PRACTICAL CONCRETE MIX DESIGN

Avijit Chaubey

CRC Press
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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
52 Vanderbilt Avenue,
New York, NY 10017

Printed on acid-free paper

International Standard Book Number-13: 978-0-367-24949-6 (Hardback)

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

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Foreword

The years 1970 to 1990 represent a glorious period in the history of concrete technology. Major new developments took place in the field of concrete technology during that period. These include the introduction of new chemical admixtures such as superplasticizers and shrinkage-reducing admixtures, new materials such as polymer and steel fibres, and new supplementary cementing materials such as silica fume and metakaolin. Other notable developments were the introduction of roller-compacting concrete, high-performance concrete, ultra-high-strength concrete, self-compacting concrete, high-volume fly ash concrete, and geopolymer concretes. To bring these new developments to the attention of the cement and concrete industry, several books appeared on the market. These include books by Professors P.K. Mehta and Paulo J.M. Monterio and a book by Professor Mario Collepardi. These are in addition to the revised editions of the classic book by Professor A.M. Neville. However, these books do not do justice to the subject of mixture proportioning. The only exception is a book by Professor Mario Collepardi et al. entitled *Mix Design*, which was published in 1970, well before the aforementioned new developments in concrete technology.

This book on mix design, *Practical Concrete Mix Design* by Avijit Chaubey, is a welcome volume that fills the gap in the published literature on the subject of mixture proportioning. The book covers mix design methods for all types of concretes, including environmentally friendly fly ash concrete. It is believed that this book will act as a reference volume to be used by concrete specification writers, concrete technologists, and ready-mix concrete producers. Graduate students doing research in concrete technology will also find this comprehensive volume very helpful.

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Preface

Our real discoveries come from chaos, from going to the place that looks wrong and stupid and foolish.

Chuck Palahniuk

The construction industry across the world is facing acute shortage of effective engineers who can lead the industry and solve some of the perennial technical and financial issues. On the other hand, pollution and sustainability issues have created pressure on the industry to be more effective in utilizing resources. This book is written with the intention to guide not only practising engineers but also those in making, to proportion the concrete and optimize it for the required performance properties. Designing concrete requires meeting more than two performance criteria at lowest possible cost, which actually seems to be a nightmare that never ends. I have tried to explain every possible step of concrete proportioning because I did not find it all in one document together. Moreover while designing concretes I came across many challenges, solutions for which do exist in different books in bits and pieces, but understanding the solutions and implementing them was a tough task. This book will help solve many problems faced by engineers in proportioning concrete.

Through a lot of trial and error, we did try some concepts and modify them to counter the challenges faced, and only those which gave results made it into this book. We were able to reduce the cost without reducing the performance of concrete through the tools mentioned, which led to huge savings and profits. An effective engineer is not so until he or she understands the cost implications of the decisions taken and does not strive to be least in terms of cost. Cost reduction does not only ensure higher profits for an organization, but it also helps solve sustainability issues.

This book is intended for students as well as practising engineers who have basic concepts of maths and mensuration clear. It has been written, explaining even the most basic of concepts, with the intention to equip every engineer with the effective knowledge of concrete proportioning. For many years, interaction with construction professionals led me to realize that effective and easy book on concepts of mix proportioning was much needed. Those who are at the forefront understand things in simple terms, whereas those who have high level of understanding of concrete are far away from implementing any changes for reasons known to them.

Many have been involved in making of this book directly or indirectly, from the development of particle-packing software, which comes as an ancillary with this book, or the actual tests done to illustrate a method is based on elephantine tests done by my colleague Srinath. Jagmal and Ruchit encouraged me to write down my ideas and concepts of concrete proportioning. Mr Anil, who raised challenges and also supported the implementation of the solutions I found, reinforced the purpose of writing this book. The late Mr. Santibratta Datta, who was the best I know for statistics and its application, helped me look at concrete better as a statistician. Inputs from Mr B. V. B. Pai, whose knowledge on concrete and cement technology is second to none, form the basis for many important concepts of this book.

Author

Avijit Chaubey completed his civil engineering from REC Durgapur (NIT Durgapur) in 1999. He has worked in various capacities from site engineer to heading the R&D division of concrete and cement manufacturing companies. During his professional tenure, he has been instrumental in implementing new technologies and materials in construction, which led to more sustainable initiatives in the construction industry that was facing an immense shortage of raw materials due to sustainability issues. His major experience and contributions are in (i) hydro power projects, fast track construction projects, ready mix concrete industries; (ii) implementation of India's second roller-compacted concrete technology for construction of dam; (iii) construction of a hotel in record time, by designing fast-strength gaining concrete to speed up construction; (iv) first implementation of crushed rock fines to replace river sand for concrete manufacture in major cities of India for structural purposes; (v) developing a concrete road that could be trafficked within 24 hours of laying; (vi) ultra-lightweight concrete with a density less than water (lighter than water); (vii) acid-resistant concrete that could withstand attack even from sulphuric acid; (viii) developed a test method for ultimate shrinkage measurement in concrete; (ix) developed a mathematical model for void prediction in a mixture of solids; (x) optimization of concrete to get maximum profits through methodologies developed, which is also discussed in this book (this also led to a reduction in cement consumption for manufacturing concrete for the same strength and properties of concrete). Avijit has published few papers in reputed journals and magazines, one of his papers under the guidance of Dr Amlan Das (Prof NIT Durgapur), "Design of Parabolic Channels" won an award from Union Ministry of Water Resources in 2001. Avijit has served in organizations like Shapoorji Pallonji, Gammon India, and ACC Concrete and is currently working with Ultratech Cement.

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1

Concrete Mix-Proportioning General Concepts

1.1 Introduction

Concrete is a mixture of cementitious materials, which binds its fillers together to form a structure that fulfills the requirements that the user desires in terms of strength, workability, economy and longevity.

The main challenge faced by a concrete designer is to match the concrete properties with the requirements of the user by finding proportions of the available materials. The challenges only increase from here as, 1). The materials used in concrete except for cement and admixture are mostly uncontrolled and are prone to high variation in terms of their properties. 2) The use of materials for the manufacture of concrete is guided by their availability, client specification, and cost restrictions. Thus most ideal material practically is never available. 3) Concrete has been referred to as the most complex material known to humans. If we see any other material, be it steel or the microchips we use in computers, none of these materials contain more than four elements, whereas concrete contains cement, which itself has more than seven elements, and if any of these elements vary even by small percentage, it can lead to huge variation in concrete property – not to mention the other materials of concrete and their innate property of variation.

Designing concrete is a science and also an art, which improves when mixes are actually designed and tested for practical applications and then troubleshot. This science incorporates concepts of chemistry, statistics, and physical material properties. Numerous methods have been developed over the years, and each of them has its advantages and disadvantages or limits of application for a purpose.

Design of concrete mixes involves determining the proportions of the given constituents, namely, cement, water, coarse and fine aggregates, and admixtures, if any, which would produce concrete possessing the specified properties both in the fresh and hardened states with the maximum overall economy. Workability is the most important property specified in the fresh state; for the hardened state, compressive strength and durability are important. The design of concrete mixes is accomplished by the use of certain relationships established from experimental data, which affords a reasonably accurate guide to select the best combination of ingredients to achieve the desirable properties.

To learn concrete mix proportioning we need to remember these two statements:

a. The compressive strength of concrete is governed only by its water cement ratio.
b. For a given aggregate characteristics, the workability of concrete is governed by its water content.

From these statements it should not be inferred that cement content is only related to strength of concrete, but that workability also plays a vital role in deciding the cement content. Moreover, people tend to confuse water cement ratio and water content and their significance; the same thing should also be understood well during understanding the mix-proportioning process.

Doing the mix-proportioning calculation should not be considered as the most important step of mix proportioning, but it is the final implementation of the designed mix in the structure after making the changes based on the feedback from its users.

NOTE: Statements a and b apply only to calculation of mix proportions and not to actual concrete. The actual concrete performance is a function of many variables and their interaction is very complex. Hence, to understand concrete, we will assume that only these statements are correct, and after testing the calculations through lab trials, performance will be ensured by adjusting the proportions to match the requirements given by the end user or the client.

1.2 Concrete Mix Proportioning

Concrete mix proportioning starts with a goal or data required to make concrete with:

- Characteristic compressive strength
- Desired workability
- Expected degree of Quality Control during manufacturing
- Properties of raw materials
- Degree of exposure

Concrete mix proportioning starts with the calculation of the target strength, which is based on characteristic compressive strength and degree of quality control expected.

$$Ft = Fck + K \cdot S$$

where Ft is the target strength, Fck is the characteristic compressive strength, K is a factor based on the allowable degree of failure for the characteristic compressive strength and S is the expected standard deviation.

1.3 Understanding 'K' Better

To understand the mix-proportioning process, it is important to understand each step thoroughly. The aforementioned formula for calculating target strength is based on a concept from statistics (i.e. 'probability distribution curve').

1.3.1 Probability Distribution Curve for a Pair of Dice

Let us look into it more deeply. Let us say we had two unbiased dice, and we had to calculate the probability of each number for occurring, right from number 2 to number 12. Now the possible number of combinations of the dices to sum up to number 2 is just one (i.e. 1 + 1). Also, the total numbers of possible different combinations are 36. Thus, the probability for 2 to occur would be 1/36 and so on. The probabilities for each number to occur when two dice are rolled would be as per Table 1.1.

TABLE 1.1

Probability Distribution for Two Dice Outcomes

Number	Probability
2	1/36
3	2/36
4	3/36
5	4/36
6	5/36
7	6/36
8	5/36
9	4/36
10	3/36
11	2/36
12	1/36

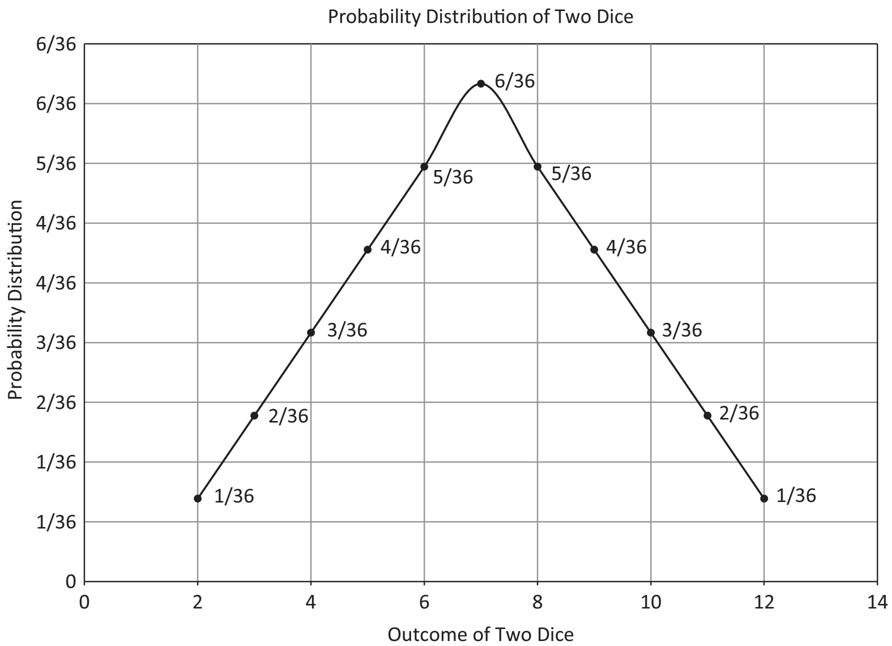


FIGURE 1.1
Probability distribution curve for outcomes of pair of dice.

The data plot as per Table 1.1, is known as probability distribution curve, and the graph would look like Figure 1.1.

Remember, this is the probability distribution curve, meaning, it only signifies the probabilities occurring for all the numbers. So in an ideal condition if we had to throw a pair of dice 36 times, we would have the same frequency as the probability distribution curve (i.e. number 2 would have come only once, 3 twice and so on). So if we had to calculate the standard deviation and average of the numbers that occurred, it would come to 2.45 and 7, respectively.

1.3.2 Relationship among Standard Deviation, Average, and Data Distribution

Now if you see, exactly 66% of the numbers will lie between average plus the standard deviation and average minus standard deviation (7 – 2.45 and 7 + 2.45 [i.e. 4.55 and 9.45]), whereas 94% of the results lie between the average–twice standard deviation and average plus twice standard deviation (7 – 4.9 and 7 + 4.9 [i.e. 2.1 and 11.9]). This is from where the theory has evolved.

Also, it will be seen that 50% of the results lie on either side of average, 83% of results lie above average minus standard deviation ($x'-\sigma$) (since

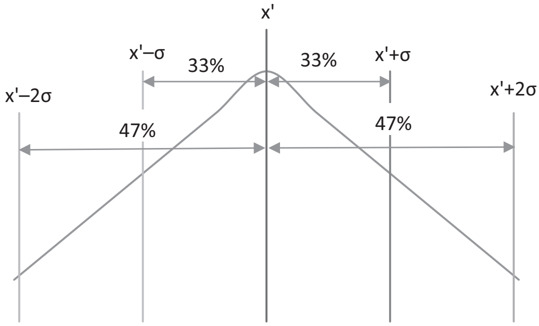


FIGURE 1.2
Normal distribution characteristics with respect to average and standard deviation.

66% lies between avg±stdev, 33% will lie on both sides of average) (refer Figure 1.2), and from here it is derived that 95% of results lie above average minus 1.65 times standard deviation (Figure 1.3). Thus, in the formula, 'Ft = Fck + K · S'.

Ft is the average strength that concrete is assumed to achieve or should achieve, and Fck is the value below which a certain percentage of results will fall, for the corresponding value of *K*.

INTERESTING FACT: It is found that 99.9997% of results fall above average minus six times the standard deviation. This means three results out of 1 million will fall below average-six times the standard deviation. Now the standard deviation is denoted by symbol σ or sigma. From here only the concept of Six Sigma theory has evolved. In the Six Sigma management principle, the target is to get a maximum of three failures out of 1 million products/services.

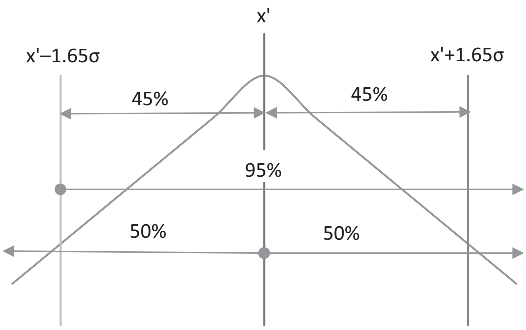


FIGURE 1.3
Normal distribution characteristics and significance of *K* value.

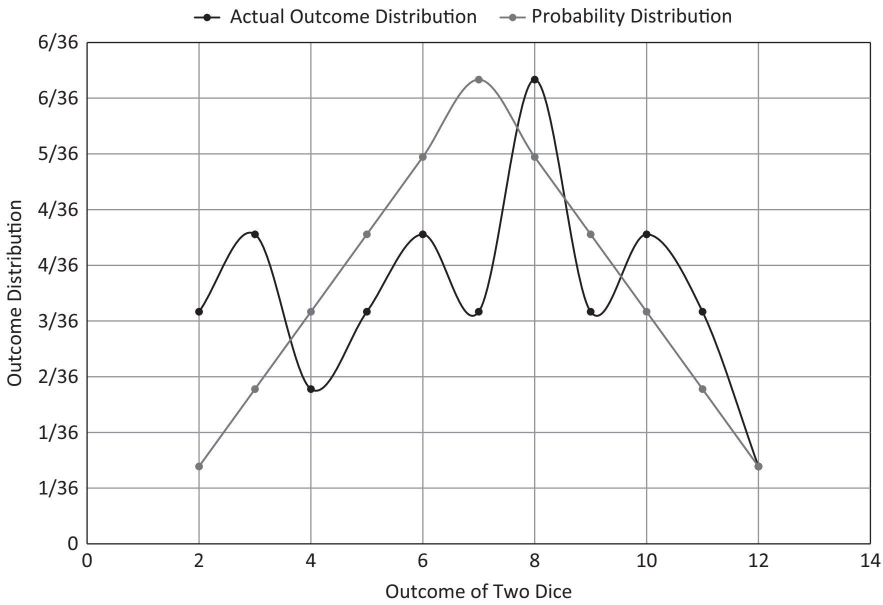


FIGURE 1.4
Case 1: Comparison of actual dice outcomes with respective probabilities for 36 samples.

But, in reality when we actually experimented with a pair of dice and plotted the frequency distribution curve it came out something like that found in Figures 1.4 through 1.6.

The reason that these curves do not exactly look similar to the probability distribution curve is because of the small sample size (poor quality of data). There were cases when only 48% of results lay between average ± standard deviation and also when this proved correct, 91% of results lay between average ± twice the standard deviation. When the same experiment was repeated and the dice were thrown 350 times, the frequency distribution curve looked like Figures 1.7 and 1.8, which resemble a little more like probability distribution curve. And when the dice was thrown 850 times the curve looked like Figures 1.9 and 1.10. Thus, when the sample size increases, the theory starts taking shape.

INTERESTING FACT: A mathematician 'Chebyshev' stated that no matter how poor the quality of data is, the percentage of data lying between average ± k times standard deviation is not less than $1 - 1/k^2$. Thus, between average ± 2 times the standard deviation, minimum 75% of results will fall as per Chebyshev.

Thus, in the target strength formula, the target strength is nothing but the average strength and the characteristic strength is the value above which 95% of the results will fall.

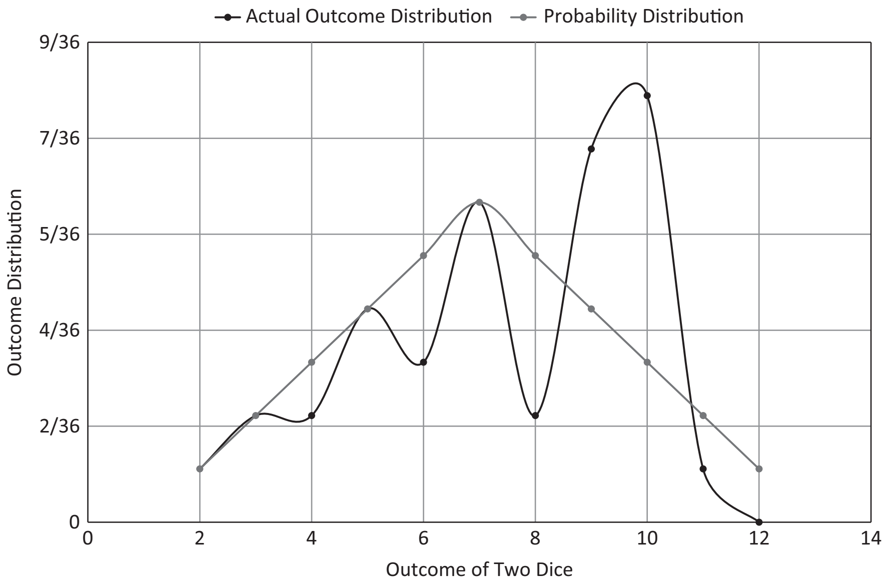


FIGURE 1.5
Case 2: Comparison of actual dice outcomes with respective probabilities for 36 samples.

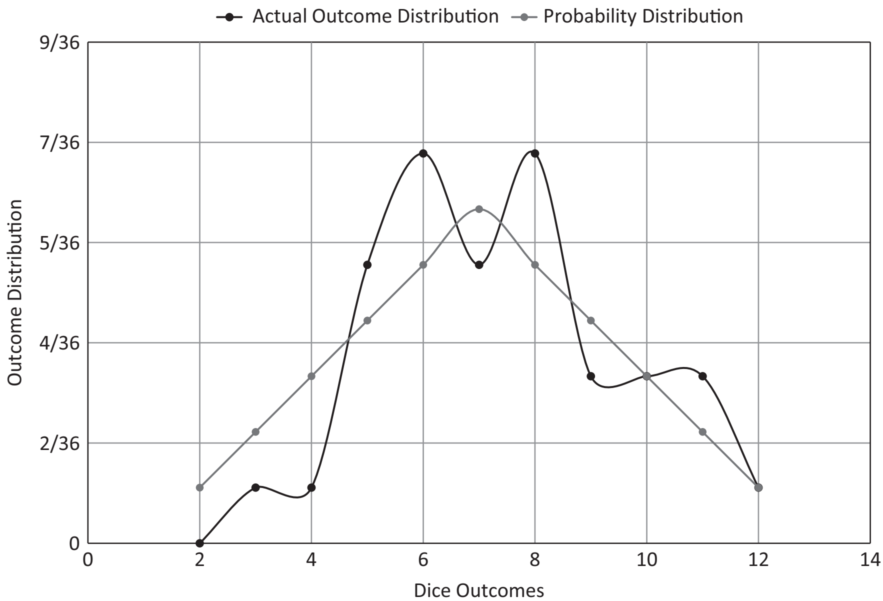


FIGURE 1.6
Case 3: Comparison of actual dice outcomes with respective probabilities for 36 samples.

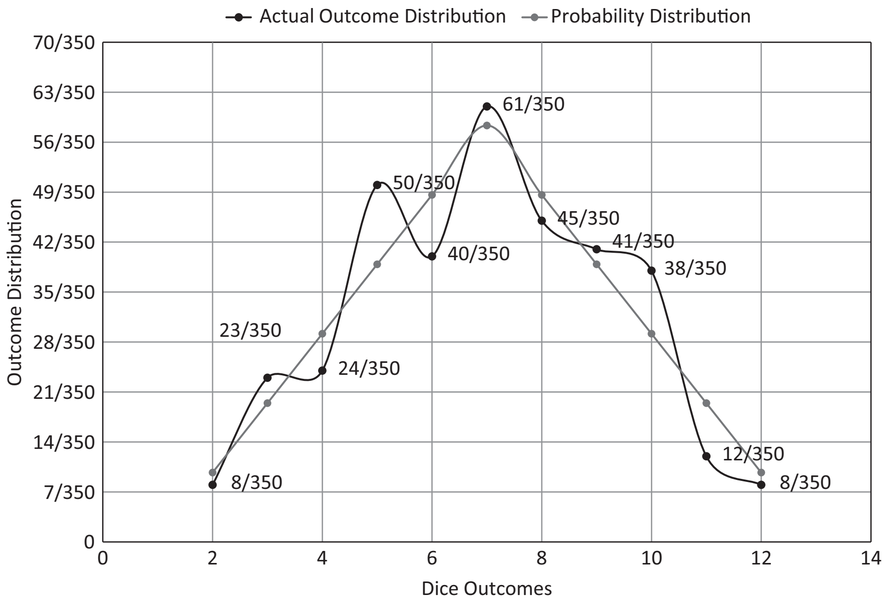


FIGURE 1.7
Case 4: Comparison of actual dice outcomes with respective probabilities for 350 samples.

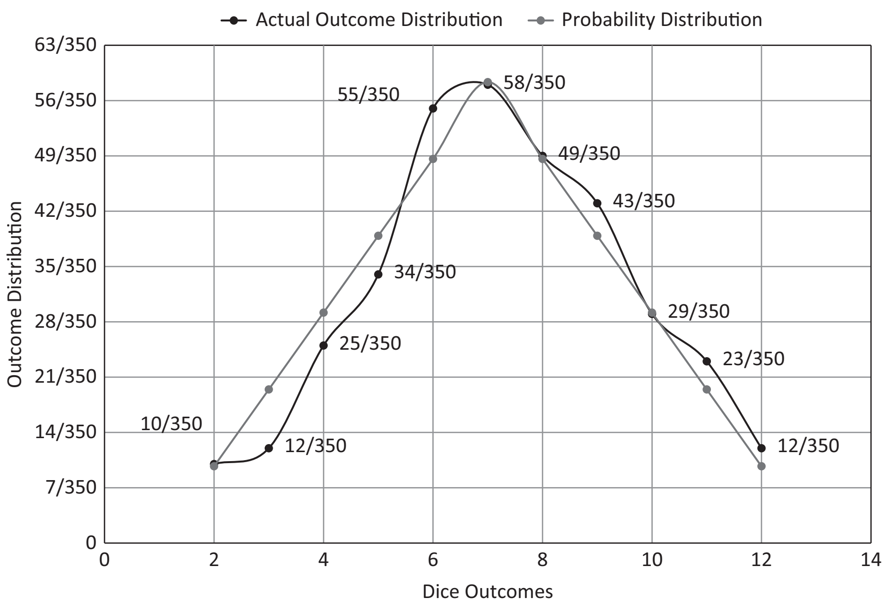


FIGURE 1.8
Case 5: Comparison of actual dice outcomes with respective probabilities for 350 samples.

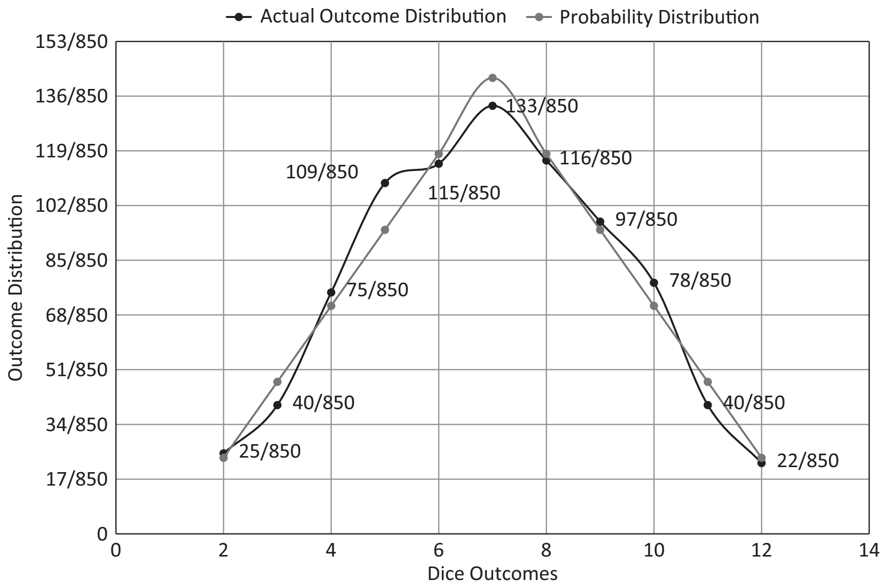


FIGURE 1.9
Case 6: Comparison of actual dice outcomes with respective probabilities for 850 samples.

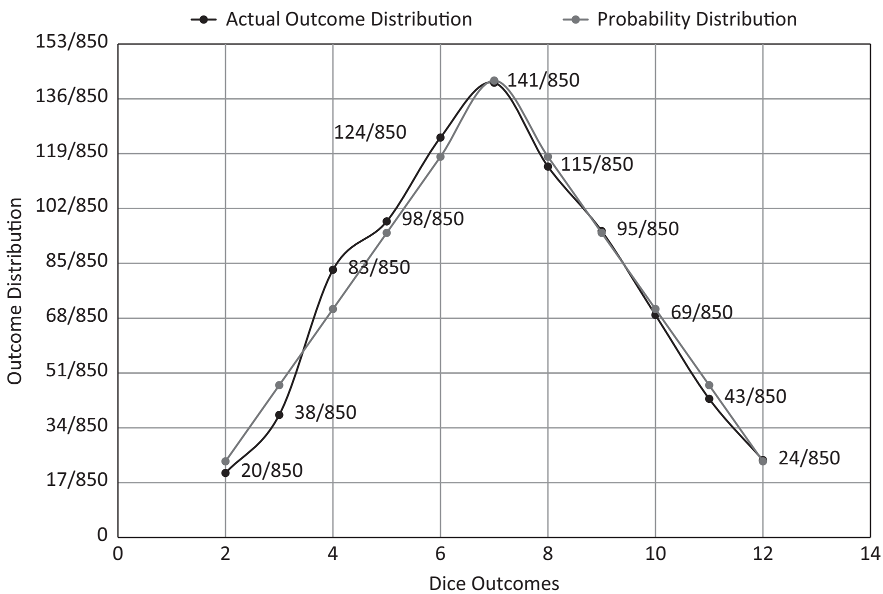


FIGURE 1.10
Case 7: Comparison of actual dice outcomes with respective probabilities for 850 samples.

1.4 Finding Water Cement Ratio for Target Strength

After finding the target strength we need to find out the water-cement ratio, which may give a strength equal to target strength. The water-cement ratio is derived from a curve or guideline provided in various guidelines or standards. These curves provide the water cement ratio for the required strength for the available grade of cement. The curves are based on either Abram's Law, Feret's Law, or Bolomey's Law.

As per Abram's Law

$$\text{Strength of concrete} = A/B^{w/c} \tag{1.1}$$

where A and B are constants depending on the cement being used, W/C is the water cement ratio by mass.

Some Standards have developed and provided curves based on this model for different classes of strength of cement. The values of A and B change for different classes of cement strengths.

Similarly Feret's Equation is:

$$\text{Strength of concrete} = F\ \left[Vc/\left(Vc + Vw + Va\right)\right]^2 \tag{1.2}$$

where F is a constant and Feret proposed a value of 290, Vc is the volume (constituent) of cement, Vw is the volume of water, and Va is the volume of air.

And Bolomey's Equation:

$$\text{Strength of concrete} = L\left(C/W - 0.5\right) \tag{1.3}$$

where L is a constant proposed as a value of 24.6 by Bolomey, and C/W is the cement water ratio.

1.5 Checking the Limits on the Water Cement Ratio

After finding the water cement ratio, the same is to be checked against the limits provided in local standards for durability requirements matching the local conditions. The engineering behind fixing the water cement ratio limit for durability is discussed in Section 1.5.1. Once the water cement ratio is fixed, the water content is decided, again based on guidelines given against the workability required and the maximum size of aggregate to be used for concrete.

1.5.1 Science Behind W/C and Minimum Cement Limit for Durability

The limits given for minimum cement content is based on the principle that the voids between the aggregates should be filled fully with the cement paste, and the standards presume a minimum void that will remain in aggregates after mixing, for worst condition, which when filled fully, will help to retarding the percolation of external threats against durability. Similarly, the maximum water cement ratio is specified to ensure that the cement paste, despite filling up the voids of aggregates, does not become vulnerable and permeable to chlorides or various chemicals, which will lead to shortening the life of the structure.

1.6 Estimation of Water Content

Water content or the quantity of water present in unit volume (usually expressed in 1-m cube) decides the workability of concrete. Higher the water content higher is the workability. Based on this characteristic of water in concrete, many studies have been done and a guideline was developed in all of the mix-proportioning methods across the world, which gives the amount of water for the required workability in concrete. The workability of concrete is also affected by the maximum aggregate size; thus, the water contents suggested are w.r.t. the maximum size of aggregate used. Larger maximum sizes of aggregates give higher workability for the same amount of water. Admixtures also on other hand tend to give higher workability (super plasticizers (SP)/water-reducing agents); the guideline for incorporating them and the changes in water content was not given for a long time, and few standards have given the guideline now. Any Super Plasticizer (SP) has a certain capacity to reduce the water, which is declared by the company manufacturing it. The same percentage reduction is applied to the water content calculated from the guidelines and tested in concrete. Also, some guidelines now have suggested reducing water content by 10% in case fly ash is used as a replacement of cement because fly ash is known to have lesser water demand as compared to concretes made with pure ordinary Portland cement (OPC) on account of its spherical shape.

1.7 Calculation of Cement Content

Based on the described steps, cement content per cubic metre is attained using following step

$$\text{Cement} = \frac{\text{Water content}}{\text{Water cement ratio}} \tag{1.4}$$

The cement content so calculated will include only the cement for which the relationship has been used for calculating the water cement ratio. This means that the graphs of strength versus water cement ratio are for cements of particular strength, and the estimated cement shall be essentially only the cement for which the relation has been used. Many times engineers use this relationship to estimate the cement content and partially replace the cement with fly ash or ground granulated blast furnace slag (GGBFS), which eventually leads to much different strength than that expected from the estimated strength. Hence, it is better to know the relationship between the actual strengths of cementitious combinations with various water cement ratios, then to find the water cement ratio, or else, it is required to calculate mixes with at least three different water cement ratios for cement of unknown strength performance. One can also back calculate the constants of cement in either of Abram's, Feret's, or Bolomey's relation and then estimate the water cement ratio for the required strength. For example, if you had a cementitious mix that gave a strength of 35 MPa at 0.5 w/c and 53 MPa at 0.4 w/c, then the A and B values can be calculated from Abram's Relation just by replacing values of w/c and strength in two equations and solving them to find values of A and B. (Note because there are two unknowns A and B, we need to have two equations. For Bolomey's or Feret's equation, just one set of known variable is enough.)

Writing both the equations we get:

$$S = A/B^{w/c}$$
$$35 = A/B^{0.5}$$
$$53 = A/B^{0.4}$$

Solving these equations we get, A = 278.68 and B = 63.4

Whereas for Bolomey's Equation we would get

$$S = L(C/W - 0.5)$$
$$35 = L(2 - 0.5) \rightarrow L = 23.33$$

The strength it would estimate for water cement ratio of 0.4 would then be

$$S = 23.33\ (1/0.4 - 0.5) = 46.66\ \text{MPa}$$

which does not seem bad as compared to the strength we got of 53 MPa. For finding constants of Feret's equation, we will need to provide more than water cement ratio (i.e. the individual volumes of cement, water, and air).

$$S = F\ [Vc/(Vc + Vw + Va)]^2$$

So here let us say the strength of 35 MPa was achieved at a cement content of 370 kg (370/3.15 = 117.46 L), Water content of 185 kg and 20 mm was the maximum size of aggregate; hence, air content was 2% or 20 L.

$$35 = F\ [117.46/(117.46 + 185 + 20)]^2$$
$$F = 263.78$$

Thus, when the water cement ratio is 0.4 (cement: 463 kg, water: 185 kg), this model would predict a strength of:

$$S = 263.78[146.98/(146.98 + 185 + 20)]^2$$
$$S = 45.99 \text{ MPa (which is similar to Bolomey's Model)}$$

It can be very well understood that Abram's model has higher freedom and can accommodate more types of cement because the slope of the curve can be changed, whereas, in the case of Feret's Equation or Bolomey's Equation, the slope is always the same.

1.8 Aggregate Content

After the water and cement content in concrete for given workability and strength is found, the weight of fillers is all that is needed.

1.8.1 Purpose of Aggregates in Concrete

Aggregates used in concrete, act as fillers and play a vital role in deciding the economy, durability, and many other aspects of concrete. For that, aggregates need to be proportioned carefully, so that 'filling effect' is to the optimum level. Here, filling effect means the maximum possible packing of aggregates per unit volume of concrete, without affecting the ability of compaction of concrete for the given amount of work or external energy.

1.8.2 Proportioning of Aggregates

Aggregates should be so proportioned that the voids of coarse aggregate get filled by smaller aggregates and the resultant voids by next smaller aggregates and so on. Ideally, the filling should be such that the voids left behind are minimum. But as pointed out previously, the filling effect should be optimum, and not maximum, meaning, had the filling up of voids been such a way that the voids are minimum, then the concrete would have become very harsh. Hence, it is always desirable to develop concrete such that the finer aggregates are a little more than that required to get minimum voids. To achieve this result, many methods have been proposed, and the most famous one is the gradation of aggregates. It was proposed that if aggregates are proportioned in particular size distribution, it would give minimum voids. And different standards had different gradation limits. Many standards provide guidelines as a rule of thumb for selecting content of coarse and fine aggregate based on the maximum size of aggregate and sand zone or fineness modulus.

TABLE 1.2
ACI 211-1 Guidelines for Aggregate Proportioning

Nominal Maximum Size of Aggregate mm	Volume of Oven-Dry-Rodded Coarse Aggregate per Unit Volume of Concrete for Different Fineness Modulus of Fine Aggregate			
	2.4	2.6	2.8	3
6.5	0.60	0.48	0.46	0.44
12.5	0.69	0.57	0.55	0.53
20	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
38	0.75	0.73	0.71	0.69
50	0.78	0.76	0.74	0.72
75	0.82	0.80	0.78	0.76
150	0.87	0.85	0.83	0.81

For Example, Coarse aggregate content as per the American Concrete Institue (ACI) for producing pumpable concrete is reproduced in table 1.2.

Also, models for getting the most ideal gradation were proposed, like Thomson's model

$$p = \left(d \div D\right)^{0.5} \tag{1.5}$$

where p is the percentage of finer aggregate (or percentage passing) for each size d (sieve size) when maximum aggregate size is D. The power of 0.5 gives a particular gradation, and if this power is reduced, the gradation of aggregates will tend towards finer grading (i.e. sand content will keep on increasing and coarse aggregates will keep on reducing). Some mix-proportioning software for designing self-compacting concrete (SCC), use the same model, and since SCC requires a higher amount of fines as compared to normal concrete, the power is kept at 0.33. This model was modified even further by various workers. But most of these methods do not take into account the effect of the shape of aggregates. In various studies of particle packing, it was found that the shape of aggregates was more important than the gradation of aggregates to get minimum voids. Flakier aggregates produced higher void volume per unit solid volume as compared to cubical or spherical aggregates. And subsequently, the finer aggregates requirement was higher in flakier aggregates as compared to cubical or spherical aggregates. Various workers have proposed mathematical models to fix or predict the particle-packing characteristics of combinations of aggregates based on their individual test properties viz, void ratio, average particle size, specific gravity, etc. On similar lines, the author also has developed a model that can predict the voids in proportions of aggregates and can help in choosing the most optimum proportion. The author's method discussed later in this book is based on the particle-packing method.

1.8.2.1 Aggregate Proportioning by Gradation or Particle-Size Distribution Method

Now let us discuss the simplest and widely used method of aggregate proportioning (i.e. proportioning aggregates to fit between gradation limits). This method has gained wide acceptability on account of the rise of concrete placement by pumping methods.

The proportioning of aggregates is done by calculating the inter-proportion of aggregates in such a way that all the sizes of the mixture lie between lower and upper limits simultaneously. We shall now see how proportioning is done. Let us say the aggregate particle sizes are available, and they are written as per the following tables: proportions of three aggregates are represented by Tables 1.3 and 1.4, followed by an illustration in Tables 1.5 and 1.6.

1.8.2.2 Explanation for Calculating Combined Gradation

After completing the sieve analysis of the aggregates, weights retained are written in respective columns (columns A, B, and C). Cumulative weight retained is calculated on each sieve by adding up the weight retained on the sieve and all sieves higher in size. The weight passing on each sieve is the total weight of aggregate taken for sieve analysis minus cumulative weight retained on each sieve. The percentage passing or smaller than sieve size is expressed as a percentage of the total weight of aggregate taken for analysis.

Now, we need to find a combination of these aggregates in such a way that sieve analysis of these combined aggregates should fall within the limits provided by the standards. We do this either by mixing those aggregates physically in some proportion and do sieve analysis, or we can calculate the particle-size distribution of each proportion of aggregates with the available test result of individual aggregates. So, for calculating the combined aggregate particle-size distribution, we consider a certain proportion of the aggregates, P, Q, and R (as shown in Tables 1.3 and 1.4). The total of P, Q, and R should be equal to 1 or 100 in percent. To calculate the percentage passing on the first sieve, we multiply P (percentage or proportion quantity of aggregate 1) with the percentage passing of aggregate 1 on first sieve (from the column A2x). Similarly, the proportion quantity of aggregate 2 and 3 are to be multiplied with percentages passing on the first sieve for respective aggregates. The total of these multiples is the percentage passing of combined aggregates in the proportion P/Q/R. Similarly, percentages passing for all aggregates are to be multiplied with P, Q, and R for each sieve size respectively to get the combined percentage passing. It is always better to plot a graph of the combined particle-size distribution on a computer and keep on varying the proportions to check the best proportion to fit between the limits because the graphs are lucid compared to data in tabular form.

TABLE 1.3

Aggregate Proportioning Through Fitting Combined Grading of Aggregates

	Weight Retained			Cumulative Weight retained			Weight Passing			% Weight Passing		
Sieve Size (mm)	**Agg 1 (A)**	**Agg 2 (B)**	**Agg 3 (C)**	**ΣAx**	**ΣBx**	**ΣCx**	**ΣA−Σax (A1x)**	**ΣB−ΣBx (B1x)**	**ΣC−ΣCx (C1x)**	**(ΣA−ΣAx) /ΣA (A2x)**	**(ΣB−ΣBx) /ΣB (B2x)**	**(ΣC−ΣCx) /ΣC (C2x)**
40	a1			a1			ΣA−a1	ΣB−0	ΣC−0	A1x/ΣA	B1x/ΣB	C1x/ΣC
20	a2	b1		a1+a2	b1		ΣA−(a1+a2)	ΣB−b1	ΣC−0	.	.	.
10	a3	b2		a1+a2+a3	b1+b2		ΣA−(a1+.+a3)	ΣB−(b1+b2)	ΣC−0	.	.	.
4.75	a4	b3	c1	a1+..+a4	b1+b2+b3	c1	ΣA−(a1+.+a4)	ΣB−(b1+.+b3)	ΣC−c1	A1x/ΣA	.	.
2.36		b4	c2		b1+..+b4	c1+c2		ΣB−(b1+.+b4)	ΣC−(c1+c2)		.	.
1.18		b5	c3		b1+..+b5	c1+c2+c3		ΣB−(b1+.+b5)	ΣC−(c1+.+c3)		B1x/ΣB	.
0.6			c4			c1+..+c4			ΣC−(c1+.+c4)			.
0.3			c5			c1+..+c5			ΣC−(c1+.+c5)			.
0.15			c6			c1+..+c6			ΣC−(c1+.+c6)			.
0.075			c7			c1+..+c7			ΣC−(c1+.+c7)			C1x/ΣC
Pan												
Total	**=ΣA**	**=ΣB**	**=ΣC**									

Note: Illustrative Formulas for calculating proportion of aggregates.

TABLE 1.4
Continuation of Table 1.3

% Weight Passing			% Proportion of Each Aggregate			
(ΣA–ΣAx)/ ΣA (A2x)	**(ΣB–ΣBx)/ΣB (B2x)**	**(ΣC–ΣCx)/ΣC (C2x)**	**P**	**Q**	**R**	**Combined Aggregate Gradation**
A1x/ΣA	B1x/ΣB	C1x/ΣC	=P.A2x	=Q.B2x	=R.C2x	=P.A2x+Q.B2x+R.C2x
.	.	.	.	.	.	.
.	.	.	.	.	.	.
A1x/ΣA	.	.	=P.A2x	.	.	.
	.	.		.	.	.
	B1x/ΣB	.		=Q.B2x	.	.
		.			.	.
		.			.	.
		.			.	.
		C1x/ΣC			=R.C2x	=P.A2x+Q.B2x+R.C2x

TABLE 1.5

Actual Calculation of Aggregate Combined Gradation Fitting Between Stipulated Limits

	Weight Retained			Cumulative Weight Retained			Weight Passing			% Weight Passing		
Sieve Size (mm)	**Agg 1 (A)**	**Agg 2 (B)**	**Agg 3 (C)**	**ΣAx**	**ΣBx**	**ΣCx**	**ΣA−Σax (A1x)**	**ΣB−ΣBx (B1x)**	**ΣC−ΣCx (C1x)**	**(ΣA−ΣAx)/ΣA (A2x)**	**(ΣB−ΣBx)/ΣB (B2x)**	**(ΣC−ΣCx)/ΣC (C2x)**
40	50			50			4950	5000	1000	99%	100%	100%
20	350	70		400	70		4600	4930	1000	92%	99%	100%
10	4500	450		4900	520		100	4480	1000	2%	90%	100%
4.75	100	4350	20	5000	4870	20		130	980	0%	3%	98%
2.36		100	60		4970	80		30	920		1%	92%
1.18		30	150		5000	230			770		0%	77%
0.6			360			590			410			41%
0.3			290			880			120			12%
0.15			100			980			20			2%
0.075			20			1000						0%
Pan												
Total	**5000**	**5000**	**1000**									

TABLE 1.6
Continuation of Table 1.5

Weight Passing (%)			Proportion of Each Aggregate (%)			
(ΣA–ΣAx)/ ΣA (A2x)	**(ΣB–ΣBx)/ΣB (B2x)**	**(ΣC–ΣCx)/ΣC (C2x)**	**26**	**33**	**41**	**Combined Aggregate Gradation**
99%	100%	100%	25.74	33	41	99.74
92%	99%	100%	23.92	32.538	41	97.458
2%	90%	100%	0.52	29.568	41	71.088
0%	3%	98%	0	0.858	40.18	41.038
	1%	92%		0.198	37.72	37.918
	0%	77%		0	31.57	31.57
		41%			16.81	16.81
		12%			4.92	4.92
		2%			0.82	0.82
		0%			0	0

1.8.2.3 Explanation for Proportion of Aggregates by Absolute Volume

The percentages so found out of aggregates are always the percentage by absolute volume and not by weight or loose volume. The reason for having these proportions as the absolute volume is that the aggregates being used can have different specific gravities. Meaning one aggregate can be heavier than another aggregate for the same absolute volume. So let us say the sand used has a specific gravity of 7 and coarse aggregate has a specific gravity of 2.8, thus for mixing these aggregates by the same proportion in weight, we would end up with 2.5 (i.e. 7/2.8) times less volume of fines for the same weight, had the fine aggregate been of specific gravity of 2.8. It does not matter whether the proportion is by weight or volume, only if all the aggregates have the same specific gravity. Thus, heavier fine aggregates will produce a noncohesive mix and lighter fine aggregates would produce a highly cohesive mix for the same proportion of aggregates by weight for the same particle size distribution.

Example 1.1

Say one set of aggregates (coarse and fine) have specific gravities of 2.6 and 7 for coarse and fine aggregate, respectively. The total weight of the aggregates to be taken is 2000 kg, and the proportion to be used is 60:40 (C/F), then the weights of both aggregates would be 1200 and 800 kg, respectively. But if the aggregate proportions are by absolute volume, then we would calculate the weights as follows:

Total weight of aggregates = 2000 = Volume of coarse aggregates ×

Specific gravity of coarse aggregates + Volume of fine aggregates × (1.6)

Specific gravity of fine aggregates

Volume of coarse aggregate = 60 / 100 × total volume of aggregates (1.7)

Volume of fine aggregate = 40 / 100 × total volume of aggregates (1.8)

From Equations (1.6 through 1.8) we get

$$2000 = 0.6\ \text{V} \times 2.6 + 0.4\ \text{V} \times 7 = 4.36\ \text{V}$$
$$\text{V} = 458.72\ \text{L}$$

Thus, the weight of coarse aggregates = 0.6 × 2.6 × 458.72 = 716 kg
Weight of fine aggregates = 0.4 × 7 × 458.72 = 1284 kg

NOTE: Here the volume of aggregates has been proportioned in the ratio 60:40, and a total of their respective weights are 2000 kg. Normally when mix proportioning is done, calculations are much simpler than this because there the aggregates by volume are proportioned to give a total absolute volume of

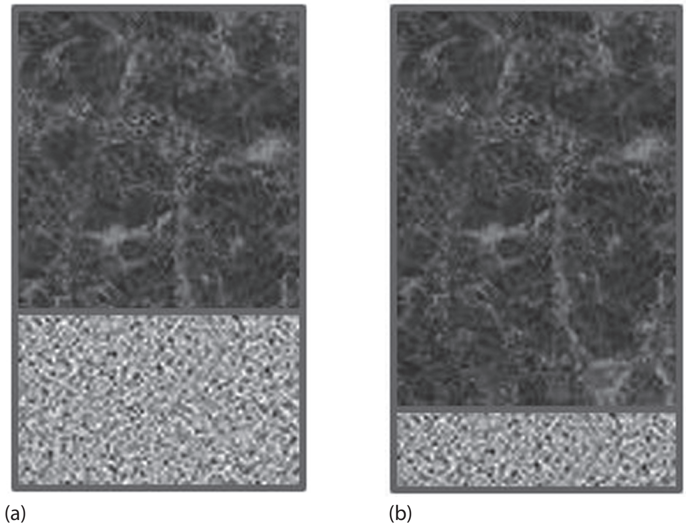


FIGURE 1.11
Comparison of aggregate size distributions for same proportion by volume and weight for sands of much higher specific gravity than coarse aggregate (a) proportion by volume and (b) proportion by weight.

aggregates (here we arrived at the total weight of aggregates) and then finding the weight of total aggregates. Some mix-proportioning methods (Department of Environment method) suggest a total weight of concrete for 1 m^3 from where the weight of total aggregates is deduced and the aggregates are proportioned, to sum up equal to the weight of total aggregates, which may end up erratically many times. Figures 1.11a and b are representations of coarse to fine aggregate proportion by absolute volume and by weight, respectively. The case depicted in Figure 1.11b has a very low amount of sand compared to Figure 1.11a because it has specific gravity much higher (much heavier sand) than coarse aggregate.

1.8.2.4 Challenges Faced in Manual Iteration for Aggregate Proportion

Now when manual iterations are done, to get particle-size distribution fully between upper and lower limits for all aggregates simultaneously, it becomes very tedious and sometimes it is doubtful whether the proportion so chosen is the best to fit between the limits. In such cases, computers have come to help, and these proportions can be found out through iterations on a computer in Excel.

1.8.2.5 Excel Solver Iteration Method

We will see how we can utilize a computer to generate a proportion of the aggregates to fit the particle-size distribution fully between the limits.

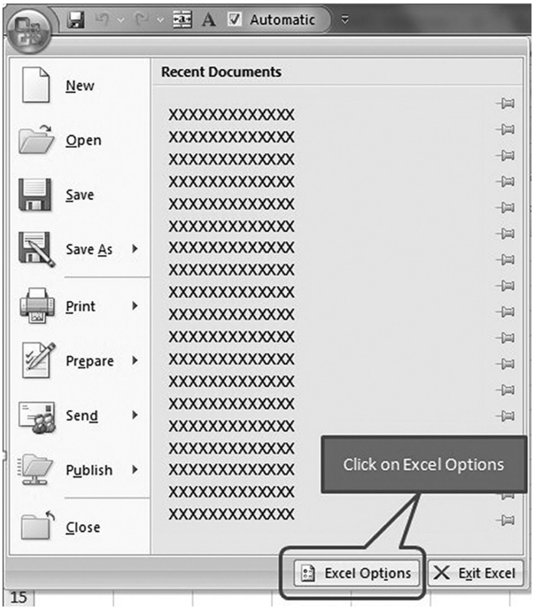


FIGURE 1.12
Step 1 for installing solver in Excel.

Excel has an Add-in called Solver, which needs to be installed first. To do this, follow the steps given in Figures 1.12 through 1.14.

1.8.2.5.1 Installing Solver in Excel

In Excel, click on the Office icon and Excel Options. A window will appear named Excel Options, click on Add-Ins, and then click on Go. A new window appears; select the Solver Add-In option and then click on OK. Excel first asks to install the Add-in (Figure 1.15) click on Yes.

Once it is installed, a new tool will appear under the Data tab (Figure 1.16, 1.17), and now you are ready to use the Solver Add-In (Figure 1.18).

1.8.2.5.2 Utilizing Solver for Aggregate Proportioning

Now key in the aggregate particle-size distribution for all the aggregates in the Excel sheet (where formulas for combined percentage passing for all aggregates are already in place) and go to data tab and click on Solver. You will get the window shown in Figure 1.18. This window has three different inputs, and this tool is used for optimization. The target cell input is for that value parameter which provides the maximum/minimum possible or a certain value. Thus for gradation, keep the cost of aggregates lowest, so in a cell you can multiply the percentage proportion of each aggregate to its respective cost and then total them. For 'Set Target Cell', you can choose this cell and select min. Likewise you can have different parameters to optimize

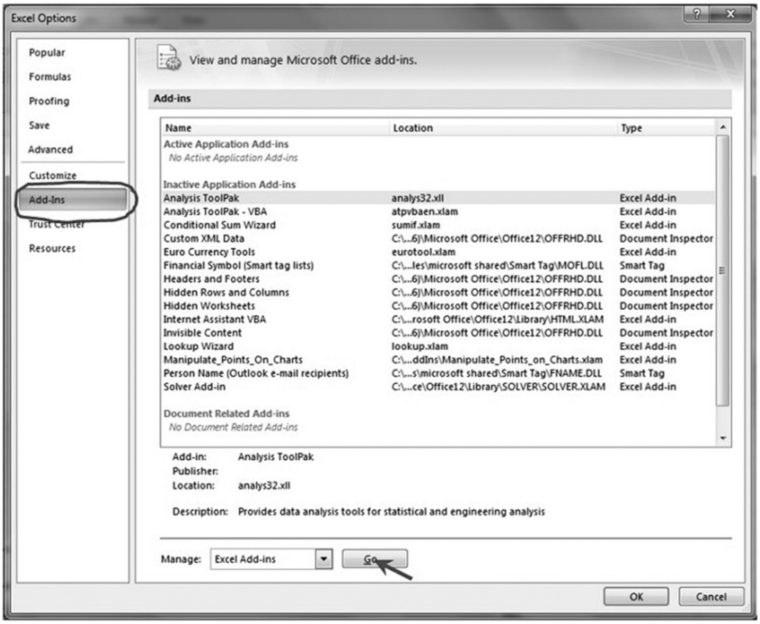


FIGURE 1.13
Step 2 installing solver in Excel.

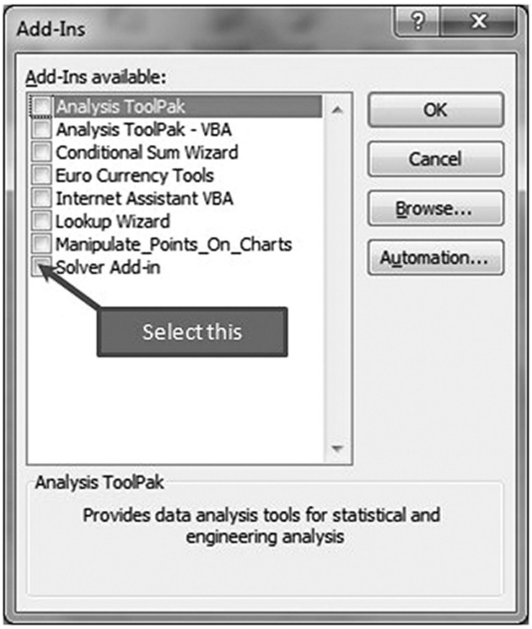


FIGURE 1.14
Step 3 installing solver in Excel.

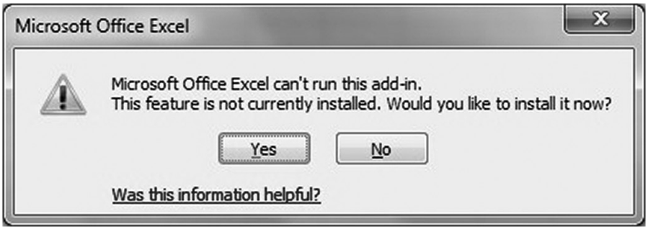


FIGURE 1.15
Step 4 dialogue box for solver installation.

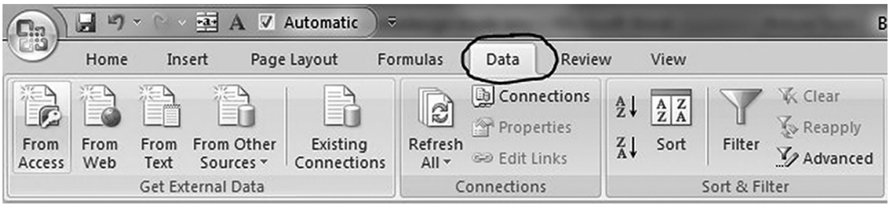


FIGURE 1.16
Installed solver under data tab.

FIGURE 1.17
Solver analysis and solving tool.

FIGURE 1.18
Typical solver window for defining target values, constraints, and variables.

while designing your concrete—perhaps the density of concrete needs to be maximized, and all aggregates have different specific gravities. So in a cell you can write a formula for the combined specific gravities of all aggregates in given proportion, and you can set that as a target cell and select on maximize.

The gradation limits can be met with many proportions, and maximizing or minimizing the target cell converges to just one proportion, that's why providing a target cell value becomes necessary. For example, in Figure 1.19, cell O16 (marked as 'D') has been selected as target cell for minimizing, which is nothing but the cost of each aggregate (marked as 'C') multiplied to its respective percentage proportion (marked as 'B') and their total sum. Remember that the target cell is a formula always and is linked directly or indirectly to the cells to be changed. To select a cell you need to click on the Select symbol just next to input box and then select the cells. Next input is the By Changing Cells, here select the cell values that need to be changed to get the most optimum result; thus, select the cells where proportions are written (marked as 'B'). The proportions that a computer should find must be such that the total of those proportions should be exactly 100%; hence, in a cell the formula of summation of all the proportions (marked as 'A') is keyed in. Now clicking on Solve makes the computer do thousands of iterations by changing the cells selected in By Changing Cells and will try to minimize the target cell. This can be done even by having negative values for proportions and with sum not equal to 100, which for obvious reasons is not required. Thus, the constraints should be defined for the parameters of proportion (i.e. they should not be negative and their sum should be 100). Next to the Subject to constraints box is the button Add, which when clicked on opens

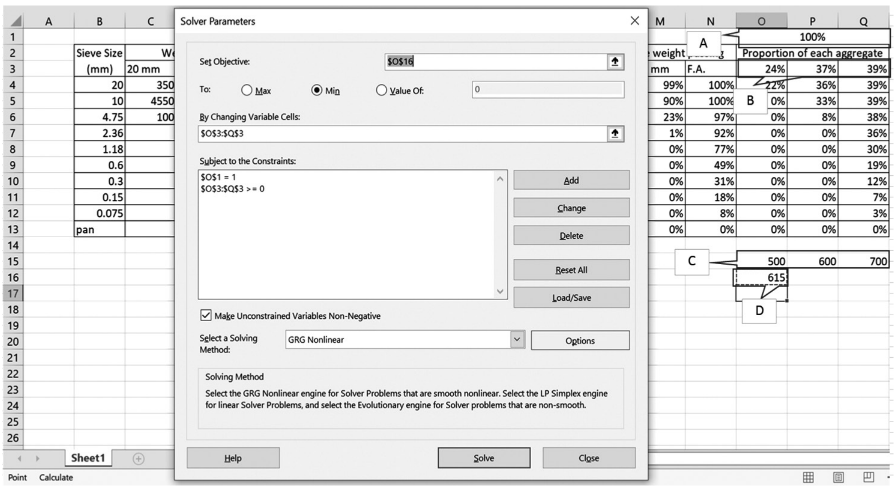


FIGURE 1.19
Example of solver for finding the best aggregate combination to fit the grading requirements.

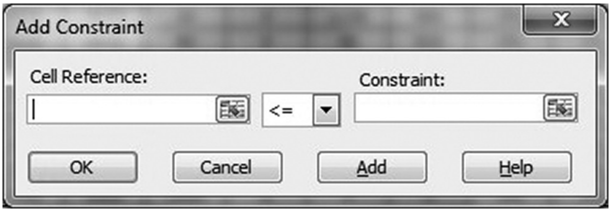


FIGURE 1.20
Solver window for defining constraint.

the window shown in Figure 1.18. In our case now, the constraints are that (i) none of the proportions must be negative, (ii) the sum of all the proportions must be 100, and (iii) the particle size distribution of combined aggregates should meet both the lower and upper limits simultaneously. These constraints need to be defined in the 'Add Constraint' dialogue box, where, in 'cell reference' the cells that meet the constraints are chosen; in the middle box, the comparator (i.e. =/</>) is selected, and in the constraint box, the required number or limit is entered.

Figure 1.20 and 1.21 explain how these constraints are fed into the computer. After defining all the constraints, click on "Solve" in the solver window (Figure 1.18). The Solver finds the proportion of aggregates with minimum cost, fitting between both lower and upper limits of aggregate gradation limits, without choosing a negative proportion (Figure 1.21). These are not the only constraints that can be used for finding the proportion of aggregates; different parameters may be adjusted, and if something goes wrong,

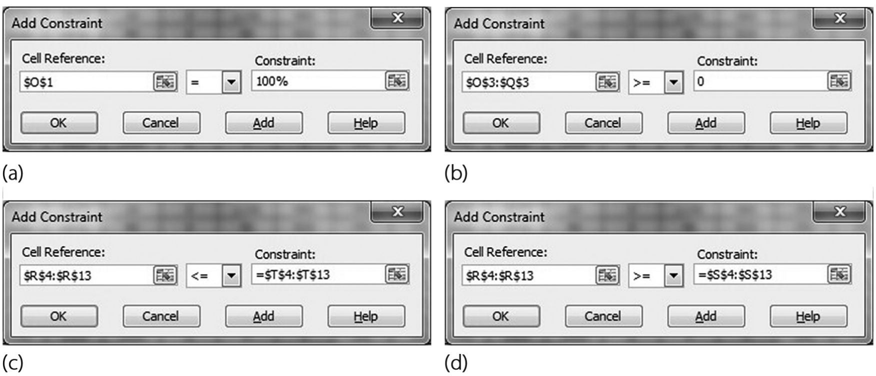


FIGURE 1.21
Example of defining constraints for finding the proportion of aggregates (a) constraint stating total of all proportions should equal to 100%, (b) constraint specifying none of the proportions selected should be negative, (c) constraint specifying all sizes percentages passing should be less than the maximum limit for each size, and (d) constraint specifying all sizes percentage passing should be more than the minimum limit for each size.

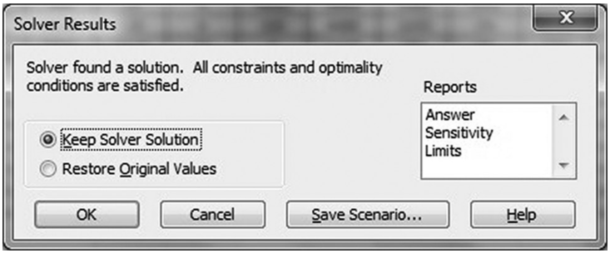


FIGURE 1.22
Solver window after finding the optimum solution against the specified constraints and targets.

correcting or adding the constraints may also be tried. Once solver finds the proportion, you get a window as shown in Figure 1.22.

Try designing concrete with minimum density where fine aggregate has a specific gravity of 2.4, 20 mm has a specific gravity of 2.9, and 10 mm has a specific gravity of 2.7. The proportion that you will find for the same aggregates with same particle-size distribution shall be different than what you will find by minimizing the cost.

1.8.3 Calculating the Aggregate Content

The weights of aggregates are found based on the absolute volume method. The basic concept is that the volume of total concrete is equated with individual absolute volumes of aggregates, cement, and water (if more materials are used, they too are considered for calculation, which we will discuss in detail once the basic concept is clear). To understand this concept properly, we need to remember just one relationship

$$\delta = \text{Mass} \div \text{Volume} \tag{1.9}$$

where δ is *absolute* density.

Now for concrete we can say that:

Volume of 1 cubic metre of concrete = Absolute volume of cement required for 1 cubic metre of concrete + Absolute volume of water required for 1 cubic metre of concrete + Absolute volume of total aggregates for 1 cubic metre of concrete + Volume of entrapped air

Or Volume of concrete = Total of all individual material absolute volumes

1.8.3.1 Air Content in Concrete

It should be noted here, that it is not possible to eliminate air out of concrete, no matter how well the concrete is compacted. Hence, we accommodate for

TABLE 1.7

Air Content to be Considered in Concrete

Maximum Aggregate Size	% Entrapped Air
10 mm	3%
20 mm	2%
40 mm	1%

this volume also when designing concrete proportion. We can consider following contents of air while designing concrete for different maximum sizes of aggregates (Table 1.7).

The entrapped air is inversely proportional to maximum size of aggregate. Entrapped air depends on other parameters also, like the gradation of aggregates (if fines are not sufficient, many voids will be left unfilled resulting in entrapped air), shape of aggregates (flaky and angular aggregates tend to create hindrance in getting proper compaction), and texture of aggregates. The mix-proportioning method seems to take care of all parameters for reducing the entrapped air, except the maximum size of aggregate parameter. Hence, a different entrapped air is assumed for each maximum size of aggregate for concrete.

1.8.3.2 Entrapped Air Compared with Entrained Air

While designing concrete, it is necessary to understand the differences between *entrained air* and entrapped air. As the name suggests, entrained air is something that is done deliberately, and entrapped air is something that is left behind without any intention. Entrapped air could be of any shape because it is air entrapped somewhere between the aggregates and cement paste, whereas entrained air is due to air entraining admixture which creates millions of micro spherical air bubbles inside the cement paste of concrete.

1.8.3.2.1 Equation for Aggregate Content

Thus, the equation for calculating aggregate content for concrete with a maximum size of aggregate as 20 mm becomes

$$1 = \text{Absolute cement vol} + \text{Abs vol of water} + \text{Abs vol of total aggregates} + \text{Abs vol air}$$

$$\text{Absolute volume} = \text{Mass}/\text{Absolute density of material}$$

Thus,

$$1 = \text{Cement mass}/\text{Abs cement density} + \text{Mass of water} + \text{Agg mass}/\text{Abs agg density} + \text{Air} \tag{1.10}$$

Now the absolute volume of total aggregates can be expressed as:

$$\text{Absolute volume of aggregates} \times \text{Percentage of fine aggregates} = \text{Absolute volume of fine aggregate}$$

$$\text{Absolute volume of fine aggregate}/\text{Percentage of fine aggregate} = \text{Absolute volume of aggregates}$$

denoting fine aggregate mass as Fa, density of fine aggregate as d, and percentage of fine aggregate as p, we can rewrite the equation as,

$$1000 = C/dc + W + Fa/(d \cdot p) + A \tag{1.11}$$

Similarly, for calculating coarse aggregates we can write equation (1.11) as,

$$1000 = C/dc + W + Ca/\left[d_{ca} \cdot (1 - p)\right] + A$$

where Ca is the mass of coarse aggregate, d_{ca} is the absolute density of coarse aggregate, and p is percentage fine aggregate of total aggregate.

In case the mix proportioning needs to incorporate additional materials, namely fly ash or micro silica, the same can be added into the preceding equations.

Concrete mix proportioning broadly is only this. But the real challenge lies in meeting the various requirements with the most economical solution.

Table 1.8 is a ready reckoner for different properties of concrete against the mix-proportion parameter.

TABLE 1.8

Reckoner for Mix–Proportion Parameter and Its Effect on Concrete Property

Property of Concrete	Mix–Proportion Parameter	Definition
Strength	Strength of cement	Tested as per standard
Strength	Water cement ratio	Ratio of total mass of free water to mass of cement per cubic metre of concrete
Workability	Water content	Total free water available per cubic metre of concrete
Workability	Maximum size of aggregate	The largest nominal size of aggregate used for manufacture of concrete
Workability	Shape of aggregate	Example: Flaky, rounded, cubical, elongated
Workability	Texture of aggregate	Example: Smooth surface, rough surface

The properties mentioned in table 1.8 are the only parameters against the mentioned properties taken into account for mix proportioning of concrete, whereas in concrete practically there are many more factors that govern the properties in the fresh and hardened state.

Example 1.2: On General Method of Concrete Mix Proportioning

Design a concrete with characteristic strength of 30 MPa, the maximum size of aggregate being 20 mm, where a standard deviation of 5 should be considered. Use Feret's relation, with F as 290, to calculate the materials that will provide you the required strength. The workability required is 120 mm, which can be achieved by a water content of 205 kg/m^3 of concrete, and using admixture reduces water by 15%. Proportion the aggregates based on as given in Table 1.5, following Thomson's model (equation 1.11) with a power of 0.45 instead of 0.5. The specific gravity of coarse aggregates is 2.9 both 20 and 10 mm, and that of fine aggregate is 2.55.

Solution

As the characteristic strength is 30 MPa, the target strength shall be

$$Ft = 30 + 1.65 \times 5 = 38.25 \text{ MPa}$$

Feret's equation is

$$S = F\,[Vc/(Vc + Vw + Va)]^2$$

Now the volume of water to be used is 205 L and as the maximum size of aggregate is 20 mm, consider the volume of air as 20 L (2% of 1 cubic meter). Thus, rewriting Feret's Equation we get:

$$38.25 = 290\,[Vc/(Vc + 205 + 20)]^2$$

Solving the equation we get the volume of cement as 128.2 L; thus, the weight of the cement is 404 kg (128 × 3.15 [i.e. the specific gravity of cement]).

But we can add admixture into concrete that can give the same workability at 15% reduced water content (i.e. 205 × 0.85 = 174 kg). Calculating the new cement content:

$$38.25 = 290\,[Vc/(Vc + 174 + 20)]^2$$

Solving this equation we get the volume of cement as 110.65 L and the weight as 349 kg (observe the reduction in cement content because of reduction in water and also the savings in the cost of concrete).

Next, we need to calculate the aggregate weights for which we know that the total of all volumes should equal to 1 m^3, and the quantities of cement and water calculated will perform only if they constitute 1 m^3 of concrete not more or less. For this, find out the volume of the materials (cement and water) and subtract it from 1 m^3 including the volume of air (i.e. 20 L).

Volume of aggregates + Vol of cement + Vol of water + Vol of air = 1 m^3 or 1000 L

1000 = Vol of agg + 110.65 + 174 + 20

Vol of agg = 1000 − 110.65 − 174 − 20 = 695.35 L

Now, we need to find the individual weights of aggregates. For that, the sieve analysis of the aggregates is derived and the proportion in which they are required to be in needs to be found. For proportioning of the aggregates, we are supposed to follow Thomson's model with a power of 0.45. For this, we can find the proportions through manual iterations, as explained previously, or once the sieve analysis is fed into the computer, Solver can be used to find out the closest particle-size distribution to the ideal curve.

Figures 1.23 and 1.24 show how the formulas are fed into the computer and Figure 1.25 shows the proportions after solver converges to the closest PSD to ideal grading. Note, in the Excel sheet, the difference of ideal curve and actual has been kept absolute (the difference will always be positive), and the sum of these differences is added and minimized. This is for ensuring the least difference between the actual and ideal curve.

The proportions found out for Agg1, Agg2, and Agg3 is 0.24:0.35:0.41. Based on the sieve analysis it should be evident that Agg1 is the coarsest aggregate, and Agg3 is the finest aggregate. Also, Agg1 seems like 20 mm nominal size aggregate, whereas Agg3 is the fine aggregate (Figure 1.26). Thus, the volume of Agg1 in 695.35 L of total aggregates is

$$\text{Agg1} = 0.24 \times 695.35 = 166.88 \text{ L}$$

And weight is this volume multiplied by the specific gravity

$$\text{Agg1} = 166.88 \times 2.9 = 484 \text{ kg}$$

Similarly,

$$\text{Agg2} = 0.35 \times 695.35 \times 2.9 = 706 \text{ kg}$$

$$\text{Agg 3} = 0.41 \times 695.35 \times 2.55 = 727 \text{ kg}$$

	A	B	C	D	E	F	G	H
1			% Passing					
2		Agg1	Agg2	Agg3				
3	Sieve Size	0.236199623820202	0.350599277617244	0.413202044622389	=SUM(B3:D3)	Actual Gradation	Ideal grading	difference between ideal & actual
4								
5	40	0.99	1	1				
6	20	0.92	0.986	1		=B6*B$3+C6*C$3+D6*D$3	=(A6/20)^0.45	=ABS(F6-G6)
7	10	0.02	0.896	1		=B7*B$3+C7*C$3+D7*D$3	=(A7/20)^0.45	=ABS(F7-G7)
8	4.75	0	0.026	0.98		=B8*B$3+C8*C$3+D8*D$3	=(A8/20)^0.45	=ABS(F8-G8)
9	2.36	0	0.006	0.92		=B9*B$3+C9*C$3+D9*D$3	=(A9/20)^0.45	=ABS(F9-G9)
10	1.18	0	0	0.77		=B10*B$3+C10*C$3+D10*D$3	=(A10/20)^0.45	=ABS(F10-G10)
11	0.6	0	0	0.41		=B11*B$3+C11*C$3+D11*D$3	=(A11/20)^0.45	=ABS(F11-G11)
12	0.3	0	0	0.12		=B12*B$3+C12*C$3+D12*D$3	=(A12/20)^0.45	=ABS(F12-G12)
13	0.15	0	0	0.02		=B13*B$3+C13*C$3+D13*D$3	=(A13/20)^0.45	=ABS(F13-G13)
14							Total	=SUM(H6:H13)

FIGURE 1.23
Illustration of Excel sheet for finding optimum aggregate proportion and sieve analysis calculations through solver for the illustrative Example 1.1.

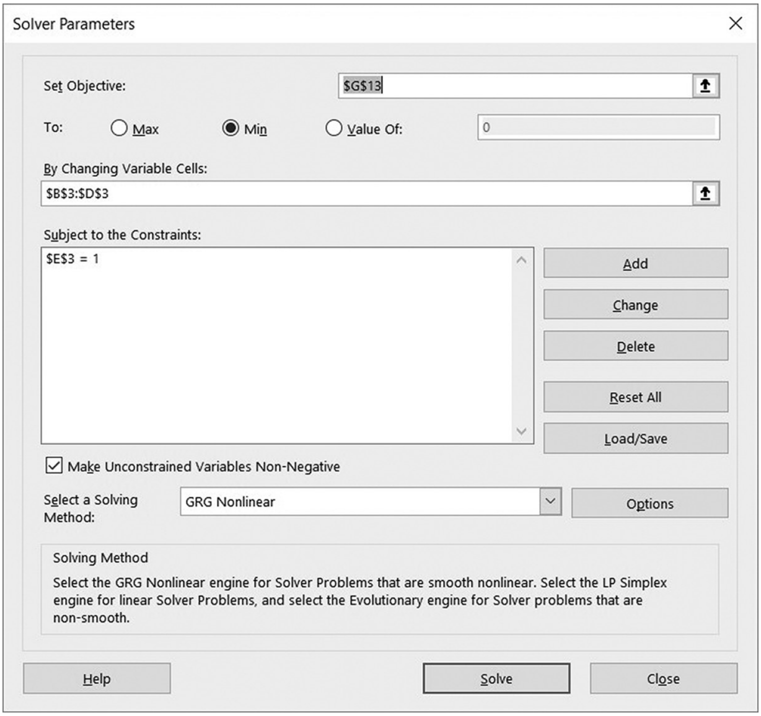


FIGURE 1.24
Solver window for solving the illustrative Example 1.1.

	A	B	C	D	E	F	G	H
1			% Passing					
2		Agg1	Agg2	Agg3				
3	Sieve Size	0.2362	0.350599	0.413202	1	Actual Gradation	Ideal grading	difference between ideal & actual
4								
5	40	99%	100%	100%				
6	20	92%	99%	100%		97.62%	100%	0.023803414
7	10	2%	90%	100%		73.21%	73%	2.01419E-05
8	4.75	0%	3%	98%		41.41%	52%	0.10960548
9	2.36	0%	1%	92%		38.22%	38%	3.28465E-09
10	1.18	0%	0%	77%		31.82%	28%	0.038342576
11	0.6	0%	0%	41%		16.94%	21%	0.036984724
12	0.3	0%	0%	12%		4.96%	15%	0.101507614
13	0.15	0%	0%	2%		0.83%	11%	0.102341674
14							Total	0.412605629

FIGURE 1.25
Outcome of optimum aggregate proportion based on the illustrative Example 1.1.

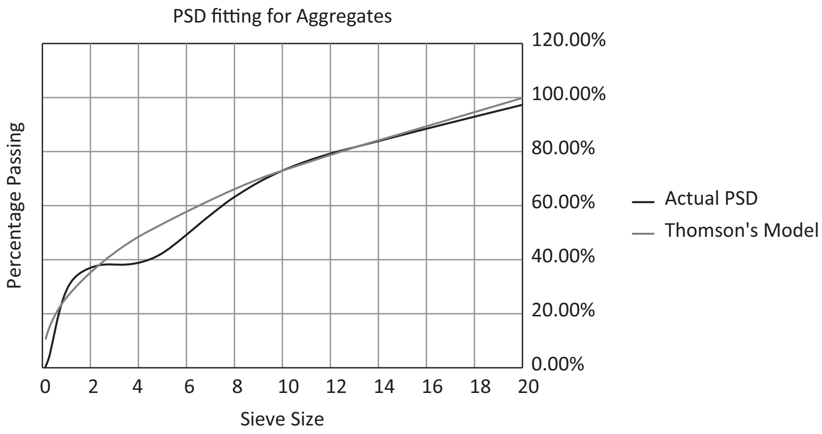


FIGURE 1.26
Graphical Representation for Combined Aggregate particle size distribution w.r.t. Ideal grading (Thomson's Model) from Example 1.1.

Thus, the entire mix proportion can be summarized as:

Cement: 349 kg
Water: 174 kg
20 mm: 484 kg
10 mm: 706 kg
Fine aggregate: 727 kg
Admixture (1% of Cement): 3.49 kg

Example 1.3

Design concrete for the grade of M40 (acceptable failure rate is 5%) for pavement quality concrete (PQC, a slump of 40 mm water content of 160 kg/m^3) for roads and also for normal conventional concrete with a slump of 120 mm (water content of 186 kg/m^3). The standard deviation that can be considered for the preliminary design is 6 MPa. The minimum cementitious content required is 350 kg and the maximum water cement ratio allowed is 0.45. The cement gave a strength of 22 MPa, in concrete at a water cement ratio of 0.56 and 38 MPa at w/c of 0.45. The aggregates to be used are the same as in Table 1.5, and in PQC, a coarser grading is required; hence, Thomson's model power to be taken is 0.5, whereas in normal concrete a power of 0.45 is good (Figure 1.27). The specific gravity of the aggregate can be taken as 2.8, 2.9, and 2.58 for 20 mm, 10 mm, and fine aggregates, respectively. You can use an admixture that gives a water reduction of 15% when 1.2% of its dosage is used.

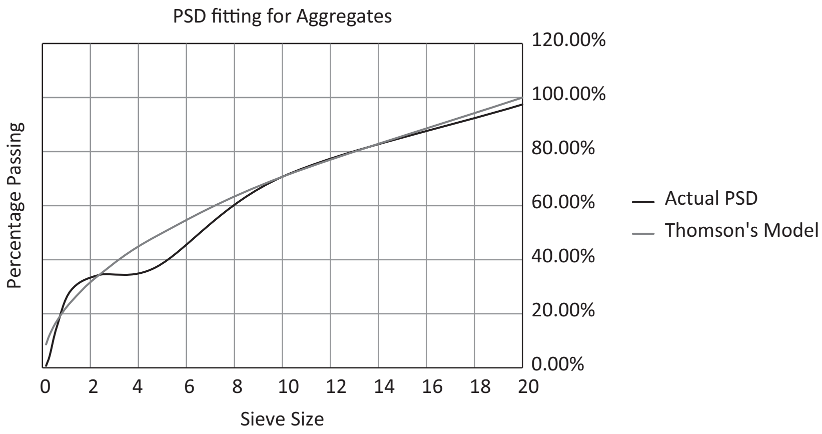


FIGURE 1.27
Graphical Representation for Combined Aggregate particle size distribution w.r.t. Ideal grading (Thomson's Model) from Example 1.2.

Solution

$$Ft = 40 + 1.65 \times 6 = 49.9 \text{ MPa}$$

Now we need to find the water cement ratio, such that we get a strength of 49.9 MPa (target strength). We have right now the data of behavior of cement of strength w.r.t water cement ratio. Thus, we can use Abram's relationship and find out the values of A and B.

$$22 = A/B^{0.56}$$
$$38 = A/B^{0.45}$$

Solving both these equations we get A = 355.47, B = 143.82.

$$49.9 = 355.47/143.82^{x}$$

Solving this equation

We get $x = 0.395$ (i.e. water cement ratio)

NOTE: As the grade of concrete is same, for both PQC and normal concrete, so shall be the target strength, leading to the same water cement ratio for both the concrete.

Water content required for a slump of 40 mm in PQC is 160 kg and with admixture 15% reduction is possible, hence

Cement content for PQC = Water content/Water cement ratio
Cement content for PQC = $(160 \times 0.85)/0.395 = 344$ kg
Cement content for normal concrete = $(186 \times 0.85)/0.395 = 400$ kg

NOTE: Even though the grades of concrete are the same, but due to change in the requirement of workability, the cement content requirement to fulfill the properties has changed drastically. Hence, it should be borne in mind, that strength and workability together decide the cement content of concrete.

Aggregate volume for PQC = 980 – 344/3.15 – 136 – 20 = 714.79 L
Aggregate volume for normal concrete = 980 – 400/3.15 – 158 – 20
= 675 L

The ideal curve shall however change as compared to the previous example, where instead of the formula $(d/D)^{0.45}$ (in column G of the Excel sheet, fig 1.25), we will have to replace the power by 0.5, and all the parameters of the solver will remain the same. Thus for a power of 0.5, we would get a proportion of 0.26:0.37:0.37 (20 mm:10 mm:Fine Aggregate) for PQC, whereas for normal concrete we can with the same proportion as in previous example (i.e. 0.24:0.35:0.41).

Weight of 20 mm in PQC = 714.79 × 0.26 × 2.8 = 520 kg
Weight of 10 mm in PQC = 714.79 × 0.37 × 2.9 = 767 kg
Weight of fine agg in PQC = 714.79 × 0.37 × 2.58 = 682 kg

Whereas in Normal Concrete

Weight of 20 mm = 675 × 0.24 × 2.8 = 454 kg
Weight of 10 mm = 675 × 0.35 × 2.9 = 685 kg
Weight of fine agg = 675 × 0.41 × 2.58 = 714 kg

The mix proportioning for both the concretes of M40 grade are

Material	**M 40 PQC**	**M 40 Normal Concrete**
Cement	344 kg	400 kg
Water	136 kg	158 kg
Admixture	4.13 kg	4.8 kg
20 mm	520 kg	454 kg
10 mm	767 kg	685 kg
Fine aggregate	682 kg	714 kg

2

Proportioning Concretes: Rapid Method

2.1 Introduction

This chapter covers the procedure for concrete mix proportioning and what aspects of proportion are changed to get a desired property in the concrete. Abrams gave an empirical rule on strength of concrete and the water cement ratio, which has been exploited in this chapter to derive the concrete proportion for the required strength. Moreover aggregate proportioning requires remembering or access of gradation limits, which has been replaced by the Fuller and Thomson model and is very easy to remember and can be utilized for proportioning almost any material to get conventional concrete. Moreover, the proportion of aggregates for given materials should never be the same for different grades of concrete, if the cement contents are different. This chapter discusses strategies to proportion aggregates by reducing fine aggregate proportion w.r.t coarse aggregates with increasing cement content and vice versa.

2.2 Calculation of Target Strength

As per this method, first, the target strength of concrete is derived from the following formula, which was discussed in detail previously in 1.2.

$$\mathrm{Ft} = \mathrm{Fck} + \mathrm{K} \cdot \mathrm{S}$$

The value of K is always 1.65, unless and until the acceptable percentage of failure is different from 5%. The value of K is taken from Table 2.1 based on an acceptable percentage of failure.

The standard deviation is to be assumed based on Equation 2.1, and the target strength is found out.

$$\text{Standard deviation} = 1.3\mathrm{Ln}\left(1.2\mathrm{Fck}\right) \tag{2.1}$$

TABLE 2.1

K Value for Acceptable Failures

Accepted Proportion of Low Results	K
1 in 5	0.84
1 in 10	1.28
1 in 15	1.50
1 in 20	1.65
1 in 40	1.86
1 in 100	2.33

The standard deviation formula is based on conditions of least variation by good quality control at a site, which includes moisture correction at frequent intervals, acceptance of materials within clearly specified upper and lower limits, etc. In case the confidence in quality does not seem ok, the standard deviation value can be increased by 1 MPa.

Thus, the target strength for a characteristic strength of 40 would be calculated as follows:

$$\text{Standard deviation} = 1.3\ \ln(1.2\text{Fck}) = 1.3\ \ln(1.2 \times 40) = 5.03\ \text{MPa}$$

$$\text{Target Strength (Ft)} = 40 + 1.65 \times 5.03 = 48.3\ \text{MPa}$$

2.3 Estimating Water Cement Ratio for Achieving the Strength

Next, the water cement ratio is determined for the required target strength. The water cement ratio can be found from the function given in Equation 2.2.

$$\text{W/C} = \left[\ln(\text{Ft}) + 0.00023\,\text{Cs}^2 - 0.0405\text{Cs} - 3.546\right] / \left[0.0076\,\text{Cs} - 3.65\right] \qquad (2.2)$$

where w/c is the water cement ratio of concrete, Ft is the strength of concrete desired (target strength), and Cs is a variable usually equal to the strength of cement when tested as per standard or the value provided against cement strength at 28 days in the manufacturer's test certificate. The value of Cs has to be calibrated in the formula by actually testing concrete with certain w/c and feeding the respective strength in the formula. This formula is also true for designing concrete for strength at any age, the only difference being Cs value for the same concrete will be different for different ages. In case the concrete has to be designed for 3-days strength of 20 MPa, either find the cement strength at 3 days when tested as per standard and substitute the same in formula, or make a batch of concrete for certain water cement ratio, test the strength of concrete at 3 days, and substitute the Ft value with the achieved strength, to figure out Value of Cs.

Example 2.1

Concrete made with water cement ratio of 0.42 gave a strength of 33 MPa at 7 days. The required strength is 39 MPa at 7 days, find the water cement ratio.

Solution

$$W/C = [\ln(Ft) + 0.00023\,Cs^2 - 0.0405Cs - 3.546]/[0.0076\,Cs - 3.65]$$
$$0.42 = [\ln(33) + 0.00023\,Cs^2 - 0.0405Cs - 3.546]/[0.0076\,Cs - 3.65],$$

thus solving for Cs

$$Cs = 44.22\text{ MPa}$$

Thus, to get a strength of 39 MPa at 7 days instead of 33 MPa, the required water cement ratio would be

$$W/C = [\ln(39) + 0.00023 \times 44.22^2 - 0.0405 \times 44.22 - 3.546]/[0.0076 \times 44.22 - 3.65]$$
$$W/C = 0.37$$

The water cement ratio is then checked against the maximum limit prescribed in the technical specifications from the specifier or for existing exposure condition as prescribed in the local building codes, and the minimum of both is taken.

NOTE: During tests, it is always preferable to test concrete for at least two different water cement ratios, between which the required strength is more likely to be expected. The exact water cement ratio can be interpolated from Equation 2.2.

2.4 Estimating the Water Content and Aggregate Interproportions

$$\text{Water} = 0.223\text{ slump} - 30\ln(\text{MSA}) + 264 \quad (2.3)$$

$$\text{Water} = 0.228\text{ slump} - 30\ln(\text{MSA}) + 257 \quad (2.4)$$

Next, the water content is found and is based on Equations 2.3 or 2.4, whichever is applicable. Equation 2.4 is to be used only when the cement content (in the next step) is higher than 450 kg for 20 mm MSA and 500 kg for 10 mm MSA for any other case, eqn 2.3 is to be used. The water content calculated for the required workability is the water to be added into concrete, in addition to the water that will be required to bring the aggregates to saturated surface dry condition from its natural condition. Saturated-surface dry (SSD) is a condition in which all the pores of the aggregates are filled with water, but the surface of aggregate is fully dry. If the aggregates in natural condition are wetter than SSD condition, water has to be deducted from the values calculated, and if it is drier, then additional water should be added. The steps are thoroughly explained in Chapter 8. The formulas given for water content are based on a visual rating of aggregates of 3 as per Figure 2.1.

Once the water content is determined for given materials and required workability, further reduction of water may be required if water reducing admixture and fly ash are used. In case, fly ash is to be used, the following formula gives the reduction in water content based on the percentage of fly ash to be used for replacement of ordinary Portland cement (OPC).

$$\text{Corrected water} = W / 10\hat{\ }(0.0013p) \tag{2.5}$$

where W is the water content found out for MSA and corrections for a visual rating in the previous step, and p is the percentage of fly ash used as OPC replacement and limited to 50% replacement.

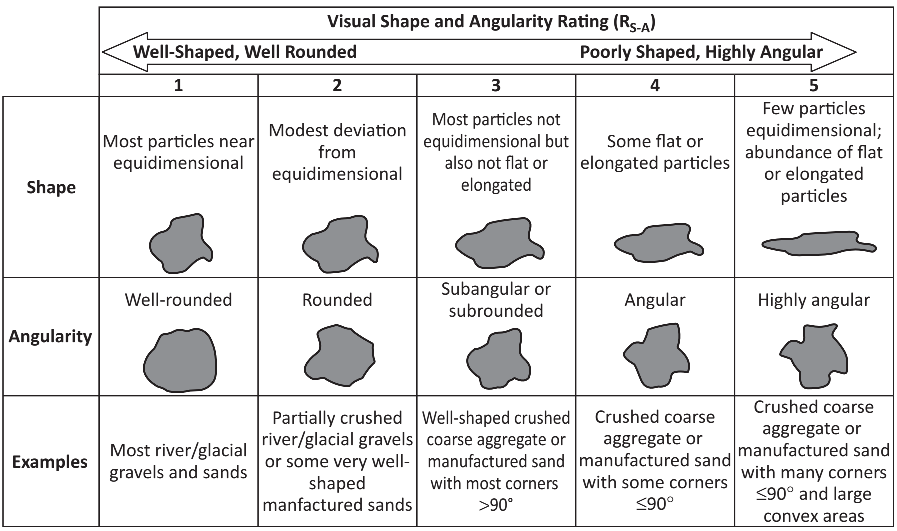


FIGURE 2.1
International Center for Aggregates Research (ICAR) visual shape and angularily rating.

Example 2.2

Water content (based on Equation 2.3) found out for 10 mm MSA (visual rating 2), a slump of 120 mm, and fly ash 35% is

$$\text{Water} = 0.223 \times 120 - 30\ln(10) + 264 = 222 \text{ kg}$$

Because the visual rating of aggregate is 2, hence adding 8 kg (i.e. 230 kg).
Corrected water due to fly ash

$$\text{Water} = W/10\hat{}(0.0013p) = 230/10\hat{}(0.0013 \times 35) = 207 \text{ kg}$$

And for the water correction based on water reducing admixture being used, just reduce further water by the percentage reduction expected because of the admixture.

2.5 Significance of Water Correction

The correction given in Table 2.2 is mainly because angular and flaky aggregates provide much less workability as compared to that when aggregates are well rounded and smooth. Both of these properties are difficult to quantify; hence, a visual rating system gives fair guidance on estimating the water content required for manufacturing concrete. The formula is based on aggregates that are crushed and have few aggregates that are flaky and elongated (usually less than 20%). Any aggregate that is better than this requires less water as compared to 3 rating aggregate; aggregates with rating 1 or 2 require more water to give the same workability.

On the other hand, fly ash has a spherical shape, lower specific gravity as compared to OPC, leading to higher paste volume; thus, it provides more workability to the concrete. Also, fly ash does not give similar strength as compared to OPC for the same water cement ratio; hence,

TABLE 2.2

Water Correction for Relevant ICAR Visual Rating

Visual Rating	Correction for Water Content
1	+15 kg
2	+8 kg
3	0
4	−8 kg
5	−15 kg

ICAR, International Center for Aggregates Research.

higher workability lower strengths are unsolicited, leading to a reduction in water content to get similar workability as compared to concrete without fly ash.

2.6 Cement Content Calculation

After applying corrections to the water content, the cement content is calculated next and is based on the formula:

$$\text{Cement} = \text{water content} / \text{water cement ratio}$$

The cement content so found out is checked for the limits prescribed in codal requirements for the given exposure conditions. The higher of both values is chosen. The limit of cement content prescribed is usually inclusive of fly ash, slag, or any other cementitious material, provided the replacement is not beyond the acceptable limit prescribed in respective specifications. Thus, if the minimum cement content specified is much higher than what is required to achieve the required strength, the cement can be partially replaced with the alternate cementitious materials to reduce cost increase.

2.7 Estimating Air Content

For a given maximum size of aggregate, there will be some entrapped air inside the concrete, no matter how good concrete is compacted. Hence, we need to assume a certain amount of air content, based on Table 2.3.

TABLE 2.3

Entrapped Air to Be Considered for Different MSAs

NMSA	Entrapped Air (%)
10 mm	3
20 mm	2
40 mm	1

NMSA, nominal maximum size aggregate.

2.8 Aggregate Proportion and Content

Next, the percentage of fine aggregate in the total aggregate is determined so that an acceptable concrete with enough cohesiveness can be obtained. It is important to know that concrete should not be segregating (non-cohesive) nor should it be over-cohesive. Noncohesive concrete will tend to have honeycomb and unsound structure, whereas over cohesiveness will lead to difficulty in fully compacting the concrete because it tends to stick to the vibrator.

Fuller and Thomson's model discussed in Chapter 1 is used to proportion the aggregates because its formula is easy to remember, and the model provides gradation that lies between almost any gradation limits of any standard.

To keep the cohesiveness constant across any grade of concrete, a strategy needs to be applied in proportioning the aggregates. A part of the cement content calculated in the previous step is considered as aggregate and the remainder is considered a binder not included in the aggregate gradation. Normally 300 kg of OPC is considered a binder, which is kept constant, while any additional fines through cement or alternate cementitious material are considered in the gradation of aggregates. This ensures that the cohesiveness of concrete is neither too high, nor does the concrete tend to segregate. In case cement contents are higher than 300 kg, then the fine aggregate is reduced to counter the extra fines of cement, whereas when cement content is less than 300 kg, extra, fine aggregate is added to compensate for the shortage of fines.

The calculations are done as follows:

1 cubic metre – Water volume – Cement volume – Air volume = Aggregate volume

Cementitious volume – 300 kg cement volume = Extra fines volume

Percentage of fines volume from cement = Extra fines volume/(Extra fines + Aggregate volume)

Thus, during gradation, the calculation will be, aggregate percent proportions + fines percentage = 1, and the solver (discussed in Chapter 1) will solve to fit the gradation curve closest possible to the model.

Example 2.3

Proportion the aggregates to fit the power curve of value 0.5 with a cementitious content of 410 kg (fly ash 35%). The water content after all due corrections is 160 kg. The gradation of aggregates is the same as given in Table 1.4.

Solution

OPC content is 65% of 410 kg (i.e. 267 kg and fly ash 143 kg). Thus, the total volume of these materials is (considering 3.15 as the specific gravity of OPC and 2.2 of fly ash)

$$267/3.15 + 143/2.2 = 150 \text{ L}$$

The volume of 300 Kgs of OPC is 95 L; thus, extra fines from cementitious is 150 – 95 = 55 L.

	A	B	C	D	E	F	G	H	I
1			% passing						
2		Agg1	Agg2	Agg3	Cement fines				
3	Sieve Size	0.258946	0.376213	0.288941	0.0759	1	Actual Gradation	Ideal Grading	Absolute difference between ideal and actual
4	40	99%	100%	100%	100%		99.74%		
5	20	92%	99%	100%	100%		97.40%	100.00%	0.02598262
6	10	2%	90%	100%	100%		70.71%	70.71%	3.71567E-07
7	4.75	0%	3%	98%	100%		36.87%	48.73%	0.118614
8	2.36	0%	1%	92%	100%		34.35%	34.35%	7.82445E-08
9	1.18	0%	0%	77%	100%		29.70%	24.29%	0.054129116
10	0.6	0%	0%	40%	100%		19.09%	17.32%	0.017681621
11	0.3	0%	0%	10%	100%		10.54%	12.25%	0.017090718
12	0.15	0%	0%	2%	100%		8.17%	8.66%	0.004923722
13								Total	0.238422245

(a)

	A	B	C	D	E	F	G	H	I
1			% passing						
2		Agg1	Agg2	Agg3	Cement fines				
3	Sieve Size	0.259929	0.368433	0.371639	0	1.000001	Actual Gradation	Ideal Grading	Absolute difference between ideal and actual
4	40	99%	100%	100%	100%		99.74%		
5	20	92%	99%	100%	100%		97.40%	100.00%	0.025951497
6	10	2%	90%	100%	100%		70.70%	70.71%	0.000153759
7	4.75	0%	3%	98%	100%		37.36%	48.73%	0.113706335
8	2.36	0%	1%	92%	100%		34.35%	34.35%	6.15255E-08
9	1.18	0%	0%	77%	100%		28.44%	24.29%	0.041518132
10	0.6	0%	0%	40%	100%		14.79%	17.32%	0.025308091
11	0.3	0%	0%	10%	100%		3.79%	12.25%	0.084552182
12	0.15	0%	0%	2%	100%		0.74%	8.66%	0.079169769
13								Total	0.370359825

(b)

FIGURE 2.2
Rapid method (calculation) for aggregate proportioning (a) considering cement as aggregate and (b) without considering cement as aggregate.

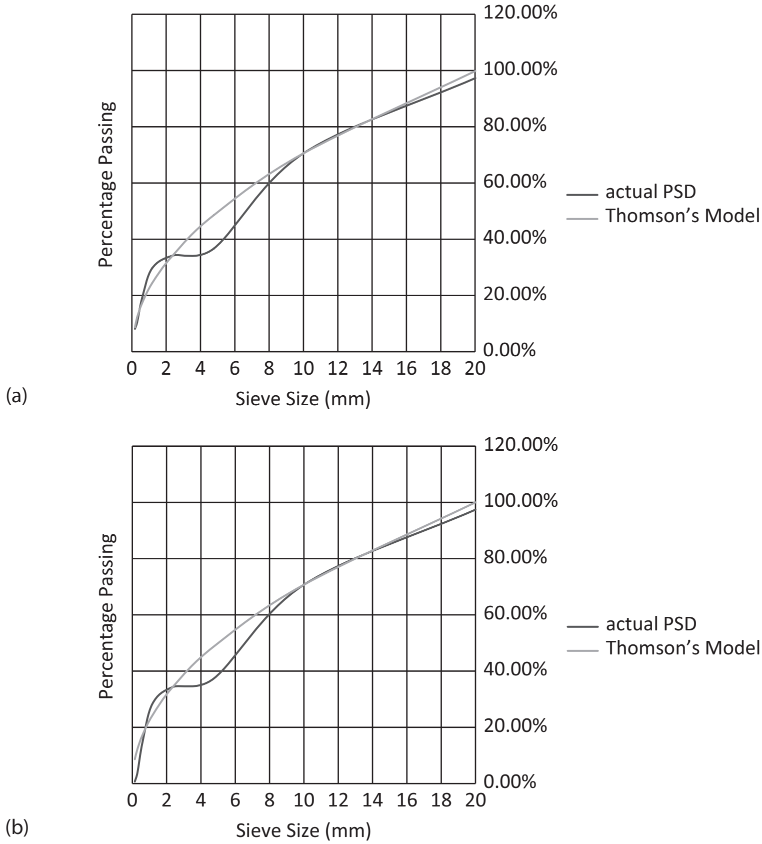


FIGURE 2.3
Particle size distribution graph for aggregate gradation (a) considering partial cement as aggregate and (b) without considering cement as aggregate.

Volume of aggregates = 1000 − Cementitious volume − Water − Air content
Volume of aggregates = 1000 − 150 − 160 − 20 = 670 L
Volume of fines from cement = 55/(55 + 670) = 7.59%
Thus, volume of aggregates = 1 − 7.59% = 92.41%

To start the gradation, consider another column of aggregates, which is finer than all the sieves used for aggregate testing. Refer to Figure 2.2a, which is the screenshot of the sheet for proportioning the aggregates considering part of cementitious materials in aggregate gradation 7.59%. Figure 2.2b is a screenshot for gradation without considering any cementitious materials like fine aggregate, and the fine aggregate required is 37%, whereas for another case it is 28%. Figure 2.3a and 2.3b are graphical representations of PSDs of 2.2a and 2.2b respectively. This difference is huge, and a higher fine aggregate than what is needed leads to a decrease in the strength of concrete.

The percentage of sand is denoted as p, and Equations 1.12 and 1.13 are used to find fine aggregates and coarse aggregate contents, respectively.

Next trials are conducted with varying water cement ratios, both lesser and higher than the calculated one and results are obtained. The concrete mix that meets the closest strength to the required strength and also the fresh concrete properties criteria is chosen and production can be started using the same.

Example 2.4

Design concrete of M30 grade, maximum aggregate size as 20 mm with workability requirement of 120 mm slump, and the maximum permissible water cement ratio is 0.5. The degree of quality control is good, coarse aggregates are angular (visual rating 3), and fine aggregates are natural river sand. The gradations of aggregates are as given in Table 1.4. The specific gravities of sand and coarse aggregates are 2.65 and 2.8, respectively. The aggregates have to be proportioned for a power curve of 0.45. The cement has a strength of 61 MPA when tested as per the standards at 28 days.

Solution

1. Target strength for the concrete is

$$Ft = 30 + 1.65 \times 1.3 \ln(1.2 \times 30) = 37.69 \text{ MPa} \sim 38 \text{ MPa}$$

2. Now because the strength of cement brand at 28 days is 61 MPa and strength required is 38 MPa, substitute the relevant values in Equation 2.2

$$W/C = \left[\ln(38) + 0.00023 \times 61^2 - 0.0405 \times 61 - 3.546\right] / \left[0.0076 \times 61 - 3.65\right] = 0.48$$

   Now, this water cement ratio will satisfy only the strength criteria, and water cement ratio limit specified for durability is 0.5. From these values, take the lower one, which is 0.48; hence, the water cement ratio is 0.48.

3. Now the water content is determined and is based on Equation 2.3 or 2.4, whichever is applicable. Start with Equation 2.3 to check first the cement content that may be derived. The maximum size of aggregate to be used is 20 mm; hence, the water content is calculated as

$$\text{Water} = 0.223 \times \text{slump} - 30\ln(\text{MSA}) + 264$$

$$= 0.223 \times 120 - 30 \times \ln(20) + 264$$

$$= 201\ \text{kg}$$

4. A correction needs to be applied to the water content found out based on the shape and texture of aggregate (visual rating), which has been defined as 3. Refer to Table 2.2 for correction based on visual rating; there is no correction to be applied to water.
5. For finding the cement content, divide the water content found in step 4 by the water cement ratio found in step 2. Thus,

$$\text{Cement} = 201/0.48 = 419\ \text{kg}$$

6. Finding the total aggregates is the next step. The volume of cement content higher than 300 kg of OPC is

$$\text{Extra cement volume} = 419/3.15 - 300/3.15 = 37.78\ \text{L}.$$

The volume of total aggregates would be

$$\text{Aggregate} = 980 - 419/3.15 - 201 = 646\ \text{L}.$$

NOTE: The volume of concrete taken is 980 instead of 1000 L because 2% entrapped air has been considered.

Thus, the volume of cementitious materials to be considered for all in aggregate gradation would be 37.78/(37.78 + 646) = 5.5%. Doing the combined gradation proportions as 23.6:35.23:35.67 are derived (refer Figure 2.2a and b). These proportions have to be converted in terms of aggregate only for further calculation purposes.
Thus, 20 mm aggregates required would be

23.6/(23.6 + 35.23 + 35.67) = 24.98%

10 mm, 35.23/(23.6 + 35.23 + 35.67) = 37.28%

Fine aggregate, 35.67/(23.6 + 35.23 + 35.67) = 37.74%

7. The air content to be considered for this case with 20 mm MSA is 2% of total concrete volume, which is 20 L for 1 m^3, as per Table 2.3.
8. Finding the sand content in concrete based on the data given and data found in previous steps is next. The sand is calculated based on Equation 1.12.

$$1000 = C/dc + W + Fa/(d.p) + A$$

$$1000 = 419/3.15 + 201 + Fa/(0.3774 \times 2.65) + 20$$

$$Fa = 646\ \text{kg}$$

9. Next we find the coarse aggregate (20 mm) content based on Equation 1.13.

$$1000 = C/dc + W + Ca/(d_{ca} \cdot p20)] + A$$

$$1000 = 419/3.15 + 201 + Ca/\left(0.2498 \times 2.8\right) + 20$$

$$Ca20 = 452 \text{ kg}$$

Similarly, 10-mm aggregate content is found by

$1000 = 419/3.15 + 201 + Ca/(0.3728 \times 2.8) + 20$
$Ca10 = 674$ kg

10. The contents of 20 and 10 mm thus are

Weight of 20 mm = $1253 \times 0.6 = 752$ kg
Weight of 10 mm = $1253 \times 0.4 = 501$ kg

Thus, the complete mix design of concrete is:

Cement: 419 kg
Water: 201 kg
20 mm: 452 kg
10 mm: 674 kg
Fine aggregate: 646 kg

Example 2.5

Design concrete of M20 Grade with MSA 40 mm, where the maximum water cement ratio allowed is 0.45. Water reducing admixture with water reducing capacity of 15% shall be used and workability required is 120 mm slump. Cement to be used gets a strength of 59.8 MPa @ 28 days. Fine aggregate available has a specific gravity of 2.6, 40 mm of 2.95, 20 mm of 2.9, 10 mm of 2.75. Aggregates have particle size distribution as given in Figure 2.4.

Solution

1. Target strength = $20 + 1.65 \times 1.3 \times \ln(1.2 \times 20) = 26.82$ MPa
2. Water cement ratio

   $W/C = [\ln(26.82) + 0.00023 \times 60^2 - 0.0405 \times 60 - 3.546]/[0.0076 \times 60 - 3.65]$
   $W/C = 0.58$

3. Maximum limit for W/c is 0.45. Hence, take minimum of both (i.e. 0.45).
4. Water content = $0.223 \times 120 - 30 \ln(40) + 264 = 180$ kg

	A	B	C	D	E	F	G	H	I	J
1		% Passing								
2		Agg1	Agg2	Agg3	Agg4	Cement fines				
3	Sieve Size	0.2743217	0.146427	0.298155	0.263997	0.0171	1	Actual Gradation	Ideal grading	Difference between ideal and actual
4										
5	40	98%	100%	100%	100%	100%		99.45%	100%	0.005486436
6	20	5%	95%	100%	100%	100%		73.21%	73%	3.01627E-05
7	10	0%	5%	83%	100%	100%		53.59%	54%	3.63089E-07
8	4.75	0%	0%	15%	98%	100%		32.05%	38%	0.062800961
9	2.36	0%	0%	4%	95%	100%		27.98%	28%	1.72442E-09
10	1.18	0%	0%	0%	84%	100%		23.89%	20%	0.034014758
11	0.6	0%	0%	0%	45%	100%		13.59%	15%	0.015193369
12	0.3	0%	0%	0%	16%	100%		5.93%	11%	0.051266252
13	0.15	0%	0%	0%	10%	100%		4.35%	8%	0.037468458
14									Total	0.206260761

FIGURE 2.4
Gradation fitting for 40 mm MSA as per given aggregate gradations.

5. Because an admixture with water reduction capacity of 15% is being used, the water can be reduced to 153 kg.
6. Cement Content = 153/0.45 = 340 kg.
7. Cement content as percentage of total aggregate for aggregate proportion correction:

   340/3.15 − 300/3.15 = 12.7 L
   Total aggregate volume = 990 − 340/3.15 − 153 = 729 L
   Cement content as aggregate proportion = 12.7/(12.7 + 729) = 1.71%

   Refer to Figure 2.4.
8. The fine aggregate proportion to be used as per the gradation curve fitting is 26.4%.
9. The correction to be applied for all aggregate contents because these proportions consider part of cementitious as aggregates. The corrected proportions of the aggregates are

   40 mm = 0.2743/(0.2743 + 0.1464 + 0.2982 + 0.264) = 27.91%
   20 mm = 0.1464/(0.2743 + 0.1464 + 0.2982 + 0.264) = 14.89%
   10 mm = 0.2982/(0.2743 + 0.1464 + 0.2982 + 0.264) = 30.34%
   Fine aggregate = 0.264/(0.2743 + 0.1464 + 0.2982 + 0.264) = 26.86%

10. Fine aggregate content is calculated as

    $1000 = 340/3.15 + 153 + Fa/(0.2686 \times 2.6) + 10$
    Fa = 509 kg

11. Coarse aggregate content is calculated as

    $1000 = 340/3.15 + 153 + Ca/(0.2791 \times 2.95) + 10$
    Ca (40 mm) = 600 kg
    $1000 = 340/3.15 + 153 + Ca/(0.1489 \times 2.9) + 10$

Ca (20 mm) = 315 kg
1000 = 340/3.15 + 153 + Ca/(0.3034 × 2.75) + 10
Ca (10 mm) = 608 kg

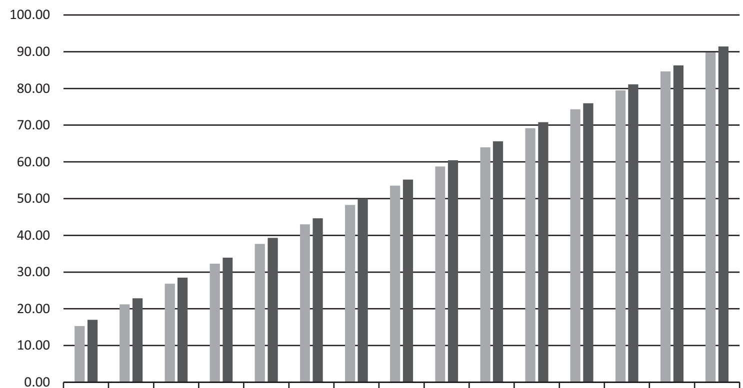
Thus, the entire mix proportion of the concrete is:

Cement = 340 kg
Water = 153 kg
Fine aggregate = 509 kg
40 mm = 600 kg
20 mm = 315 kg
10 mm = 608 kg
Admixture = As per the dosage required to get 15% reduction in water.

2.9 Rapid Method Graphical

The same rapid method steps for concrete mix proportioning are converted to graphical format, in which the calculation part has been minimized. A mix can be designed by looking at relevant graphs (Figures 2.5 through 2.37). Example 2.4 is worked out through the graphical method:

1. Calculate the target strength for M30 grade, good quality control from the following graph, which is 37.69 MPa.



	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
target strength good QC	15.33	21.20	26.82	32.30	37.69	43.02	48.30	53.56	58.78	63.99	69.17	74.35	79.50	84.65	89.79
target strength poor QC	16.98	22.85	28.47	33.95	39.34	44.67	49.95	55.21	60.43	65.64	70.82	76.00	81.15	86.30	91.44

FIGURE 2.5
Target strength estimation for requisite characteristic strength of concrete, against good and poor quality control practices anticipated during production.

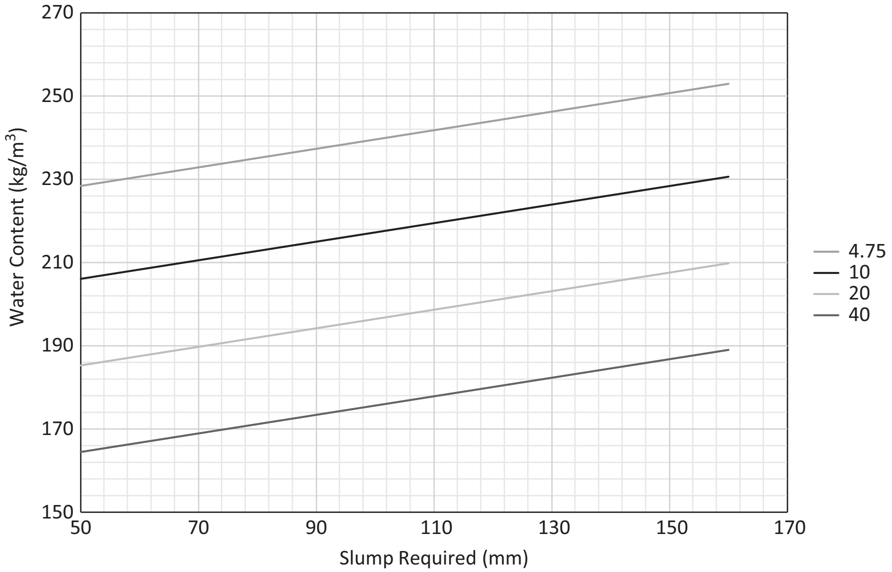


FIGURE 2.6
Water content versus slump for different nominal maximum size aggregates (NMSAs) up to cement content of 450 and 500 kg/m^3 for 20 and 10 mm, respectively.

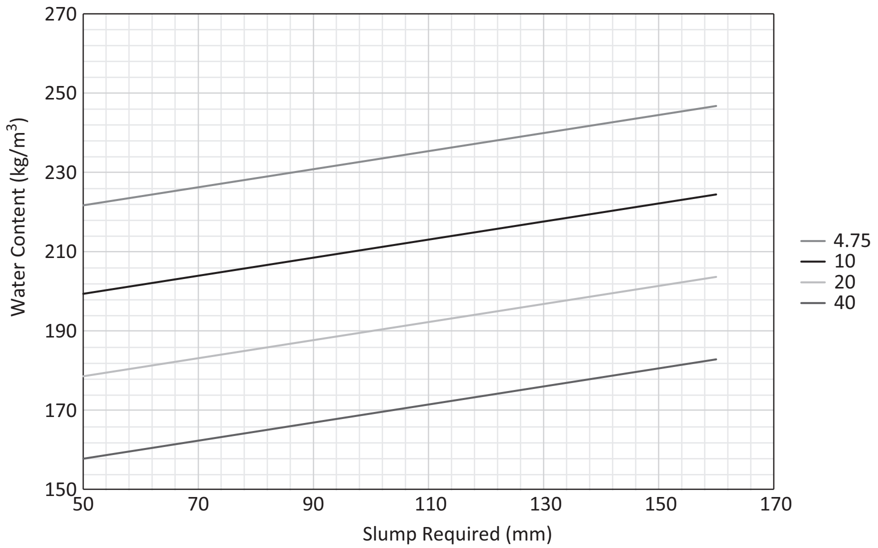


FIGURE 2.7
Water content versus slump for different NMSAs above cement content of 450 and 500 kg/m^3 for 20 and 10 mm, respectively.

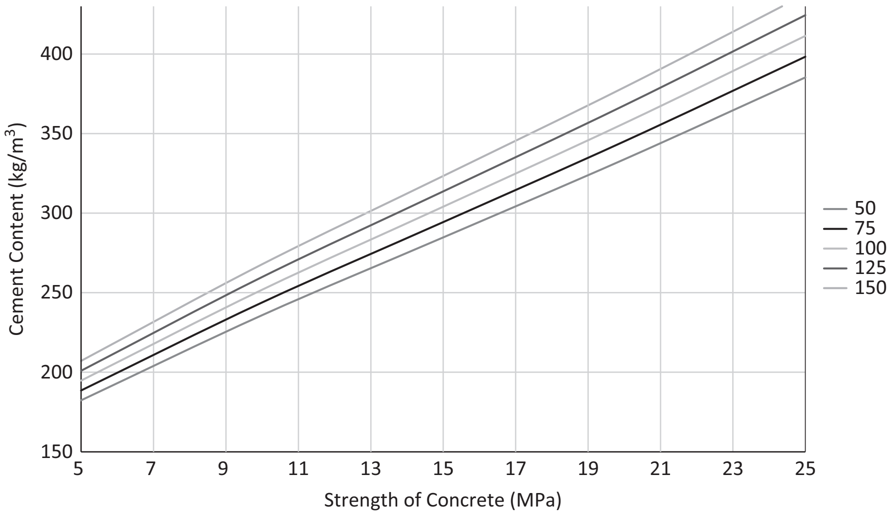


FIGURE 2.8
Cement content versus strength of concrete, cement strength 34 MPa, 40 mm MSA for strengths up to 25 MPa for the required workability.

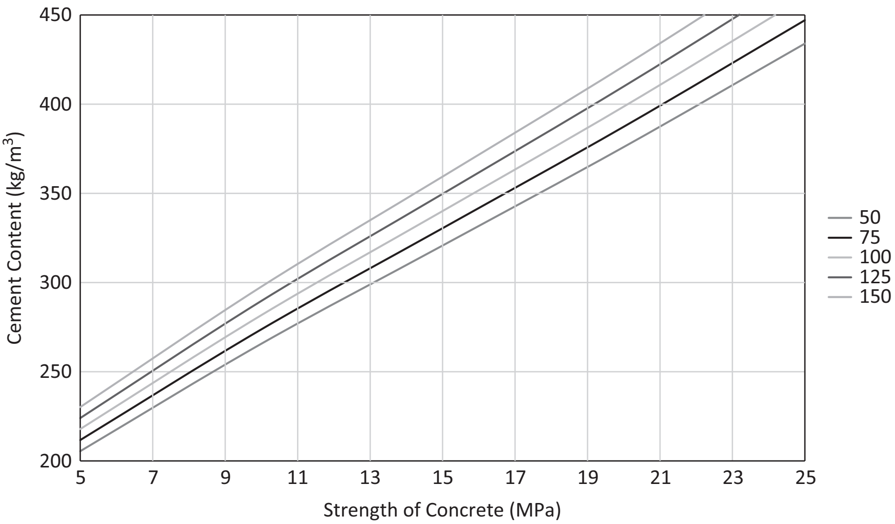


FIGURE 2.9
Cement content versus strength of concrete cement strength 34 MPa, 20 mm MSA for strengths up to 25 MPa for the required workability.

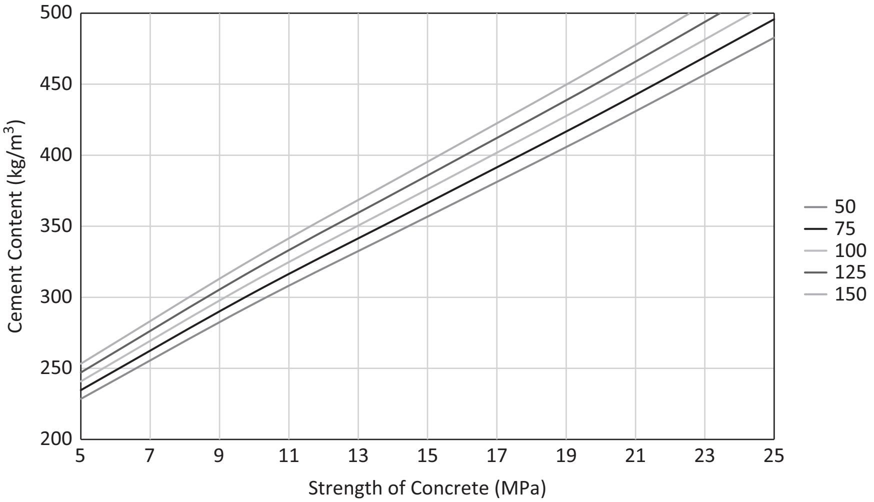


FIGURE 2.10
Cement content versus strength of concrete, cement strength 34 MPa, 10 mm MSA for strengths up to 25 MPa for the required workability.

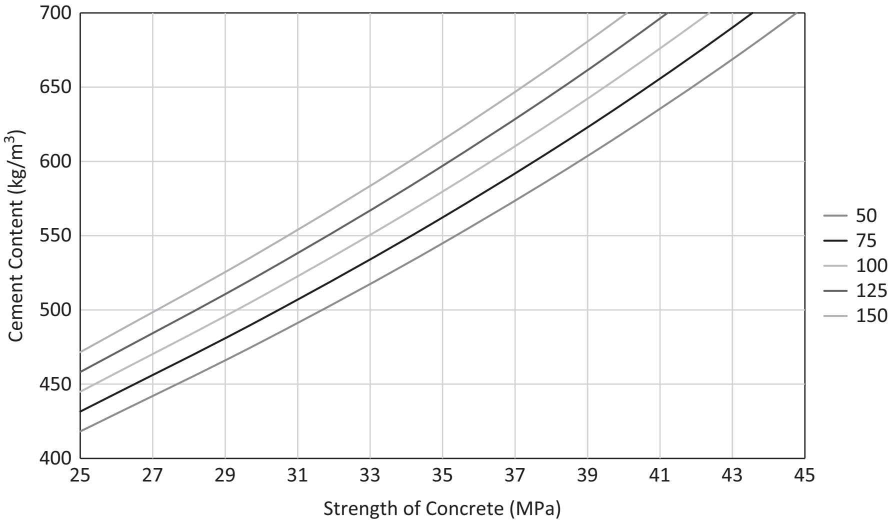


FIGURE 2.11
Cement content versus strength of concrete, cement strength 34 MPa, 20 mm MSA, for strengths above 25 MPa for the required workability.

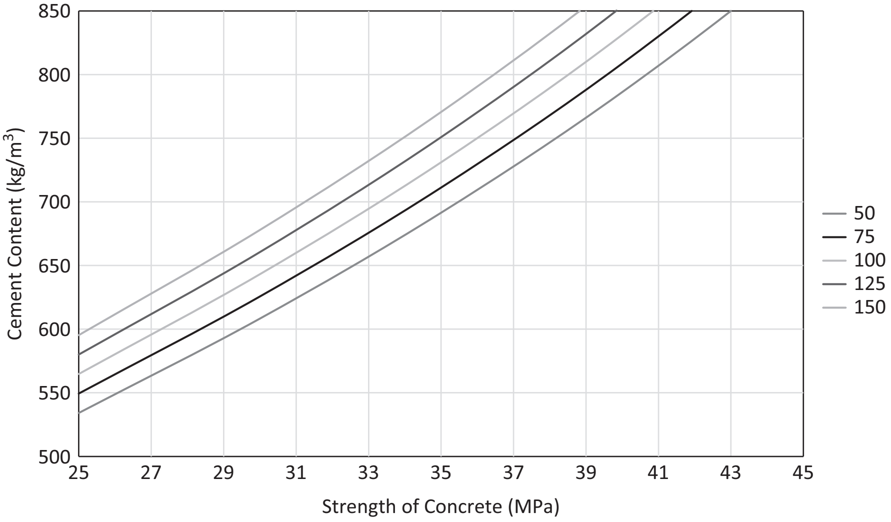


FIGURE 2.12
Cement content versus strength of concrete, cement strength 34 MPa, 10 mm MSA, for strengths above 25 MPa for the required workability.

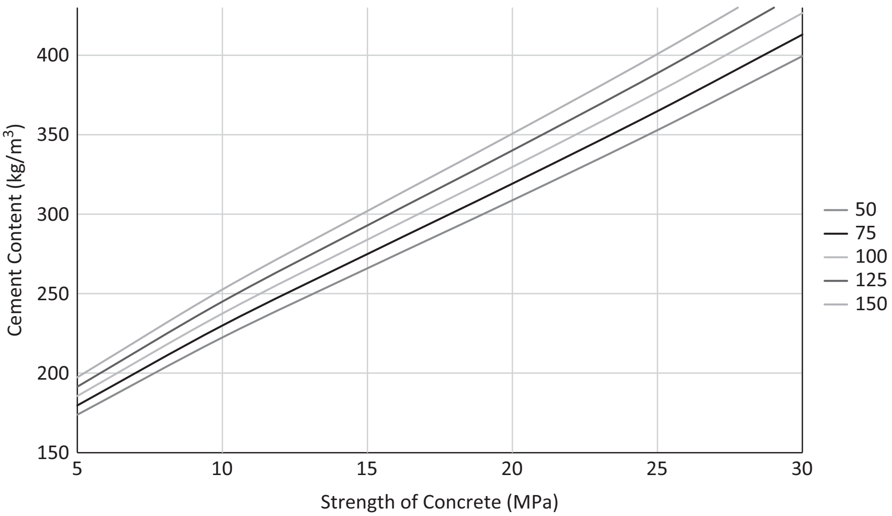


FIGURE 2.13
Cement content versus strength of concrete, cement strength 39 MPa, 40 mm MSA, for strengths up to 25 MPa for the required workability.

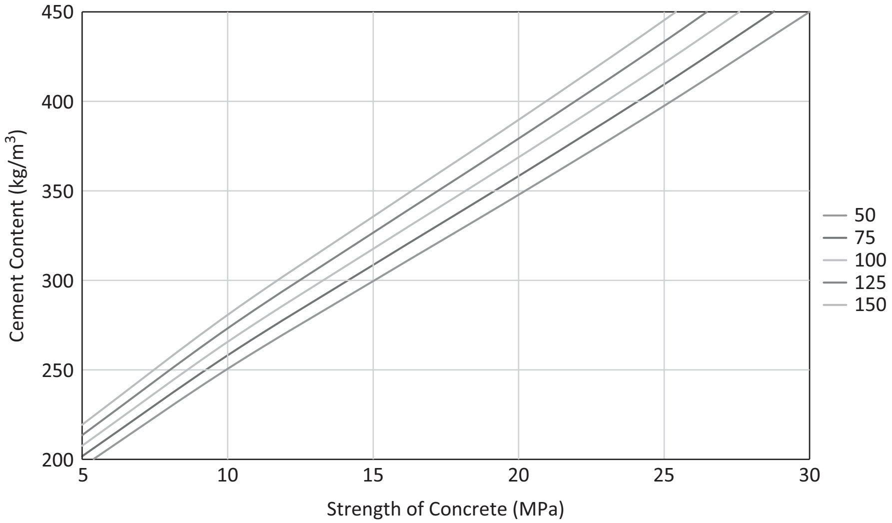


FIGURE 2.14
Cement content versus strength of concrete, cement strength 39 MPa, 20 mm MSA, for strengths up to 25 MPa for the required workability.

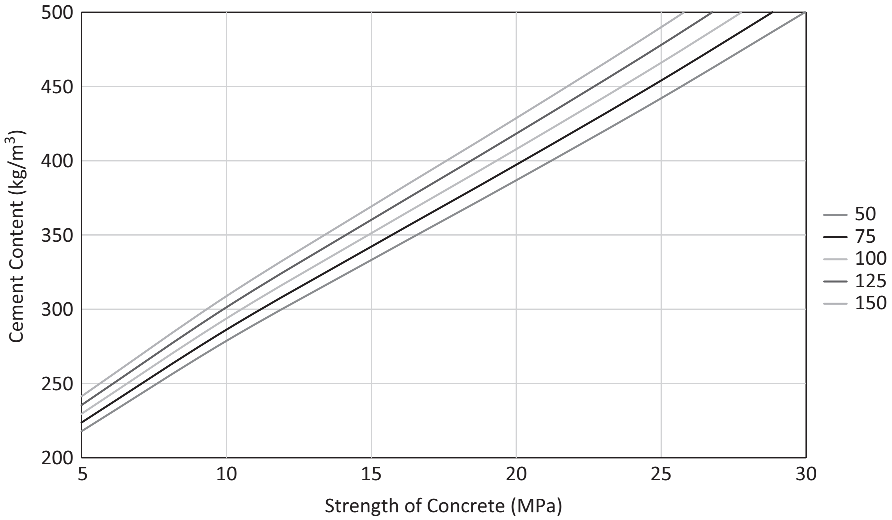


FIGURE 2.15
Cement content versus strength of concrete, cement strength 39 MPa, 10 mm MSA, for strengths up to 25 MPa for the required workability.

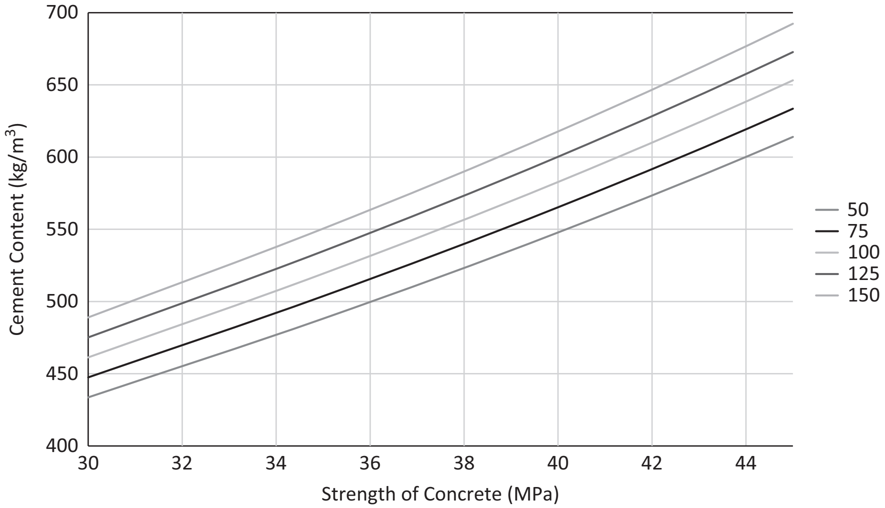


FIGURE 2.16
Cement content versus strength of concrete, cement strength 39 MPa, 20 mm MSA, for strengths above 25 MPa for the required workability.

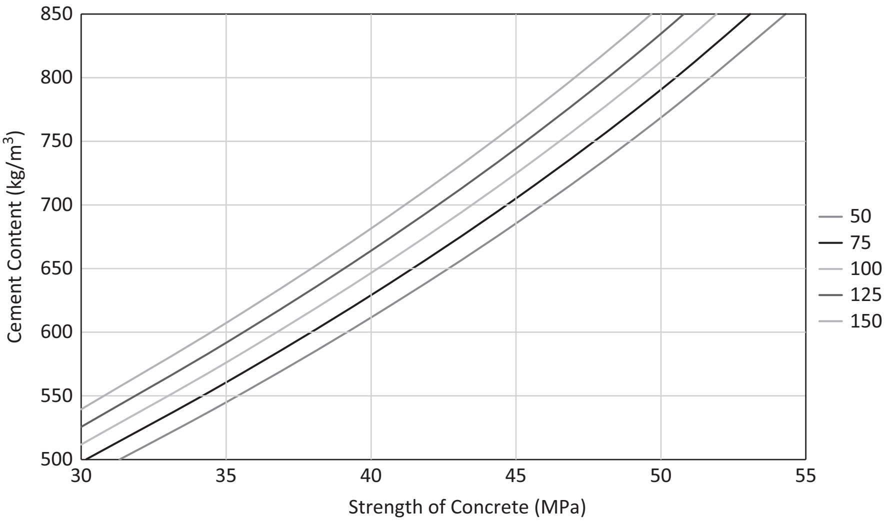


FIGURE 2.17
Cement content versus strength of concrete, cement strength 39 MPa, 10 mm MSA, for strengths above 25 MPa for the required workability.

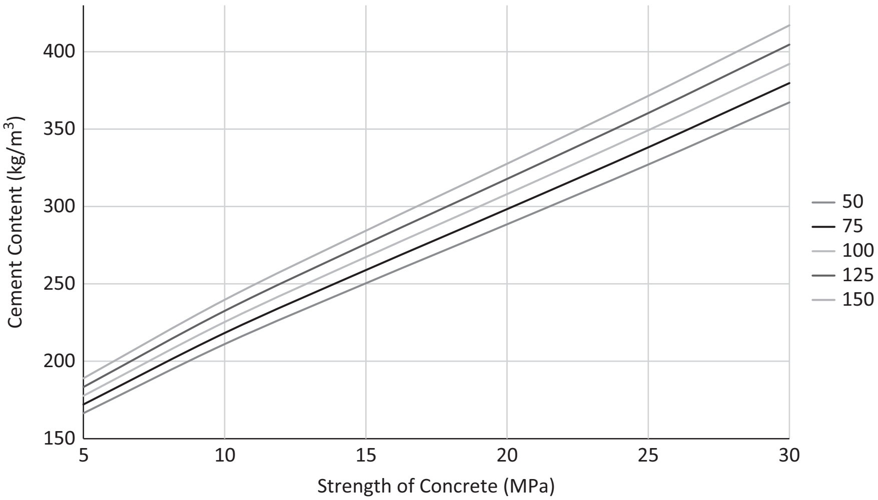


FIGURE 2.18
Cement content versus strength of concrete, cement strength 44 MPa, 40 mm MSA, for strengths up to 30 MPa for the required workability.

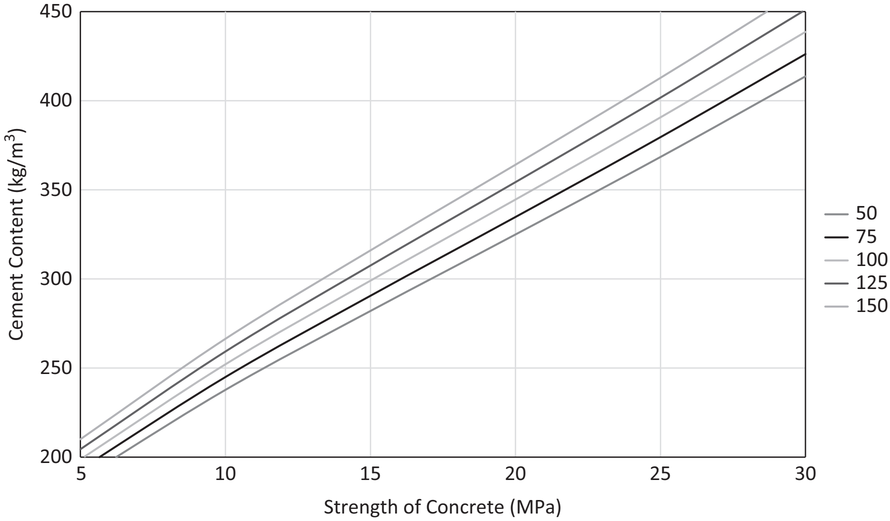


FIGURE 2.19
Cement content versus strength of concrete, cement strength 44 MPa, 20 mm MSA, for strengths up to 30 MPa for the required workability.

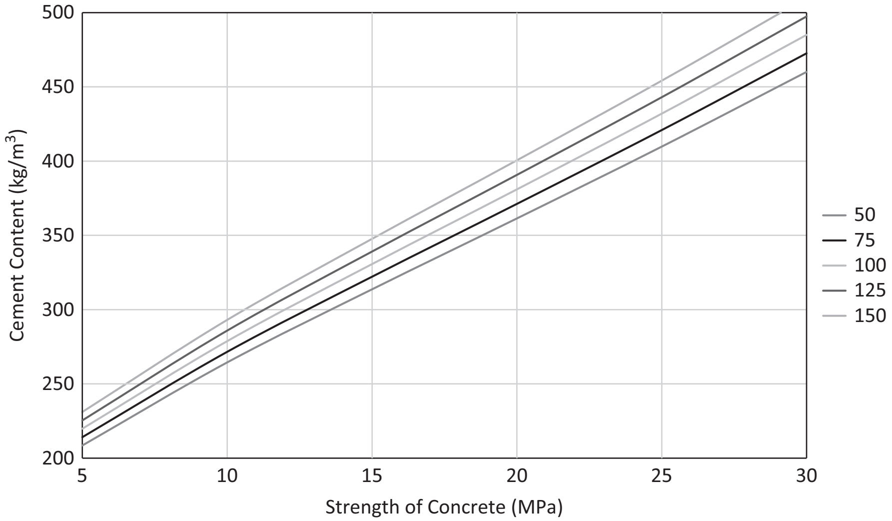


FIGURE 2.20
Cement content versus strength of concrete, cement strength 44 MPa, 10 mm MSA, for strengths up to 30 MPa for the required workability.

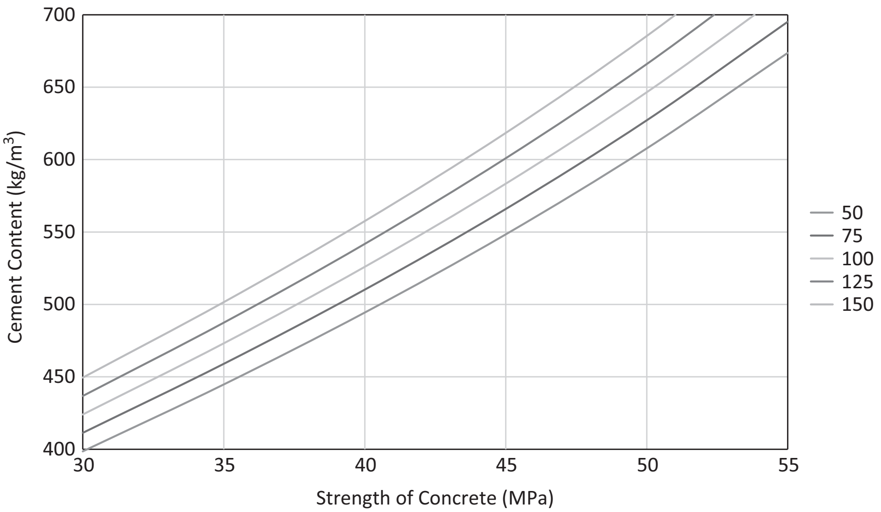


FIGURE 2.21
Cement content versus strength of concrete, cement strength 44 MPa, 20 mm MSA, for strengths above 30 MPa for the required workability.

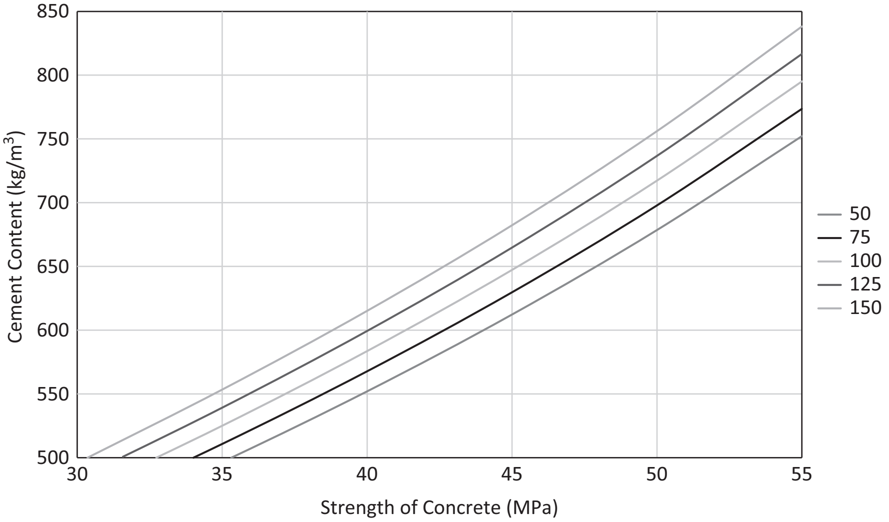


FIGURE 2.22
Cement content versus strength of concrete, cement strength 44 MPa, 10 mm MSA, for strengths above 30 MPa for the required workability.

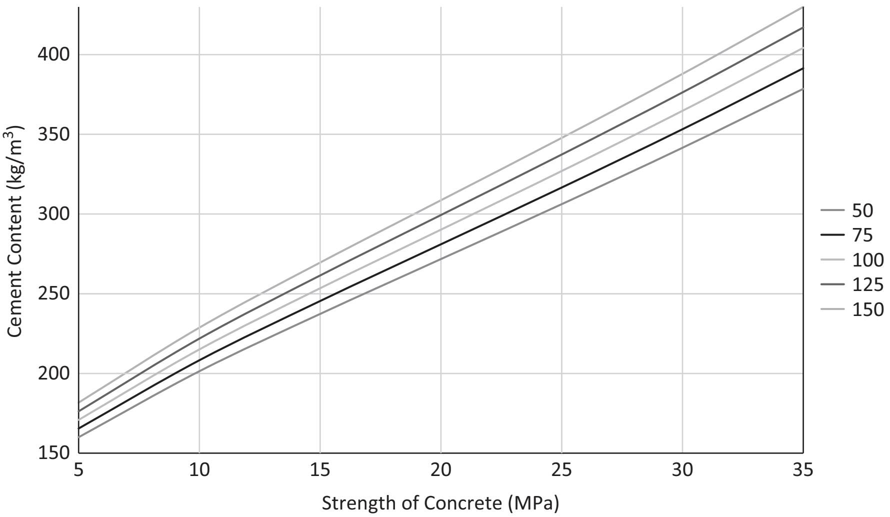


FIGURE 2.23
Cement content versus strength of concrete, cement strength 49 MPa, 40 mm MSA, for strengths up to 35 MPa for the required workability.

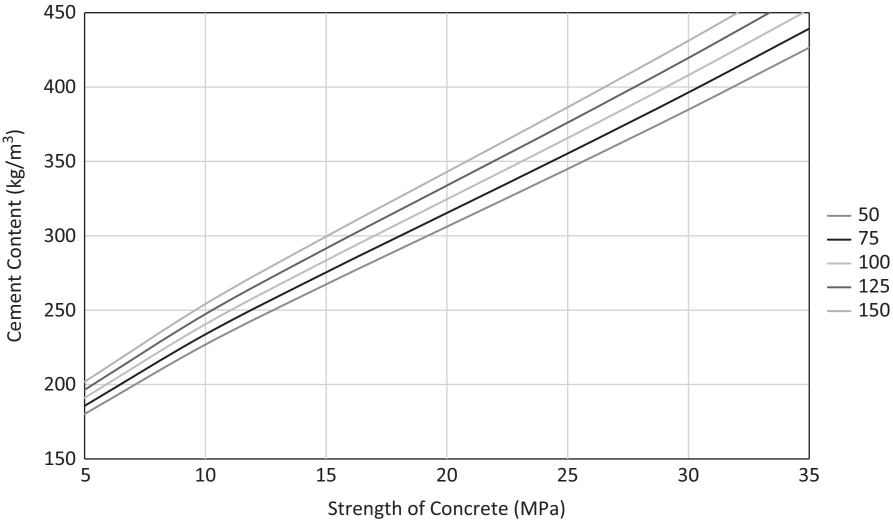


FIGURE 2.24
Cement content versus strength of concrete, cement strength 49 MPa, 20 mm MSA, for strengths up to 35 MPa for the required workability.

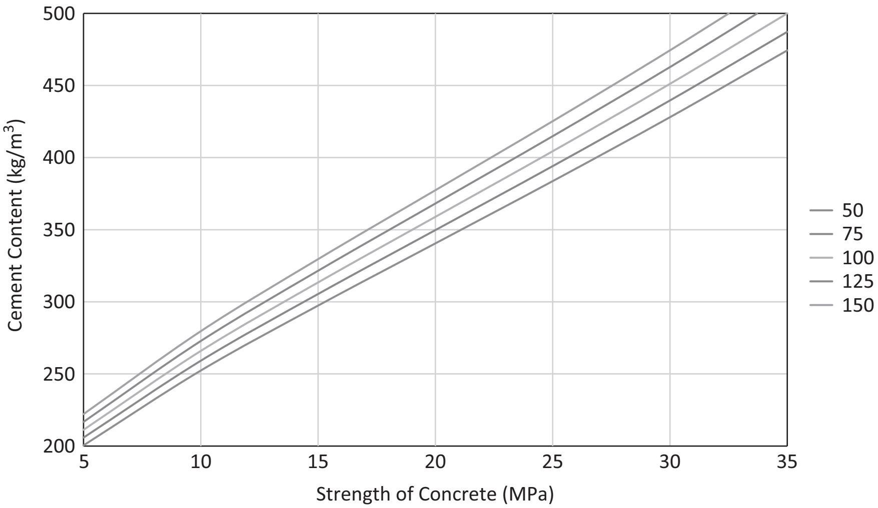


FIGURE 2.25
Cement content versus strength of concrete, cement strength 49 MPa, 10 mm MSA, for strengths up to 35 MPa for the required workability.

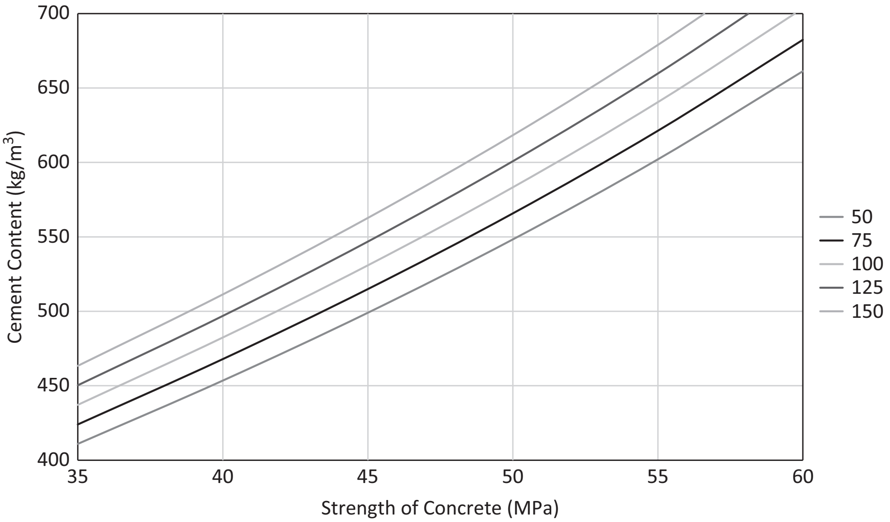


FIGURE 2.26
Cement content versus strength of concrete, cement strength 49 MPa, 20 mm MSA, for strengths above 35 MPa for the required workability.

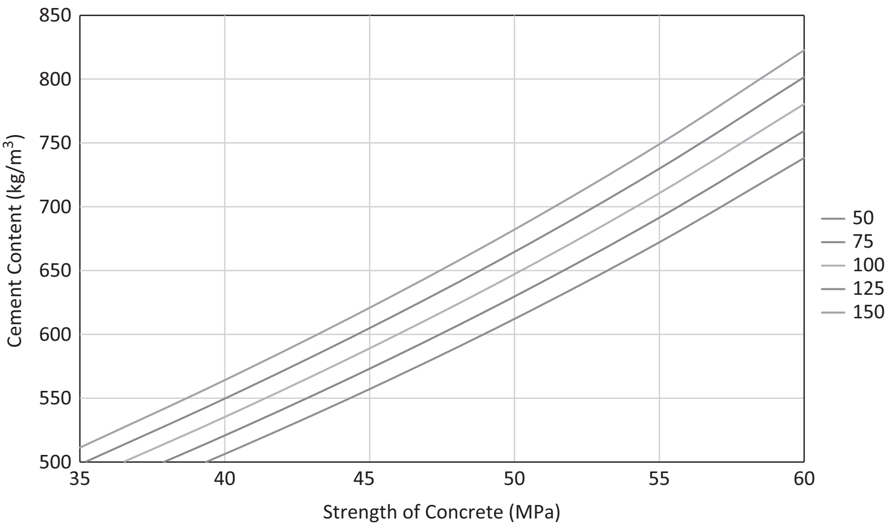


FIGURE 2.27
Cement content versus strength of concrete, cement strength 49 MPa, 10 mm MSA for strengths above 35 MPa for the required workability.

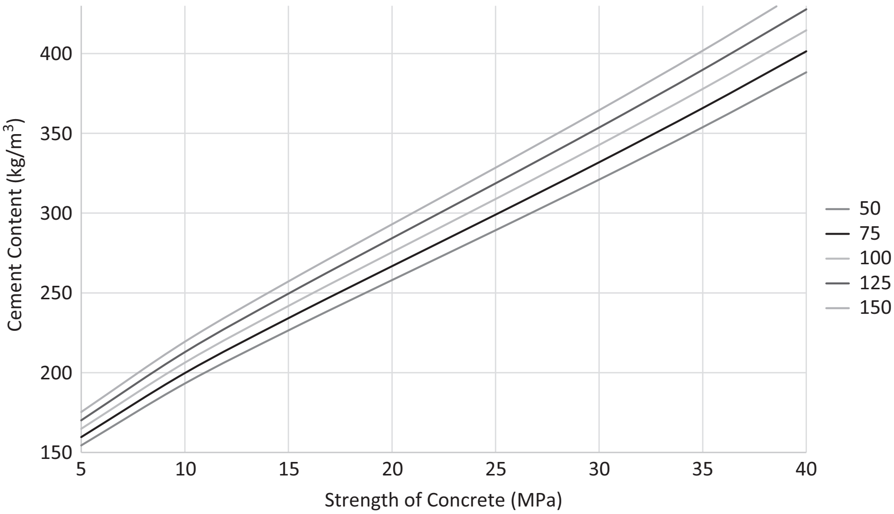


FIGURE 2.28
Cement content versus strength of concrete, cement strength 54 MPa, 40 mm MSA, for strengths up to 40 MPa for the required workability.

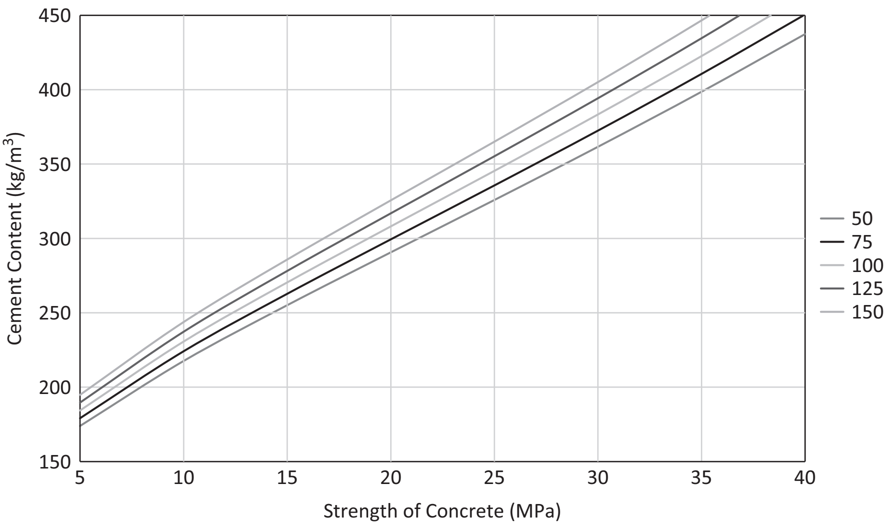


FIGURE 2.29
Cement content versus strength of concrete, cement strength 54 MPa, 20 mm MSA, for strengths up to 40 MPa for the required workability.

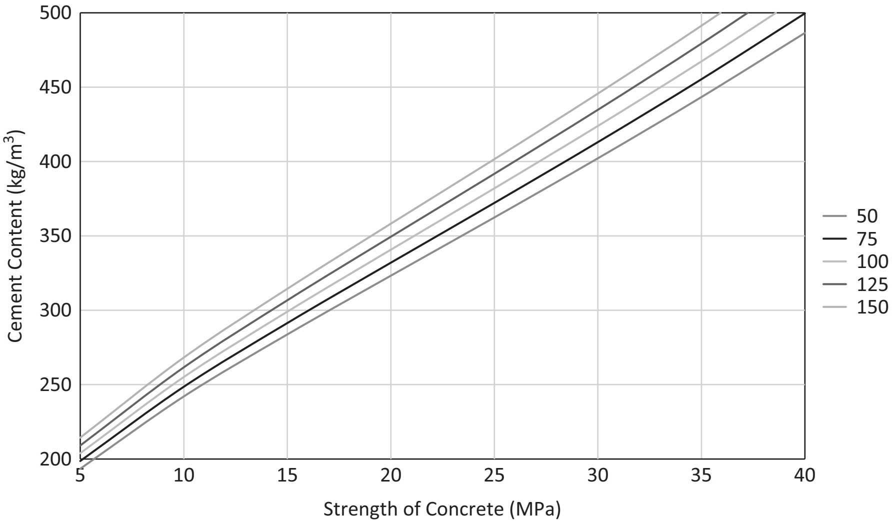


FIGURE 2.30
Cement content versus strength of concrete, cement strength 54 MPa, 10 mm MSA, for strengths up to 40 MPa for the required workability.

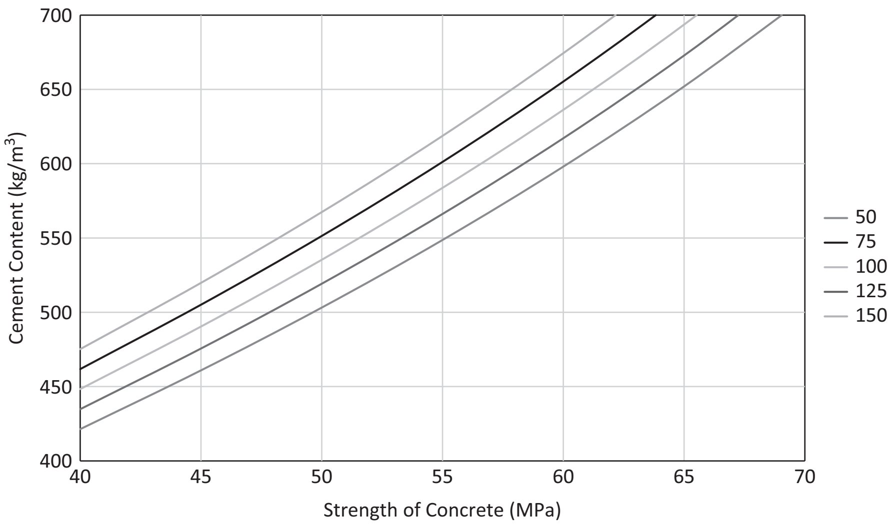


FIGURE 2.31
Cement content versus strength of concrete, cement strength 54 MPa, 20 mm MSA, for strengths above 40 MPa for the required workability.

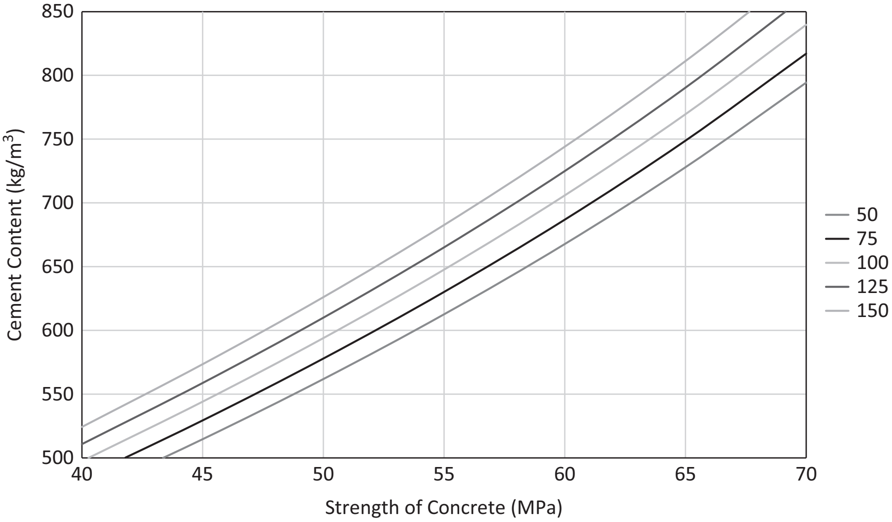


FIGURE 2.32
Cement content versus strength of concrete, cement strength 54 MPa, 10 mm MSA, for strengths above 40 MPa for the required workability.

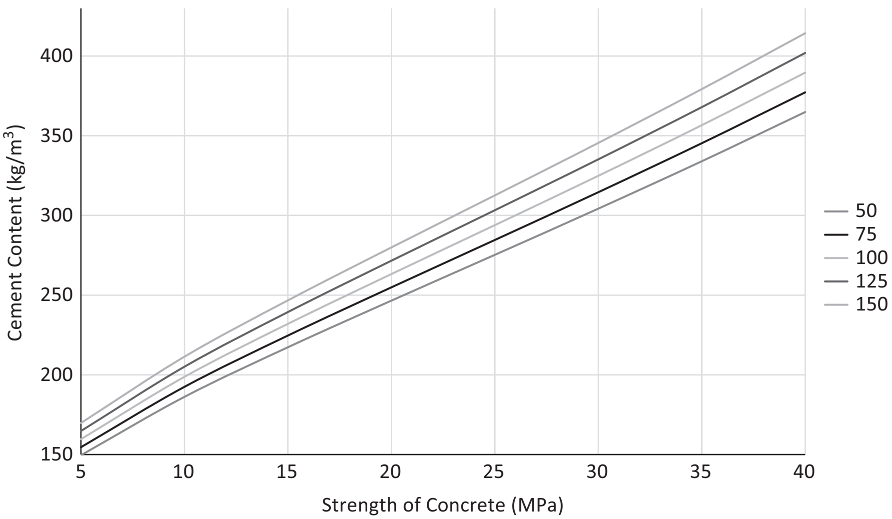


FIGURE 2.33
Cement content versus strength of concrete, cement strength 59 MPa, 40 mm MSA, for strengths up to 40 MPa for the required workability.

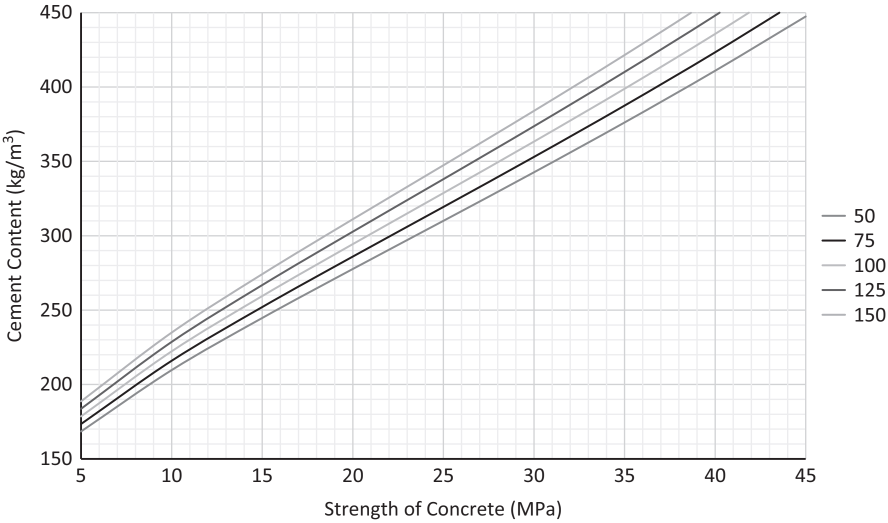


FIGURE 2.34
Cement content versus strength of concrete, cement strength 59 MPa, 20 mm MSA, for strengths up to 40 MPa for the required workability.

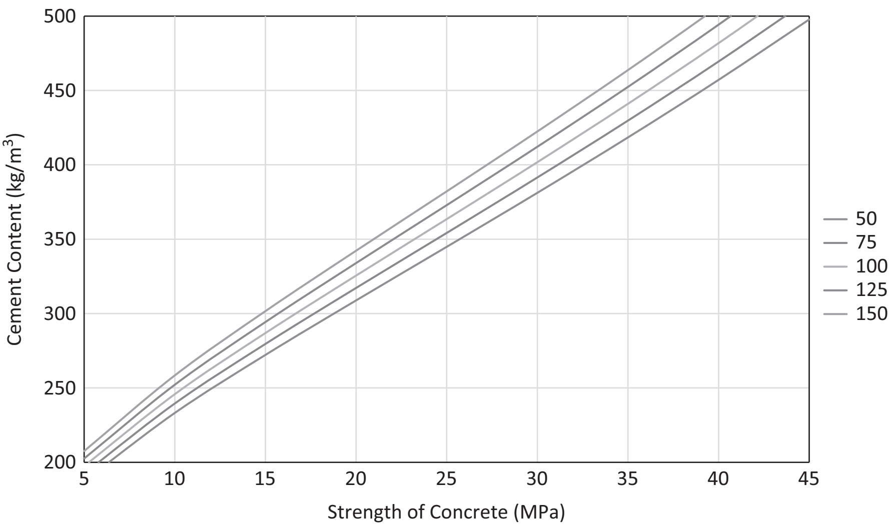


FIGURE 2.35
Cement content versus strength of concrete, cement strength 59 MPa, 10 mm MSA, for strengths up to 40 MPa for the required workability.

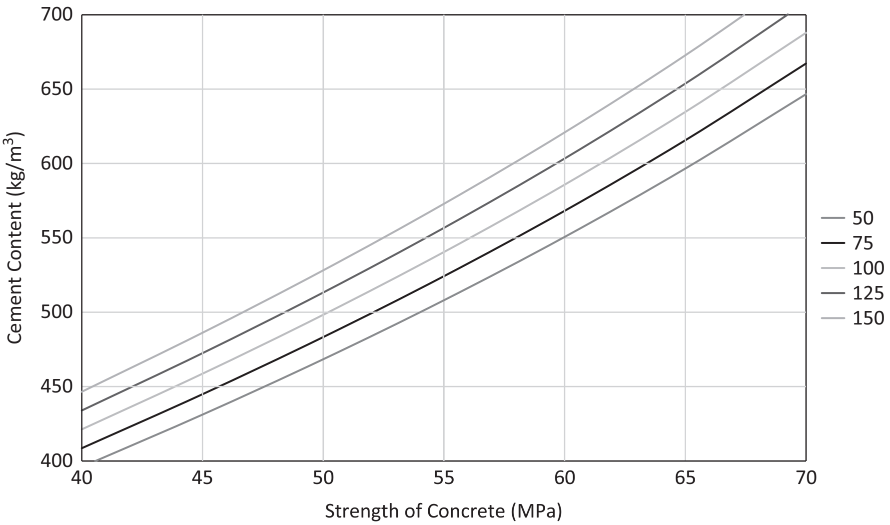


FIGURE 2.36
Cement content versus strength of concrete, cement strength 59 MPa, 20 mm MSA, for strengths above 40 MPa for the required workability.

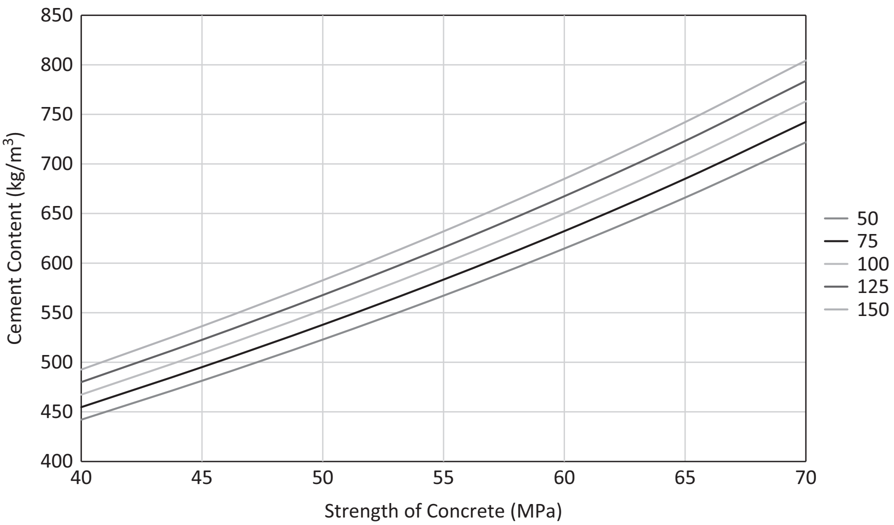


FIGURE 2.37
Cement content versus strength of concrete, cement strength 59 MPa, 10 mm MSA, for strengths above 40 MPa for the required workability.

Figure 2.5 target strength for various grades with either good and poor expected quality control water content for getting a slump of 120 mm from the graph seems to be near 200. Because the visual rating is 3, continue with the same water content. If the admixture being used has a water-reducing property, then the water content can be reduced by the percentage capacity of the admixture. In this case, no admixture is being used for water reduction; hence, no reduction in this water content.

2. Next, the target strength can directly provide the cement content for different workabilities in terms of slump. The graphs are for various MSAs and strengths of cement. For each MSA and cement strength curve combination, there are two graphs, one with lower grades of concrete and another for higher-grade and higher-cementitious content. Thus, for 61 MPa strength cement, a slump of 120 mm, MSA 20 mm, and a target strength of 37.69 MPa, cement content required is approximately 432 kg as seen from Figure 2.34. In Example 2.4, the cement calculated is 419 kg, which is due to the accurate substitution of cement strength in the formula, but this difference can be neglected if proportioning is by visual interpretation of the graph, and is acceptable. Again if admixture is being used, then the cement content can also be reduced by the same percentage, the water has been reduced in the previous step.

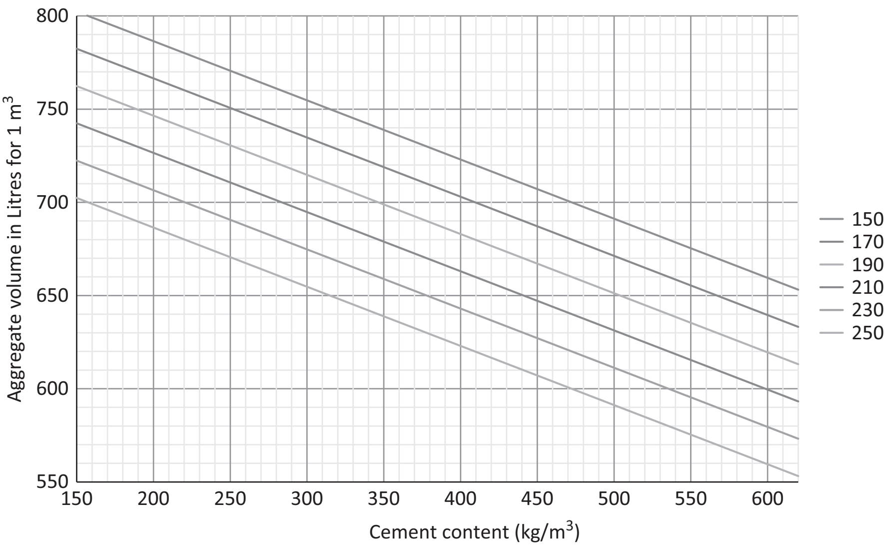


FIGURE 2.38
Aggregate volume versus cement and water content per metric cube of concrete.

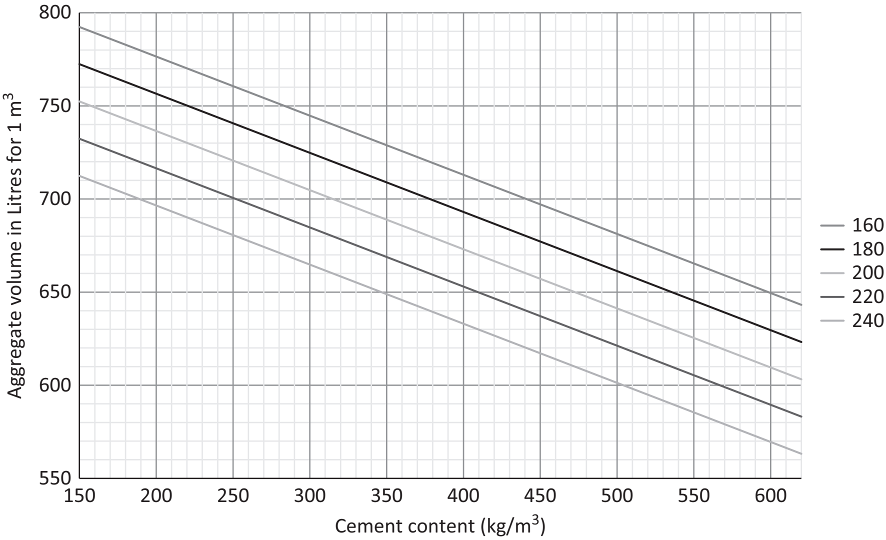


FIGURE 2.39
Aggregate volume versus cement and water content per metric cube of concrete.

3. After finding the water content and cement content, refer to Figure 2.38 or 2.39 for finding the total aggregate absolute volume in concrete. Thus, the aggregate absolute volume is close to 663 L (Figure 2.39). If the aggregate absolute volume was calculated, it will be equal to 643 L, which is pretty close. The aggregate content given in the graph is based on OPC cement, which has a specific gravity of 3.15. Thus, if a different cement with different specific gravity is being used, apply the following correction for cement content:

$$C1 = C/3.15 \text{ X } Sc$$

where C1 is the Cement content to be used (with a different specific gravity) in the graph for finding aggregate volume, C is the cement content calculated in previous steps, and Sc is the specific gravity of cement being used.

NOTE: C1 is to be used only for finding the aggregate content in the graph; this shall not affect the actual cement content to be used, which was calculated in previous steps.

4. The percentage of fine aggregate will need certain calculations though and then the calculation of their contents.

3

ACI Method of Proportioning Concretes

3.1 Introduction

The American Concrete Institute (ACI) has a different approach towards mix design of concrete, in terms of aggregate proportion calculations, setting acceptance criteria for concrete strengths, and deciding the water cement ratio.

In this method, the same calculations for water cement ratio and cement content are done, except for water content and aggregate calculation. Aggregate proportions are calculated not by fitting the particle sizes in a particular curve or based on the zone of sand, but the aggregate is proportioned based on the dry loose bulk density of coarse aggregates and fineness modulus (FM) of sand. The steps shown herein will explain this method more clearly.

3.2 Estimating Water Cement Ratio

1. For the required strength, the water cement ratio is found as per Table 3.1.

3.3 Estimating Water Content

2. For the required workability and the given maximum size of aggregates, the water content is as per Table 3.2.
3. Calculate the cement content based on the previous two steps (i.e. water content/water cement ratio).

TABLE 3.1

Guideline for Estimating Water Cement Ratio for Required Compressive Strength

Compressive Strength at 28 days (MPa)	Water Cement Ratio by Weight	
	Non–Air-Entrained Concrete	Air-Entrained Concrete
41.37	0.41	—
34.47	0.48	0.4
27.58	0.57	0.48
20.68	0.68	0.59
13.79	0.82	0.74

Source: Reproduced from ACI 211.1 committee report, Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete. With permission.

TABLE 3.2

American Concrete Institute's Guidelines for Estimating Water Content for Desired Workability, NMSA, and Air Content

	Water kg/m³ of Concrete for Indicated Maximum Sizes of Aggregate							
Slump mm	10 mm	13 mm	20 mm	25 mm	40 mm	50 mm	80 mm	150 mm
Non–Air-Entrained Concrete								
25–60	208	199	187	178	163	154	131	113
60–115	228	217	202	193	178	169	145	125
115–180	243	228	214	202	187	178	160	—
Entrapped air (%)	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.2
Air-Entrained Concrete								
25–60	181	175	166	160	148	142	122	107
60–115	202	193	181	175	163	157	133	119
115–180	217	205	193	184	172	166	154	—
Recommended Air (%)								
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
Severe exposure	7.5	7.0	6.0	5.5	5.5	5.0	4.5	4.0

Source: Reproduced from ACI 211.1 committee report, Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete. With permission.

3.4 Proportioning and Calculating Aggregate Contents

4. Calculate the coarse aggregate content by multiplying oven-dry rodded bulk density (DRBD) with the volume of coarse aggregate per unit volume of concrete from Table 3.3. Apply correction factors

TABLE 3.3
American Concrete Institute's Guidelines for Proportioning Aggregates

Nominal Maximum Size of Aggregate (mm)	Volume of Oven-Dry Rodded Coarse Aggregate per Unit Volume of Concrete for Different Fineness Modulus of Fine Aggregate			
	2.4	**2.6**	**2.8**	**3**
6.5	0.60	0.48	0.46	0.44
9.5/10	0.5	0.48	0.46	0.44
12.5	0.69	0.57	0.55	0.53
20	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
38/40	0.75	0.73	0.71	0.69
50	0.78	0.76	0.74	0.72
75/80	0.82	0.80	0.78	0.76
150	0.87	0.85	0.83	0.81

Source: Reproduced from ACI 211.1 committee report, Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete. With permission.

Note: The volumes given in this table are for producing concrete of suitable workability for reinforced concrete. For concrete with less workability like road pavement etc., the coarse aggregate contents in this table can be increased by 10%. For concretes of higher workability, as in the case of concretes to be pumped, the coarse-aggregate content in this table can be reduced by 10%.

for various applications like pumping of concrete or just dumping/ Non Pumpable concrete.

INTERESTING FACT: In this method of proportioning aggregates, the concept is very interesting and provides a good insight into the different ways concrete needs to be proportioned and their respective advantages and disadvantages. A concrete's behavior in a fresh state depends a lot on the shape of the constituent aggregates. Flaky aggregates tend to provide less workability for the same mix proportion with the same aggregate gradation as compared to concrete made with more cubical or spherical aggregates. The reason being, void content in flaky aggregates is much higher than cubical or spherical aggregates, and so does the interparticle friction between the aggregates because of a larger contact area and the locking tendency of aggregates; the result is lesser workability for the same wetness of concrete. To get the same fresh property in concrete, the mortar content should be higher in flaky aggregates than in cubical aggregates, so that the flaky aggregates can be moved apart further and the interparticle friction can be reduced considerably. It should be noted that the void content also is higher in flaky aggregates as compared to cubical aggregates. An aggregate with higher flakiness index will show a lower DRBD w.r.t. aggregate with low flakiness or elongation index despite having the same specific gravity. When both of these aggregates are to be used for manufacturing concrete, as per this method, the DRBDs need to be multiplied with the factors given in the table, and because the DRBD of flaky aggregates will be less than the DRBD of cubical/spherical aggregates, the amount calculated for the aggregate content automatically shall be less in case of flaky aggregates than the cubical aggregates. Thus, to manufacture concrete, higher amount of mortar into concrete with flaky aggregates than concrete with cubical aggregates. This concept, though apt for aggregate proportioning in concrete, may pose some limitations, where higher or very-low grade concretes are designed and is also true with any other method. The corrections for extra fines from cementitious materials for higher grades or deficient fines for low grades have not been incorporated. The aggregate's shape becomes more critical when the aggregate size is smaller, meaning if fine aggregates are flaky and coarse aggregates are ok, then this concrete will have less workability than concrete made with rounded fine aggregates but flaky coarse aggregates. This issue does not get resolved in the aggregate proportioning part of this method and for that matter in no other standard proportioning methods.

When concrete is manufactured with low cementitious content, the concrete seems harsh, easily segregated, and highly cohesive for higher cementitious content when the aggregate proportion is used based on this method. Ideally, aggregate proportioning exercise should take into consideration the cementitious content also in the concrete, so that any deficiency or surplus of fines resulting from cementitious content can be compensated or reduced by increasing or decreasing the proportion of fine aggregate.

5. Calculate the fine aggregate content by subtracting absolute volumes of all calculated materials including air from 1 m^3 of concrete.

The graphical guidelines are provided from Figures 3.1 to 3.10, which are nothing but a graphical representation of guidelines given in tables that will help you to roughly deduce guidelines for

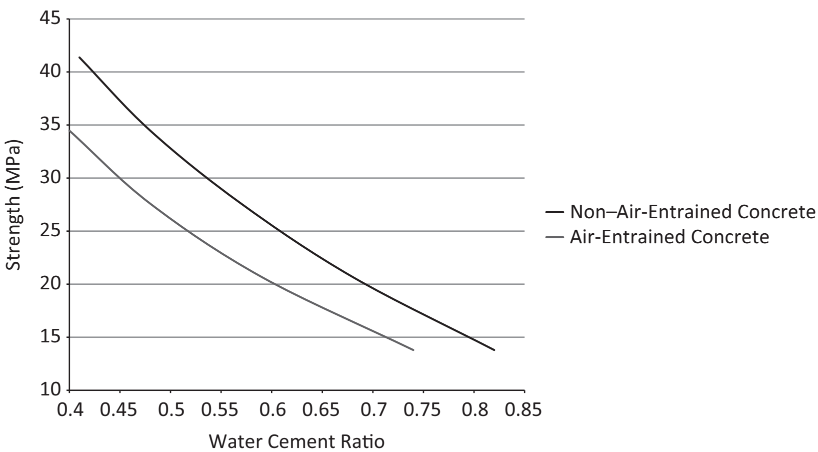


FIGURE 3.1
The American Concrete Institute (ACI) guide (graphical) for water cement ratio against required strength based on Table 3.1. (Based on ACI 211.1 committee report Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete method for proportioning.)

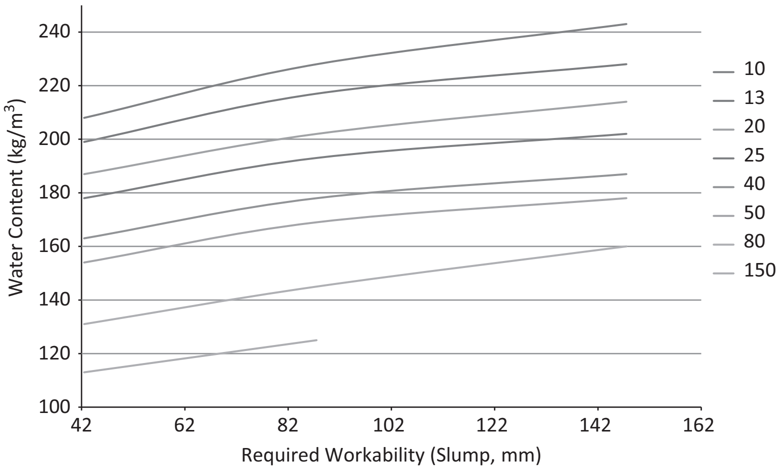


FIGURE 3.2
Slump versus water content for different MSAs (non–air-entrained concrete). (Based on ACI 211.1 committee report Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete method for proportioning.)

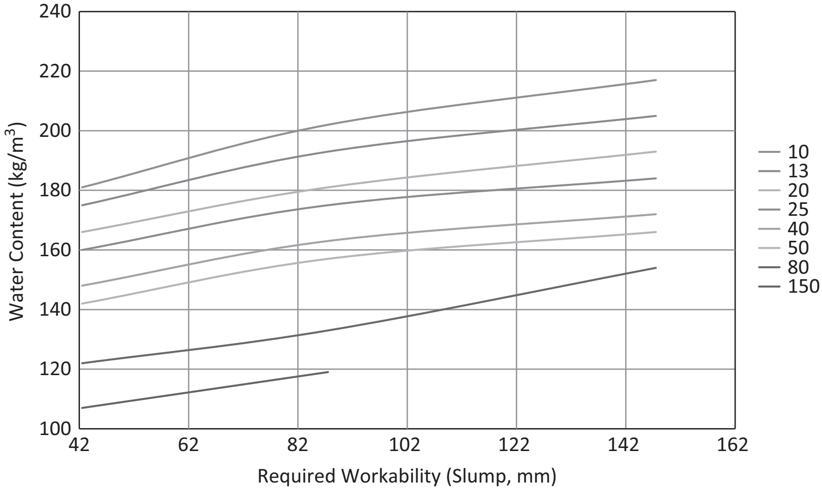


FIGURE 3.3
Slump versus water content for different MSAs (air-entrained concrete). (Based on ACI 211.1 committee report Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete method for proportioning.)

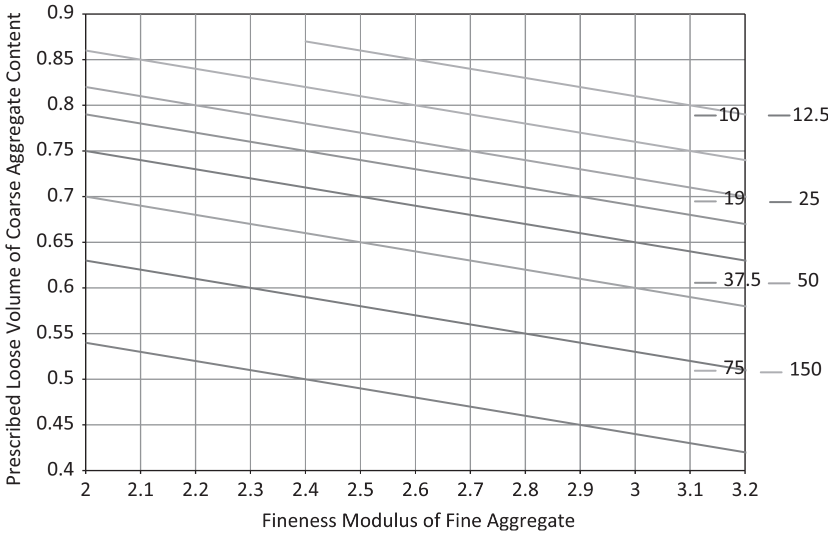


FIGURE 3.4
Volume of oven-dry-rodded coarse aggregate per unit volume of concrete for different fineness modulus of fine aggregate (x-axis) for different maximum sizes of aggregates (legend). (Based on ACI 211.1 committee report Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete method for proportioning.)

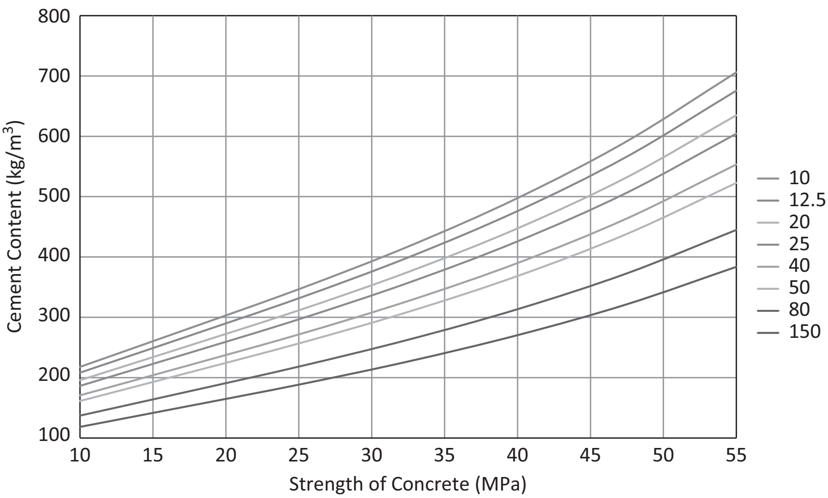


FIGURE 3.5
Cement content versus strength for different NMSAs, slump 25 to 60 mm, non–air entrained concrete. (Based on ACI 211.1 committee report Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete method for proportioning.)

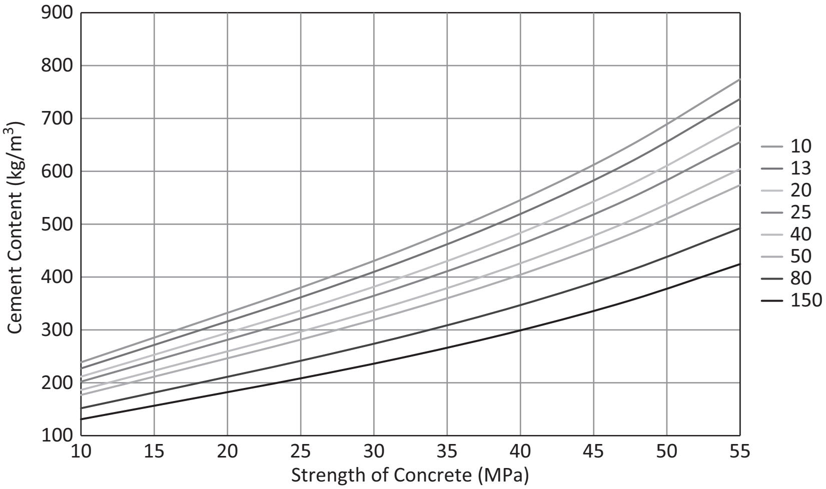


FIGURE 3.6
Cement content versus strength for different NMSAs, slump 60 to 115 mm, non–air-entrained concrete. (Based on ACI 211.1 committee report Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete method for proportioning.)

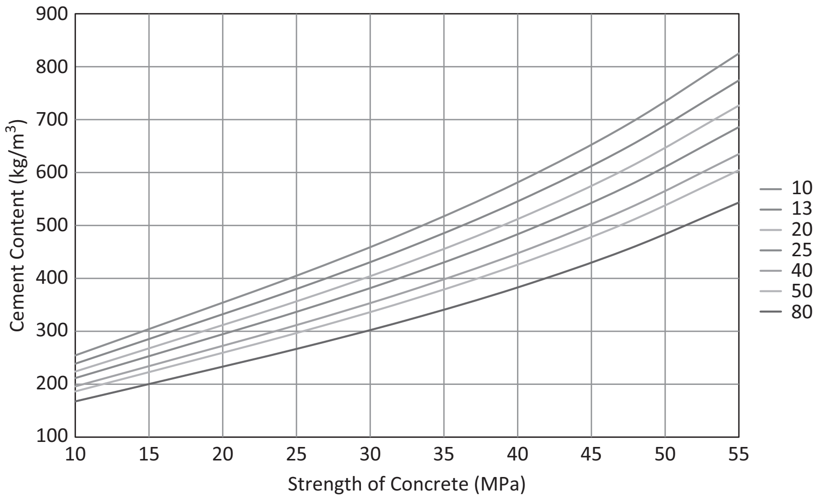


FIGURE 3.7
Cement content versus strength for different NMSAs, slump 115 to 180 mm, non–air-entrained concrete. (Based on ACI 211.1 committee report Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete method for proportioning.)

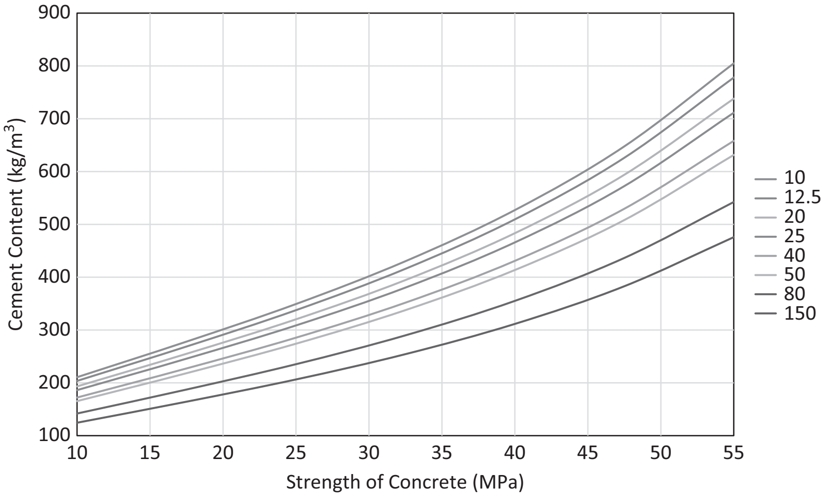


FIGURE 3.8
Cement content versus strength for different NMSAs, slump 25 to 60 mm, air-entrained concrete. (Based on ACI 211.1 committee report Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete method for proportioning.)

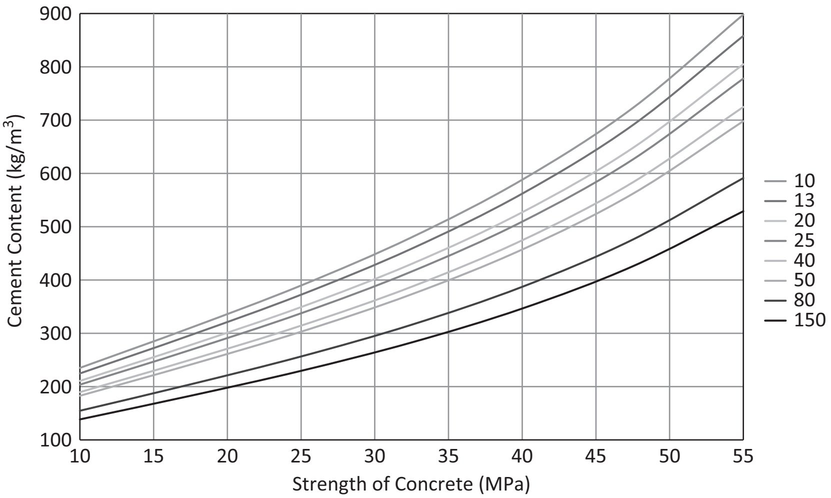


FIGURE 3.9
Cement content versus strength for different NMSAs, slump 60 to 115 mm, air-entrained concrete. (Based on ACI 211.1 committee report Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete method for proportioning.)

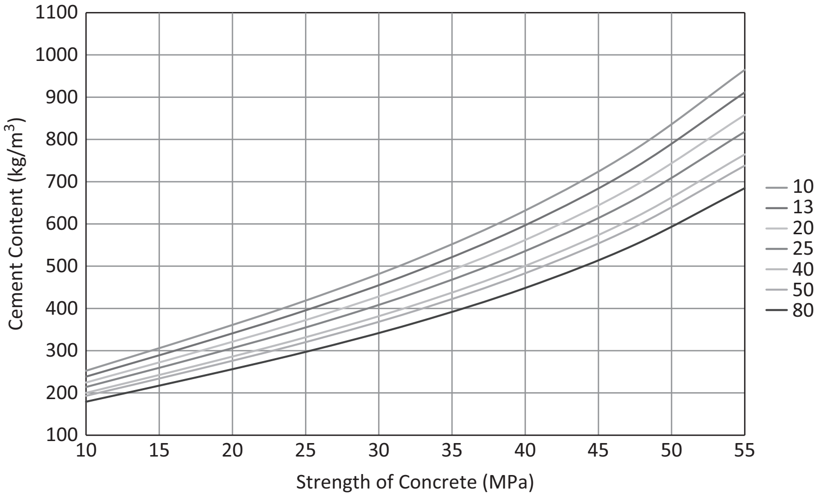


FIGURE 3.10
Cement content versus strength for different NMSAs, slump 115 to 180 mm, air-entrained concrete. (Based on ACI 211.1 committee report Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete method for proportioning.)

parameters not exactly defined and have to be interpolated. The coarse aggregate factor for FM of fine aggregate is 2.5 (which is not given in the table), so an imaginary line can be drawn between 2.4 and 2.6 and fine aggregate content for the relevant NMSA.

Example 3.1

Design a mix of M30 grade (non-air entrained) having a maximum size of aggregate as 20 mm, slump requirement of 120 mm, and to be laid by pumping. The FM of sand being used is 2.95, a specific gravity of 2.81, and DLBD is 1750 kg/m^3. The coarse aggregate has a DLBD of 1820 kg/m^3 and its specific gravity is 2.93. Assume a standard deviation of 5 MPa for this concrete based on the level of quality control being exercised.

Solution

Step 1: The target strength for M30 grade concrete is

$$Ft = 30 + 1.65 \times 5 = 38.25 \text{ MPa}$$

Step 2: As per Table 3.1, the water cement ratio required to get a strength of 41.37 MPa is 0.41 and for 34.47 w/c is 0.48. Then for 38.25, the w/c through interpolation would be 0.44.

Step 3: The water content required for a workability of 120 mm slump is 214 kg/m^3 of concrete as per Table 3.2.

Step 4: The cement content required for the given workability and strength is

Cement content = water content/water cement ratio
Cement content = 214/0.44 = 486 kg

Step 5: For the given DLBD of coarse aggregates and FM of fine aggregate, find the coarse aggregate content per cubic meter of concrete. The multiplier for coarse aggregate from Table 3.3 is 0.605 by interpolation (for a maximum size of aggregate as 20 mm, FM of 2.8 the multiplier is 0.62 and for FM 3 multiplier is 0.6, hence for FM of 2.95, the multiplier is 0.605). Also because the concrete needed is to be pumped, the multiplier needs to be decreased by up to 10%; thus, the multiplier becomes 0.545.
Thus, coarse aggregate content = 0.545 × 1820 = 992 kg.

Step 6: To calculate the fine aggregate content, apply the absolute volume method, in which the volume of sand will be calculated based on subtracting the individual volumes of all other ingredients found in previous steps from 1 m^3 of concrete, and then multiplying this volume with the specific gravity of sand to get the weight of sand required per cubic meter of concrete to constitute a 1-m cube.

- Volume of cement = 486/3.15 = 154.29 L
- Volume of coarse aggregate = 992/2.93 = 338.57 L
- Volume of air = 2% of 1 m^3 = 20 L (refer Table 3.2)
- Volume of water = 214 L
- Volume of sand required to make 1 m^3 of concrete = 1000 – 154.29 – 338.57 – 20 – 214 = 273 L
- Weight of sand = 273 × 2.81 = 767 kg

Example 3.2

Design M25 grade of non–air-entrained concrete with a maximum size of aggregate of 40 mm and workability required is a slump of 150 mm; the concrete is for an RCC structure laid manually without pumping. Use a water-reducing admixture that has a capacity to reduce water by 15%. The DLBD of the coarse aggregate is 1680 kg/m^3 and has a specific gravity of 2.71. The fine aggregate has a FM of 2.6, DLBD of 1550 kg/m^3, and a specific gravity of 2.58. The maximum water cement ratio to be used is 0.5, and the minimum cement content is 400 kg. You can use fly ash as a replacement of ordinary Portland cement (OPC) by not more than 35%. Assume a standard deviation of 4 MPa.

Solution

Step 1:

Ft = Fck + 1.65 × SD = 25 + 1.65 × 4 = 31.6 MPa

Step 2: By interpolation, the water cement ratio from Table 3.1 is 0.57 for the strength of 31.6 MPa for non–air-entrained concrete.

But because the maximum water cement ratio that can be used is 0.5, use 0.5 as the water cement ratio for this concrete.

Step 3: Water content required for a workability of 150 mm as per Table 3.2 is 187 kg for MSA of 40 mm. Now the admixture that is to be added has the capacity to provide the same workability even when the water content is reduced by 15%. So the water that needs to be added is 159 kg.

Step 4: The cement content to be added is

Cement content = Water content/Water cement ratio
= 159/0.5 = 318 kg

But as per the requirement, the minimum cement to be added is 400 kg. Hence, out of the two options, take the maximum, which in this case is 400 kg. Also, we are allowed to use fly ash as replacement of cement by up to 35%; hence, the OPC content thus becomes 65% of 400 kg and fly ash 35% of 400 kg. The OPC required is 260 kg and the fly ash required is 140 kg.

Step 5: Coarse aggregate content is to be calculated by selecting a multiplying factor from Table 3.3, and that is 0.73. Thus, coarse aggregate content is DLBD multiplied by the multiplying factor.

Coarse aggregate = 1680 × 0.73 = 1226 kg

Because the concrete is not to be pumped and has a normal slump requirement, no changes ought to be done for the coarse aggregate content calculated herein.

Step 6: Fine aggregate content now will be calculated by absolute volume method.

- Volume of cement = 260/3.15 = 82.54 L
- Volume of fly ash = 140/2.2 = 63.64 L (considering specific gravity of fly ash to be 2.2)
- Volume of coarse aggregate = 992/2.71 = 452.40 L
- Volume of air = 1% of 1 m^3 = 10 L (refer Table 3.2)
- Volume of water = 159 L
- Volume of sand required to make 1 m^3 of concrete = 1000 – 82.5 4 – 63.64 – 452.4 – 10 – 159 = 232.42 L
- Weight of sand = 232.42 × 2.58 = 600 kg

4

DOE Method of Proportioning Concretes

4.1 Introduction

The Department of Environment (DOE) method gives more freedom for the designer to estimate the proportions of concrete with strength requirements at an early age, provided the strength of cement when tested as per standard method is known for that same age. The DOE method provides guidelines through graphs rather than in tables and numbers (like other methods discussed previously), making it much easier for the process of mix proportioning.

4.2 Target Strength Calculation

Start with the calculation of target strength, which is as follows:

$$Ft = Fck + M$$

here M is margin and is equal to $k \cdot S$ (k is the statistical factor to be used for allowable percentage failure and S is the standard deviation).

For 10% defective allowable products, k = 1.28.

For 5% defective allowable products, k = 1.64.

For 2.5% defective allowable products, k = 1.96.

For 1% defective allowable products, k = 2.33.

Now, as usual, it is a 5% allowable failure in concrete, thus, k = 1.64.

For finding the value of S, assume a value from Figure 4.1, based on number of past test results. If past test results are less than 20, then higher of the values from Figure 4.1 on curve A or the actually calculated standard deviation is to be used. For higher than 20 results line B or the actual standard deviation (whichever is higher) is to be referred.

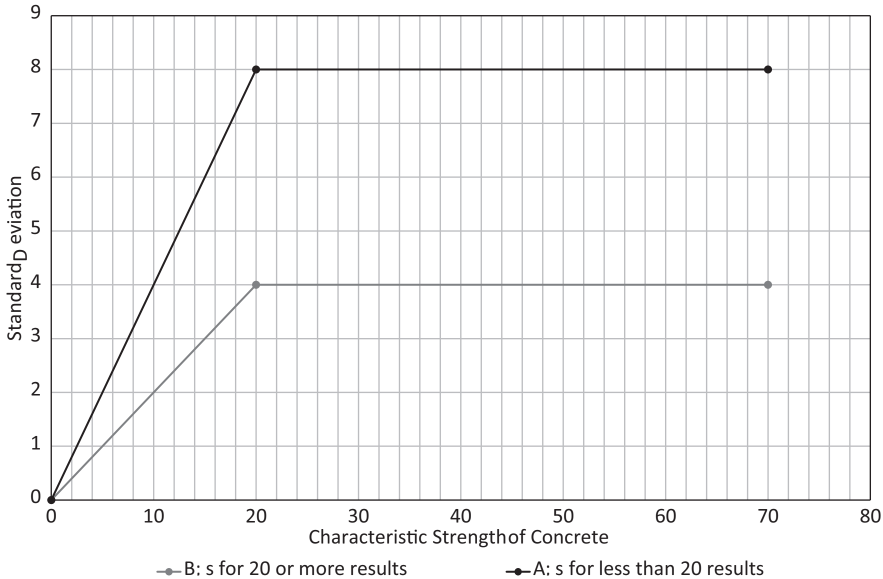


FIGURE 4.1
Guideline for calculating standard deviation. (From © IHS Markit, reproduced with permission from *Design of normal concrete mixes* 2E [BR 331].)

So to design M20 and the standard deviation calculated was 1.5 MPa from 15 available results, then use a value of 8 MPa from Figure 4.1 curve A. If the actual standard deviation calculated from 10 available results for M20 grade was 9 MPa, then the value of 9 MPa would be selected even though the figure says to use a value of 8 MPa. If there were 30 results and the standard deviation was 3.2 for M30 grade, then a value of 4 as per the curve B of Figure 4.1 would be used.

4.2.1 Target Strength for Air-Entrained Concrete

Air-entrained concrete strength is reduced for the same water cement ratio as compared to normal concrete. Hence, a higher target strength is defined for air-entrained concrete, which is given by the following formula

$$Ft = \frac{(Fck + M)}{(1 - 0.055a)}$$

where a is the air content percentage per unit volume of concrete. The coefficient 0.055 signifies a strength reduction of 5.5% for every 1% of air; hence, the target strength is increased to compensate for the reduced strength.

4.3 Estimating Water Cement Ratio to Achieve the Strength

After the target strength value is calculated, the water cement ratio is determined, which will give us the required target strength in concrete, and for which Table 4.1 and Figure 4.2 are referred to. This mix design method allows concrete to be designed for strength not only at 28 days but also for

TABLE 4.1

Approximate Compressive Strengths of Concrete Made with w/c 0.5

		Age (Days)			
Type of Cement	**Type of Coarse**	**3**	**7**	**28**	**91**
OPC or SRC	Uncrushed	22	30	42	49
	Crushed	27	36	49	56
RHPC	Uncrushed	29	37	48	54
	Crushed	34	43	55	61

Source: © IHS Markit, reproduced with permission from Design of normal concrete mixes 2E (BR 331).

OPC, ordinary Portland cement; SRC, sulphate-resisting cement; RHPC, rapid-hardening Portland cement.

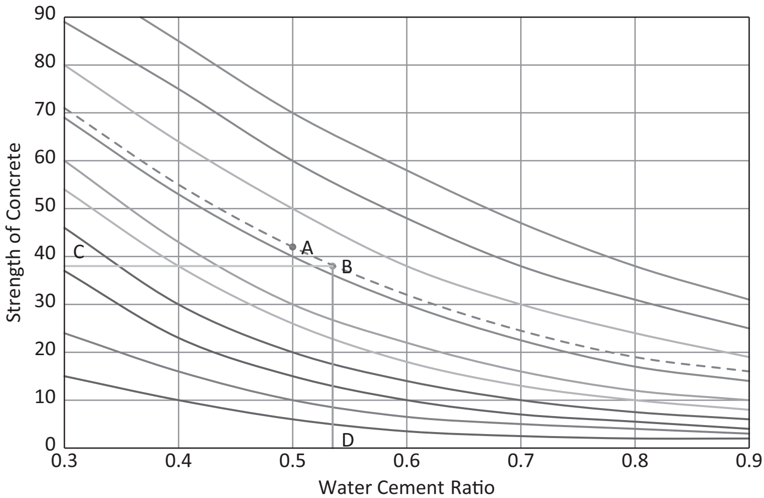


FIGURE 4.2
DOE guideline for estimating water cement ratio to get the required strength. (From © IHS Markit, reproduced with permission from *Design of normal concrete mixes* 2E [BR 331].)

any other age. Table 4.1 offers a guideline first to read Figure 4.1. Based on the cement used and the age desired to design the strength of concrete, choose the strength from Table 4.1. If you are using ordinary Portland cement (OPC) with uncrushed aggregates and want to design the concrete for 28 days, the strength to be chosen is 42 MPa as per Table 4.1. Similarly, if you are using rapid-hardening cement with crushed aggregates and the strength to be targeted is for 3 days, then as per the table, 34 MPa is to be chosen. A curve (refer Figure 4.2) is then manually drawn (dotted line) parallel to the closest curve passing through point A (point A is 42 MPa). This curve now becomes a guide in designing any grade of concrete. If a strength equivalent to point C (38 MPa) in Figure 4.2 is desired, plot a horizontal line until it meets the curve (point B) and from there, drop a vertical line that meets the ordinate (point D), which is the required water cement ratio to get the target strength. In case there are specifications of maximum water cement ratio, then the minimum of both the values are to be adopted for the mix design (w/c from the curve for the required strength and w/c from the specifications).

In case of cement replacement with fly ash, the guidelines propose interesting changes. A concept called *equivalent cement content* is introduced, which states that when fly ash is used for the replacement of cement, it does not contribute equivalent strength as ordinary Portland cement/sulphate-resisting cement or rapid-hardening Portland cement (OPC/SRC or RHPC). The fly ash used gives strength equivalent to 20%–40% of its weight when portland cement (PC; henceforth used commonly for OPC, SRC, and RHPC) is used instead. A factor called *cementing efficiency index* is used for finding the equivalent water cement ratio.

$$\frac{W}{(C + e \cdot F)} = \frac{W1}{C1}$$

where W is water content, C cement content, and F fly ash content used in concrete containing cement and fly ash. The term e is the cementing efficiency index, which is 0.3.

W1 and C1 are the water and cement contents used in another concrete with pure PC and no fly ash, which gives the same strength as that containing PC- C kg and fly ash- F kg.

In the case of cement replacement with fly ash, the water cement ratio found from Table 4.1 and Figure 4.2 has to be converted to equivalent water cement ratio including fly ash, which is lower. Thus, the cementitious content found in the next step will be higher than the OPC content if used alone without fly ash.

4.4 Finding the Water Content

After finding the water cement ratio, next the water content needs to be found, which can be obtained from Table 4.2. Table 4.2 gives the required water content per cubic meter for the required workability in terms of slump or VEEBEE time and maximum size and type (crushed/uncrushed) of aggregate. Table 4.3 is to be used for correction (reduction) of water content found in Table 4.2 to reduce water for corresponding percentages of fly ash usage as cement replacement. So let us say if we needed a slump of 100 mm for a concrete, which has MSA as 20 mm and it is crushed aggregate, the water

TABLE 4.2

DOE Guideline for Water Content w.r.t Workability and NMSA

Slump (mm) → VEEBEE Time (sec) →		**0–10 >12**	**10–30 6–12**	**30–60 3–6**	**60–180 0–3**
MSA	**Aggregate Type**	**Water Contents (kg/m³)**			
10	Uncrushed	150	180	205	225
	Crushed	180	205	230	250
20	Uncrushed	135	160	180	195
	Crushed	170	190	210	225
40	Uncrushed	115	140	160	175
	Crushed	155	175	190	205

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DOE, Department of Environment; NMSA, nominal maximum size aggregate.

TABLE 4.3

Corrections to be Applied for Water Contents for Different Percentages of Fly Ash

Slump (mm) → VEEBEE Time (sec) →	**0–10 >12**	**10–30 6–12**	**30–60 3–6**	**60–180 0–3**
Fly Ash in Total Cementitious (%)	**Reduction in Water Contents (kg/m³)**			
10	5	5	5	10
20	10	10	10	15
30	15	15	20	20
40	20	20	25	25
50	25	25	30	30

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required, as per Table 4.2, would be 225 kg/m^3 of concrete. In case if both fine and coarse aggregates are manufactured or made from two different types, meaning one is crushed and other uncrushed, then the formula given in the footer of the table needs to be used, and corrected water is to be used. Thus, if the coarse aggregates were of a crushed type and fine aggregates were uncrushed, then as per the formula, water content would be:

$$W = \tfrac{2}{3}\ Ff + \tfrac{1}{3}\ Fc = \tfrac{2}{3} \times 195 + \tfrac{1}{3} \times 225 = 205\ \text{Kg}.$$

4.5 Cement Content

After finding the water content and the water cement ratio, find the cement content by dividing the water content by the water cement ratio.

$$\text{Cement content} = \text{Water content}/\text{Water cement ratio}$$

The cement content so found has to be compared with the specification of minimum cement content if any in such cases maximum of the two is to be adopted.

4.5.1 Cement Content Calculation When Fly Ash Is Used as Replacement

The water cement ratio found is always for water and PC without fly ash; hence, a correction is required to calculate the PC and fly ash from the water content and water cement ratios found in previous steps.

Let us say the water cement ratio found is w′, the percentage of fly ash is p (in decimals) and the weight of water W.

Let O be denoted for PC content to get required strength in concrete without fly ash and C and F the PC content and fly ash content, respectively, for getting similar strength as that with O.

Then

$$O = \frac{W}{w'} \tag{4.1}$$

$$O = C + e \cdot F = C + 0.3F \tag{4.2}$$

Also

$$F = \frac{C}{(1-p)} \times p \tag{4.3}$$

Based on these equations

$$C = \frac{W(1-p)}{\left[w'(1-0.7p)\right]} \tag{4.4}$$

To calculate cement content for concretes containing fly ash, Equation 4.4 is used, and fly ash is calculated based on Equation 4.3.

NOTE: The calculations for cement contents holds true for 28-days' strength only; for ages less than 28 days, the value of cementing efficiency index is still lesser, whereas for beyond 28 days, the index is higher.

4.6 Aggregate Proportion and Content

Next, to design the concrete, the content and the proportion of aggregates need to be found; refer Figures 4.3 through 4.5. There are three sets of figures that are to be referred for deciding fine aggregate percentage, and each set of figures represents the MSA that would be used for manufacturing concrete. In each figure/graph, there are five sets of curves, and each curve represents the percentage of 600 μ passing in the fine aggregate that will be used for manufacturing in concrete. The x-axis represents the water cement ratio that would be used for manufacturing the concrete, and from the y-axis, the percentage of fine aggregate in the total aggregate to be used to get required properties is found. The graph is chosen based on the required workability, which is denoted above each graph. Additionally, there are guidelines given for the proportioning of aggregates when zones of sand are known (zone 1 for coarsest and zone 4 for finest) in Figures 4.6 and 4.7.

Figure 4.8 is for finding the expected density when using the given set of materials used for calculating aggregate contents in concrete.

The weight of fine aggregate to be found is based on Figure 4.3, 4.4, or 4.5 and the following formula:

$$\text{Fine aggregate} = \%\text{ of fine aggregate} \times (D - C - W)$$

where D is the fresh density of concrete calculated from Figure 4.8, C is the cement content kg/m^3, and W is water content kg/m^3. The expression, D – C – W, is nothing but the total aggregate content.

Coarse aggregate content = Total aggregate content – Fine aggregate content

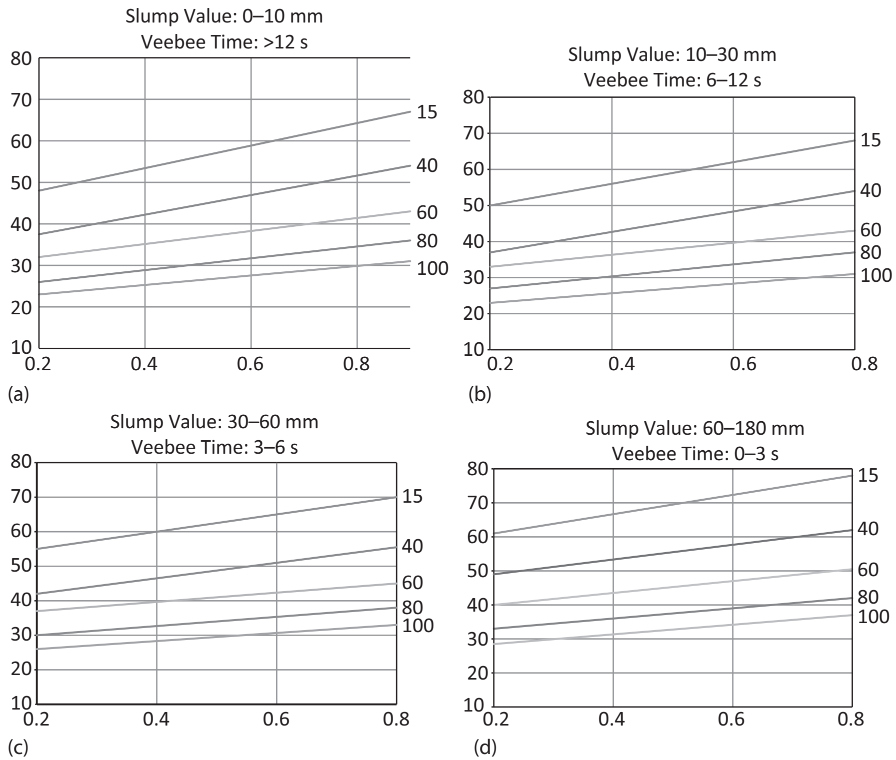


FIGURE 4.3
Guidelines for proportioning aggregates by selecting fine aggregate as percentage of total aggregates for MSA of 10 mm: (a) when workability required is between slump value of 0 and 10 mm or Veebee time higher than 12 s; (b) when workability required is between slump value of 10 and 30 mm or Veebee between 6 and 12 s; (c) when workability required is between slump value of 30 and 60 mm or Veebee time higher than 3–6 s; (d) when workability required is between slump value of 60 and 180 mm or Veebee time higher than 0–3 s. (From © IHS Markit, reproduced with permission from *Design of normal concrete mixes* 2E [BR 331].)

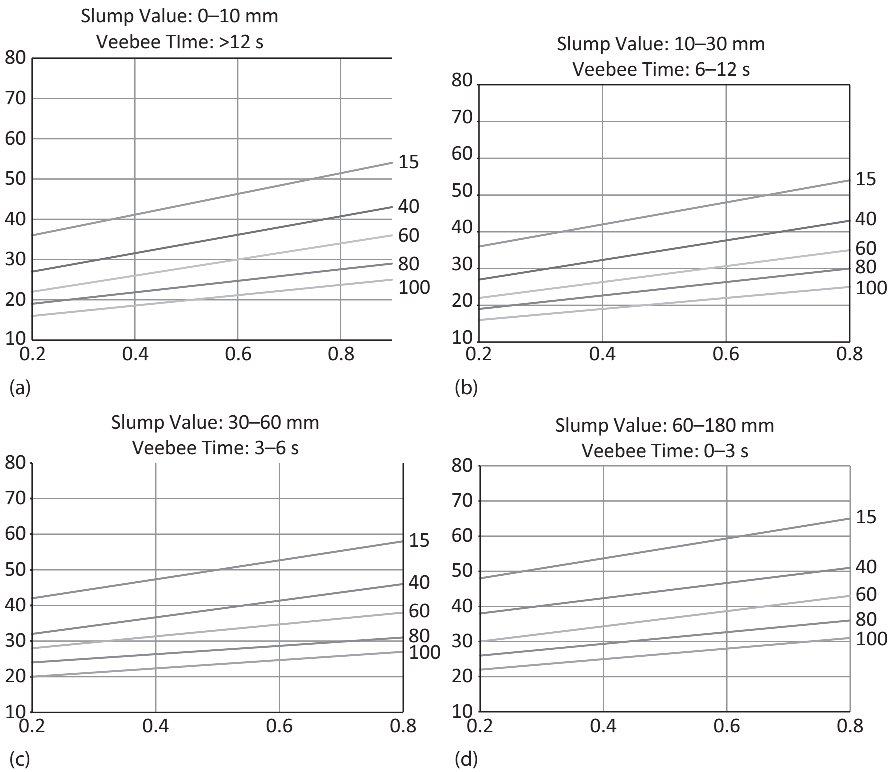


FIGURE 4.4
Guidelines for proportioning aggregates by selecting fine aggregate as percentage of total aggregates for MSA of 20 mm: (a) when workability required is between slump value of 0 and 10 mm or Veebee time higher than 12 s; (b) when workability required is between slump value of 10 and 30 mm or Veebee between 6 and 12 s; (c) when workability required is between slump value of 30 and 60 mm or Veebee time higher than 3–6 s; (d) when workability required is between slump value of 60 and 180 mm or Veebee time higher than 0–3 s. (From © IHS Markit, reproduced with permission from *Design of normal concrete mixes* 2E [BR 331].)

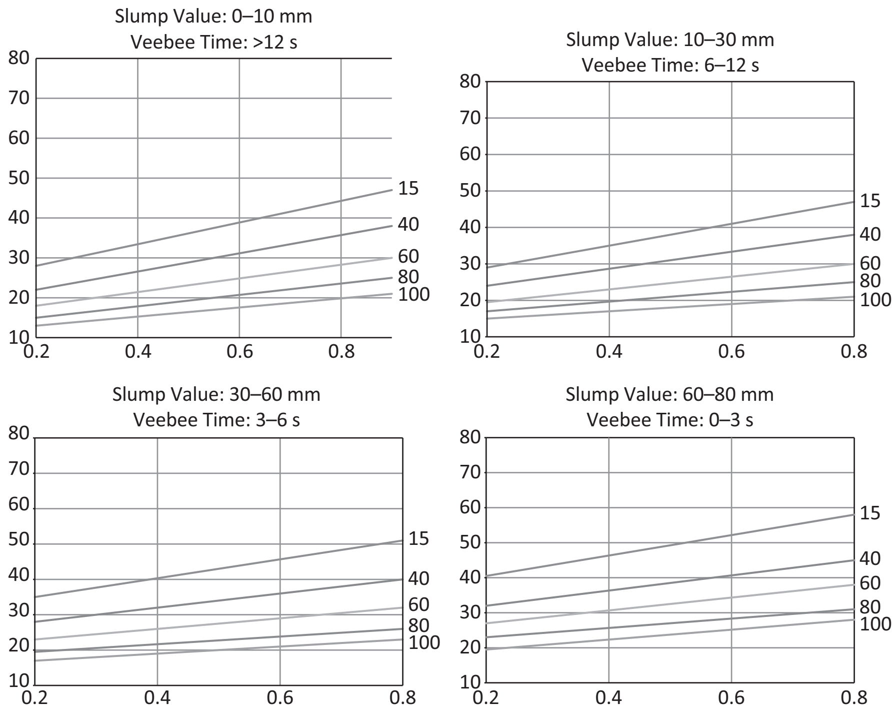


FIGURE 4.5
Guidelines for proportioning aggregates by selecting fine aggregate as percentage of total aggregates for MSA 40 mm: (a) when workability required is between slump value of 0 and 10 mm or Veebee time higher than 12 s; (b) when workability required is between slump value of 10 and 30 mm or Veebee between 6 and 12 s; (c) when workability required is between slump value of 30 and 60 mm or Veebee time higher than 3–6 s; (d) when workability required is between slump value of 60 and 180 mm or Veebee time higher than 0–3 s. (From © IHS Markit, reproduced with permission from *Design of normal concrete mixes* 2E [BR 331].)

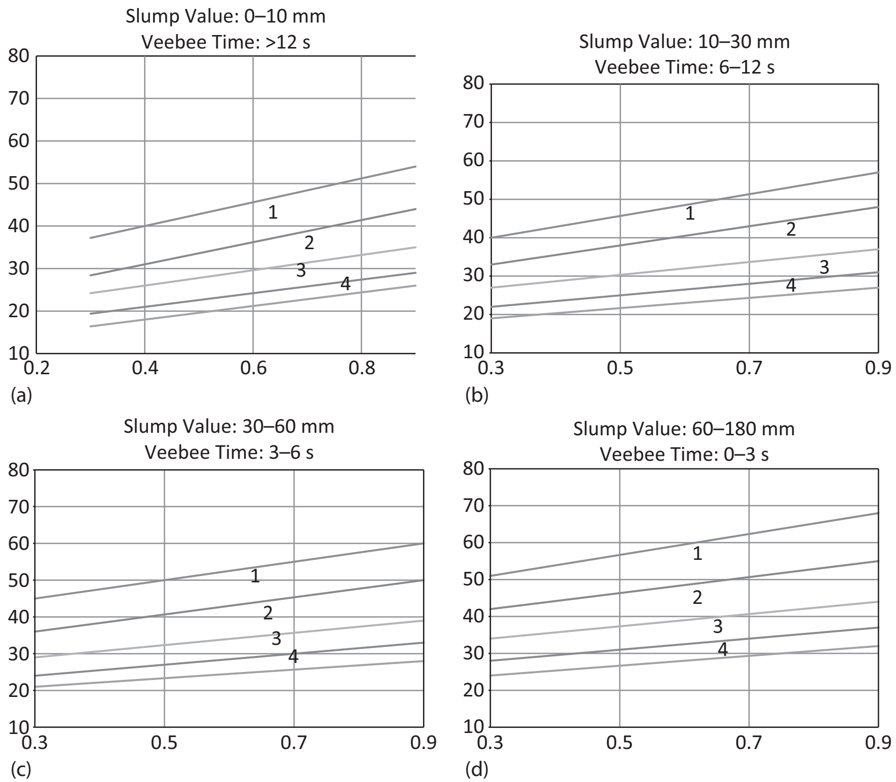


FIGURE 4.6
Guidelines for proportioning aggregates based on zone of fine aggregate by selecting fine aggregate as percentage of total aggregates for MSA 20 mm: (a) when workability required is between slump value of 0 and 10 mm or Veebee time higher than 12 s; (b) when workability required is between slump value of 10 and 30 mm or Veebee between 6 and 12 s; (c) when workability required is between slump value of 30 and 60 mm or Veebee time higher than 3–6 s; (d) when workability required is between slump value of 60 and 180 mm or Veebee time higher than 0–3 s. (From © IHS Markit, reproduced with permission from *Design of normal concrete mixes* 2E [BR 331].)

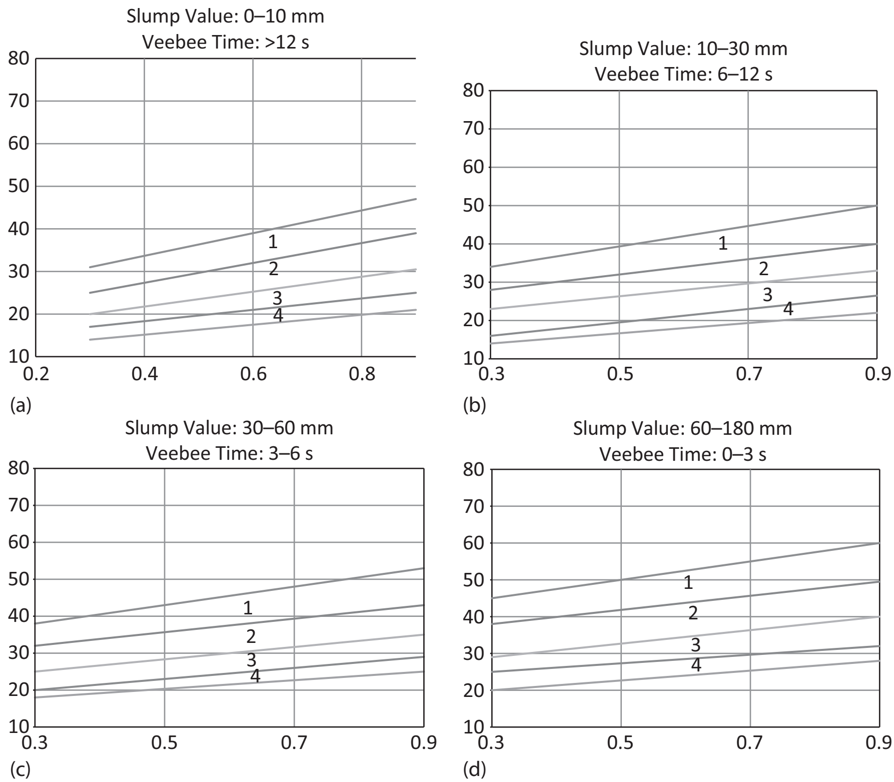


FIGURE 4.7
Guidelines for proportioning aggregates based on zone of fine aggregate by selecting fine aggregate as percentage of total aggregates for MSA 40 mm: (a) when workability required is between slump value of 0 and 10 mm or Veebee time higher than 12 s; (b) when workability required is between slump value of 10 and 30 mm or Veebee between 6 and 12 s; (c) when workability required is between slump value of 30 and 60 mm or Veebee time higher than 3–6 s; (d) when workability required is between slump value of 60 and 180 mm or Veebee time higher than 0–3 s. (From © IHS Markit, reproduced with permission from *Design of normal concrete mixes* 2E [BR 331].)

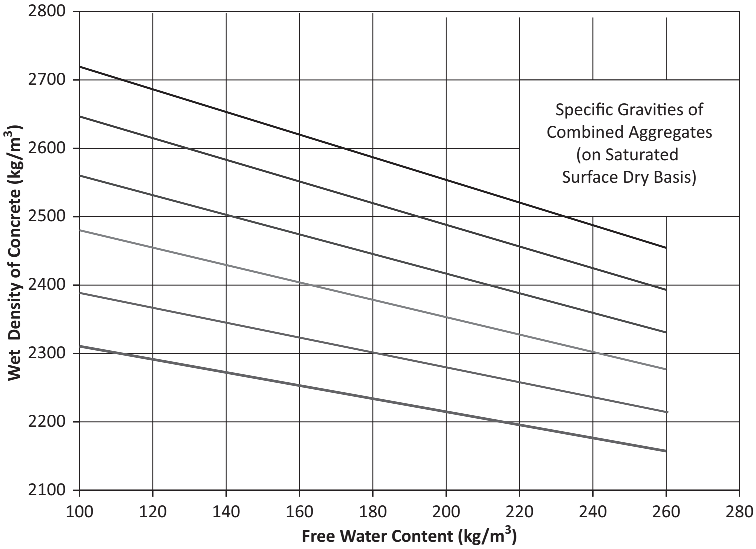


FIGURE 4.8
Guideline for estimating concrete density for different specific gravities of combined aggregates. (From © IHS Markit, reproduced with permission from *Design of normal concrete mixes* 2E [BR 331].)

The coarse aggregate can be divided into various sizes based on shape and particle-size distribution; but as a general rule, if 20 mm MSA is to be used, 10 and 20 mm are to be divided into 1:2 proportion, respectively, and if 40 mm is to be used, then 1:1.5:3 for 40 to 20 to 10 mm aggregates, respectively.

Example 4.1

Design an M35 grade concrete with a workability of 50 mm slump using the DOE method. There are no previous trial results available for this concrete. Aggregates to be used are crushed for coarse and river sand for fine aggregates. The maximum size of aggregate that can be used is 20 mm because of the thickness of the section being just 100 mm. The maximum water cement ratio allowed is 0.55 and the minimum cement content is 320 kg. The fine aggregate has 35% of 600 μ passing. The average specific gravity of the aggregates is 2.7.

Solution

Target strength = 35 + 1.64 × 8 = 48.2 MPa

(The standard deviation 8 is taken from Figure 4.1, and the curve is selected because no results are available.)

As per Table 4.1, 0.5 w/c ratio for crushed aggregates gives strength equal to 49 MPa. As per Figure 4.2, at 0.5 w/c, the closest curve is the one passing through 50 MPa. Thus, to achieve a target strength of 48.2 MPa, we may have to take a w/c ratio of 0.51 approximately. The water cement ratio of 0.51 is less than the upper limit prescribed of 0.55; hence, the water cement ratio can be used to design the concrete.

Refer to Table 4.2 to find water content. The coarse aggregates are crushed and fine aggregates are from a river, which means they are not crushed. The water content required for crushed aggregates is 210 and 180 kg/m^3, respectively, for uncrushed aggregates. The formula for calculating water contents when coarse and fine aggregates are different in terms of type, we need to calculate the water content using the following formula:

$$W = \tfrac{2}{3}\ Ff + \tfrac{1}{3}\,Fc = \tfrac{2}{3}180 + \tfrac{1}{3}210 = 120 + 70 = 190 \text{ Kgs}$$

So, the cement content that satisfies the criteria of w/c = 0.51 for the water content of 190 kg is 190/0.51 = 373 kg

The cement content is higher than the minimum cement content limit of 320 kg; hence, this cement can be used for designing concrete.

The fine aggregate percentage to be used is 41% based on Figure 4.4c (20 mm MSA) for the graph shown for slump between 30 and 60 mm.

Thus,

$$\text{Fine aggregate} = \%\text{ of fine aggregate} \times \left(D - C - W\right)$$
$$= 0.41 \times \left(2440 - 373 - 190\right) = 770 \text{ Kg}$$

and Coarse aggregate = (1 − % fine aggregate) × (D − C − W) = 0.59 × (2440 − 373 − 190) = 1107 kg

The coarse aggregates can be divided to fit in the gradation curve of coarse aggregates, or as per the guidance of DOE method, 20 and 10 mm can be divided into 2:1 proportion; thus, 20 mm shall be calculated as

20 mm aggregate weight = 2/(1 + 2) × Weight of coarse aggregates
= 2/3 × 1107 = 738 kg

10 mm aggregate weight = 1107 − 738 = 369 kg

The concrete mix thus is:

Cement: 373 kg
Water: 190 kg
20 mm aggregates: 738 kg
10 mm aggregates: 369 kg
Fine aggregates: 770 kg

After conducting the trial, the strength achieved is 43 MPa instead of 48 MPa. Mark a point on the graph in Figure 4.2 intersecting 0.51 water cement ratio and strength of 43 MPa. This point lies on the dotted line (between points marked as A and B). Now the w/c ratio required to get the strength of 48.2 with these materials can be found out by checking the w/c on the dotted line. The dotted line depicts that the water cement ratio for a strength of 48 MPa is 0.45.

Thus, the new mix will be calculated as follows:

Cement = 190/0.45 = 422 kg (changes because w/c has changed to achieve the target strength)
Water = 190 kg (remains constant because workability was achieved)
Fine aggregates = 0.41 × (2440 − 422 − 190) = 750 kg (proportion remains the same but quantity is reduced because the cement quantity has increased in 1 m^3)
Coarse aggregates = 0.59 × (2440 − 422 − 190) = 1079 kg (proportion remains the same but quantity reduced because cement quantity has increased in 1 m^3)
20 mm = 2/3 × 1079 = 719 kg
10 mm = 1079–719 = 360 kg

Example 4.2

Design a concrete with a workability of 120 mm slump, which should achieve a strength of 15 MPa in 3 days, using the DOE method. There are previous trial results available for this concrete, and the standard deviation is 4.5 MPa from the previous 50 mixes at 3 days. Aggregates to be used are uncrushed for coarse and fine aggregates. The maximum size of aggregate that can be used is 20 mm. The maximum water cement ratio allowed is 0.5 and the minimum cement content is 320 kg. The fine aggregate has 30% of 600 μ passing. The average specific gravity of the aggregates is 2.7.

Solution

Target Strength = 15 + 1.64 × 4.5 = 22.4 MPa

(The standard deviation, 4.5, is taken from the previously available data because it is more than the specified standard deviation in Figure 4.1.)

As per Table 4.1, 0.5 w/c ratio for crushed aggregates gives strength equal to 27 MPa at 3 days. As per Figure 4.2, at 0.5 w/c the closest curve is the one passing through 30 MPa. Thus, to achieve a target strength of 22.4 MPa, take a w/c ratio of 0.6 approximately. The water cement ratio of 0.6 is higher than the upper limit prescribed of 0.5; hence, the water cement ratio to be used to design the concrete shall be 0.5.

Next, find the water content by referring to Table 4.2. The coarse aggregates are crushed and fine aggregates are not crushed. The water content required is 195 kg/m^3 for uncrushed aggregates.

So, the cement content that satisfies the criteria of w/c = 0.5 for the water content of 195 kg is

195/0.5 = 390 kg

The cement content found out is higher than the minimum cement content limit of 320 kg; hence, this cement can be used for designing concrete.

The fine aggregate percentage to be used is 47 based on Figure 4.4c (20 mm MSA) for the graph shown for slump between 60 and 80 mm.

Thus,

$$\text{Fine aggregate} = \%\text{ of fine aggregate} \times (D - C - W)$$
$$= 0.47 \times (2440 - 390 - 195) = 872\,\text{kg}$$

and Coarse aggregate = (1 − % fine aggregate) × (D − C − W) = 0.53 × (2440 − 390 − 195) = 983 kg

The coarse aggregates can be divided to fit in the gradation curve of coarse aggregates, or as per the guidance of DOE method, 20 and 10 mm can be divided into 2:1 proportion; thus 20 mm shall be calculated as

$$\text{20 mm aggregate weight} = 2/(1+2) \times \text{Weight of coarse aggregates}$$
$$= 2/3 \times 983 = 655\text{ kg}$$
$$\text{10 mm aggregate weight} = 983 - 655 = 328\text{ kg}$$

The concrete mix, thus, is:

Cement: 390 kg
Water: 195 kg
20 mm aggregates: 655 kg
10 mm aggregates: 328 kg
Fine aggregates: 872 kg

5

BRMCA Method of Proportioning Concretes

5.1 Introduction

The British Ready-made Concrete Association (BRMCA) method is also known as 'family of mixes' method by many. This method is the extension of mix-design proportioning done by any other method. In this method, mix design proportions for a minimum of four different cementitious contents are tested. While conducting trials of designed mixes, if some adjustments are required to make the concrete workable or to tweak the fresh property of concrete by increasing or decreasing a material, the same is done and recorded. Then for each trial mix, proportions are calculated based on corrections done during the trials. At different ages when strengths are tested, a graph is plotted by regression for cement versus strength, cement versus aggregate, cement versus water content, and so on. Each graph curve shows a particular kind of relationship with cement content (i.e. linear, polynomial, etc.). From these trends, the closest possible relationship between them in terms of linear function or binomial function is found. And then based on the requirement, mix proportions are calculated from these relationships.

5.2 Methodology

The BRMCA method does not require guidelines of water cement ratio or water content to arrive at a proportion for meeting the specifications. The method can be best understood by an example.

To design concrete for M30 grade of concrete, instead of going for a trial with a particular w/c ratio, trials for a minimum of four different cement contents are preferred. Thus, if the cement contents are of 290, 340, 390, 450 kg, then we plot a graph after finding the strengths for each cement content, which would look something like Figure 5.1.

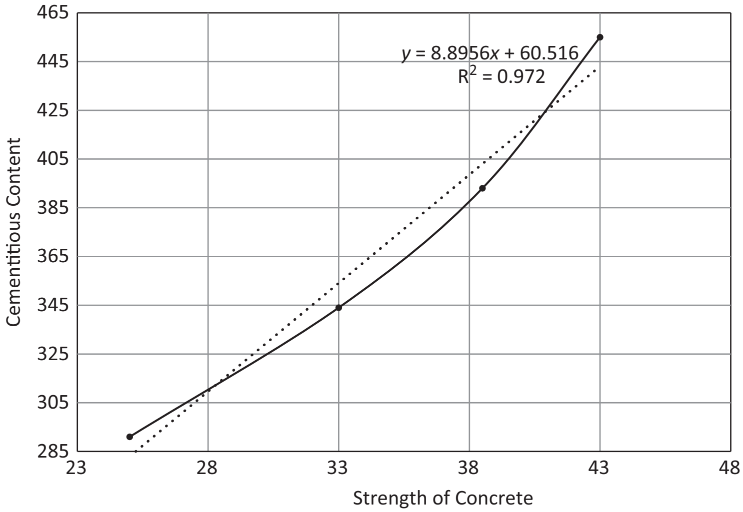


FIGURE 5.1
Example of plotting cement content versus strength achieved as per British Ready-made Concrete Association (BRMCA) method.

Usually, strength curves are linear, but in case of concretes using low-range water-reducing admixture, the increase in strength decreases above a certain strength, thus making it a polynomial type of curve with a power of 2. Also, in most cases, the water or admixture dosage fixed does not perform in terms of workability requirement, or fresh property. In such cases, add additional water or admixture or both to achieve the required workability. The added extra water or admixture should be recorded, and it is better to recalculate backward the mix proportion for the concrete.

5.2.1 Mix Corrections and Records

To understand mix corrections and the relevant changes in mix proportions, look at a family of mixes trials.

Four mixes were designed as in Table 5.1.

All the materials depicted are in kilograms and are assumed to constitute 1 m^3 of concrete (assumed, because no matter how perfect the calculations are, the mixes calculated rarely make up the required volume). Then the quantities required for conducting the trial for suitable batch size, say 30 L, and the respective weights for each trial are calculated and shown in Table 5.2. In the same table, extra water added or water held, if any, to get the required workability at the required period (say slump retention of 3 h) is also recorded against the water contents.

Before proceeding further, corrections based on actual results need to be applied, so that errors as a result of the assumptions are filtered out (water required to get desired workability, cement content, entrapped-air content, etc.).

TABLE 5.1

Example of Mix Proportioning System by BRMCA Method

Material	Trial 1	Trial 2	Trial 3	Trial 4
Cement	300	350	400	450
Water	160	160	160	155
20 mm	850	820	780	700
10 mm	340	330	320	310
Sand	800	790	780	770
Super Plasticizer	3	3.5	4	4.5

TABLE 5.2

Tabulation Example for BRMCA Method of Proportioning for Actual Batch Weights and the Relevant Strength Achieved

Material	Trial 1	Trial 2	Trial 3	Trial 4
Cement	9	10.5	12	13.5
Water	4.8 + 0.45	4.8–0.3	4.8	4.65 + 0.55
20 mm	25.5	24.6	23.4	21
10 mm	10.2	9.9	9.6	9.3
Sand	24	23.7	23.4	23.1
Super Plasticizer	0.09	0.105	0.12	0.135
Total weight	74.04	73.305	73.32	72.235
Average cube weight of the trial (15-cm cube)	8.071	8.114	8.108	8.211
28-day average strength (MPa)	25	33	38.5	43

BRMCA, British Ready-made Concrete Association.

Calculate mix proportions based on trial1 and the changes done during the trial.

The density of the concrete actually is

$$\text{Density of concrete} = \text{Weight of concrete cube} / \text{volume of the cube}$$

or

$$\text{Density of concrete} = \text{Weight of cube in air} /$$

$$\left(\text{wt of cube in air} - \text{wt of cube in water}\right)$$

The second formula for the absolute density of concrete is more accurate because it corrects the dimensional errors of cube/Specimen.

Density = 8.071/[(0.15)^3] = 2391 kg/m^3 (0.15 as 8.071 is weight of the 15-cm cube)

TABLE 5.3

Corrected Mix Proportions of Mixes in Table 5.1 Based on Actual Densities and Corrections Applied

Material	Trial 1	Trial 2	Trial 3	Trial 4
Cement	291	344	393	455
Water	170	148	157	175
20 mm	824	807	767	707
10 mm	329	325	315	313
Sand	775	777	767	778
Super Plasticizer	2.91	3.44	3.93	4.55

Density is nothing, but the total weight of the same material when the volume is 1 m^3. And if we proportionately divide the concrete components in the same proportion as that used in concrete, the constituents for 1 m^3 are achieved. Thus, the new cement weight will be

Cement = density of the concrete × Cement in trial batch/total weight of ingredients in the trial batch

Cement = 2391 × 9/74.04

Cement = 290.64 kg as against the design weight of 300 kg.

Similarly, other ingredients of the mix per cubic meter can be found. The calculated correct weights per cubic meter of concrete are shown in Table 5.3.

5.3 Curve Fitting and Concrete Proportioning

Based on the trial and results, the best possible linear function based on cement content and strength can be found by using the least squares method. First, the strength versus cement content pattern must be analyzed (Table 5.4).

The graph depicts strength on the x-axis and the cement content on the y-axis. This can be changed to cement on the x-axis and strength on the y-axis, the only difference being that the outcome of both the methods will be different.

To find the function in terms of cement is to find the strength by the line fitting closest possible to all the points in the graph. The function will look like $y = mx + c$.

We need to find values of m and c.

TABLE 5.4

Table for Finding Best Fit Curve for Cement v/s Strength

Cement Content	Strength
291	25
344	33
393	38.5
455	43

TABLE 5.5

Calculation of Best Fit Curve Manually for Data in Table 5.4

Cement Content	Strength						
Y	x	x′	y′	x–x′ (a)	y–y′ (b)	(x–x′)^2	a × b
291	25	34.875	370.75	–9.875	–79.75	97.51563	787.5313
344	33			–1.875	–26.75	3.515625	50.15625
393	38.5			3.625	22.25	13.14063	80.65625
455	43			8.125	84.25	66.01563	684.5313
					Total	180.1875	1602.875

m can be calculated based on least squares method, and it will be (Table 5.5):

$$m = \left[\frac{\sum(a \times b)}{\sum(x - x')^{\wedge}2}\right]$$

thus, $m = 1602.88/180.19 = 8.896$

and $c = y' - mx'$

thus, $c = 370.75 - 8.896 \times 34.875 = 60.502$

thus, the equation that best describes the strength versus cement content relationship is given by

$$y = 8.896x + 60.502$$

5.3.1 Significance of Numbers

This equation has a lot of meaning: the coefficient of slope means for every increase in cement by 8.896 kg/m^3, the strength increases by 1 MPa, or vice versa. This is known as the "specific cement content" and is defined as the additional cement content required per cubic meter of concrete to increase the strength by 1 MPa from the strength value, which needs to be higher than 1 MPa. When strength (x) is replaced with zero, the derived value of y (the intercept or 'c' in the equation) (which is nothing but the intercept) is the quantity of cement, below which the strength of concrete is zero, and only above this value, the concrete starts gaining some strength. This value is also known as the strength yield point and is defined as the maximum cement content up to which in a given set of materials, the concrete does not yield any strength and just beyond this cement content, the strength of concrete starts increasing.

5.3.2 Mix Proportion from the Curve

Based on these trial reports and analyses, the mix design for each grade is easily found. To design M20 grade concrete, for which the target strength is 26.5 MPa, the cement would be calculated from the equation found from the family of mixes, that is,

$$y = 8.896x + 60.502$$

thus, $y = 8.896 \times 26.5 + 60.502 = 296.246 \sim 300$ kg.

Similarly, other components can be calculated by finding the family for each material and calculating it for the required target strength.

5.4 Curve Fitting through Excel

To find 'family of mixes', there are easier and faster ways by using a computer, especially Excel.

After calculating the corrected trial weights per cubic meter, and duly tabulating it in an Excel sheet, click on the Insert tab and then click on Scatter in Charts. Choose the first graph, that is points without lines (Figure 5.2). As in Figure 5.3, right-click on the blank chart that has been created and click on Select data or click on Select Data on the toolbar in Chart Tools tab in the Design Tab.

After clicking on Select data, a window like the one shown in Figure 5.4 appears, which prompts to specify the data for analysis. Click on Add, and another window opens where data for the x-axis and y-axis are selected. Accordingly, select the data of strength in Series X Values and Cement data in Series Y Values as given in Figure 5.5.

A graph like Figure 5.6 will be the result. The linear equation closest possible to the points determined in the trials needs to be found. As shown in Figure 5.7, right-click on any series point on the graph and click on Add Trendline, after which a window as shown in Figure 5.8 appears. Click on the type of curve to be fitted, so that the curve best represents the points. Remember all of this is done so that interpolation can be easily done for the strength wanted. To get the equation of the curve, check Display Equation on Chart. To see how good

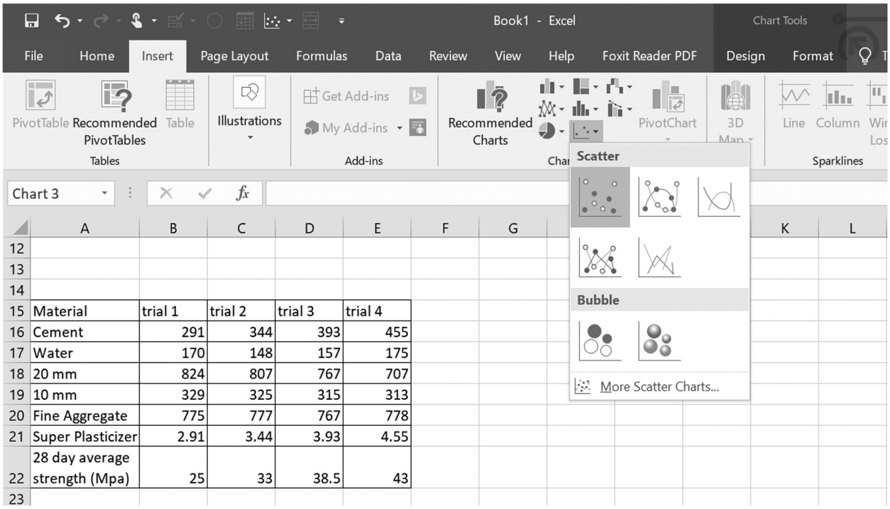


FIGURE 5.2
Step 1 for plotting curve, in Excel, for cement versus strength achieved.

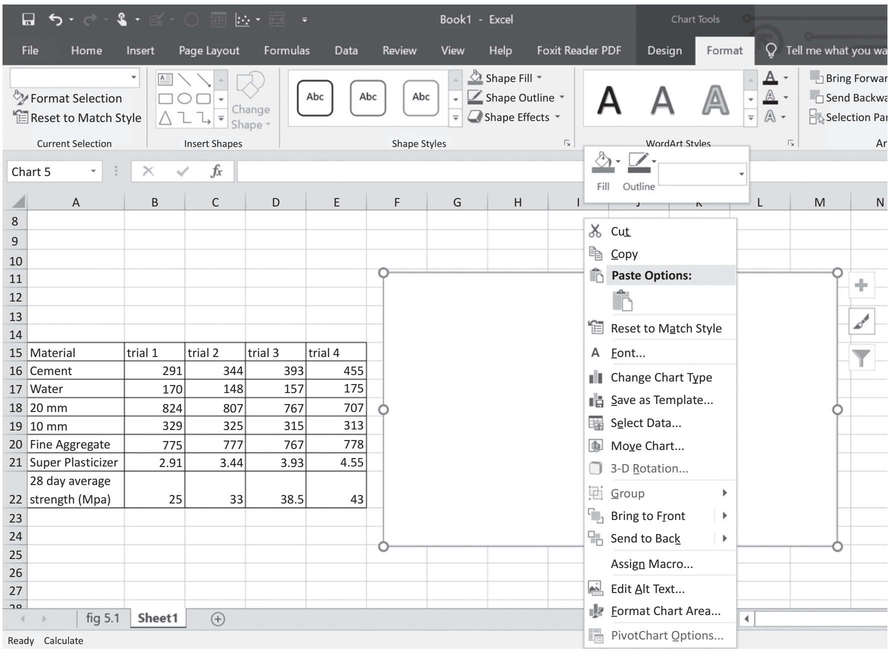


FIGURE 5.3
Step 2 for plotting curve, in Excel, for cement versus strength achieved.

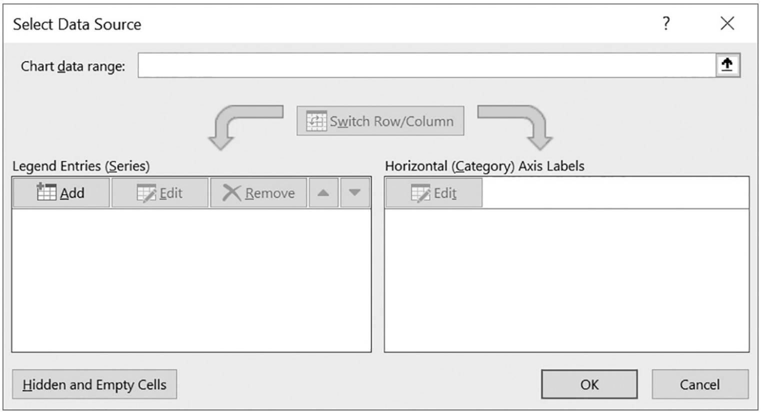
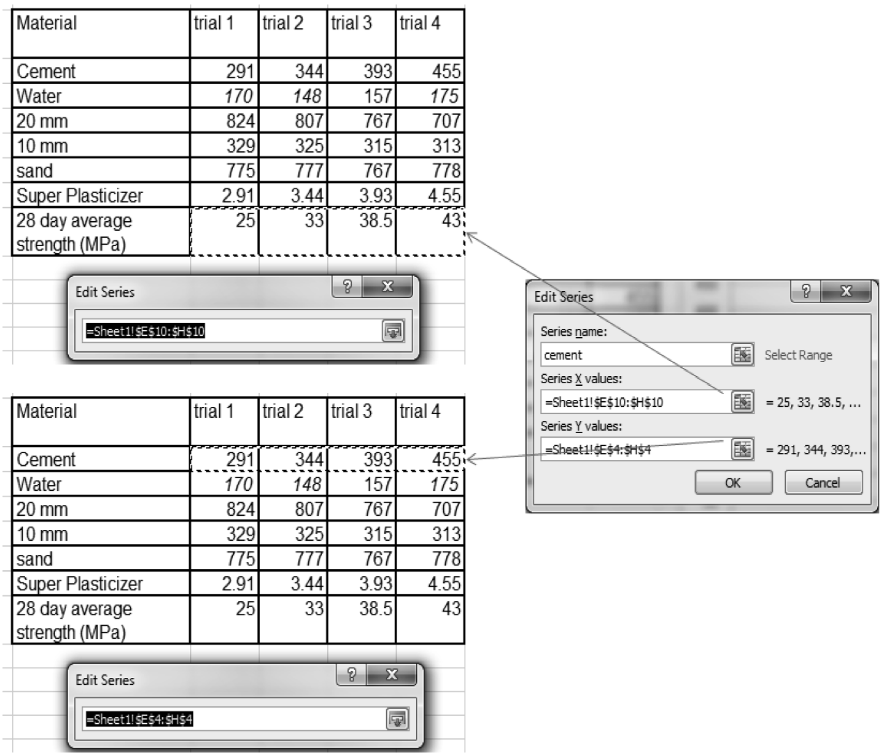


FIGURE 5.4
Step 3 for plotting curve, in Excel, for cement versus strength achieved (window for selecting data).



Material	trial 1	trial 2	trial 3	trial 4
Cement	291	344	393	455
Water	*170*	*148*	157	*175*
20 mm	824	807	767	707
10 mm	329	325	315	313
sand	775	777	767	778
Super Plasticizer	2.91	3.44	3.93	4.55
28 day average strength (MPa)	25	33	38.5	43

FIGURE 5.5
Step 4 for plotting curve, in Excel, for cement versus strength achieved (selecting relevant data for x- and y-axes).

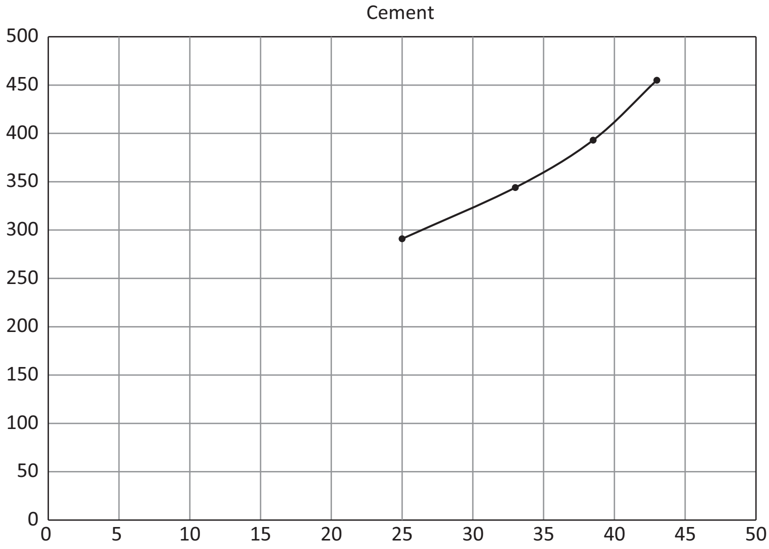


FIGURE 5.6
Plot for cement versus strength, in Excel, as per given example.

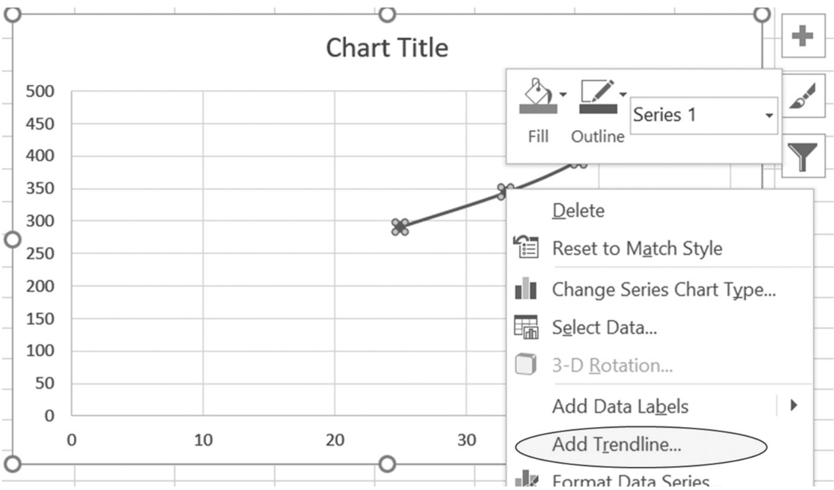


FIGURE 5.7
Finding best fit curve equation for estimating cement content for required strength, Step 1.

the correlation between the curve and the points is, check the Display R square value on the chart, then click on Close to get a graph like Figure 5.9.

To calculate other materials, the family method could also be used. All that we need to do is to plot 'scatter' graphs of each material against the strength as shown in Figures 5.10 and 5.11 for aggregates and water, respectively.

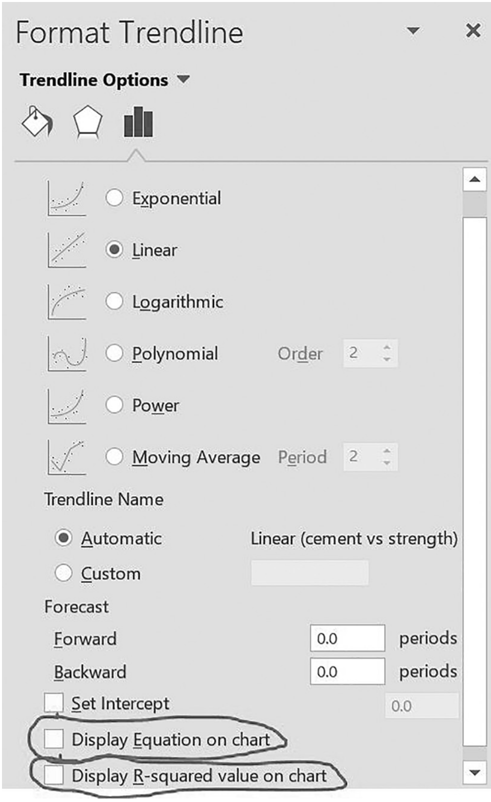


FIGURE 5.8
Step 2 finding best fit curve for cement versus strength achieved.

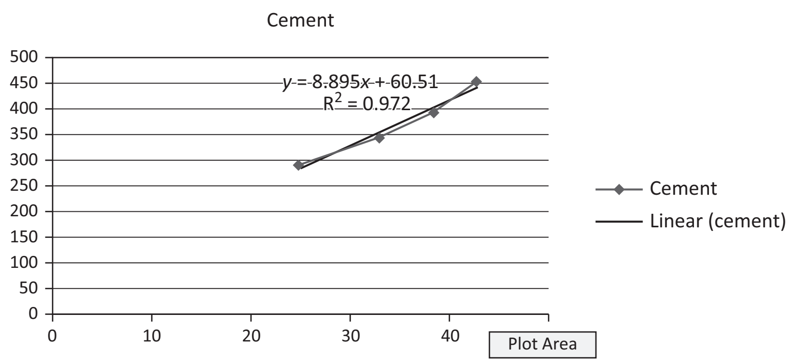


FIGURE 5.9
Curve with best fit and the equation outcome.

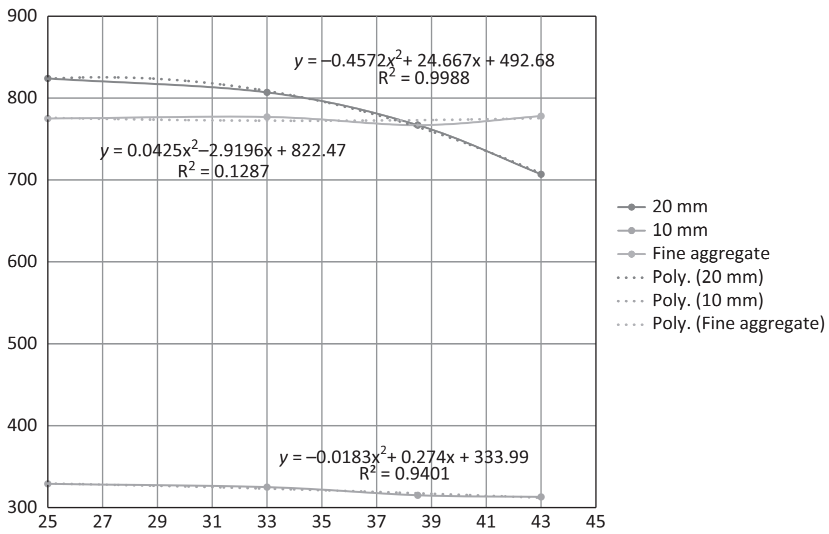


FIGURE 5.10
Curves fitting for other materials of concrete against the strength achieved.

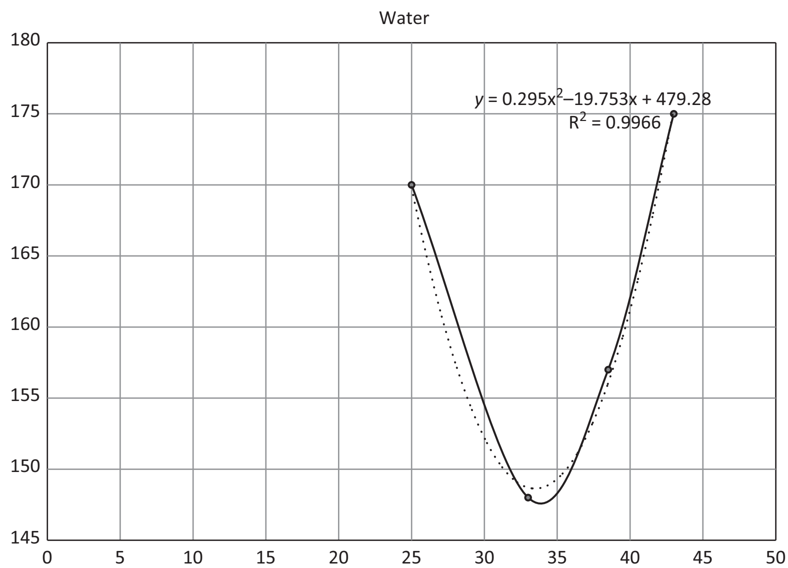


FIGURE 5.11
Curve fitting for water content against the strength achieved.

NOTE: The R square value for fine aggregate regression equation is very less, despite minimal difference between the actual values and that suggested by the equation. This is due to small range of fine aggregate content (min 767 Kgs and max 778 kgs, i.e. a difference of just 11 kgs for average of 774 kgs). Hence in this case R Square may not be relevant.

The family of mixes method can be used to compare different types of cement in terms of strength, economy, or any property desired (Figure 5.6). For example, to replace 30% Ordinary Portland Cement (OPC) with fly ash, you want to know, what cementitious content would achieve the required strength as compared to that of pure OPC, so just juxtapose graphs of strengths achieved for both types of cement.

6

Unconventional Proportioning Methods and Special Concretes

6.1 Author's Method: Proportioning through Void Content Optimization

A method has been developed that provides a good idea about the material and its behavior in concrete. To understand this method, some basic concepts need to be understood first.

6.1.1 Introduction

Let us say we have 1 m^3 of a tank, and we fill it with 20-mm coarse aggregates fully. The weight contained in the tank of 20 mm will be the Dry Loose Bulk Density of the aggregates. Now let us say voids between 20-mm aggregates get occupied by 10-mm aggregates, the remaining voids by the sand and the residual voids by the cement paste. The concrete cost usually will be minimum only when the cement (costliest material) content is minimum. Thus when aggregates are proportioned to produce least voids the cement paste required to fill them would also be less, resulting in reduced cost of concrete. Though, in this method, aggregates are combined to get a particular void content and an average size. A software (Excel) sheet is developed (Modelling Void Content) and is available as ancillary with this book, a link or some address for indicating the access to the software may be provided here, or somewhere in the book which predicts the void of the mixture of the aggregates and the average aggregate size of the aggregate combination. Most methods of mix design are based on one concept that minimum voids can be attained if the combination of aggregates is done such that the particle-size distribution of the combined aggregates fits between the standard upper and lower limits. Whereas many works now show that particle packing is just *not* the function of particle-size distribution but also the shape of the aggregate used, in fact, it is supposed to be more important than the gradation of aggregates.

6.1.2 Methodology

In the Excel sheet, each aggregate's logarithmic average particle size and void content are required. The method to calculate logarithmic average size is as given in the following example.

A sample of aggregate has particle-size distribution as given in Table 6.1. To calculate the average logarithmic size of aggregates, first, the products of weight retained and the logarithm to the base 10 of the respective sieve needs to be found. The summation of these products and 10 raised to the power of summation is the average logarithmic size of aggregates. Table 6.2 will help in understanding the calculation process better.

$$\text{Average logarithmic size} = 10\hat{}\left(\sum \text{b.log}_{10}\text{a} / \sum \text{b}\right) \tag{6.1}$$

$$\text{Average logarithmic size} = 10\hat{}(4530.82 / 4430) = 10.54 \text{ mm}$$

For calculating the void content of an aggregate, the following formula is to be used

$$\text{Void content} = \left(\text{Specific gravity} - \text{DLBD}\right) / \text{Specific gravity} \tag{6.2}$$

NOTE: DLBD is dry loose bulk density of the aggregate.

TABLE 6.1

Particle-Size Distribution in Terms of Weight Retained of Sample Aggregate

Sieve Size	Weight Retained (g)
20 mm	150
12.5 mm	950
10 mm	3250
4.75	45
pan	35

TABLE 6.2

Calculation Method for Finding Logarithmic Average Size of Aggregate

Sieve Size (mm) (a)	Weight Retained (g) (b)	$\text{b.log}_{10}\text{a}$
20	150	195.15
12.5	950	1042.06
10	3250	3250.00
4.75	45	30.45
2.375	35	13.15
Sum	**4430**	**4530.82**

6.1.3 Heat Map and Interpretation

Based on the inputs (average logarithmic size, void content), a heat map gets plotted that shows the void content in dry loose condition (refer to Figure 6.1). The heat map will be generated for a mixture of maximum combination of three types of aggregates at a time. Figure 6.1 is an example of a mixture of 20 mm, 10 mm, and fine aggregates. Read the heat map by first selecting any point on it and drawing an imaginary vertical line and checking the percentage of 20 mm denoted by number at the bottom.

Now the vertical line is a representation of the percentage of 20 mm in the total aggregate mix. This means that if the vertical line is at the leftmost end of the heat map, then 20 mm is 100% and no other material is added, whereas if it is at the right most end, 20 mm is 0% and the mixture of 10 mm and fine aggregate (FA) is 100%. Next, draw a horizontal line from the point, and this horizontal line is an indicator of proportion of the fine aggregate to 10 mm and fine aggregate combined. If the line is at the bottommost portion of the map, it would mean proportion of fine aggregate to 10 mm is 100:0, and if the horizontal line is at the uppermost portion of the map, it would mean proportion of fine aggregate to 10 mm is 0:100. Now the proportion of 20:10:FA is to be calculated by first subtracting the percentage of 20 mm from 100% and the remainder is to be divided into two portions of FA and 10 mm as per the horizontal line. In Figure 6.1, the point depicted is 50% 20 mm, and from the remaining aggregates, 70% is FA (horizontal line meeting at 70) and 30% 10 mm. Also, the point on the heat map is between dark green and light green color, and the value of these colors is given on adjacent legend, which is 32.56%. Thus, if aggregates are mixed in 50:15:35 (20mm:10mm:FA), a void content between 32.04% and 32.56% is achieved.

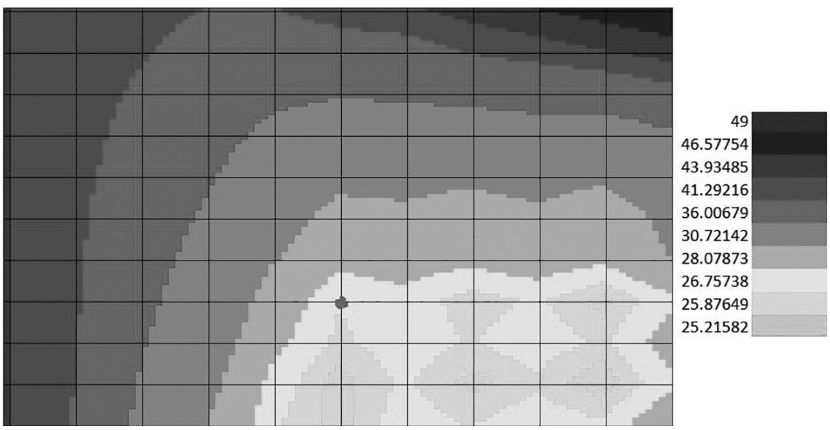


FIGURE 6.1
Screenshot of modelling sheet for estimating void content of aggregate mixtures.

6.1.4 Strategy for Fixing Void Content to Get Optimized Concrete

To get a good workable normal concrete, it is preferred that the cement paste fills 80%–90% of the volume of voids predicted by the Excel sheet for the mixture of aggregates. The concrete performs well at just 80%–90% of fill degree (cement paste volume/total void volume in aggregates) for lower grades of concrete and higher fill degrees at higher grades of concrete. Because, when lower grades are designed at higher water cement ratios, the cement paste is weaker than the aggregates, and cement paste fails before the aggregates. Thus, when the fill degree is less than 100%, it makes the aggregates stay in contact with each other, and the load is taken up by the skeleton of aggregates. But when the water cement ratio is lower, the cement paste starts becoming stronger, and the viscosity of the cement paste starts getting very high. To get high strength it is required that cement paste is present everywhere so that the load is taken up by it. But because of high viscosity, it does not reach easily between the aggregate voids leaving behind a weak space, whereas if its content is kept high, then the probability of having cement paste at all places is high. It may be required that the fill degree may be higher than 100% of void content even while designing normal-grade concretes because lower fill degree makes the concrete prone to segregation and poor in pumpability. The concrete does not perform that well when the slurry fill percentage is either lower or higher than 80%–90% because at lower fill degrees the concrete becomes susceptible to honeycombs or segregation in hardened concrete, and for higher fill degrees, the load gets transmitted through cement paste also to a considerable degree; hence, the cement slurry being weak means that the failure of concrete occurs at comparatively lesser loads.

6.1.5 Calculating Mix Proportions Based on Void Content

The sequence of proportioning in this method is a bit different as compared to standard methods. In this method, the paste content is first calculated, and then based on the fill degree or any other requisites of the prescriptive specifications, the aggregate proportions are calculated.

6.1.5.1 Calculating the Paste Content

The first step involves deciding the water content, in which any number between 130 and 220 kg of water can be chosen and is based on the maximum size of aggregate and type of admixture being used and the performance required. Various guidelines can be used to select the water content discussed in earlier chapters. For getting the required strength, choose a water cement ratio from any of the guidelines discussed in previous chapters.

Based on the type of placement and compaction to be done, choose the fill degree (i.e. for concretes that will be compacted by thorough and heavy vibration, choose lesser fill degree between 90% and 100%). In case the concrete will be compacted by a heavy roller like in case of roller-compacted concrete for road (where concrete permeability may not be a big issue unlike roller-compacted concrete for a dam), a still lower fill degree between 80% and 90% can be chosen. In case the concrete desired is self-compacting concrete, or where good surface finish is of paramount importance, choose a fill degree more than 100% and up to 140% based on economic constraints, if any. For cases in which the concrete needs to be pumpable, in addition to fill degree being more than 90%, ensure that the fines (300 μ and lesser size) per cubic meter is not less than 400 kg for a maximum size of aggregate as 20 mm.

Based on the chosen fill degree and the volume of calculated cement and water contents, choose a proportion of aggregates that will give the required void content based on the heat map. For 160 kg water and 400 kg cement (specific gravity of 3.15), the total paste volume would be 287 L. For a fill degree of 80%, aggregates with total void content are 287/0.8 = 359 L in 1 m^3 of concrete (i.e. 35.9%). There can be many proportions of aggregates that give that kind of void content (high void content can be achieved in many combinations, but the least void content in aggregate is achieved only by one proportion). And the final proportion would have a total aggregate content equal to the volume of the concrete after deducting the cement paste volume. And each aggregate weight would be equal to weights that give volumetric proportions as decided from the heat map.

NOTE: Paste content cannot be decided based on least void content because the paste content so decided (with 100% fill degree) leads to a water content that is less (for concretes with low water cement ratio) and may lead to a concrete proportion that cannot be manufactured at all. Hence, total water content is the major deciding factor for manufacturing concrete, which may be comparatively less when the average aggregate size of proportioned aggregates is big. In any case, the minimum water content for a maximum size up to 40-mm aggregates and a very-high-range water-reducing admixture (water reduction capacity of 40%) cannot be less than 120 kg/m^3. Commercially very few or no equipments are available for manufacturing and laying concretes with maximum sizes of aggregates above 40 mm. Concretes with MSAs bigger than 80 mm if at all used, the bigger aggregates are placed manually into concrete, in-situ.

After deciding the mix, test the mix by conducting a lab run trial and correct the mix further as discussed in Chapter 7.

Example 6.1

Design a mix with fill degree of 90% paste constituting a water cement ratio of 0.4. Choose a water content of 170 kg/m^3. The particle size distribution of the aggregates is given in Table 6.3.

TABLE 6.3

Sieve Analysis Data

Sieve Size (mm)	Weight Retained 20 mm NSA[a] (g)	Weight Retained 10 mm NSA[a] (g)	Weight Retained Fine Aggregate (g)
20	1010		
10	2500	210	
4.75	12	2850	30
2.36		110	210
1.18		25	330
0.6			380
0.3			210
0.15			139
0.075			80
Pan			50

[a] Nominal size of aggregate.

Specific gravities:

20 mm MSA: 2.9
10 mm MSA: 2.87
Fine Aggregate: 2.59
Dry loose bulk densities:
20 mm MSA: 1496 kg/m^3
10 mm MSA: 1435 kg/m^3
Fine Aggregate: 1680 kg/m^3

Putting these data into an Excel sheet and running the program, a heat map is derived as shown in Figure 6.2.

Since the water content is 170 kg/m^3 and the water cement ratio of 0.4, the cement content would be 425 kg. This paste volume should only fill 90% of the voids in loose condition; hence, the aggregate proportion should be such that the voids are 10% higher than the paste volume. The paste volume of this cement and water content is 305 L; thus, the volume of voids should be 305/90% (i.e. 339 L) and 339 L is 33.9 or 34% voids. The entire orange band in the heat map has a void content between 32% and 38% (shown in the legend); hence, any proportion across the orange band of the heat map can be chosen but preferably closer to the yellow band (34 is closer to 32 than 38). Based on this, the mix proportion is achieved. Similarly, test concrete for other proportions of aggregates and water cement ratios and combine this method with the British Ready-Mix Concrete Association (BRMCA) method of proportioning.

NOTE: The heat map is more helpful in finding why concretes behave the way they do, rather than for predicting the behavior.

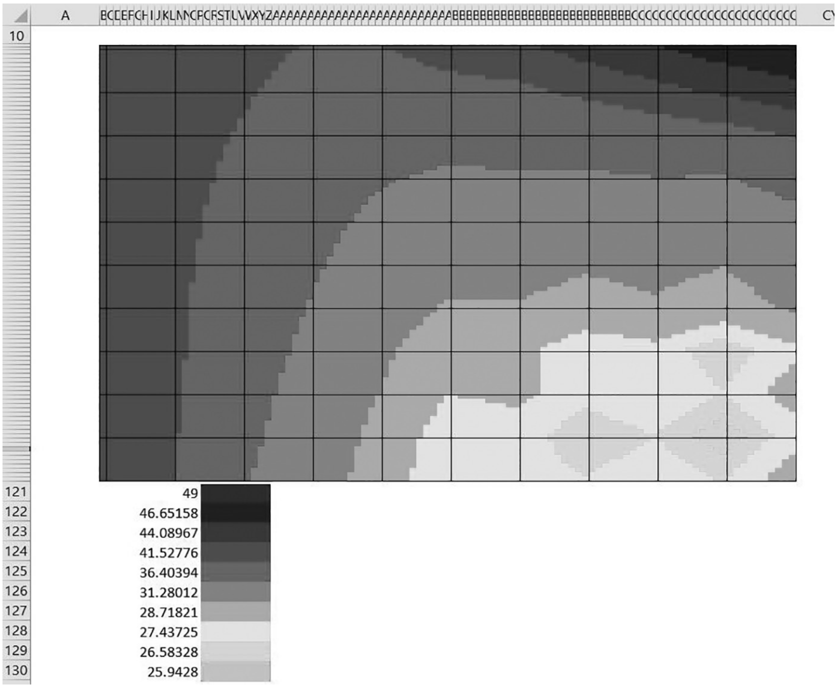


FIGURE 6.2
Screenshot of void content for aggregates as given in example.

6.2 Mix Proportioning of Self-Compacting Concrete

The construction industry is facing an acute shortage of manpower to work on compaction of concrete and ensure a quality concrete throughout the structure. Self-compacting concrete resolves issues pertaining to compaction of concrete because it does not require external effort for its compaction. Self-compacting concrete has resolved many challenges faced by the construction industry but still has the challenge of capably producing the concrete on account of skills required in proportioning the concrete and its production control.

6.2.1 Introduction

A concrete can qualify as self-compacting provided it meets the fresh-state performance criteria for self-compacting concrete. The criteria were first laid in EFNARC guidelines from Europe in which certain test parameters were specified, viz.

1. Slump flow ranges in three classes. SF1 – 550–650 mm; SF2 – 660–750 mm; SF3 – 760–850 mm
2. T 500 (viscosity) – 2–5 s
3. V Funnel – 6–15 s

And others, but these three tests are critical, and it is actually a feat to qualify a concrete as self-compacting by conforming to all the requirements simultaneously. The mix design procedures do not address the challenges faced by an engineer in the field. We need to see what the different methods of mix design say and how they are applied to achieve self-compacting properties in concrete.

6.2.2 EFNARC Guidelines

The EFNARC guidelines for attaining self-compacting properties in concrete are:

1. Water powder (–150 μ) Ratio by volume: 0.8–1.1
2. Total paste content: 300–380 L/m^3
3. Water: 150–210 kg/m^3
4. Coarse aggregate content: 28%–35% of Concrete (i.e. 280–350 L/m^3).

Procedure:

1. Assume a certain percentage of air (refer to Table 2.3 given for air content in Chapter 2).
2. Choose a certain proportion of coarse aggregate in the range of 280–350 L/m^3.
3. Choose a certain paste content between 300 and 380 L/m^3.
4. Find the fine aggregate content by subtracting all the assumed quantities from 1 m^3 of concrete.
5. Design the paste composition by testing on mini slump cone and mini V funnel such that the flow of paste is achieved between 240 and 260 mm, and a mini V funnel flow time is achieved between 7 and 11 s. The dimensions of mini slump cone and mini V funnel are given in Figures 6.3 and 6.4, respectively. The water powder ratio in the paste should be increased if the time in V funnel is more than 11 s and reduced when the time is less than 7 s. In case of a slight increase in water powder ratio increases the workability beyond a requirement, the paste will not be robust and will be too difficult to handle, so either decrease the admixture dosage or add viscosity modifying agent (VMA). Similarly, if the flow of mortar is less than 240, then either increase the paste content or the water powder

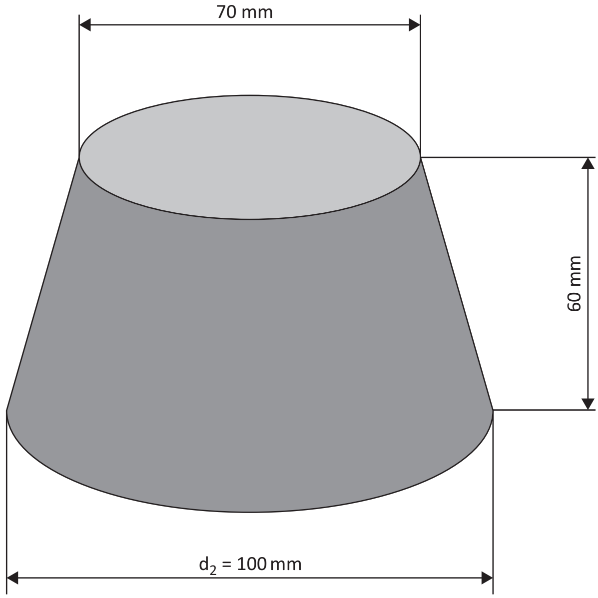


FIGURE 6.3
Mini slump cone for designing mortar of self-compacting concrete. (EFNARC, Self Compacting Concrete Guidelines, 2002.)

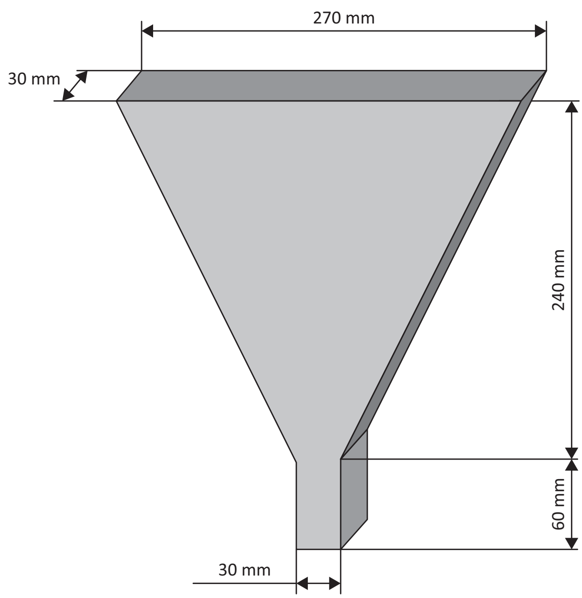


FIGURE 6.4
Mini V funnel for designing paste/mortar for self-compacting concrete. (EFNARC, Self Compacting Concrete Guidelines, 2002.)

ratio in the paste. If V funnel time is acceptable and slump flow is not being achieved, then increase the paste content. And if V funnel time is also high and slump flow also is less, then first increase the water powder ratio and check. In short, viscosity is governed more by water powder ratio, and shear stress or slump flow is governed by paste content, water content, or the fill degree ratio.

Example 6.2

Design a self-compacting concrete of M40 grade with MSA 20 mm. Coarse aggregates have a specific gravity of 2.8 and fine aggregate 2.7.

1. Air content for 20 mm MSA is taken as 2% or 20 L/m^3.
2. Let us keep aggregate content of 300 L/m^3, thus, 300 × 2.8 = 840 kg.
3. Let us keep paste content 340 L, and thus sand content is 1000–20–300–340 = 340 L (1 m^3 air-aggregate volume-paste volume). Thus, the sand content per cubic meter is 340 × 2.7 = 918 kg.
4. Based on a test for mini V funnel flow and mini Slump flow, the water powder ratio is fixed at 0.31 by weight and admixture dosage at 0.75% of cementitious.
5. Because paste content to be kept is 340 L and water cementitious ratio are maintained at 0.31, mathematically this can be expressed as (neglecting the admixture content):

$$Cv + W = 340$$

$$Cv = \text{Cement volume}$$

$$W = \text{Water volume / Weight}$$

$$C / Sc + W = 340 \tag{6.3}$$

$$C = \text{Cement weight}$$

$$Sc = \text{Specific gravity of cement}$$

$$W / C = 0.31$$

$$W = 0.31\ C \tag{6.4}$$

Replacing value of W with 0.31 C in Equation (6.3), and Sc as 2.85 (a combination of 75% OPC and 25% Fly Ash), the result is:

$$C / 2.85 + 0.31C = 340$$

Solving, C is 515 kg, and water is 160 kg. Admixture is 0.75% of 5, hence, 3.863 kg.

NOTE: In most of the calculations for mix design, big quantities have been rounded off to multiples of 5 because this does not have much effect on concrete property, but admixture has been rounded off to 0.001 kg because its slight variation leads to very high costs and also changes in concrete performance.

When designing concrete, meeting the requirement of the water powder ratio leads to a dilemma for many as the requirement can be met from the powder of fine aggregate or cementitious materials or both. Moreover the strength achieved after designing concrete can be higher or lower than what is needed, and guidelines to achieve both simultaneously (the strength and the fresh property) are not known.

Self-compacting concrete (SCC) can be designed in many ways, and numerous methods are available. But most methods do not address all the significance of each step of the mix design process; most of them give guidelines for achieving the required workability in the fresh state, but they do not speak about how strength can be achieved and optimized without sacrificing or achieving the required workability. Moreover, the mix design methodology does not exactly help in pinpointing the paste content in concrete to get the desired properties in the fresh state and how it can be optimized.

6.2.3 ICAR Guidelines

Another method for the design of SCC is by the ICAR method. As per this method, first find the void content of aggregate combination in a predetermined proportion, for which any grading requirements can be used, and then physically void content of this combination is found in the compacted state. The concrete can become self-compacting when the paste content fills up these voids in the compacted state and additional paste separates the aggregates such that this paste acts as a vehicle to transport the aggregates; the entire concrete becomes self-compacting concrete. The formula for finding the additional paste content is as follows:

$$V_{\text{paste -spacing}} = 6 + 2R_{s-a}$$

The value of $R_{s\text{-}a}$ is found using Figure 6.5.

The total paste content in 1 m^3 of concrete is calculated as:

$$V_{\text{paste – filling\_ability}} = 100 - \frac{\left(100 - V_{\text{paste-spacing}}\right)\left(100 - \%\text{voids}_{\text{compacted\_agg}}\right)}{100} \quad (6.5)$$

Thus, if the void content in compacted aggregate combination is 31%, and $R_{s\text{-}a}$ is found as 3, then $V_{\text{paste-spacing}}$ = 12 and $V_{\text{paste-filling ability}}$ = 39.28%; thus, the paste content = 393 L.

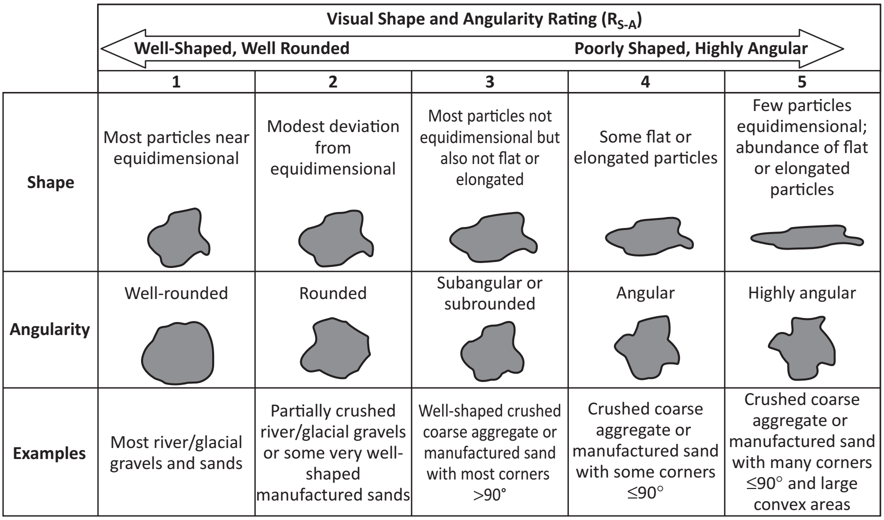


FIGURE 6.5
Visual rating guidelines for aggregate based on shape and texture. (ICAR, Self compacting concrete guidelines.)

Example 6.3

Design self-compacting concrete of M30 grade with aggregates having a specific gravity of 2.8, 2.75, and 2.65 for 20 mm, 10 mm, and fine aggregates, respectively. Their dry-rodded bulk density (DRBD) is 1900 kg/m^3 when mixed in proportion 35:5:60 (by weight). The aggregates have a visual rating of 4. To get the strength of M30, the w/c ratio required is less than 0.44. The specific gravity of the cementitious mix is 2.9.

Solution

The combined specific gravity of the aggregates in 35:5:60 proportion is

$$S = (\text{total weight of materials}) / (\text{total absolute volume of individual materials})$$

$$S = \frac{(W1 + W2 + \ldots Wn)}{(W1/S1 + W2/S2 + \ldots\ldots..Wn/Sn)} \tag{6.6}$$

$$S = \frac{(35 + 5 + 60)}{(35/2.8 + 5/2.75 + 60/2.65)} = 2.706$$

where W is the weight of individual material, and S is the specific gravity of the material.

$$V_{paste-spacing} = 6 + 2 \times 4 = 14$$

$$\text{Void content} = (\text{Specific gravity} \times 1000 - \text{DRBD}) / (\text{Specific gravity} \times 1000)$$

$$= (2706 - 1900) / 2706$$

$$\text{Void content} = 0.2979 = 29.79\%$$

$$\text{Paste required} = 100 \quad (100 - \text{Paste spacing})(100 - \%\text{voids}) / 100$$

$$= 100 - (100 - 14)(100 - 29.79) / 100 = 39.62\,\% \text{ or } 396 \text{ L}$$

Water cement ratio to be maintained = 0.44.

0.44 = W/C
W + C/2.9 = 396
0.44C + C/2.9 = 396
C = 505 kg
W = 220 kg

It should be noted that a paste of only cement and water without admixture has a high tendency to bleed (clean water separating out of cement paste); thus in making self-compacting concrete, it becomes essential to use water-reducing admixtures because they are good dispersants (even if the concrete has flowing properties without addition of water reducing admixtures). Additional admixtures can be added to modify the rheology of the mix.

Aggregates are proportioned as 35:5:60 by weight; thus, the weights of aggregates are:

Weight of total aggregates = (Concrete volume−Paste volume) × Combined specific gravity
= (980−396) × 2.706 = 1580 kg
Weight of 20 mm = 1580 × 0.35 = 553 kg
Weight of 10 mm = 80 kg
Weight of fine aggregates = 948 kg

6.3 Mix Proportioning of Low-Density, Lightweight or High-Density, Heavyweight Concrete

6.3.1 Introduction

Many engineers usually get confused while designing high-density or lightweight concrete, even though they have vast experience in designing normal concretes perhaps because the significance of each step and formula of mix design is not well understood. In this section, the steps for designing the density of concrete are reviewed.

6.3.2 Methodology

1. Find out the specific gravity of the materials to be used for manufacturing the concrete. If the concrete required is lightweight, then use lightweight aggregates, and if high-density concrete is required, then use heavier-density aggregates as compared to normal aggregates.
2. Design the cement and water content as per normal procedure (i.e. rapid method, American Concrete Institute [ACI], or Department of Environment [DOE] method).
3. To get the required density of concrete, find the proportion of light weight/heavyweight aggregate versus normal weight aggregate. To find the proportion of aggregates, the following formulae are used.

$$1000 = C / Sc + W + A / Sa + \left(D - C - W - A\right) / Sl + R \tag{6.7}$$

$$L = D - C - W - A \tag{6.8}$$

   where C is the cement weight per cubic meter of concrete, Sc is the specific gravity of cement, W is the weight of water per cubic meter of concrete, A is the weight of normal aggregates per cubic meter of concrete, Sa is the specific gravity of normal weight aggregates, and L is the weight of lightweight/heavyweight aggregates per cubic meter of concrete. Sl is the specific gravity of lightweight/heavyweight aggregates, D is the density of concrete required in kg/m^3, and R is the volume of air per cubic meter of concrete. If the value of A or L is negative after solving Equation (6.7 or 6.8), it signifies that the specific gravity of the lightweight/heavyweight aggregate is not sufficient to produce the required density, so either the required density needs to be compromised or a special aggregate needs to be arranged. To find the required aggregates' specific gravity that will meet the required specifications of concrete, find Sl by finding the permissible value of L (required density minus other mandatory materials) and replacing it in Equation (6.7) in addition to other values.
4. Conduct the trial and find the actual density by the standard test method. Correct the mix proportion to match/close the gap between required and achieved density.

Example 6.4

Design concrete with density 1300 kg/m^3, using cement 350 kg/m^3 with specific gravity 3.15, w/c of 0.45, normal aggregates with specific gravities as under:

> 20 mm: 2.8, 10 mm: 2.8, fine aggregate: 2.55, Lightweight polystyrene beads: 0.02.

The proportion of the normal aggregates is 30:30:40. Assume entrapped air as 2%.

Solution

Specific gravity of combined aggregates is

Sa = 100/(30/2.8 + 30/2.8 + 40/2.55) = 2.69

Aggregate Content to be used

1000 = 350/3.15 + 158 + A/2.69 + (1300 − 350 − 158 − A)/0.02 + 20
A = 784 kg
L = 1300 − 350 − 158 − 784 = 8.392 kg

So the mix design for lightweight concrete with density 1300 kg/m^3 is

Cement: 350 kg
Water: 158 kg
20 mm: 235 kg
10 mm: 235 kg
Fine aggregate: 314 kg
Lightweight aggregate: 8.392 kg

Example 6.5

Design concrete of density 3200 kg/m^3 using aggregates with specific gravities as follows: 20mm: 2.8, 10 mm: 2.78, fine aggregate: 2.66, heavy aggregate: 4.1. The Water Cement ratio required to get the desired strength is 0.39, and water content is 165 kg. Heavy aggregates are available in all sizes and have similar particle-size distribution as normal aggregates; thus, the interproportion of aggregates is 25:40:35 (20 mm:10 mm:fine aggregate). Entrapped air to be considered is 2% because MSA is 20 mm.

Solution

Combined specific gravity of normal aggregates = 100/(25/2.8 + 40/2.78 + 35/2.66) = 2.742

$$\text{Cement weight} = \text{Water} / \text{Water cement ratio} = 165 / 0.39 = 423 \text{ kg}$$

Weight of normal aggregates

1000 = 165 + 423/3.15 + 20 + A/2.742 + (3200 − 423 − 165 − A)/4.1
A = 361 kg
L = 3200 − 423 − 165 − 361 = 2251 kg
20 mm Normal aggregate = 361 × 0.25 = 90 kg
20 mm Heavy aggregate = 2251 × 0.25 = 563 kg
10 mm Normal aggregate = 361 × 0.40 = 144 kg
10 mm Heavy aggregate = 2251 × 0.40 = 900 kg
Normal Fine aggregate = 361 × 0.35 = 126 kg
Heavy Fine aggregate = 2251 × 0.35 = 788 kg

The concrete mix design, thus, is

Cement: 423 kg
Water: 165 kg
20 mm Normal aggregate = 90 kg
20 mm Heavy aggregate = 563 kg
10 mm Normal aggregate = 144 kg
10 mm Heavy aggregate = 900 kg
Normal Fine aggregate = 126 kg
Heavy Fine aggregate = 788 kg

6.4 Mix Design of Pervious Concrete or No Fines Concrete

6.4.1 Introduction

The design method for pervious concrete is totally different from any other concrete. In this concrete, specific gravities of aggregates may not be known for designing the concrete, but the dry loose bulk density of the coarse aggregates (MSA) does need to be. The process requires conducting actual trials and then calculating the proportions, rather than other way round. The strength of this concrete is not based on the water cement ratio but on the void content in aggregate, and the void content becomes less by reducing the maximum size of aggregate and increasing the paste volume to coat the higher surface area.

6.4.2 Methodology

The process of mix proportioning is as follows:

1. To start with, based on lab-mixer capacity, take a certain amount of coarse aggregates, W kg.
2. Consider any water cement ratio from 0.3 to 0.45, and make a slurry/paste, which can adhere to the aggregates' surface and not just flow off. To make the required quantity of cement slurry (Y), with water cement ratio, Z, calculate water and cement contents as

$$\text{Cement} = \text{Y} / (1 + \text{Z}) \tag{6.9}$$

$$\text{Water} = \text{Y} / (1 + \text{Z}) \times \text{Z} \tag{6.10}$$

3. Take the cement slurry premixed in the decided proportion and keep on adding slowly while mixing the aggregates in a mixer. When all the aggregates are coated with the cement slurry, stop adding the cement slurry, and find the quantity of cement slurry added into the concrete. Let this be Y1.

4. After the concrete is mixed, measure its unit weight in a standard bucket of known volume. Let the unit density (weight contained in the bucket divided by the volume of the bucket) of concrete be D, expressed in kg/m^3.
5. The mix proportion for the pervious concrete for 1 m^3 is calculated by the following formulae:

$$\text{Aggregate} = D/(Y1 + W) \times W \tag{6.11}$$

$$\text{Cement} = D/(Y1 + W) \times Y1/(1 + Z) \tag{6.12}$$

$$\text{Water} = D/(Y1 + W) \times Y1/(1 + Z) \times Z \tag{6.13}$$

NOTE: The strength of pervious concrete does not increase so significantly with a decrease in water cement ratio, but it increases with a decrease in average aggregate size, in addition, to an increase in paste content.

6.5 Mix Proportioning of Shotcrete

6.5.1 Introduction

Shotcrete is a type of concrete that requires spraying on a surface (usually vertical) with a high velocity with minimum losses in terms of rebound. Particle-size distribution plays the most important role in deciding its success. The particle-size distribution of this concrete is kept on the finer side, so that concrete remains cohesive and stable after being hit on a vertical surface. For conventional concretes economy is achieved by adding highest possible amount of coarse aggregates, that may reduce consumption of cement, while for shotcrete, economy is achieved by keeping *comparatively* higher amount of fine aggregates, so that rebound losses are the least. The particle-size distribution is provided in ACI 506 and the same is reproduced here.

6.5.2 Procedure

To keep concrete cohesive, design the concrete with minimum ordinary Portland cement (OPC) content of 390 kg, in addition to other cementitious additions, preferably fly ash and micro silica. The water cement ratio is kept between 0.35 and 0.5 with water-reducing admixtures. The aggregates should be so proportioned that all in aggregate grading falls in between the limits given in Table 6.4.

TABLE 6.4

American Concrete Institute Guidelines for Particle-Size Distribution for Shotcrete

Sieve Size	Passing by Weight (%)
10 mm	100
4.75 mm	95–100
2.36 mm	80–98
1.18 mm	50–85
600 μ	25–60
300 μ	10–30
150 μ	2–10

Source: Reproduced from ACI 506 committee report, Guide to Shotcrete. With permission.

Example 6.6

Design shotcrete of M25 grade with aggregates having particle-size distribution as shown under. The specific gravity of 10 mm aggregate is 2.85 and that of fine aggregate is 2.75.

Particle-size distribution:

Sieve Size (mm)	Percentage finer (by weight) 10 mm NSA (%)	Passing by Weight Fine Aggregate (%)
10 mm	100	100
4.75	65	98
2.36	10	96
1.18	0	84
0.6	0	74
0.3	0	38
0.15	0	13

NSA: Nominal Size Aggregate.

Solution

Take the cement content of 390 kg (to start with, and a complete family of mixes can be done to select the best mix) and 20% fly ash of total cementitious (start with no fly ash also), a water content of 150 kg (slump required is between 50 and 70 mm, and after trial admixture or water or both can be changed to adjust the slump within required range). Based on the sieve analysis result, the ratio of coarse and fine aggregates can be kept at 25:75 proportion, and while seeing the graphical representation of the particle-size distribution (Figure 6.6), it is noted that if the coarse aggregates are reduced further, the lower sizes rise above the upper limits (below 300 μ), due to which coarser (i.e. 2.36 and 4.75 mm) have been kept as non-conforming.

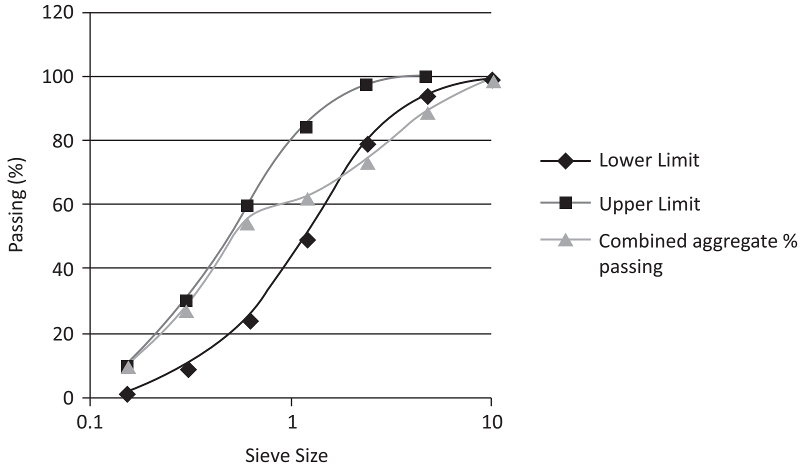


FIGURE 6.6
Particle-size distribution for shotcrete as per the example w.r.t guidelines for designing shotcrete. (ACI, 506 R-16 Guide to Shotcrete.)

$$970 = 390/3.15 + 98/2.2 + 150 + Ca/(0.25 \times 2.85)$$
$$Ca = 464 \text{ kg}$$
$$970 = 390/3.15 + 98/2.2 + 150 + Fa/(0.75 \times 2.75)$$
$$Fa = 1344 \text{ kg}$$

This mix has to be confirmed for strength and workability based on actual strength results on mockups of vertical surfaces. Hence, it is better to conduct trials like a family of mixes and interpolate the required mix for required properties.

Sieve Size	10-mm Aggregate 0.25	Fine Aggregate 0.75	Lower Limit	Upper Limit	Combined Aggregate Passing (%)
10	100	100	100		100
4.75	65	98	95	100	89.75
2.36	10	96	80	98	74.5
1.18	0	84	50	85	63
0.6	0	74	25	60	55.5
0.3	0	38	10	30	28.5
0.15	0	13	2	10	9.75

6.6 Roller-Compacted Concrete Design

6.6.1 Introduction

Roller-compacted concretes are used majorly in two kinds of applications: dams (roller-compacted concrete dams) and base of concrete roads (also known as dry lean concrete). Roller-compacted concretes are necessarily concretes with zero slump an they are required to be compacted by a heavy vibratory roller machine. A conventional vibratable concrete cannot be compacted by a vibratory roller because it will start sinking into the concrete. On the other hand if the workability of concrete is less, the effort required to compact the concrete will be high in terms of the increased number of passes by the vibratory roller for compacting the concrete. Roller-compacted concrete for dams requires more care in proportioning as compared to roller-compacted concrete for the base of roads. The mix proportioning of roller-compacted concrete requires meeting following specifications and requirements

1. Strength at 6 months or 1 year (for roller-compacted concrete dams)
2. Workability of concrete in terms of veebee time during the laying of concrete
3. For dams, minimum initial setting time (usually 18 to 30 h) and maximum final setting time (up to 48 h) from the time of manufacture needs to be targeted. This specification is to avoid cold joints between layers of compacted concrete for minimum initial setting time (IST) and final setting time to confirm if the hydration process has taken off smoothly and the concrete will take loads of additional layers above.
4. Least possible heat of hydration because the construction cycle is very fast, and the dam is a mass concrete. In case heat of hydration for mass concrete is not controlled, it may lead to massive thermal cracks and subsequent failure of the structure.
5. Low permeability because the dam has to retain water with a very high pressure at the bottom of the reservoir.
6. The concrete designed should be economical.
7. The concrete should not segregate on account of coarse gradation or too much dryness.

6.6.2 Mix Proportioning

There have been many methods developed and adopted across the world to proportion concrete. The steps are common, but they require a lot of testing and validation of the mix in the laboratory and the plant as well, rather than just relying on empirical formulae and guidelines. As the economy is of paramount importance and cement is the costliest material (in addition to being heat evolving, shrinking, etc.), roller-compacted concrete utilizes the least cement and the deficiency of fines is made up from aggregates or alternate cementitious materials through proportioning.

The steps involved are:

1. Finding the water cementitious ratio for the required target strength at a specified age.
2. Estimating the water content for the nominal maximum size aggregate (NMSA) used for getting the desired workability, as per rough guidelines or experience.
3. Calculating the cementitious content and fixing the proportion of OPC with the available alternate cementitious materials like fly ash, slag, etc.
4. Fixing the percentage of fine aggregates in total aggregates, and calculating the entire aggregate content per unit volume of concrete.
5. Conducting tests on arrived the proportion of concrete and measuring the density and veebee time after compaction in a veebee consistometer test.
6. Increasing or decreasing the water contents in the same mix and checking the performance of density and veebee time, again respective to the previous mix.
7. Plot a graph of density versus water content, and check the water content to get the highest density.
8. Repeat the testing process for at least five different increments of fine aggregate contents and check the veebee times, density, and overall mix cohesiveness.
9. Finalize a mix with a higher fine aggregate content as compared to concrete with lowest void content (to make the mix robust against the segregation in case of a sudden change in fine aggregate gradation during production) and with veebee consistency within a specified range.
10. Retarder and other admixtures, in case of adjusting the initial and final setting time within the stipulated time, should be further tested and adjusted for their dosage into the concrete.
11. Conduct trials with a different percentage of water replacement by ice to check the decrease in temperature w.r.t. percentage of ice, raw material temperatures, and temperature change of concrete w.r.t. ambient temperature. This is required in case of hot weather concreting when temperatures of concrete are expected to go beyond 32°F. Specific heats of materials can be found by mixing concretes with varying proportions and checking temperatures of these concretes and raw materials by solving the heat balancing equation.

Temperature of concrete

$$= \frac{(Wc.Tc.Sc + Wca.Tca.Sca + Wfa.Tfa.Sfa + Wa.Ta.Sa + Ww.Tw + Wi.Ti.Si)}{(Wc.Sc + Wca.Sca + Wfa.Sfa + Wa.Sa + Ww + Wi.Si)} \tag{6.12}$$

where prefix W stands for weight, T stands for temperature, and S stands for specific heat of materials denoted by suffixes.

Suffix c stands for cement, ca stands for coarse aggregate, fa stands for fine aggregate, a stands for alternate cementitious material, w stands for water, and i stands for ice.

NOTE: All the units should follow cgs system in the formula because the specific heat for water is 1 cal/g/deg Celsius; hence the coefficient for water has been kept 1.

6.7 Designing Concretes for Targeted Chemistry of Concrete

Many times, concrete needs to be designed for achieving a certain percentage of an element or ion in the concrete, such as a concrete requiring 6% sulphate content of cementitious weight (super-sulphated cement). In general cases, the specification can also be in terms of maximum content of chlorides, sulphates, etc., and this method can be employed there as well. The general description of the procedure is

1. Find, through testing, the percentage of a required component in different raw materials and it's total.
2. Calculate the difference of the required component and that available in various raw materials.
3. Based on the difference of component and the percentage content of the required component in the additive, calculate the amount of additive to be added into the concrete.

Example 6.7

Calculate the amount of gypsum to be added into concrete such that the sulphate content in concrete is equal to 6% of cementitious content. The cement has 1.5% of sulphates, and gypsum has a purity of 88.39%.

Remember, we require here Sulphate content of 6%, not calcium sulphate or any compound containing sulphate as 6%. As sulphate to be added into concrete is 6% of cementitious content, let's use calcium sulphate or gypsum. The chemical formula of gypsum is $CaSO_4.2H_2O$, and the atomic mass of each element can be found from the periodic table (Figure 6.7).

H Hydrogen 1.00797																	He Helium 4.0026
Li Lithium 6.941	Be Beryllium 9.01218											B Boron 10.81	C Carbon 12.011	N Nitrogen 14.0067	O Oxygen 15.9994	F Fluorine 18.9984	Ne Neon 20.179
Na Sodium 22.98977	Mg Magnesium 24.305											Al Aluminum 26.98154	Si Silicon 28.0855	P Phosphorus 30.97376	S Sulfur 32.06	Cl Chlorine 35.453	Ar Argon 39.948
K Potassium 39.0983	Ca Calcium 40.08	Sc Scandium 44.9559	Ti Titanium 47.9	V Vanadium 50.9415	Cr Chromium 51.996	Mn Manganese 54.938	Fe Iron 55.847	Co Cobalt 58.9332	Ni Nickel 58.7	Cu Copper 63.546	Zn Zinc 65.38	Ga Gallium 69.72	Ge Germanium 72.59	As Arsenic 74.9216	Se Selenium 78.96	Br Bromine 79.904	Kr Krypton 83.8
Rb Rubidium 85.4678	Sr Strontium 87.62	Y Yttrium 88.9059	Zr Zirconium 91.22	Nb Niobium 92.9064	Mo Molybdenum 95.94	Tc Technetium -98	Ru Ruthenium 101.07	Rh Rhodium 102.9055	Pd Palladium 106.4	Ag Silver 107.868	Cd Cadmium 112.41	In Indium 114.82	Sn Tin 118.69	Sb Antimony 121.75	Te Tellurium 127.6	I Iodine 126.9045	Xe Xenon 131.3
Cs Cesium 132.9054	Ba Barium 137.33	La Lanthanum 138.9055	Hf Hafnium 178.49	Ta Tantalum 180.9479	W Tungsten 183.85	Re Rhenium 186.207	Os Osmium 190.2	Ir Iridium 192.22	Pt Platinum 195.09	Au Gold 196.9665	Hg Mercury 200.59	Tl Thallium 204.37	Pb Lead 207.2	Bi Bismuth 208.9804	Po Polonium -209	At Astatine -210	Rn Radon -222

FIGURE 6.7
Periodic table and atomic masses of various elements.

$$\text{The atomic mass of Ca} = 40.078, \text{S (Sulphur)} = 32.06, \text{O} = 15.999, \text{H} = 1.008$$

$$CaSO_4.2H_2O = 40.078 + 32.06 + 15.999 \times 4 + 2 \times 1.008 \times 2 + 2 \times 15.999 = 172.164$$

Which means 1 mole of gypsum is 172.164 g.

$$\text{Sulphate } (SO_3) \text{ atomic weight} = 32.06 + 15.999 \times 3 = 80.057$$
$$\text{Sulphate content in pure gypsum} = 80.057 / 172.164 = 46.5\%$$

Now, the sulphate content thus calculated is theoretical and is never obtained in actual tests because the gypsum available is never 100% pure. So based on purity, the sulphate content is always less than what is calculated.

The target sulphate content in cement is 6% and the actual sulphate content tested is 1.5%. To adjust the sulphate content, additional gypsum is added using the following methodology.

Additional gypsum required will be to compensate 6 − 1.5 = 4.5% of sulphate.

Since the purity of gypsum is 88.4% it contains 41.1% sulphate (purity of 88.39%, 46.5 × 88.39% = 41.1%); thus, to get an additional 4.5% of sulphate, add 4.5/0.411 = 10.95% of gypsum. Thus, a mixture of 89.05% cement and 10.95% of gypsum will be required for manufacturing the concrete.

The required content of sulphate is adjusted by adding gypsum or cement to suit the requirements of the specification.

7

Optimization of Concrete

7.1 Introduction

A mix-proportioning process is not complete until it is confirmed that the proportion arrived at is the most economical one to achieve the desired fresh and hardened properties. Usually, many engineers take for granted that a normal mix design method is sufficient to arrive at an optimized mix of concrete. But this is not the case, once you go through the methods explained in this chapter. Some engineers also do a comparison of two mixes, which yields different strengths and different costs and based on their gut feeling they zero down on a mix. The most economical proportion depends on the cost of materials used, the performance of materials, and the ratio of their costs. Thus, the most economical mix may not be economical throughout because the cost of different raw materials keeps on increasing or decreasing. Finding the most economical concrete proportion is a daunting task because the interactions between the materials are complex, and it is easier to understand many interactions only through statistics rather than the real physical cause. 'Entropy Buster', a tool that has been developed by the author, clears the confusion of filtering out the most optimum mix proportion from all of the available materials, and it also helps in deciding whether some of the materials should or should not be included.

7.2 Entropy Buster for Optimizing Concrete

'Entropy' is defined as a lack of predictability due to a lot of chaos, which reigns supreme in concrete. This very chaos leads to confusion of the most optimum mix for desired hardened and fresh properties of concrete. In the previous chapters the family of mixes method for designing concrete was discussed, the method can further be used to optimize concrete. A concrete technologist is constantly under the pressure to reduce cost because it constitutes major cost of any construction project and also because there is always a scope of cost reduction. Because of constant raw material price fluctuations, a mix that was optimum once can become costly one compared to another mix. To filter out such mixes, these methods are discussed in detail.

7.2.1 Entropy Buster Methodology

To design a mix with ordinary Portland cement (OPC) and fly ash, what would have been the optimum percentage of fly ash or mix for M30, M40, and M50 grade of concrete? Would it be 10%, would it be 20% or 50%? Would the optimum percentage be the same or different for all grades of concrete?

The answer to these questions may not be available from normal mix design procedures or any available rule of thumb in the industry, but can be determined and will be specific to the materials used and their prices. To find the answer to these questions, mixes need to be designed with different percentages of fly ash to get the same strength and see which mix is the most economical. This can be done by conducting a set of family of mixes with different percentages of fly ash as explained in Chapter 5. For each percentage of cementitious content with different percentages of fly ash versus strength, a curve is plotted. Further, plot curves for the cost of each mix versus the strength of concrete, and for each grade, the lowest-cost mix with the percentage of fly ash can be determined. The concept will be further described in the following example.

Example 7.1

Decide on the minimum to maximum percentage of fly ash to be used. So, start with a minimum of 0% fly ash and a maximum of 50% fly ash of total cementitious. Thus, the plan for mixes would look like Table 7.1,

Tables 7.2 through 7.5 are the actual strength results achieved when those trials were done, and the cost of concrete for each proportion when individual raw material prices are indicated.

TABLE 7.1

Trial Plan for Different Percentages of Fly Ash

			Cementitious				
		Material (%)	**300**	**375**	**450**	**525**	**600**
Set 1	OPC	100%	300	375	450	525	600
	Fly Ash	0%	0	0	0	0	0
Set 2	OPC	85%	255	318.75	382.5	446.25	510
	Fly Ash	15%	45	56.25	67.5	78.75	90
Set 3	OPC	70%	210	262.5	315	367.5	420
	Fly Ash	30%	90	112.5	135	157.5	180
Set 4	OPC	50%	150	187.5	225	262.5	300
	Fly Ash	50%	150	187.5	225	262.5	300

OPC, ordinary Portland cement.

TABLE 7.2

Results of Mixes for Family of Pure OPC Concrete

				Cementitious				
		Material (%)	**Cost**	**300**	**375**	**450**	**525**	**600**
Set 1	OPC	100%	6	300	375	450	525	600
	Fly Ash	0%	1.8	0	0	0	0	0
	Water		0.1	165	160	168	170	172
	Admixture 1		35	1.00%	1.20%			
	Admixture 2		65			1.10%	1.20%	
	Admixture 3		120					1.00%
	20 mm	36%	0.68	722	702	674	648	622
	10 mm	24%	0.68	478	465	446	429	412
	Fine Aggregate	40%	0.8	768	747	717	690	662
	Strength			27	43	51	58	68
	Cost/m^3			3353	3814	4375	4861	5570

OPC, ordinary Portland cement.

TABLE 7.3

Results of Mixes for Family of 15% Fly Ash as Cement Replacement in Concrete

				Cementitious				
		Material (%)	**Cost**	**300**	**375**	**450**	**525**	**600**
Set 2	OPC	85%	6	255	318.75	382.5	446.25	510
	Fly Ash	15%	1.8	45	56.25	67.5	78.75	90
	Water		0.1	160	155	163	165	167
	Admixture 1		35	0.90%	1.00%			
	Admixture 2		65			1.10%	1.20%	
	Admixture 3		120					1.20%
	20 mm	36%	0.68	722	700	670	643	615
	10 mm	24%	0.68	481	467	447	428	410
	Fine Aggregate	40%	0.8	802	778	745	714	684
	Strength			24	37	48	53	62
	Cost/m^3			3181	3576	4110	4545	5347

OPC, ordinary Portland cement.

TABLE 7.4

Results of Mixes for Family of 30% Fly Ash as Cement Replacement in Concrete

				Cementitious					
		Material (%)	**Cost**	**300**	**375**	**450**	**525**	**600**	**675**
Set 3	OPC	70%	6	210	262.5	315	367.5	420	472.5
	Fly Ash	30%	1.8	90	112.5	135	157.5	180	202.5
	Water		0.1	155	151	158	160	162	160
	Admixture 1		35	0.85%	0.90%				
	Admixture 2		65			1.00%	1.00%		
	Admixture 3		120					0.80%	0.85%
	20 mm	36%	0.68	720	697	666	637	608	577
	10 mm	24%	0.68	480	465	444	425	405	385
	Fine Aggregate	40%	0.8	800	775	740	708	675	641
	Strength			14	18	38	50	59	68
	Cost/m³			2983	3320	3788	4134	4665	5070

OPC, ordinary Portland cement.

TABLE 7.5

Results of Mixes for Family of 50% Fly Ash as Cement Replacement in Concrete

				Cementitious					
		Material (%)	**Cost**	**300**	**375**	**450**	**525**	**600**	**675**
Set 4	OPC	50%	6	150	187.5	225	262.5	300	337.5
	Fly Ash	50%	1.8	150	187.5	225	262.5	300	337.5
	Water		0.1	150	146	153	155	157	160
	Admixture 1		35	0.85%	0.90%				
	Admixture 2		65			1.00%	1.00%		
	Admixture 3		120					0.80%	0.90%
	20 mm	36%	0.68	717	691	654	622	591	558
	10 mm	24%	0.68	478	461	436	415	394	372
	Fine Aggregate	40%	0.8	797	768	727	691	657	620
	Strength			3	5	28	38	56	65
	Cost/m³			2725	2993	3385	3662	4127	4505

OPC, ordinary Portland cement.

The tables may be difficult to interpret if seen only for a particular strength. Hence, one can plot graphs and compare each family with another in terms of cost for each strength of concrete as shown in Figures 7.1 and 7.2. It how data can be fed into an Excel sheet. The arrows marked, show the same strength of concrete. What could be the difference

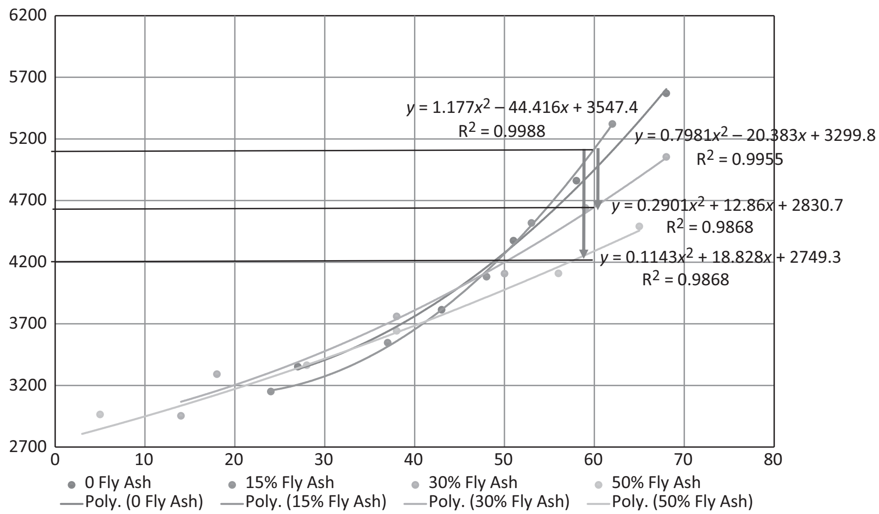


FIGURE 7.1
Entropy Buster tool, cost of concrete versus strength for various percentages of fly ash.

	A	B	C	D	E	F	G	H	I
19		OPC	85%	6	255	318.75	382.5	446.25	510
20	Set2	Fly Ash	15%	1.8	45	56.25	67.5	78.75	90
21		water		0.1	160.05	155.2	162.96	164.9	166.84
22		admixture1		35	0.90%	1.00%			
23		admixture2		65			1.10%	1.20%	
24		admixture3		120					1.20%
25		20 mm	36%	0.68	722	700	670	643	615
26		10 mm	24%	0.68	478	463	444	425	407
27		Fine Aggregate	40%	0.8	767	744	713	684	654
28	Strength of concrete (MPa) →				24	37	48	53	62
29	Cost of Concrete →				3151	3547	4082	4518	5321

FIGURE 7.2
Screenshot of mix tabulation for Entropy Buster.

in cost if proportions are changed? Figure 7.3 is the plot of strength versus cementitious for various percentages of fly ash.

The difference in cost may seem to be huge to many, but there have been numerous instances when such huge savings have actually been realized on the ground. Some organizations have even turned around their loss, making business into profit. This is not good just for an organization but also for the entire state, nation, environment, and sustainability by making efficient use of every resource and producing more from the same resources.

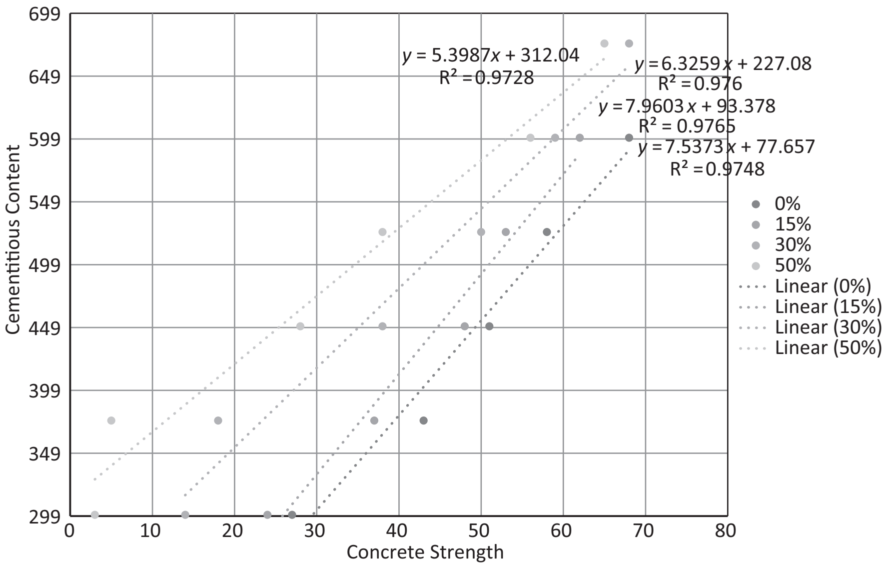


FIGURE 7.3
Cementitious vs strength for various percentages of fly ash.

Figure 7.4 is a plot of the relation between various raw material content versus the strength achieved for the family depicted in set 3 (Table 7.5). Once the lowest-cost mix for a particular grade is found, the raw materials from such plots can be calculated. The quantity of fine aggregate is not plotted in Figure 7.4 because it is calculated manually from the quantities of coarse aggregate, cement found from the graph. If all the materials are calculated based on the plot, the concrete volume may not be 1 m^3; hence, fine aggregates mostly have to be adjusted to compensate for volume increase or decrease.

The relation between strength and cost expressed as an equation in linear or quadratic form can also be found. The equations for costs versus strengths of concrete in Figure 7.1 for pure OPC concrete are as follows (where y is the cost of concrete per m^3 and x is the strength of concrete achieved at 28 days),

$$y = 0.7981x^2 - 20.383x + 3299.8$$

for 15% fly ash,

$$y = 1.1753x^2 - 44.391x + 3577.7$$

for 30% fly ash,

$$y = 0.2832x^2 + 13.228x + 2855.7$$

for 50% fly ash,

$$y = 0.117x^2 + 18.425x + 2779.9$$

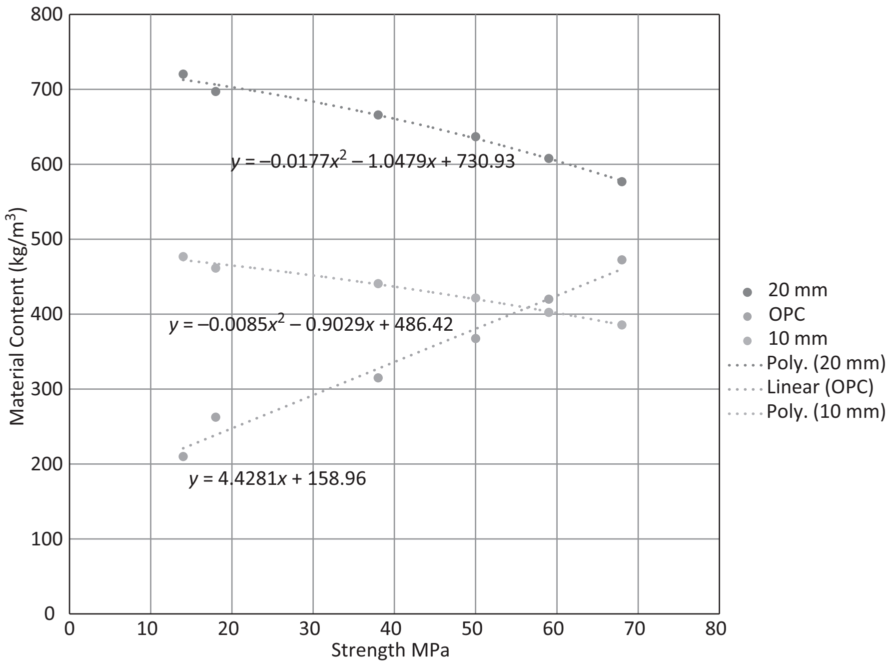


FIGURE 7.4
Trends/equations for calculating materials for various grades of concrete.

Using these equations, the optimum proportion of concrete for any strength can easily be found and achieved during the trials. Every time the raw material cost is updated, the cost of concrete also will change, and the new most economical mix of concrete may be different from the previous one. The most optimum mix will be indicated in the graph plotted. Selecting the most economical mix from the graph may become a bit difficult and inaccurate because it will depend on visual observation. Particularly in those regions where many curves cross each other or are very close to each other, it will be difficult to observe visually. Excel can be of tremendous help in such situations as well.

7.2.2 Automation of Optimization Process

The problem can be solved by performing regression on the available data of trials. There is a built-in formula in Excel to find out linear functions for the best fit in data, viz. 'LINEST'. So if you have two sets of data (i.e. known values of x and the corresponding known values of y, you can use '=LINEST(array of known Ys, array of known Xs)'. This can be done to some extent on cement versus strength data to interpolate cement content, but when the relation is a quadratic function, in those cases, Excel does not have a built-in formula. The quadratic relation can still be found through the following procedures. The quadratic function is in the form:

$$ax^2 + bx + c = y$$

Finding values of a, b, and c such that this function becomes best fit in the set of data found through trials can be done by solving these simultaneous equations:

$$a\sum x_i^4 + b\sum x_i^3 + c\sum x_i^2 = \sum x_i^2 y_i \quad (7.1)$$

$$a\sum x_i^3 + b\sum x_i^2 + c\sum x_i = \sum x_i y_i \quad (7.2)$$

$$a\sum x_i^2 + b\sum x_i + c\sum n = \sum y_i \quad (7.3)$$

Replacing respective numbers from Table 7.6,

$$30181170a + 562274b + 10902c = 7088099$$
$$562274a + 10902b + 224c = 147597$$
$$10902a + 224b + 5c = 3350$$

NOTE: n is the number of data points, which in this case is 5.

Solving these equations: a = −0.04007, b = 0.5502, and c = 732.724.

Excel does these calculations with ease. Moreover, if formulas are fed into the sheet, the input data can be added to or changed, and the output will be calculated immediately (Figures 7.5 and 7.6).

Excel can calculate the sum of squares of numbers in array or sum of multiples of sets of numbers through just a simple formula. Figure 7.5 shows how to calculate a sum of numbers raised to the power of 4. Similarly, the

TABLE 7.6
Calculation for Regression

	Strength	**20 mm**					
	x_i	y_i	x_i^4	x_i^3	x_i^2	$x_i^2y_i$	x_iy_i
	24	722	331776	13824	576	415872	17328
	37	700	1874161	50653	1369	958300	25900
	48	670	5308416	110592	2304	1543680	32160
	53	643	7890481	148877	2809	1806187	34079
	62	615	14776336	238328	3844	2364060	38130
Sum	**224**	**3350**	**30181170**	**562274**	**10902**	**7088099**	**147597**

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1		OPC	85%	6	255	319	383	446	510					
2		Fly Ash	15%	1.8	45	56	68	79	90					
3		water		0.1	160	155	163	165	167				Matrix 1	
4		admixture1		35	0.90%	1.00%						=SUM((E10:I10)^4)		10902
5		admixture2		65			1.10%	1.20%			20 mr	SUM(**number1**, [number2], ...)		24
6	Set2	admixture3		120					1.20%			10902	224	5
7		20 mm	36%	0.68	722	700	670	643	615			30181170	562274	10902
8		10 mm	24%	0.68	478	463	444	425	407		10 mm	562274	10902	224
9		Fine Aggregate	40%	0.8	767	744	713	684	654			10902	224	5
10					24	37	48	53	62					
11					3150	3547	4082	4518	5321					
12														

FIGURE 7.5
Excel sheet example for regression analysis and curve fitting manually, Step 1.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1		OPC	85%	6	255	319	383	446	510										
2		Fly Ash	15%	1.8	45	56	68	79	90										
3		water		0.1	160	155	163	165	167				Matrix 1				Matrix 2		
4		admixture1		35	0.90%	1.00%						30181170	562274	10902	=SUM((E10:I10)^2*(E7:I7))				
5		admixture2		65			1.10%	1.20%			20 mm	562274	10902	224			SUM(**number1**, [number2], ...)		
6	Set2	admixture3		120					1.20%			10902	224	5	=		3350		
7		20 mm	36%	0.68	722	700	670	643	615			30181170	562274	10902			4691798		
8		10 mm	24%	0.68	478	463	444	425	407		10 mm	562274	10902	224			97692		
9		Fine Aggregate	40%	0.8	767	744	713	684	654			10902	224	5			2217		
10					24	37	48	53	62										
11					3150	3547	4082	4518	5321										
12																			

FIGURE 7.6
Excel sheet example for regression analysis and curve fitting manually, Step 2.

	L	M	N	O	P	Q	R
1							
2							
3		Matrix 1				Matrix 2	
4	=SUM((E10:I10)^4)	=SUM((E10:I10)^3)	=SUM((E10:I10)^2)	=		=SUM((E10:I10)^2*(E7:I7))	
5	=M4	=N4	=SUM(E10:I10)	=		=SUM((E10:I10)*(E7:I7))	
6	=M5	=N5	=COUNT(E10:I10)	=		=SUM(E7:I7)	

FIGURE 7.7
Excel sheet matrix 1 and 2 components formulae for regression.

summation of numbers raised to any power can also be calculated. When the summation of numbers raised to a power is done, press Ctrl + Shift + Enter together, or else it may return an error. Figure 7.6 shows how to calculate the summation of multiple one array squared and another array. Thus, matrices can be built as shown in Figure 7.7.

The matrices are done to find the roots of the equation. The inverse of matrix 1 multiplied by matrix 2 will give a matrix with values a, b, and c (refer Figures 7.8 through 7.12).

The Excel functions used in finding the roots of the regression equations are:

1. SUM: This function calculates the sum of the array selected.
2. MINVERSE: Used for finding the inverse of matrix selected.
3. MMULT: Multiplying two matrices.

	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
1																
2																
3			Matrix 1				Matrix 2				Inverse of Matrix 1				Mat1 inv X Mat2	
4		30181170	562274	10902	=		7088099			8.61E-06	-0.00073	0.014103			-0.04007	
5	20 mm	562274	10902	224	=		147597			-0.00073	0.063705	-1.2535			0.55021	
6		10902	224	5	=		3350			0.014103	-1.2535	25.605383			732.724	

FIGURE 7.8
Excel sheet matrix layout for calculating roots of quadratic equation.

	K	L	M	N	O	P	Q	R	S	T	U	V
1												
2												
3			Matrix 1				Matrix 2				Inverse of Matrix 1	
4		30181170	562274	10902	=		7088099			=MINVERSE(L4:N6)		0.014103
5	20 mm	562274	10902	224	=		147597			-0.00073	0.063705	-1.2535
6		10902	224	5	=		3350			0.014103	-1.2535	25.605383

FIGURE 7.9
Excel sheet step for calculating inverse of a matrix with 'MINVERSE' Excel formula.

	P	Q	R	S	T	U	V	W	X	Y	Z	A
1												
2												
3		Matrix 2				Inverse of Matrix 1				Mat1 inv X Mat2		
4		7088099			8.61E-06	-0.00073	0.014103			=MMULT(T4:V6,Q4:Q6)		
5		147597			-0.00073	0.063705	-1.2535			0.55021		
6		3350			0.014103	-1.2535	25.605383			732.724		

FIGURE 7.10
Excel sheet step for multiplication of matrices with 'MMULT' Excel formula.

=MINVERSE(L4:N6)	=MINVERSE(L4:N6)	=MINVERSE(L4:N6)
=MINVERSE(L4:N6)	=MINVERSE(L4:N6)	=MINVERSE(L4:N6)
=MINVERSE(L4:N6)	=MINVERSE(L4:N6)	=MINVERSE(L4:N6)

FIGURE 7.11
Excel sheet expansion of each component for inverse matrix.

	=MMULT(T4:V6,Q4:Q6)	
	=MMULT(T4:V6,Q4:Q6)	
	=MMULT(T4:V6,Q4:Q6)	

FIGURE 7.12
Excel sheet expansion for each component for matrix multiplication.

Once the cement and coarse aggregates have been calculated, the water can be taken as the average of whatever has been used while conducting concrete trials in the family of mix (assuming the required workability has been achieved by increasing or decreasing the admixture dosage and keeping the water constant). The slump value; the viscosity may not be similar of concretes made workable by adding water alone as compared to those made workable with the addition of admixture. For application purposes, slump value can be safely taken as a workability measurement and benchmarking test; if workability requirements are different, the water and admixture adjustment will have to be changed. Once the water content is fixed for each mix in the family, the fine aggregate using the absolute volume formula as given in Equation 1.4 can be found.

Now, we need to develop a system through which Excel filters out the lowest-cost mix for any strength, every time the raw material cost changes. From each family, for every strength of concrete, the function of quantities of materials w.r.t. strength of concrete has been found; these very calculations need to be added into the Excel sheet, which is shown in Figure 7.13. The highlighted portion in Figure 7.13 is the formula based on the best fit found for the respective family for the given material and is linked to the respective set of trials. The material for grade 5 is calculated only for one mix (Figure 7.13) because only one mix achieved the strength close to the target strength of 8.3 MPa; this is because materials or proportions are safer to interpolate, but extrapolation poses a lot of risks as a result of sudden change in the behavior of concrete with change in proportion beyond certain levels. The column depicting the cost of each mix is calculated based on the mix proportion, and the cost of raw materials is updated in column A. Any change in raw material cost upward or downward will lead to a change in the overall economics of the concrete, and this sheet will accurately filter out

J42 =Sheet1!$U$48*$F39^2+Sheet1!$U$49*$F39+Sheet1!$U$50

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
38					Grade	Target Strength	OPC	Fly Ash	Water	20 mm	10 mm	Fine Aggregate	admixture 1	admixture 2	admixture 3	Cost/m3
39					5	8.3										10000
40					5	8.3										10000
41	OPC	6			5	8.3										10000
42	Fly Ash	1.8		5	5	8.3	178	178	154	695	461	735	3.21			2893.5
43	Water	0.1			10	14.125										10000
44	20 mm	0.68			10	14.125										10000
45	10 mm	0.68			10	14.125	222	95	158	713	472	762	2.53			3019.3
46	Fine Aggre	0.8		10	10	14.125	194	194	154	682	453	722	3.49			3001.9
47	admixture	35			15	19.125										10000
48	admixture	65			15	19.125										10000
49	admixture	120			15	19.125	244	104	158	704	466	745	2.96			3161.1
50				15	15	19.125	208	208	154	671	446	712	3.74			3094.9
51					20	24.95	266		167	727	481	794	2.66			3160
52				20	20	24.95	248	44	162	721	477	777	2.63			3113
53					20	24.95	269	115	158	694	459	727	3.46			3326.7
54					20	24.95	223	223	154	658	438	700		4.47		3353
55					25	31.6	316		167	718	475	765	3.47			3456.6
56				25	25	31.6	293	52	162	710	470	747	3.45			3389.3

FIGURE 7.13
Excel sheet setting up of Excel sheet for filtering out most optimum mix for each grade of concrete based on tests.

the most economical mix among all available family of mixes. Column D contains pointers of the lowest-cost concrete based on the minimum value of cost in column P for a given grade of concrete. It uses the 'IF' and 'MIN' functions, or some of the other ways, to filter out the least cost mix.

7.3 Optimizing in Multidimensions

In the previous section of Entropy Buster, the concrete was optimized across different percentages of fly ash, and the most optimum fly ash percentage for each grade of concrete was determined. But the real optimization does not end there, especially when there is more than one parameter to check and optimize, like admixture dosage, other cementitious combinations (more than two), aggregate proportions, and so on. Also, the biggest doubt that arises in the example of the Entropy Buster tool is whether the optimum percentage of fly ash is exactly in the percentages of fly ash tested or somewhere between them.

To solve these issues of optimization, another tool, Regression, is available in Excel, which helps in doing a 360-degree optimization, encompassing all the desired parameters.

7.3.1 Methodology

The methodology involves tabulating all the trials in a single table, including the variables and the test results. The example given in the Entropy Buster method can be tabulated as follows:

Fly Ash (%)	Cementitious	Strength
0.00%	300	27
0.00%	375	43
0.00%	450	51
0.00%	525	58
0.00%	600	68
15%	300	24
15%	375	37
15%	450	48
15%	525	53
15%	600	62
30%	300	14
30%	375	18
30%	450	38
30%	525	50

(*Continued*)

Fly Ash (%)	Cementitious	Strength
30%	600	59
30%	675	68
50%	300	3
50%	375	5
50%	450	28
50%	525	38
50%	600	56
50%	675	65

Excel has an Add-in called Data Analysis, which should be added into Excel just like Solver (Analysis tool-pak and Analysis tool-pak VBA; refer to Figures 7.14 and 7.15). The Data Analysis Add-ins have many inbuilt functions, out of which Regression will be used to optimize concrete when there are more than one parameter.

These results are added into the Excel sheet, and the regression function is run from the data analysis pack. After this, the dialogue box shown in Figure 7.16 opens. The regression function requires some

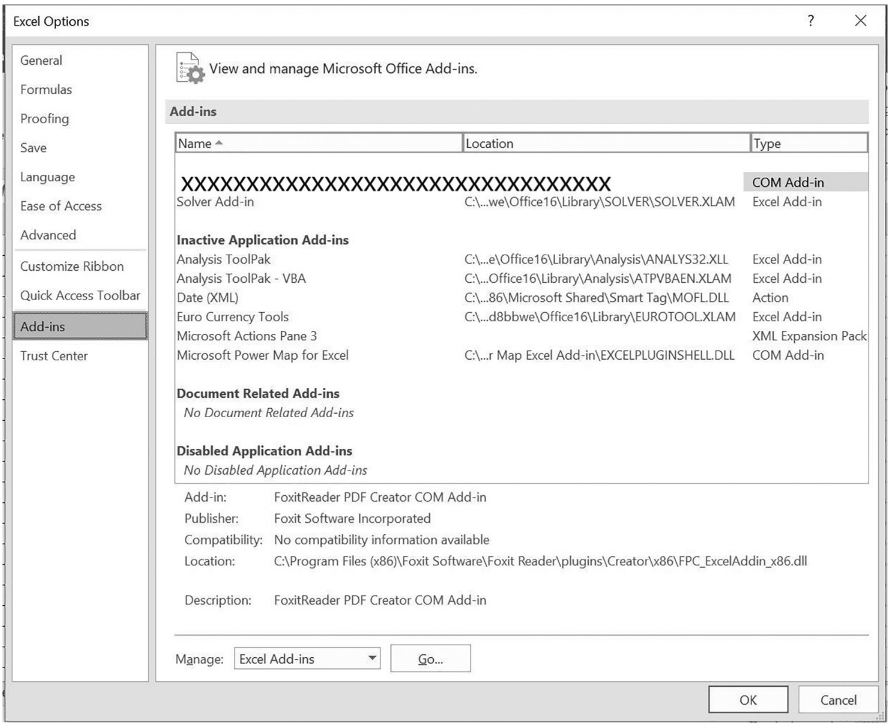


FIGURE 7.14
Step 1 setting up analysis tool pak.

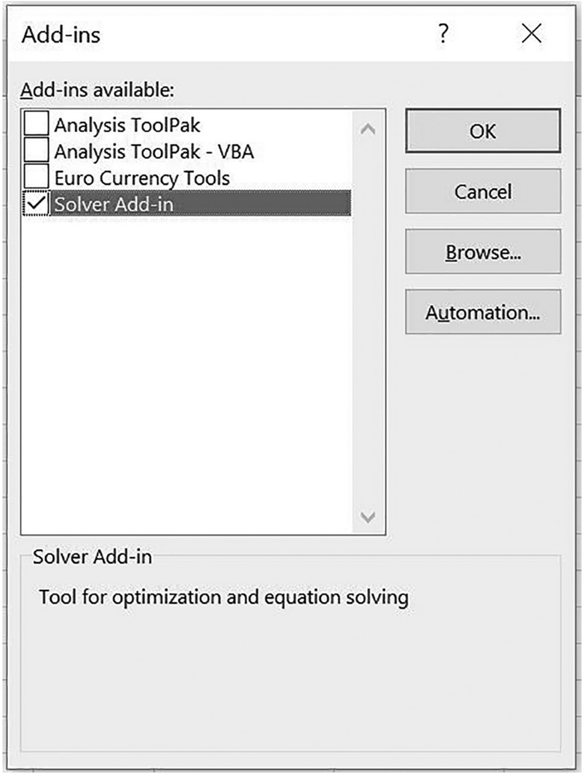


FIGURE 7.15
Step 2 setting up analysis tool pak.

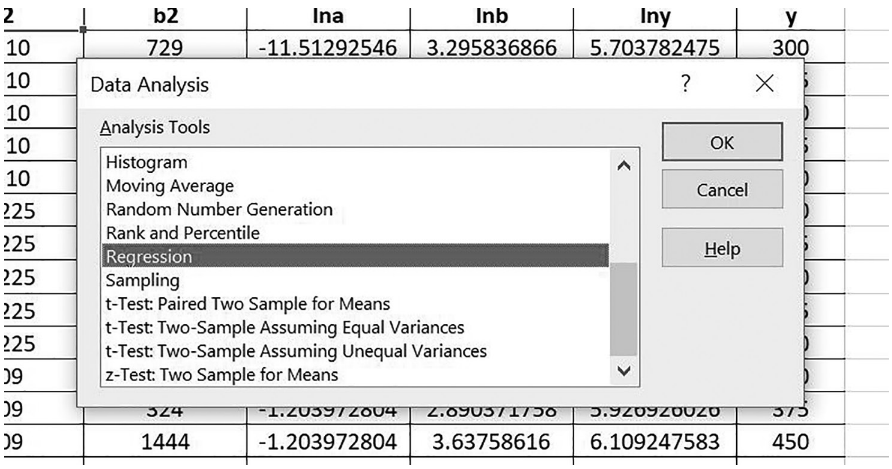


FIGURE 7.16
Window for analysis tool pak.

manual intervention and is not automated as in when graphs are plotted. Hence, additional columns of squares, the product of various possible combinations, natural logs of input, as well as output results (Figure 7.17) should be made. When the regression dialogue box appears, select relevant data into input ranges of it as shown in Figure 7.18. Click OK, and a new sheet appears with a report of regression (Figure 7.19). Based on the values of Adjusted R square, standard error, p Value, and so on, some parameters may have to be omitted and regression with remaining parameters is done.

	A	B	C	D	E	F	G	H	I
1	% fly ash	strength							cementitious
2	a	b	ab	a2	b2	lna	lnb	lny	y
3	0.00%	27	0.00027	1E-10	729	-11.51292546	3.295836866	5.703782475	300
4	0.00%	43	0.00043	1E-10	1849	-11.51292546	3.761200116	5.926926026	375
5	0.00%	51	0.00051	1E-10	2601	-11.51292546	3.931825633	6.109247583	450
6	0.00%	58	0.00058	1E-10	3364	-11.51292546	4.060443011	6.263398263	525
7	0.00%	68	0.00068	1E-10	4624	-11.51292546	4.219507705	6.396929655	600
8	15%	24	3.6	0.0225	576	-1.897119985	3.17805383	5.703782475	300
9	15%	37	5.55	0.0225	1369	-1.897119985	3.610917913	5.926926026	375
10	15%	48	7.2	0.0225	2304	-1.897119985	3.871201011	6.109247583	450
11	15%	53	7.95	0.0225	2809	-1.897119985	3.970291914	6.263398263	525
12	15%	62	9.3	0.0225	3844	-1.897119985	4.127134385	6.396929655	600
13	30%	14	4.2	0.09	196	-1.203972804	2.63905733	5.703782475	300
14	30%	18	5.4	0.09	324	-1.203972804	2.890371758	5.926926026	375
15	30%	38	11.4	0.09	1444	-1.203972804	3.63758616	6.109247583	450
16	30%	50	15	0.09	2500	-1.203972804	3.912023005	6.263398263	525
17	30%	59	17.7	0.09	3481	-1.203972804	4.077537444	6.396929655	600
18	30%	68	20.4	0.09	4624	-1.203972804	4.219507705	6.514712691	675
19	50%	3	1.5	0.25	9	-0.693147181	1.098612289	5.703782475	300
20	50%	5	2.5	0.25	25	-0.693147181	1.609437912	5.926926026	375
21	50%	28	14	0.25	784	-0.693147181	3.33220451	6.109247583	450

FIGURE 7.17
Excel sheet for regression of multivariables.

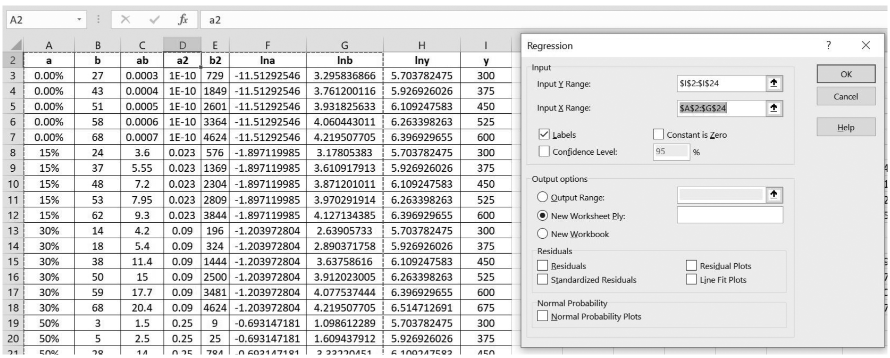


FIGURE 7.18
Selecting data for regression analysis through regression tool in analysis tool pak.

	A	B	C	D	E	F	G	H	I
1	SUMMARY OUTPUT								
2									
3	*Regression Statistics*								
4	Multiple R	0.991209							
5	R Square	0.982495							
6	Adjusted F	0.973742							
7	Standard I	19.91033							
8	Observatic	22							
9									
10	ANOVA								
11		*df*	*SS*	*MS*	*F*	*gnificance F*			
12	Regressior	7	311495.5587	44499.37	112.2528	3.28E-11			
13	Residual	14	5549.895855	396.4211					
14	Total	21	317045.4545						
15									
16		*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*pper 95.0%*
17	Intercept	-38.9163	80.34441495	-0.48437	0.635614	-211.238	133.4053	-211.238	133.4053
18	a	679.5995	283.8058142	2.394593	0.03119	70.89657	1288.302	70.89657	1288.302
19	b	-0.66654	3.310766466	-0.20132	0.84334	-7.76743	6.434349	-7.76743	6.434349
20	ab	-4.90415	1.738040866	-2.82166	0.013588	-8.63188	-1.17643	-8.63188	-1.17643
21	a2	-247.361	384.9387384	-0.6426	0.530868	-1072.97	578.2505	-1072.97	578.2505
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

FIGURE 7.19
Regression output for analysis done.

7.3.1.1 Interpretation of Regression Analysis

In the first table, Regression statistics, the terms Multiple R and R Square can be found. This is a figure that shows how good is the correlation found between inputs and outputs as per the regression done; the closer this number is to 1, the better the correlation is. The Adjusted R Square that helps to weed out unnecessary inputs that do not have effect significantly on the outputs.

Because variables are manually selected, it is important to know which variables are good to take and which are not, as increasing the number of variables yields a higher value of R, but when 'adjusted R' is checked, it shows how efficiently the variables have been chosen. When R has a higher value, but adjusted R has a lower value, it shows that some variables chosen do not have much effect on the output, and they need to be taken out.

The term 'Standard error' gives an idea of how reliable the predicted result would be. Predicted value ± 2 times. The standard error tells that 95% chances are that the actual results will lie within this range. The range is called a 'confidence interval' and is also dependent on a number of test results minus 1, which is called the 'degree of freedom' (df). Thus, in this case, the degree of freedom is 22-1 (i.e. 21). For the confidence level to be high, it is also required that the degree of freedom be high, or else for getting a 95% confidence limit for a lower number of tests, the coefficient of standard error taken needs to be higher.

The analysis of variations (ANOVA) shows the df against regression in the table, which is the number of variables considered; residual is df minus regression.

The table is the most important because it gives an equation/curve fitted between the points with coefficients and intercept. The table has a column called the 'p Value', which helps us in removing nonrelevant parameters and keeping those that affect the output most. This is the probability value indicating whether the change in output with respect to the input variable is by chance or if it actually is affecting the output. It may be noted that these probability values are also relative, meaning w.r.t other parameters. A P value of less than 5% is a sure-shot variable, which should be considered in developing the equation for predicting the output. There may be cases when some p values are above 5% and none below 5%; in those cases, take 1/5th (20%) of all the values that have the lowest p values.

The equation developed in this case is:

$$C = 502.76p - 4.83pS + 0.071S^2 + 68.85.\ln(S) - 2.52$$

where C is the cementitious content, S is the strength of concrete, and P is the percentage of fly ash.

The optimization can further be done by adding equations of cost in the Excel sheet and solving it to get the lowest cost.

NOTE: The statistical significance explained here may seem too crude for a seasoned statistician, but this is just enough for a concrete technologist who wishes to optimize and design concrete.

It must be noted that the equation is valid only within the boundaries of values it is tested for. This method is particularly useful when the number of variables are more than 1 (e.g. optimization of cementitious containing fly ash, slag, microsilica). Equations can be developed in many other ways, for which following guidelines can be used:

1. Adjusted R square should be as high as possible.
2. The standard error is the range within which 80% of results will fall above and below the predicted values.
3. The p values guide to filter out the least-affecting parameters on the outputs.

8

Conducting Laboratory Tests and Validation of Mixes

8.1 Introduction

Without this step, no mix design is complete. The laboratory test and validation of concrete mix design are usually taken for granted, assuming that the calculations done to arrive at the mix proportion are enough and the tests would ultimately achieve the required strength at the required age. Workability and yield (actual volume of concrete for the mix given for 1 m^3) are some of the outputs that go unnoticed for the validity of the mix developed. Concrete mix design is not complete until it has been tested up to the final level of implementation and it satisfies all the requirements of its users.

Some of the basic steps necessary in conducting the trial mixes, applying the corrections in mixes, and backward calculating the mix proportions are reviewed here.

8.2 Correction for Moisture Content and Absorption in Aggregates

Aggregates mostly are not entirely solid material, but they do have micropores and cracks as a result of crushing during the manufacturing stage or due to its innate property in the parent rock. These pores contain water in natural condition and are held there because of capillary action. When mixed in concrete, the water in these aggregates is not necessarily involved (at normal water cement ratios above 0.3) in a chemical reaction with cement. Hence, while designing concrete, it has been a standard practice to calculate water contents and aggregate contents for aggregates in saturated surface dry condition. The weights of aggregates calculated in the steps should be fully saturated with water in the pores and cracks, but their surfaces are dry. Obviously, natural state aggregates very rarely available in this condition. Hence, they are analyzed for moisture content and corrections are done accordingly to ensure that the total of water and aggregates in the natural condition is exactly similar to calculated weights of aggregates in saturated-surface dry (SSD) condition and the water.

8.2.1 Different Conditions of Aggregates with respect to Moisture Content

Aggregates can be available in any of the following four conditions:

1. Moist condition with presence of surface moisture
2. SSD condition
3. Partially SSD condition
4. Oven-dry condition

For aggregates in drier states as compared to SSD condition (i.e. oven dry and partially saturated), extra water is added into the mix to compensate for the less amount of water in aggregates to bring them to SSD condition, whereas for moist aggregates, water in the concrete proportion is reduced. The cement reacts only with the water that is not absorbed into minute pores of the aggregates (i.e. free moisture) and that water comes from water externally added into concrete and surface moisture, if any, minus the water that the aggregates absorb. In some methods of mix proportioning, calculation and records are done for aggregates instead in oven-dry condition, which is fine because the entire mix remains the same after correction whether for SSD or oven-dry condition; it is just another way to express the proportion. The oven-dry condition and SSD calculations will be discussed in detail later. But first let us see how corrections are done, for aggregates and water, in mix design so that SSD condition mix proportion is achieved.

8.2.2 Moisture Absorption Calculation and its Significance in Proportioning

Moisture absorption is tested by soaking aggregates fully in water and then drying just the surface of the aggregates either by a dry cloth (for coarse aggregates) or hair dryer (usually for fine aggregates). The mix proportion correction for SSD condition will depend usually on the formula applied for calculating the moisture absorption (i.e. whether the absorption is calculated based on the oven-dry condition of aggregate or SSD condition). The difference in both of these methods is miniscule, but mathematically the difference would be surely there.

Moisture absorption of aggregates is expressed as

$$A = (S - O) / O \tag{8.1}$$

where A is the moisture absorption, S is the weight of aggregate in SSD condition, and O is the weight of aggregate in oven-dry condition.

Another term that comes into picture while correcting mixes for SSD condition is moisture content, which is nothing but the moisture available in the aggregates, and is measured by taking a standard amount of aggregate and heating it to evaporate out the entire water. The difference expressed w.r.t. the dry weight of the aggregate is the moisture content and is expressed as

$$M = (W - O)/O \tag{8.2}$$

where M is the moisture content, W is the mass of the aggregate before heating (in the available natural condition), and O is the mass of the aggregate after oven drying.

Example: A sample of aggregate that weighed 500 g in SSD condition was tested, and when it was heated, the same sample was reduced to 475 g; the water absorption is expressed as

$$A = (500-475)/475 = 5.263\%$$

Now suppose the mix design contains 750 kg of this aggregate in SSD condition. The moisture content of the aggregate is 3.5%; what should the aggregate content in the same condition be, so that the weight of aggregate in this condition is equivalent to weight of aggregate in SSD condition? Now remember, when the moisture content of the aggregate is more than the water absorption, it implies the aggregate is in moist condition; but if it is less than the water absorption, it implies partially saturated/dry condition.

When aggregates are in a moist condition, the weight of the aggregates shall be higher than the weight required in SSD condition; as part of the aggregate weight is the weight of water. Whereas for partially or fully dry aggregates, the weight of the aggregates shall be less than that required in SSD condition. The best way to remember the formula for correction is 'Increase the wet aggregates and reduce the dry'.

$$\text{Aggregate weight} = S \times (1 + M)/(1 + A) \tag{8.3}$$

$$\text{Aggregate weight} = 750 \times 1.035/1.05263 = 737.44 \sim 737\text{ kg}$$

where S is the weight of aggregates in the mix in SSD condition, M is the moisture content in the aggregate, and A is the moisture absorption of the aggregate. The component S/(1+A) is the weight of oven-dry aggregates. And when this term is multiplied with (1+M), it is for the moisture present in the aggregates. Equations 8.1 and 8.2 are for applying corrections in any state of aggregates, although to make things clear, the other relations between different conditions of aggregates should also be seen.

Equation 8.1 can also be written as

$$S = O + O.A$$

$$O = S/(1 + A) \tag{8.4}$$

Similarly Equation 8.2 can be written as

$$W = O + O.M = O(1 + M) = S \times (1 + M)/(1 + A) \tag{8.5}$$

Replacing O with Equation 8.4 yields Equation 8.5 for weight correction. Remember the term W is for the weight of aggregates to be batched in the available condition so that the mix is equivalent to materials batched in SSD condition equal to the proportion of the mix derived.

These calculations have been simple, but when the moisture content and absorption are not expressed in terms of oven-dry weight, then the calculations change for correction. But most standards express both moisture absorption and content in terms of oven-dry weight.

Similarly, corrections also need to be applied to water content. The rule for water correction is to reduce water in the mix equivalent to water present in the aggregates and to increase water for the absorption.

Thus, water to be increased is expressed by the following formula (Equation 8.6):

$$W = S \times (A - M)/(1 + A) \tag{8.6}$$

where S is the weight of aggregate in the mix, A is the absorption of the aggregate, and M is the moisture content in the aggregate.

NOTE: If the value is negative, water will have to be reduced, and if it is positive, it will have to be increased.

8.2.3 What Would Happen If Moisture Correction Was Not Done

Aggregates contain capillary voids and fissures in them, which absorb water from concrete if dry. The water thus absorbed or if present previously in the capillary voids of aggregates does not react with cement and is thus not taken into consideration for determination of water cement ratio. Consider Figure 8.1a, which shows on left-hand side a pictorial representation of aggregates, with absorbed water, marked as * and # for water that needs to be added into concrete externally. Essentially these are SSD aggregates incorporated into concrete that need no correction. While Figure 8.1(b) is aggregate that is oven dry (no water in the voids) and has

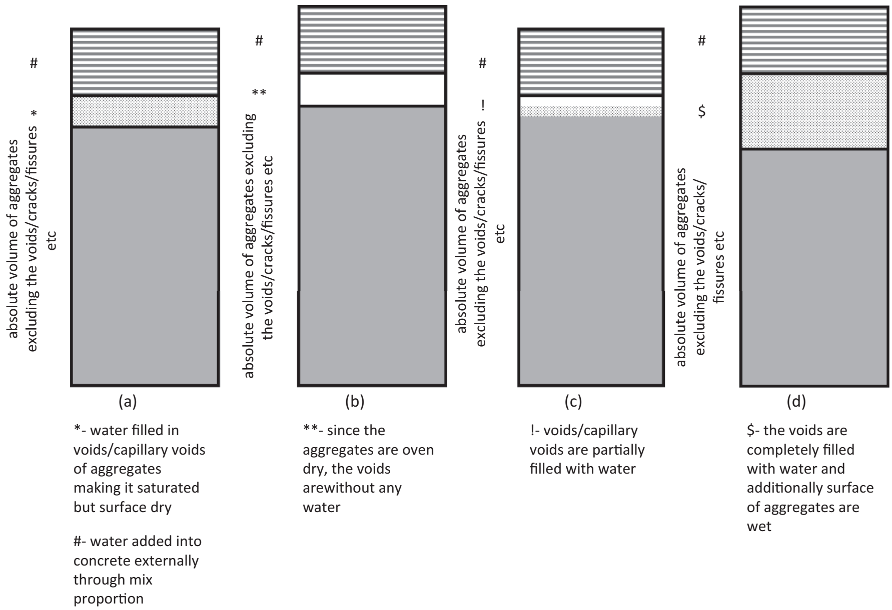


FIGURE 8.1
Pictorial representation of concrete mix without correction applied on account of moisture content of aggregates. (a) Schematic representation of correct proportion of concrete with saturated-surface dry (SSD) aggregates and water from the concrete mix. (b) Schematic representation of oven-dry aggregates weighed equal to the required SSD condition aggregates, resulting in more volume of aggregates, and less than that required water in the concrete mix without provision for absorption of dry aggregates. (c) Schematic representation of semi-dry aggregates (condition between SSD and oven dry) weighed equal to the required SSD condition aggregates, resulting in more volume of aggregates and water in the concrete mix without provision for absorption of dry aggregates, resulting in less water than required. (d) Schematic representation of moist aggregates (condition of wetter aggregates compared to SSD) weighed equal to the required SSD condition aggregates, resulting in less volume of aggregates and water in the concrete mix without provision of extra water from moist aggregates, resulting in more water than required.

been weighed equal to the weight required of SSD aggregates, which leads to a higher quantity of aggregates than required. Moreover, because water is also not corrected, all the water from the mix will not be available as part of it will be sucked up by the aggregates, thereby reducing the workability and water cement ratio of concrete.

Figure 8.1c is a comparison of non-corrected partially saturated aggregates with SSD aggregates, which will give similar issues as Figure 8.1b but by a smaller magnitude on account of partial saturation of voids.

Figure 8.1d is a comparison of SSD aggregates with moist aggregates, where not only aggregate voids are saturated with water but the surface of aggregates is also wet, which will be available in concrete for hydration of cement. If this correction is not done, and the weight of wet aggregates are taken to be the same as that of SSD aggregates, the amount of actual aggregates will be less than what was required, and water quantity in concrete will be much higher.

Figure 8.2 is a representation of corrections done in various conditions of the aggregates. Figure 8.2b and c shows pictorially how the aggregate quantity is taken less than the SSD weights and water content in the mix is increased corresponding to the expected water absorption by the aggregates when the available aggregates are dry or semi-dry.

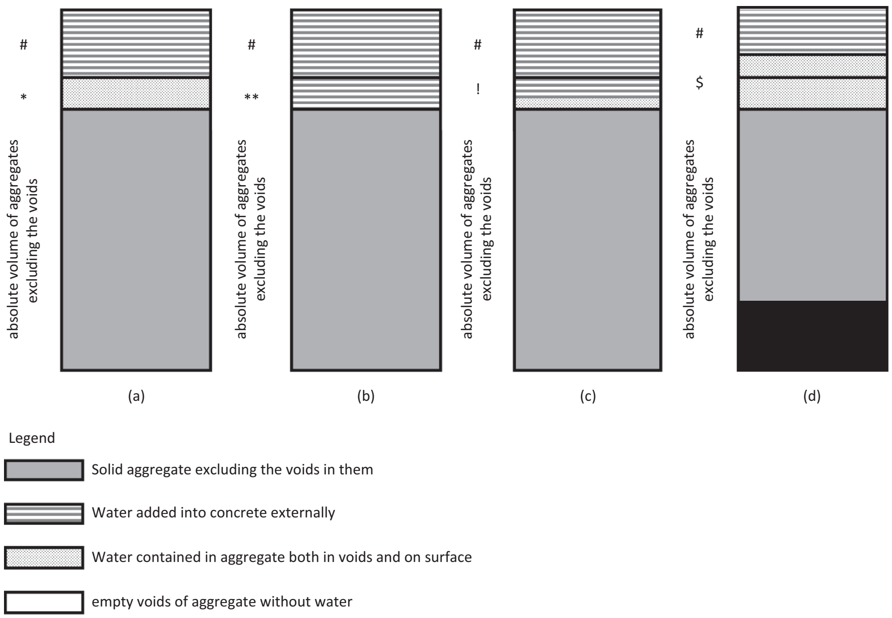


FIGURE 8.2
Pictorial representation of concrete mix with correction applied on account of moisture content of aggregates. (a) Schematic representation of correct proportion of concrete with saturated-surface dry (SSD) aggregates and water from the concrete mix. (b) Schematic representation of oven-dry aggregates weighed less than the required SSD condition aggregates, and water in the concrete mix with provision for absorption of dry aggregates, resulting in a mix equivalent to SSD condition mix of concrete. (c) Schematic representation of semi-dry aggregates weighed equal to the required SSD condition aggregates, resulting in more volume of aggregates and water in the concrete mix without provision for absorption of dry aggregates, resulting in less water than required less than the required SSD condition aggregates, and water in the concrete mix with provision for absorption of dry aggregates, resulting in a mix equivalent to SSD condition mix of concrete. (d) Schematic representation of moist aggregates weighed more than the required SSD condition aggregates, resulting in equivalent volume of aggregates w.r.t SSD condition and less amount of water in the concrete mix for provision of extra water from moist aggregates, resulting in total water content equal to that required.

In Figure 8.2d for extra water available from moist aggregates, the corresponding quantity of water in mix proportion is reduced, and the quantity of wet aggregates increased, so that the quantity of aggregates is the same as that of SSD condition.

Example 8.1

A mix contains the following proportion of materials in SSD condition of aggregates. Absorption and water content of the aggregates are provided against the weights. What should the proportion of materials in natural condition be so that it exactly resembles the mix in SSD condition?

Material	Weight (kg)	Moisture Absorption (%)	Moisture Content (%)
Cement	360		
Water	165		
20 mm Aggregates	950	0.6	0.5
10 mm Aggregates	150	0.9	0.65
Fine Aggregates	815	6.8	2.1

Solution

The aggregate weights need to be corrected, and the formula is

Aggregate Weight = S × (1+M)/(1+A)

20 mm Aggregates = 950 × (1 + 0.5/100)/(1 + 0.6/100) = 949.06 ~ 949 kg

10 mm Aggregates = 150 × (1 + 0.65/100)/(1 + 0.9/100) = 149.63 ~ 150 kg

Fine Aggregates = 815 × (1 + 2.1/100)/(1 + 6.8/100) = 779.13 ~ 779 kg

Water Correction = 950 × (0.6/100 − 0.5/100)/(1 + 0.6/100) + 150 × (0.9/100 − 0.65/100)/(1 + 0.9/100) + 815 × (6.8/100 − 2.1/100)/(1 + 6.8/100) + 165 = 0.944 + 0.372 + 35.87 + 165 = 202.186 ~ 202 kg

8.2.4 Moisture Correction for Oven-Dry Condition

SSD condition testing is prone to error, as SSD condition, while testing, depends on the visual observation of the tester, and what may seem SSD condition for someone may not seem so for another. Thus, many quality control engineers prefer expression of mixes into oven-dry condition instead of SSD condition. Thus, when a concrete mix proportion is calculated, it is converted into oven-dry condition simply by decreasing the amount of aggregates equivalent to the absorption of the aggregates and increasing the water content equivalent to the absorption. The advantage of this method of calculation is the simplicity of corrections once the water content of aggregates is found. The final mix is derived in just one step instead of correction in two steps. For the sake of example mix proportion, given in Table 8.1 for SSD condition can be expressed in oven-dry condition as in Table 8.2.

TABLE 8.1

Correction Applied Based on Moisture Content of Aggregates

Material	Weight (kg)	Moisture Absorption (%)	Moisture Content (%)	Corrected Mix (kg)
Cement	360			360
Water	165			202
20 mm Aggregates	950	0.6	0.5	949
10 mm Aggregates	150	0.9	0.65	150
Fine Aggregates	815	6.8	2.1	779

TABLE 8.2

Expression of SSD Weight of Mix in Oven-Dry Condition

Material	SSD Weight (kg)	OD Weight (kg)
Cement	360	360
Water	165	224
20 mm Aggregates	950	944
10 mm Aggregates	150	149
Fine Aggregates	815	763

OD, oven dry; SSD, saturated-surface dry.

TABLE 8.3

Mix After Correction of Oven-Dry Weights

Material	OD Weight (kg)	Moisture Content (%)	Corrected Mix (kg)
Cement	360		360
Water	224		202
20 mm Aggregates	944	0.5	949
10 mm Aggregates	149	0.65	150
Fine Aggregates	763	2.1	779

OD, oven dry.

And while conducting the trials, only one correction is to be applied (i.e. moisture content). After applying the moisture content correction, the mix proportion resembles exactly with the corrected mix for SSD condition (compare Tables 8.1 and 8.3). The corrections applied to aggregate contents are:

$$\text{Aggregate Weight} = \text{O} \times (1 + \text{M})$$

where O is the weight of aggregate to be taken for the mix, had it been in oven-dry condition, and M is the moisture content in the aggregates.

The corrected water content for the mix is calculated as:

$$\text{Water} = \text{W} - \text{O} \times \text{M}$$

where W is the water in the mix proportion (Oven Dry Condition) per cubic meter of concrete.

Oven-dry based mixes are preferred over SSD mixes, where an upper limit on water added into concrete is set for moisture correction. Many concrete manufacturing plants resort to adding water when required workability is not met, and it is done by increasing the moisture absorption of aggregates. But when the mix proportions are converted into oven-dry mixes and the absorption values are frozen, the production team has the only option of reducing the water for moisture content. This though may not help in reducing problems of variations in concrete workability during production, but will definitely raise an alarm for the person who reserves the right to change the moisture absorption values of aggregates, and for root cause analysis.

8.3 Corrections in Batch and Their Effect on Mix Design

Almost every time, certain results in concrete do not follow the normal trend, and the reason for this behaviour is not known. Most of the cases in which concrete shows a different trend than the norm is due to, improper calculation of mix proportion as a result of the change in absolute proportion of materials on account of compaction, air content, or batch correction during the trial (addition of extra water, etc.). When these corrections are applied to the proportion, things start falling in place, and results conforming to trends, are observed almost always (a statistician's dilemma leads to such statements as 'almost always'). We shall see how these errors are checked and corrections applied.

8.3.1 Change in Mix due to Compaction or Density Variation

Concrete design is done based on a certain percentage of air (meaning not fully compacted) or with some amount of entrained air (using air-entraining admixtures to keep air content to suit specifications for freezing and thawing conditions, or the water-reducing admixture has an additional effect of air entrainment). It is not at all predictable as to how much air content will be present in the concrete after compaction. This leads to a change in contents of the materials (not their inter-proportion though); that is, if the air content is less than the assumed quantity, all the materials are physically more in quantity inside the concrete than what they were designed for, and vice versa. This has led to cases when concrete with slightly higher cement content and lower water cement ratio has achieved less strength than concrete with lower cement content and a higher W/C ratio. But when their densities were thoroughly analyzed, and material contents were back-calculated, the concrete with less strength had lower cement content than concrete with higher strength (and lower designed cement content). The correct way to calculate the density of hardened concrete is by using the following method.

Take the weight of hardened concrete density in the air (W1) and take its weight while fully submerged but hanging in water (W2).

The density of concrete then is calculated as

$$\text{Density} = \text{W1}/\left(\text{W1} - \text{W2}\right)$$

This method is appropriate than the usual method of calculating the volume of concrete based on known dimensions normally, as it tends to produce erroneous results because of surface deformations and defects but gets accounted in the water-submersion method.

The calculated density and measured density of concrete are compared and corrections are done so that the total weight of materials in the concrete sum up to the actual density tested.

Example 8.2

Concrete is made with the following proportions for 1 m^3.

As per calculations, the corrected batch weight was as given in Table 8.4, but after completing the trial, the density of concrete found was 2300 kg/m^3. What is the actual mix proportion to produce 1 m^3 of concrete?

When the total weights of all materials as per design and density of concrete are compared, the actual density is lower than that expected, meaning either the concrete cannot achieve its full compaction, there is higher entrained/entrapped air, or some materials have changed in property (i.e. their specific gravities are less than that used for calculating the weights of the materials). The root cause for change in the density does not need to be known, but all that needs to be done is to find the actual density and a factor that will help us arrive at the closest mix for 1 m^3.

For this, divide the actual density by the total theoretical weights for 1 m^3 of concrete.

TABLE 8.4

Calculated Mix Proportion for Testing

Material	Weight
Cement	400
Water	165
20 mm	850
10 mm	500
Fine Aggregate	520
Admixture	4
Total (expected density)	2439

TABLE 8.5

Corrected Mix of Table 8.4 Based on Test

Material	Weight	New Weights
Cement	400	377
Water	165	156
20 mm	850	802
10 mm	500	472
Fine Aggregate	520	490
Admixture	4	3.77
Total (expected density)	2439	2300

Factor = 2300/2439 = 0.943, Thus, each material weight of concrete needs to be reduced by multiplying it by 0.943 so that the concrete produced is equal to 1 m^3 or closer. Thus, the new mix becomes as shown in Table 8.5.

It must be noted that the mix is not changed in terms of proportion, but the volume of concrete was reduced to make it 1 m^3.

8.3.2 Change in Mix due to Adjustments or Changes During Trials

Previously it was shown how the level of compaction achieved in concrete can lead to change in volume and when subsequent changes in mix contents are done, the required volume of concrete is delivered and is not underyield or overyield. This section reviews correcting the proportions of concrete, if during trials any material has been added extra or less than whatever was the target.

The following batch weights for a trial batch of 1 m^3 and laboratory scale are given: When the mix given in Table 8.6A, was carried out, the workability found was less and extra water of 0.5 kg was added to suit the workability requirement. Add 0.5 to 4.125 kg in the batch sheet and increase quantity of water by converting 0.5 kg of water for 25 L to 1 m^3 (0.5/0.025 = 20)

TABLE 8.6A

Batchweights for Laboratory Test of Concrete Mix

Material	SSD Weights (for 1 m^3) (kg)	Moisture Absorption	Moisture Content	Natural Condition Weights (for 1 m^3) (kg)	Lab Trial Scale Weights (for 25 L)
Cement	375			375	9.375
Water	146			165	4.125
20 mm	865	1%	0.40%	860	21.5
10 mm	514	1.20%	0.50%	510	12.75
Fine Aggregate	545	4%	2.10%	535	13.38
Admixture	4.1			4.1	0.1025

and adding it to make it 185 kg. But the entire trial batch done was for 25 L, and when the 0.5 kg of water was added, the batch size increased to 25.5 L (assuming water density as 1000 kg/m^3). Thus, it is advisable to not just increase the water but also to correct all other batch weights in the mix. It is even better to correct the mix as per the actual density of the corrected mix, as done in Section 5.2.1.

Right now we will look into the batch correction and accordingly the mix for 1 m^3, and not for the actual compaction.

The calculation in Table 8.6C has been done to back-calculate per cubic metre weights of materials from actually used weights for conducting the trials. Now in Table 8.6A batch weights for 25 L were calculated by multiplying each weight by 0.025. Assuming that these weights when mixed and compacted will actually yield 25 L volume, by adding 0.5 kg water to this, the volume of this mix will increase to 25.5 L. Also the weight of water will become 4.625. Now dividing each weight of the batch by 0.0255, weights for 1 m^3 of concrete are achieved, which has been included in the third column of the table. These weights are in natural condition, so that when mixed and compacted, they will form 1 m^3 of concrete. But now these weights need to be converted to SSD weights from the available data of moisture absorption and content.

The mix can also be corrected for 1 m^3 by checking the actual density of concrete when tested in the laboratory, after water is mixed, and maintaining the same proportion of materials to get total weight equal to the measured density of concrete. So for example, the density of the same concrete was measured (Table 8.4) after adding 0.5 kg water, and it was 2380 kg/m^3. Thus, increase the materials in the mix to get exactly the same interportion as the batch trial weight and a total of 2380 kg (Table 8.6B).

The total of weights of materials in batch is 61.733 kg and this needs to be increased to 2380, so each weight needs to be multiplied by factor equal to 2380/61.733 = 38.553.

TABLE 8.6B

Correction of Concrete Mix for the Actual Density

Material	Lab Trial Scale Weights	Eq 1 m^3 Weights (Natural Condition)	Absorption	Content	Equivalent SSD Weights
Cement	9.375	361			361
Water	4.625	178			160
20 mm	21.5	829	1%	0.40%	834
10 mm	12.75	492	1.20%	0.50%	495
Fine Aggregate	13.38	516	4%	2.10%	525
Admixture	0.1025	3.952			3.952
Total		2380	Total		2380

SSD = saturated-surface dry.

TABLE 8.6C

Correction of Concrete Mix to Accommodate the Extra Water Added into Concrete

Material	Lab Trial Scale Weights	Eq 1 m^3 Weights (Natural Condition)	Absorption	Content	Equivalent SSD Weights
Cement	9.375	368			368
Water	4.625	181			163
20 mm	21.5	843	1%	0.40%	848
10 mm	12.75	500	1.20%	0.50%	503
Fine Aggregate	13.38	525	4%	2.10%	534
Admixture	0.1025	4.020			4.020

SSD, saturated-surface dry.

NOTE: These corrections may seem not necessary, but they provide good pointers when concrete trial results are not as expected. These adjustments will also ensure the economy of mixes and accuracy of the volume of concrete produced and compacted. The compaction degree is not always the same, and it never is close to the theoretical values (assumptions of entrapped air or entrained air); thereby, adjustments and calibration of mixes become imperative.

Another way of correcting this mix is by dividing each material weight by its specific gravity (in SSD condition), finding its absolute volume and the total volume of the mix, followed by finding the factor to convert this volume to 1 m^3 or a standard volume with an assumed percentage of air.

8.4 Deciding Water-Reducing Admixture Dosage

The question of deciding the admixture dosage has intrigued many concrete technologists but has only left them baffled for its most optimum or perfect content into the concrete it is used. To get the answer to this question, a few properties of water-reducing admixtures need to be understood.

1) Water-reducing admixtures reduce the thickness (thixotropy) of the cement paste, meaning just the cement and water paste, (not the entire concrete as it may appear visually). 2) For concretes of higher water cement ratios, proportionately lesser water-reducing admixture is required to get the same consistency as that required for concretes with lower water cement ratio with same cement and admixture. In other words, the percentage of admixture required of cement content in concretes with lower water cement ratios is higher than the percentage admixture required for higher water cement ratios. 3) The thixotropy keeps on decreasing with increasing the water-reducing admixture dosage up to the capacity of admixture, and beyond

that, further admixture dosage does not reduce the thixotropy. 4) Water-reducing admixture dosage beyond a certain point may lead to the delayed setting of concrete. 5) Higher water-reducing admixture dosage reduces the thixotropy, and additionally, it increases the strength too of the concrete despite the same water cement ratio; This is due to better compaction (particle packing) of concrete as compared to concrete with the same water cement ratio but higher thixotropy of cement paste. 6) The other admixture used for manufacturing concrete is the retarder (usually when we talk of water-reducing cum retaining type admixtures, they are mixtures of retarders and water-reducing admixtures), which helps in retaining the workability for a longer time. Retarders help in retaining the workability, but they reduce the early age strength of concrete, and if their dosage is kept within limits, they do not affect the later-age strengths. Thus, depending on the requirement of concrete performance, of early age strength, and retention time of workability, a balance is struck between water-reducing and retarding admixtures.

At high water cement ratios, concrete looks wet and may also have a workability with a slump of up to 40 mm, for which the admixture dosage required is less. Hence, for higher workability concretes, the water content must be enough to at least have a control slump (workability without admixture addition) of 10 mm or something in which concrete is wet. At lower water cement ratios, the mix usually looks dry without admixture. Here, a high range water-reducing agent is needed that makes the concrete fluid from a dry state. The admixture should be dosed into the mix slowly and patiently and observed for increment in flowability in the mix if any (for trials during the mix-proportioning stage). With every increment of water-reducing admixture into the concrete, the fluidity of concrete will keep on increasing. Continue adding the admixture until the desired flow or workability is achieved. In case the highest recommended dosage of admixture into the concrete is exceeded, despite not getting the desired workability, in such cases, the water content into the concrete will need to be increased. Once the concrete property seems to be fine for usability, the admixture dosage should be recorded and will form the basis for mix proportion. Also, many at times when retention of concrete workability is desired for longer durations, the admixture added initially may not seem to hold the workability for a longer duration, in such cases add additional admixture whenever the workability is reduced below the required level. The total amount of admixture added into concrete (even in splits) will eventually be very close to the total admixture required in the first instance to get the workability performance in terms of duration.

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