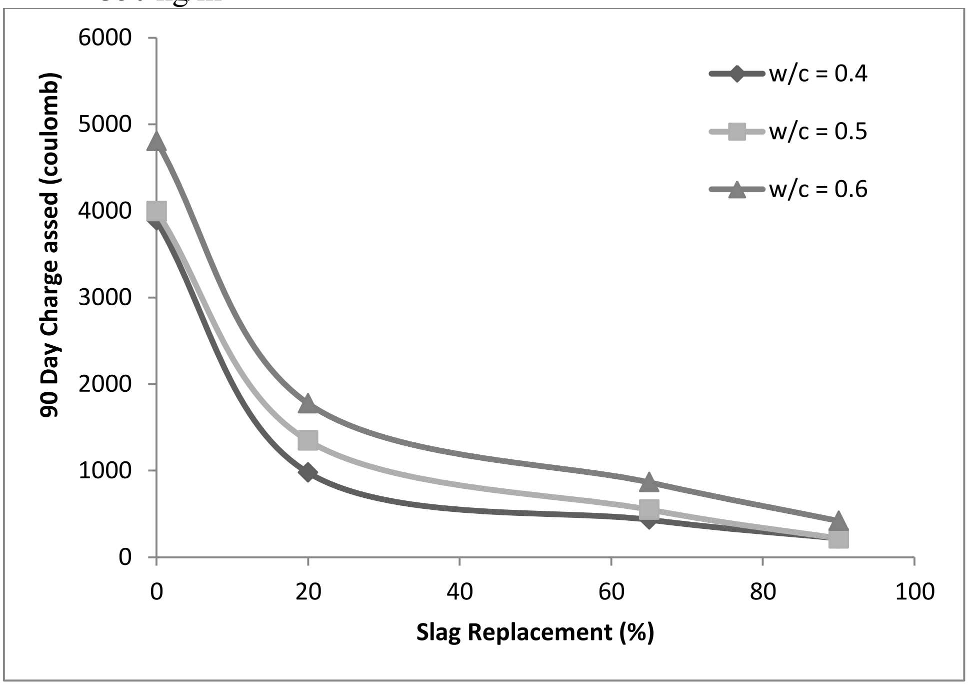

Figure F.2: Variation of 90 Day Charge Passed with Slag Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 425 kg/m^3

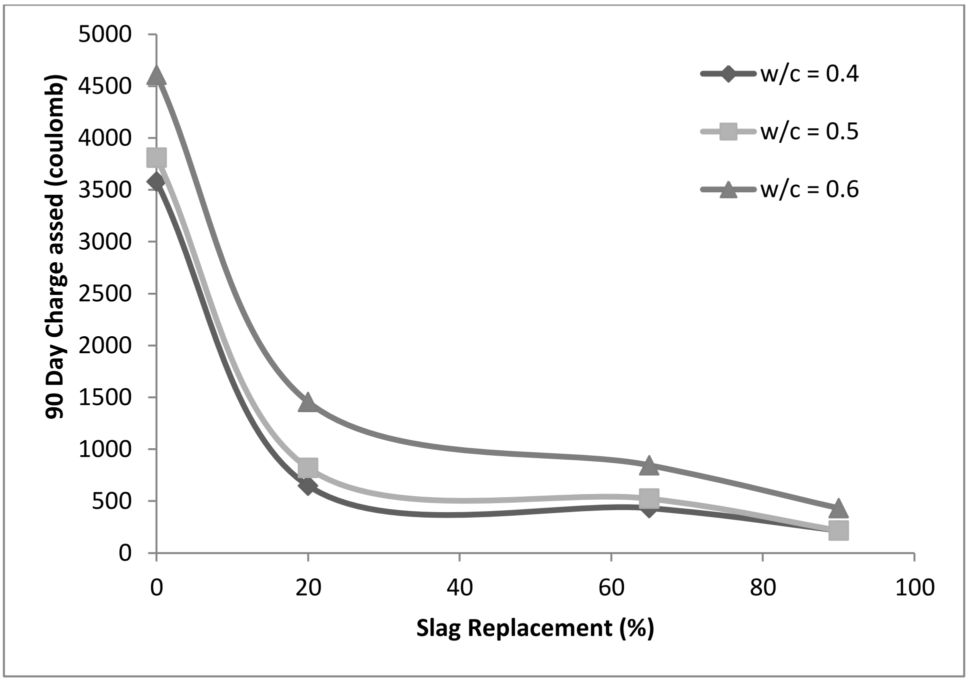

Figure F.3: Variation of 90 Day Charge Passed with Slag Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 500 kg/m^3

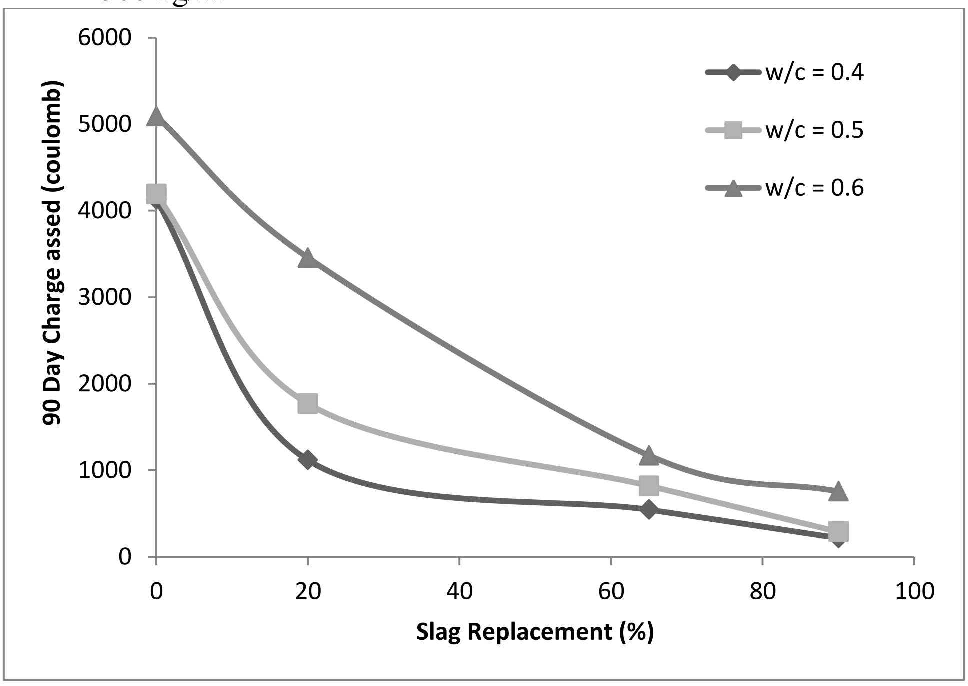

Figure F.4: Variation of 90 Day Charge Passed with Slag Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 350 kg/m^3

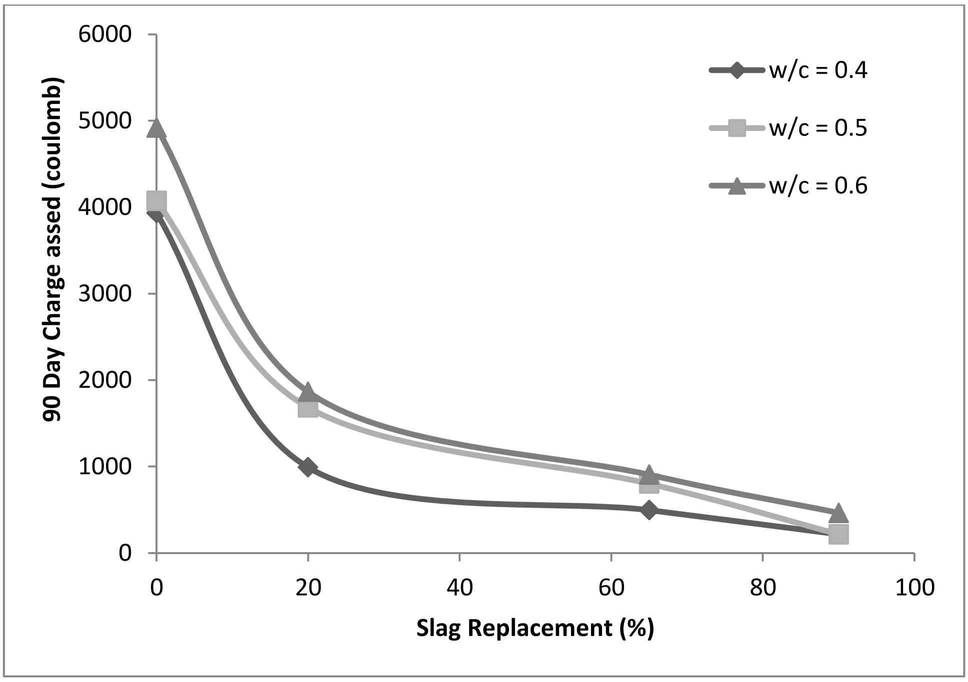

Figure F.5: Variation of 90 Day Charge Passed with Slag Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 425 kg/m^3

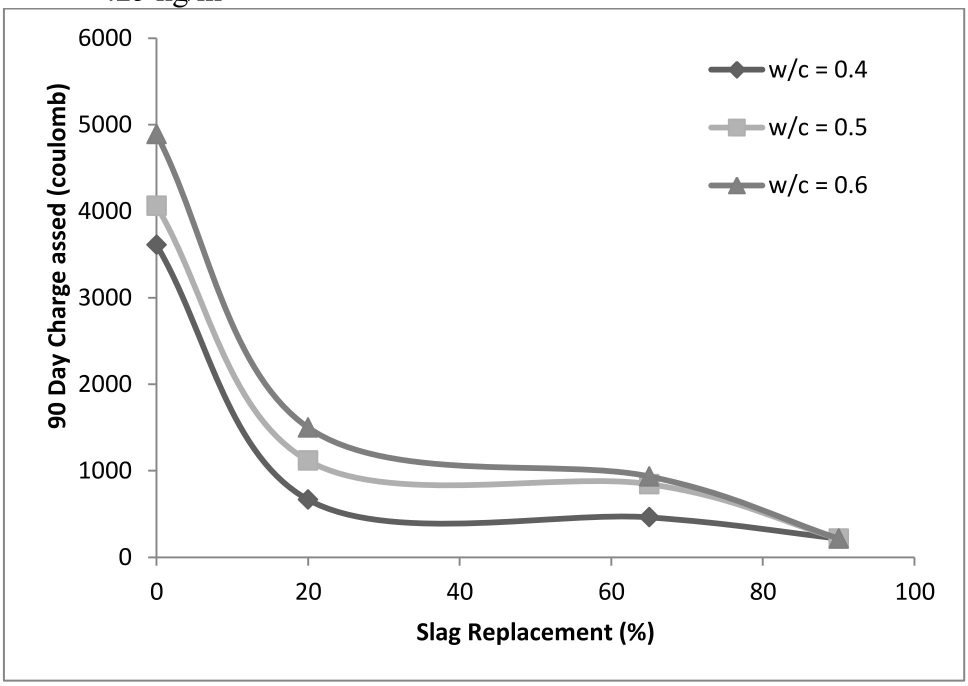

Figure F.6: Variation of 90 Day Charge Passed with Slag Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 500 kg/m^3

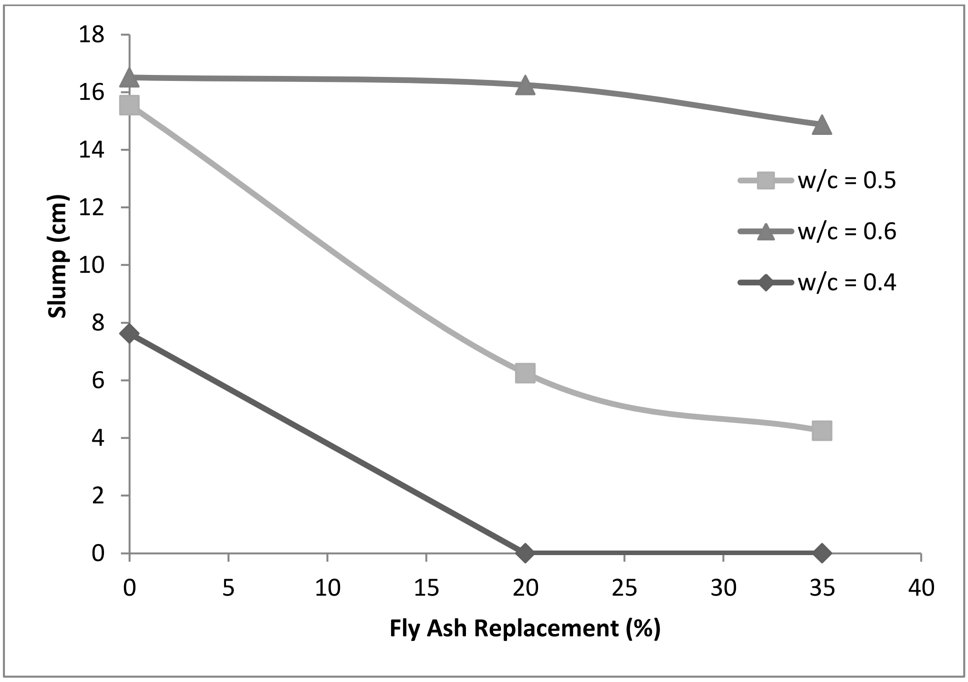

Figure G.1: Variation of Slump with Fly Ash Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 350 kg/m^3

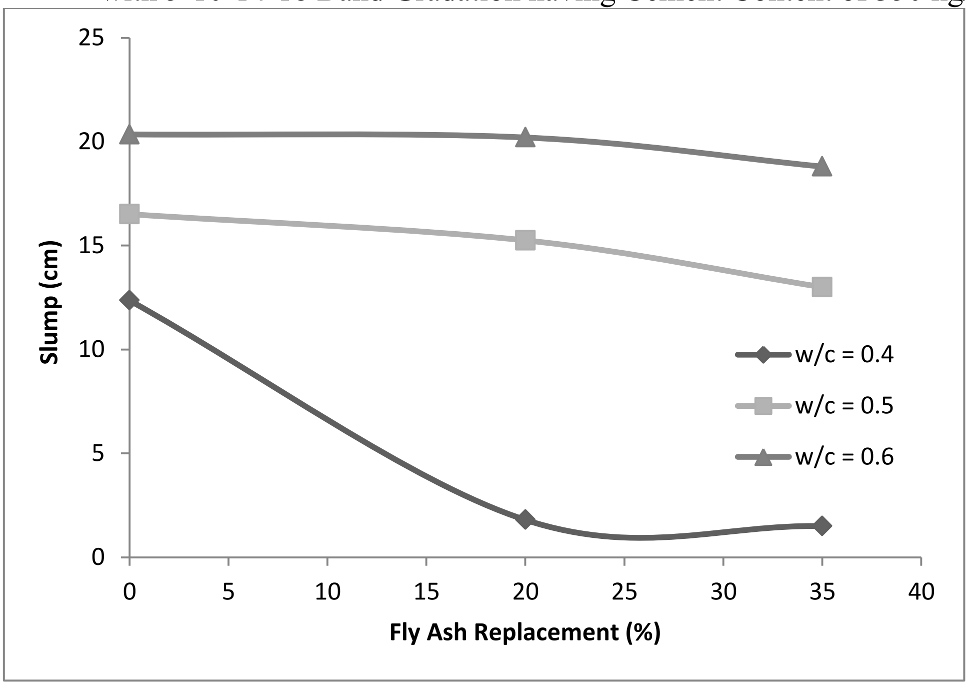

Figure G.2: Variation of Slump with Fly Ash Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 425 kg/m^3

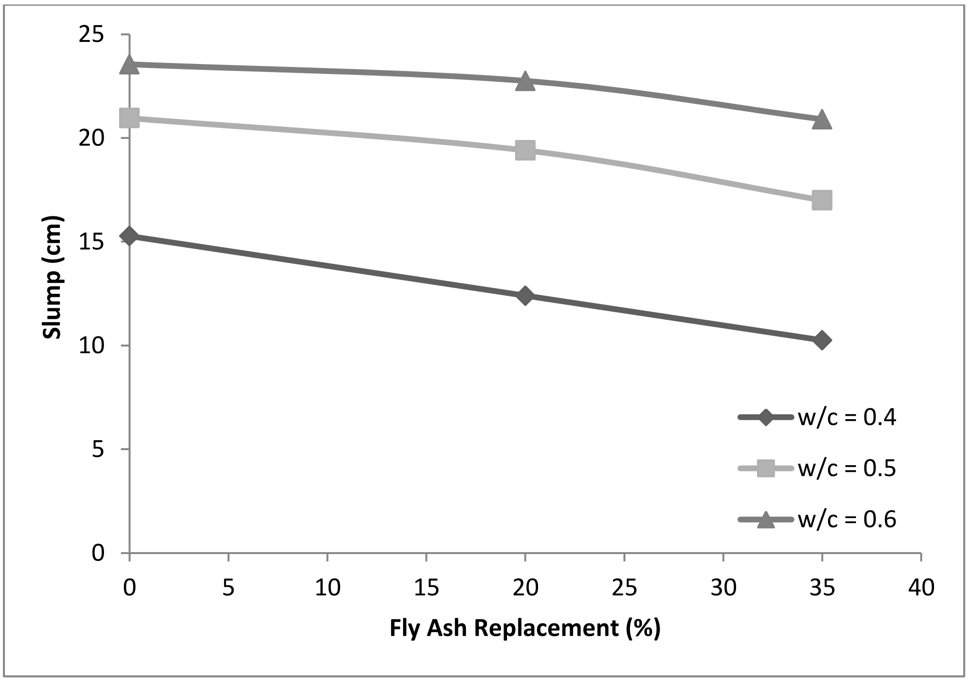

Figure G.3: Variation of Slump with Fly Ash Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 500 kg/m^3

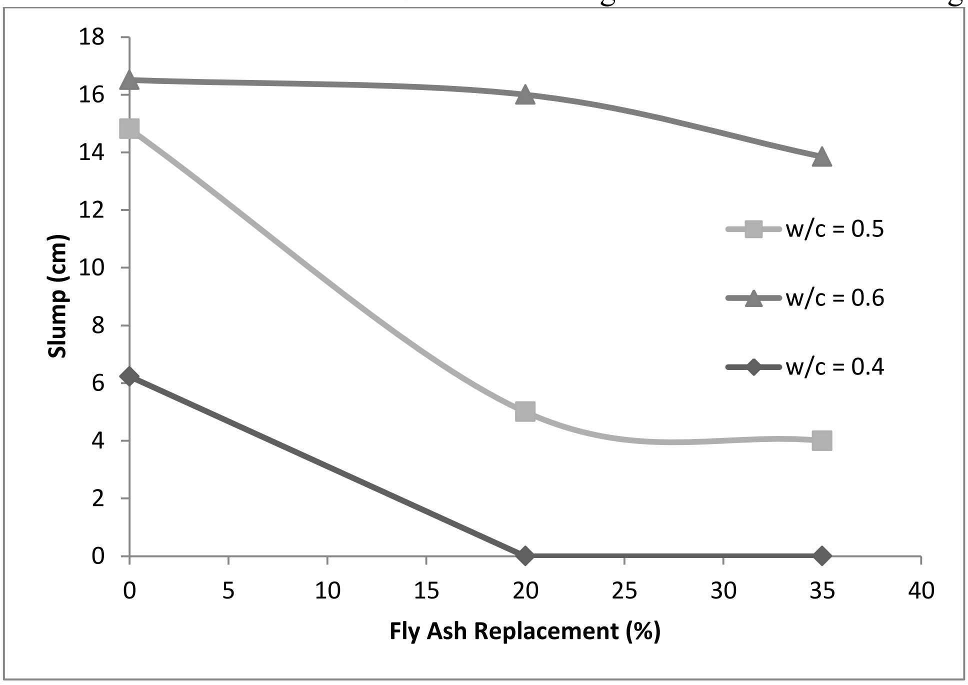

Figure G.4: Variation of Slump with Fly Ash Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 350 kg/m^3

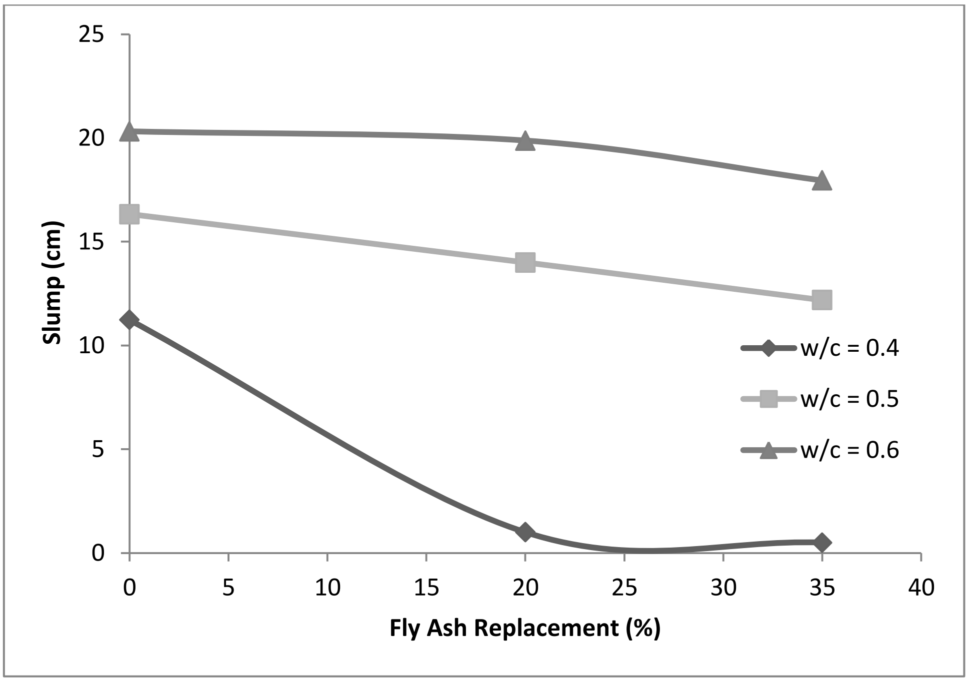

Figure G.5: Variation of Slump with Fly Ash Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 425 kg/m^3

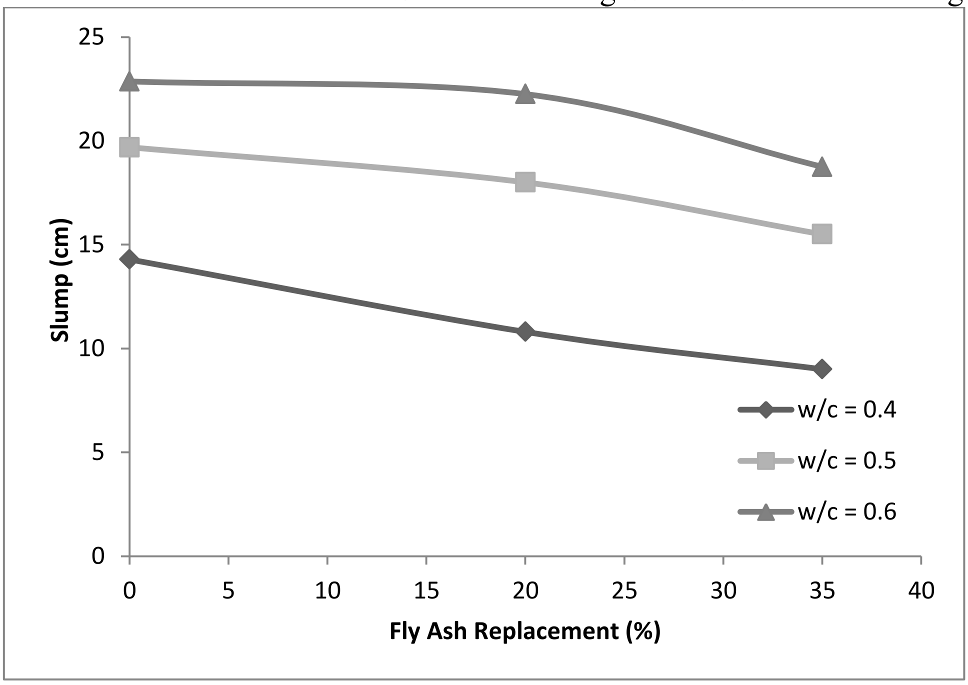

Figure G.6: Variation of Slump with Fly Ash Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 500 kg/m^3

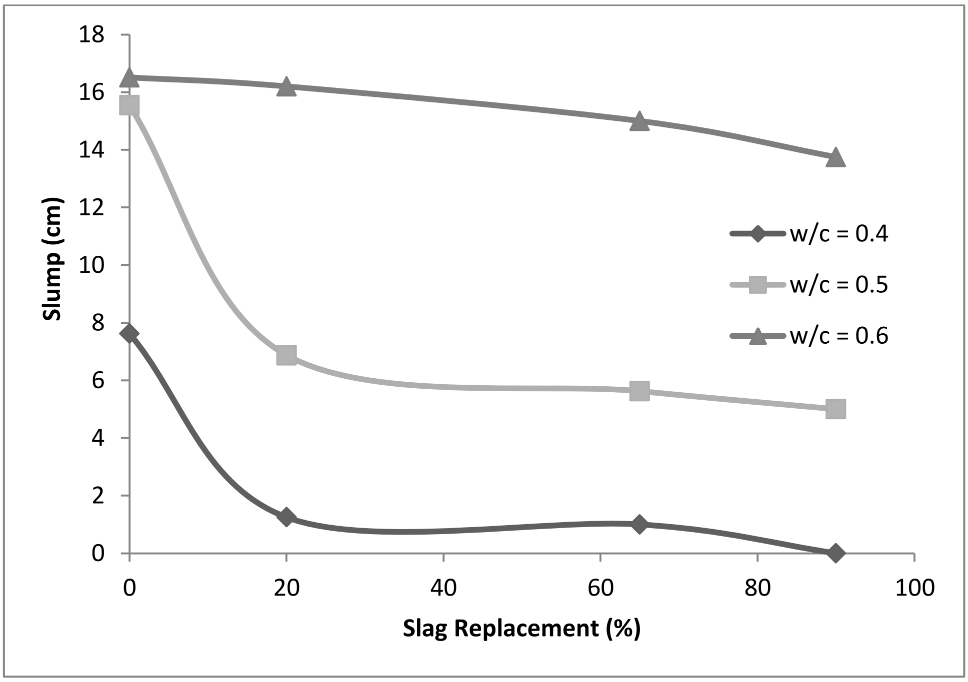

Figure H.1: Variation of Slump with Slag Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 350 kg/m^3

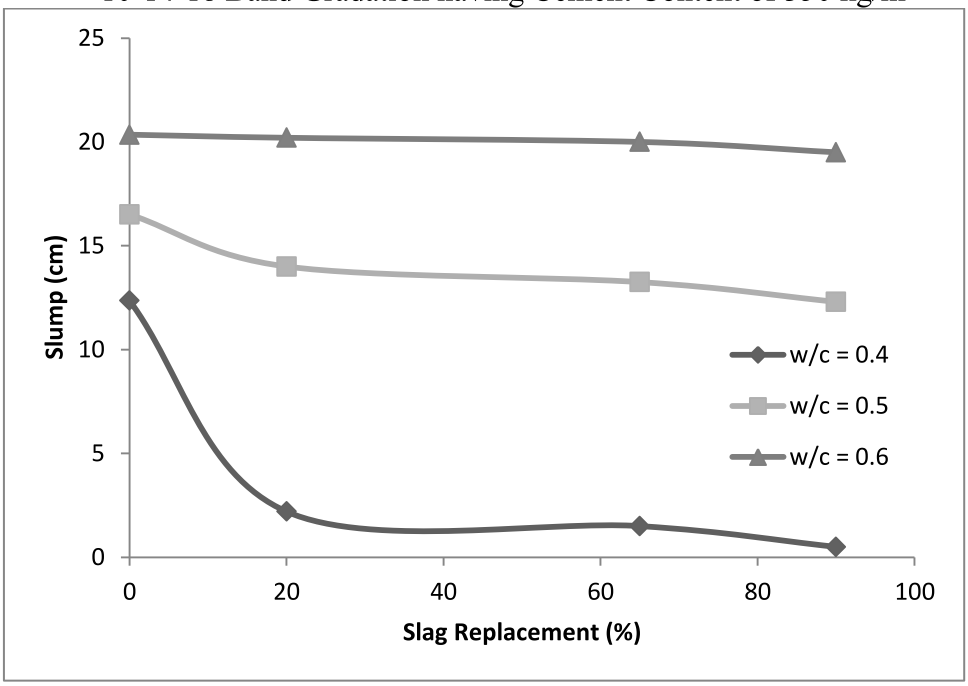

Figure H.2: Variation of Slump with Slag Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 425 kg/m^3

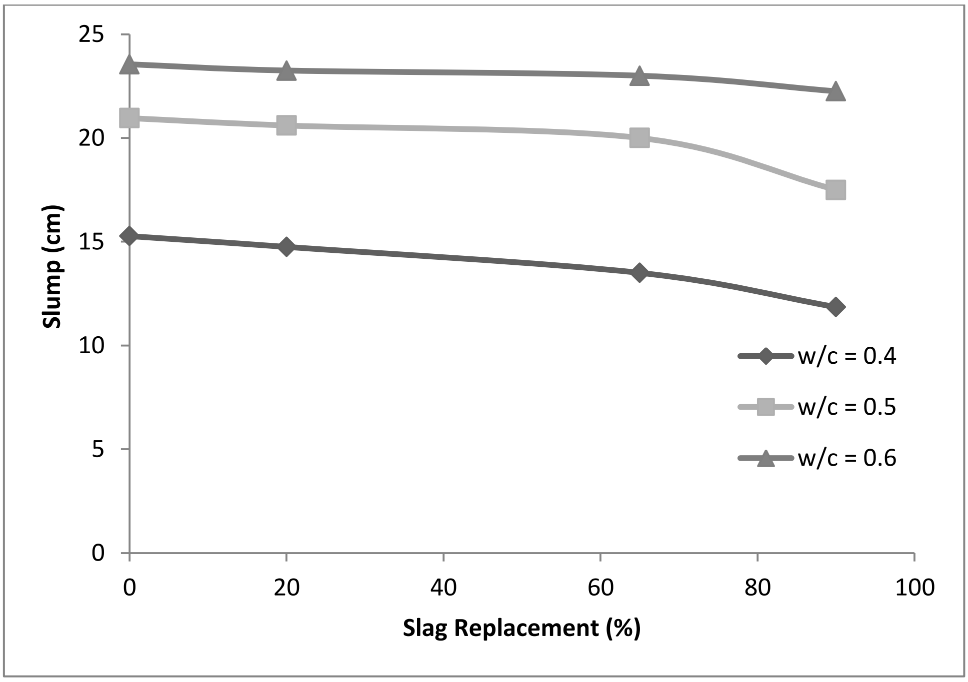

Figure H.3: Variation of Slump with Slag Replacement for Concrete Prepared with 5-10-14-18 Band Gradation having Cement Content of 500 kg/m^3

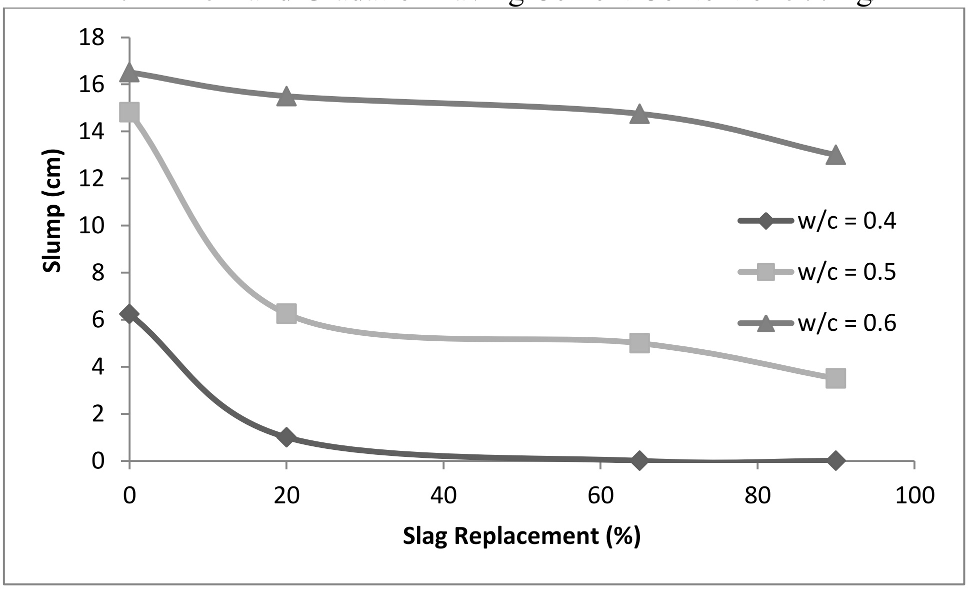

Figure H.4: Variation of Slump with Slag Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 350 kg/m^3

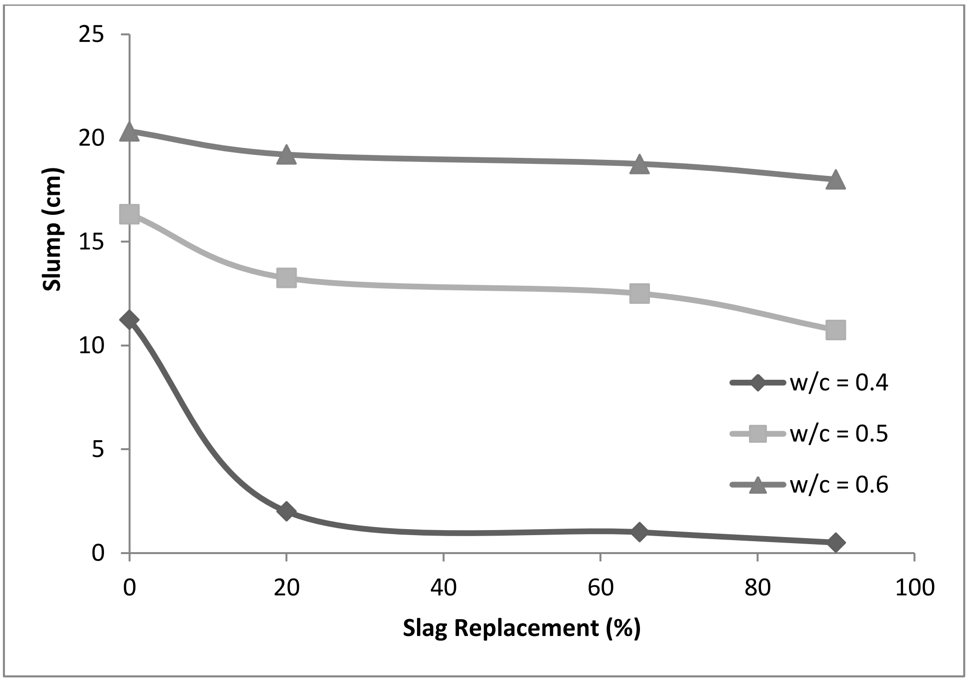

Figure H.5: Variation of Slump with Slag Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 425 kg/m^3

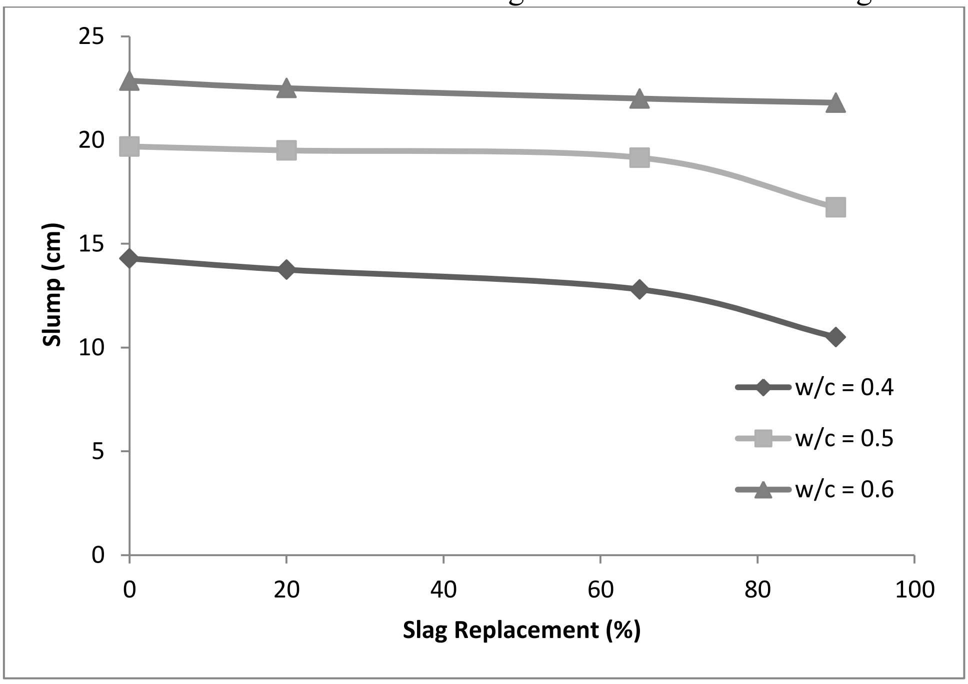

Figure H.6: Variation of Slump with Slag Replacement for Concrete Prepared with 5-10-18-22 Band Gradation having Cement Content of 500 kg/m^3