# PART III. CONCRETE MIX DESIGN

CEMENT CONCRETE
& AGGREGATES AUSTRALIA

## CONTENTS



## 1. OUTLINE

The selection of concrete mix constituents and their proportions is commonly referred to as 'Mix Design'. In Part II of this Guide the various constituents of concrete, their properties and their specification have been discussed. In Part IV of this Guide the various specifications for concrete in Australia are discussed and how some of the specifications will have an impact on a suitable concrete mix design for supply to a given structure during construction. In addition, Part VIII of this Guide also discusses the properties of concrete and how specified concrete properties and quality assurance have an influence on the required concrete mix design.

In this part, the process of concrete mix design is outlined and various methods of carrying out mix design are highlighted. The impact on concrete mix design of specified concrete properties, the influence of Australian Standards, constituent material selection and construction methods are each discussed.

## 2. THE MIX DESIGN PROCESS

### 2.1 GENERAL

The process of concrete mix design requires two key starting points. The first point is a specified concrete for supply to a given structure. The second point, which may be influenced by the first, is the concrete will be produced from a combination of constituents that will need to be selected prior to a mix design taking place.

The process for mix design is often an iterative one where various concrete mix constituents are assessed through the mix design and testing process in order to determine the most effective constituent combination to achieve the specified properties of the required concrete mix.

In Australia the two key documents used to specify the minimum requirements for concrete used in concrete structures are AS 3600 *'Concrete structures'* [1] and AS 1379 *'Specification and supply of concrete'* [2]. The requirements of these Standards are discussed in Part IV of this Guide but it should be pointed out that using AS 1379, a structural designer may choose to specify a Special-Class concrete with requirements that exceed the minimum requirements set out in these Standards.

### 2.2 COMMON MIX SPECIFICATION REQUIREMENTS

For 'Normal-Class' concrete, as specified in AS 1379, the key properties of the concrete and its constituents are the following:

- Characteristic compressive strength set out in Table 1.1 of AS 1379 (MPa);

- Maximum aggregate size (either of 10 mm, 14 mm or 20 mm);
- Target slump of concrete at delivery (from 20 mm to 120 mm in 10 mm increments);
- Method of placement of concrete into forms (e.g. pumping of concrete, direct feed from delivery vehicle etc.);
- Proportion of air entrainment (as a % of the volume of concrete up to a maximum of 5% if required).

In addition, there are assumed properties for 'Normal-Class' concrete that are set out in AS 1379 including:

- Selection of mix constituents complying with their relevant Australian Standards (set out in Part II of this Guide);
- Specification of Project Assessment testing on site if required;
- A concrete mass per unit volume between 2,100 kg/m$^3$ and 2,800 kg/m$^3$;
- Acid soluble chloride and sulfate contents of concrete in accordance with limits set out in AS 1379;
- Concrete drying shrinkage not greater than 1,000 micro-strain at 56 days;
- The mean compressive strength of concrete at 7-days curing is greater than the values given in Table 1.2 of AS 1379;
- No lightweight aggregate as defined in AS 2758.1;
- Volume of concrete supplied is in accordance with Clause 1.7.2 of AS 1379.

AS 3600 assumes certain durability classifications for concrete are satisfied by achieving a minimum characteristic strength of concrete but the Normal-Class concrete mix design may not meet the AS 3600 durability classifications unless the aggregates used in the concrete mix also comply with AS 2758.1 [3] requirements for the specified durability class of concrete. It is for this reason that concrete designed to meet AS 3600 exposure classifications B2, C1, C2 or U is deemed to be 'Special Class' under AS 1379. Any specification requirements other than those for 'Normal-Class' concrete as defined in the foregoing will indicate the concrete is 'Special Class' as defined in AS 1379 and the specifier will be responsible for defining the additional or modified requirements as required by AS 1379 clause 1.5.4 and Appendix B.

Some common examples of Special-Class specification include:

- Early strength requirements for concrete (e.g. 32 MPa at 24 hours);
- Lower maximum shrinkage requirements (e.g. 600 micro-strain at 56 days);
- Minimum cement content of a mix (e.g. 32 MPa at 28 days with a minimum cement content of 400 kg/m$^3$);
- Maximum Water/Cement ratio (W/C) requirement (e.g. 32 MPa with maximum W/C ratio of 0.45);
- Specifier details a mix proportion to be used in a mix design;
- Mix to achieve a nominated characteristic flexural tensile strength;
- Mix to have a slump spread of 650 mm.

Each of these Special-Class requirements will most likely prevent a Normal-Class concrete from being used. To comply with AS 3600 minimum strength for durability in exposure classifications B2, C1, C2 or U and with AS 2758.1 aggregate properties for these exposure classifications, the concrete supplier will need to design a Special-Class mix to meet the special requirements. The specifier will also need to be very careful to fully specify all of the requirements in each of the examples of Special-Class concrete as well as a means of assuring compliance of the concrete.

For more information on standards and specification of concrete it is recommended to see Part IV, Section 8 of this Guide as well as the referenced Australian Standards.

## 2.3 MIX DESIGN STEPS

There are many different mix design methods used. In reality, the number of mix design methods is probably close to the number of 'concrete technologists' working in the concrete construction industry. Some methods are based on computer-based systems and some methods are more manual. All are useful in their own way if they support the user in developing mix designs in a rapid and accurate way. In this section two of the more manual methods are referred to as they provide a better understanding of the principles involved.

In all methods the process followed should contain the following steps:

1. Analysing the desired outcome from the specifications for the concrete mix;
2. Checking the specifications against the minimum requirements of relevant Standards;
3. Considering the mixing and placing methods;
4. Choosing constituent combinations that will support the desired outcome;
5. Doing a theoretical mix design using a suitable method;
6. Undertaking laboratory trials of the mix and making adjustments to the mix to ensure it meets specified properties;
7. Undertaking field trials and making any required further adjustments to mix design to cope with site requirements.

Some of these steps are an iterative process and may be repeated a number of times to get to the final result. In Step 5 – the mix proportioning aspect of mix design – there is one thing that is common to all mix methods and that is the need to estimate the mix paste content. This involves the estimation of each of the following:

- The water content;
- The binder (cement + SCM) content;
- The entrained air content.

Estimating these three quantities – those that form the paste portion of mix – is normally related to consideration of the specified or inferred strength and durability requirements. These three factors are also influenced by the consistency of the concrete (typically specified by target slump), coarse and fine aggregate selection (type, size and shape) and the admixture selection.

The paste makeup and volume can be estimated using tools derived from past experience using the following steps:

(a) Use the specified slump and maximum aggregate size of the concrete to estimate the water content of the mix based on suitable charts. Some more computer-based tools use estimation of total mix packing density algorithms to estimate mix water content at a specified consistency and air content;
(b) From the specified maximum W/C ratio a minimum cement (or cement + SCM) content of the mix can be determined to achieve this W/C ratio;
(c) From the specified characteristic strength of the concrete the minimum target strength of the concrete can be determined so as to take account of variability in the production and testing processes. From the minimum target strength of the concrete a W/C ratio versus average concrete strength chart for the cement blend used can be used to determine the maximum W/C ratio to achieve the characteristic strength specified. From this maximum W/C ratio a minimum cement (or Cement + SCM) content of the mix can be determined to achieve this W/C ratio;
(d) The greater cement (or cement + SCM) content as determined in steps (b) and (c) is used as the content for the initial mix design;
(e) If the mix air content is specified, then this volume of air is used in the mix design. If it is not specified, then the typical air content will be estimated based on maximum aggregate size and admixtures used;
(f) The volume of paste is now estimated and is simply the volumes of water + cement + SCM + air.

Having estimated the volume of paste, the remaining volume of the mix is entirely composed of coarse and fine aggregates. The general principle is that a unit volume (e.g. 1.00 $m^3$) of concrete is being designed. Based on this, if the paste volume is estimated to be 0.30 $m^3$, then the solid volume of coarse and fine aggregates will be 0.70 $m^3$.

Methods for determining the proportions of individual aggregates vary significantly, and the proportions can be impacted by the maximum size of aggregate, binder content and specified consistency. This is a more complex part of the mix design process, but the end result is a table of theoretical mix design components for testing, assessment and correction (**Table III.1**).

The following provides further detailed information on methods commonly used in building up the theoretical mix design based on the foregoing.

## 2.4 CHARACTERISTIC STRENGTH AND TARGET STRENGTH

Compressive strength is one of the most important properties of concrete. A number of other properties of concrete, such as durability, tensile strength, elastic modulus and creep factor are to some degree related to the compressive strength of concrete.

*Table III.1 – Example of Theoretical Mix Design Table*

| **Materials** | **1.0 m³ Batch Weights** |
|---|---|
| Cement | 210 kg |
| Fly Ash | 70 kg |
| Total Free Water | 170 litres |
| 20 mm Aggregate | 680 kg |
| 10 mm Aggregate | 340 kg |
| Coarse Sand | 530 kg |
| Fine Sand | 300 kg |
| Air Entraining Admixture | 80 mL/m³ |
| Water Reducing Admixture | 400 mL/100 kg cement |
| Target Entrained Air Content | 4% ± tolerance |
| Target Slump | 80 mm ± tolerance |

Australian Standards AS 3600 and AS 1379 and most international concrete standards specify a concrete using its ‘characteristic compressive strength’. The characteristic strength is defined by a statistical approximation which is stated in these Standards as follows:

*‘Value of the material strength, as assessed by standard test that is exceeded by 95% of the material’.*

This means that at least 95% of all standard compressive strength tests taken on a given mix design concrete will exceed the characteristic compressive strength (assuming that the concrete supplier has a very large number of tests to make that assessment). The reality is that the concrete supplier rarely has such a large number of tests to carry out this assessment and because of this fact AS 1379 provides a range of assessments based on satisfying both supplier risk and consumer risk, using statistical principles to assess smaller numbers of tests for compliance to the requirement for a particular characteristic strength.

More information on this is provided in Part IV, Section 8 of this Guide as well as in AS 1379 and its Supplement 1 document [4].

If the statistical principle applicable to characteristic strength is applied, assuming that the compressive strength test data randomly follows what is called a ‘normal distribution’, then it is reasonable to assume that the expected average strength of this large number of tests will exceed the characteristic strength (F’c) by a factor that is dependent on the variability of the set of tests assessed. This variability factor is calculated using a statistical formula and is generally referred to as the ‘standard deviation’ (SD) of the test sample population. The general formula relating F’c, SD and average strength is simply:

$$F'c = \textit{Average Strength} - k \times SD \quad \textbf{.....Eq.III.1}$$

In this formula ‘k’ is a constant that is statistically derived and depends on the number of test samples used to calculate the average strength and standard deviation. Aspects of these calculations as they relate to AS 1379 are covered in more detail in Part IV, Section 8 and Part VIII, Section 26 of this Guide.

When carrying out a mix design and generally when setting up quality control systems for the compressive strength of concrete, the mix designer uses a strength that is referred to as the 'Target Strength' of the concrete mix being designed or supplied. It is different from both the characteristic strength and the average strength of the test sample population. In general, its value is more an 'intended' average strength for the mix design and in general it will be either equal to or greater than the average compressive strength. To calculate the Target Strength the following simple formula is used:

*Target strength* $\geq$ *F'c + (k × SD)* …..**Eq.III.2**

From this formula it can be seen that provided a reasonable value of SD is made and that F'c is specified then an estimate of Target Strength can be made. For the purpose of mix design and using the definition of characteristic strength defined in AS 3600 and AS 1379 (assuming a very large population of test results) it can be shown that the constant k = 1.65 (approximately).

The SD of a concrete mix is a measure of variability of the concrete compressive strength test results and is dependent on both materials and manufacturing variables, including:

- Variability in cement and SCM quality;
- Variability in coarse and fine aggregate quality;
- Variability in admixture quality;
- Variability of batching accuracy at the concrete manufacture facility;
- Impact of varying ambient temperatures during and after manufacture of the concrete mix;
- Variability in mixing of the concrete mix during production;
- Variability in time from batching to placement and testing of the concrete mix;
- Variability in the testing procedures used to assess the concrete over time;
- The strength of the concrete mix being assessed.

A concrete supplier with a well-controlled quality management system will be able to actively reduce the concrete mix supply variability and SD but if no reliable data is available then **Table III.2** provides some guidance of SD values that can be used in a preliminary mix design.

Using data from **Table III.2** for a concrete with specified characteristic strength of 40 MPa, the minimum target strength can be calculated using **Eq.III.2** as being approximately 46.4 MPa.

*Table III.2 – Approximate Standard Deviation for Mix Design*

| **Standard Deviations for concrete where no data is available** | |
|---|---|
| **Characteristic Strength (MPa)** | **Approximate Standard Deviation (MPa)** |
| 20 | 3.0 |
| 25 | 3.3 |
| 32 | 3.6 |
| 40 | 3.9 |
| 50 | 4.2 |

## 2.5 W/C RATIO AND TARGET STRENGTH

In 1919, concrete technologist and researcher Duff Abrams noted a relationship between the average strength of a concrete mixture and its water/cement ratio and he created a mathematical formula to describe the relationship. In general, this relationship is dependent on the particular cement and aggregate properties but indicates that for a particular set of materials the higher the W/C ratio is, then the lower the strength will be. Since Abrams there have been numerous researchers on this topic and more detailed formulae have been produced. No single formula will work universally for all materials as variation in constituents will require a variation in the relationship.

Cement and concrete suppliers will develop their own formulae for specific blends of materials. Some typical examples are given in graphs for two types of cement blends in **Figure III.1** and **Figure III.2**. While characteristic strength in AS 3600 normally refers to the 28-day strength, these graphs do demonstrate the range of average strengths at other ages that may be specified for mix designs. In some cases, the early age strength is specified as a characteristic strength. In this case a suitable Target Strength at the early age must be estimated in the same way as would be done for the standard 28-day characteristic strength.

In the mix design process, a characteristic compressive strength is specified at 28 days. The Target Strength of the concrete is estimated as noted in sub-section 2.4 and, using the Target Strength and a formula (such as that graphed in **Figures III.1** and **III.2**), the average W/C ratio can be estimated for the mix design.

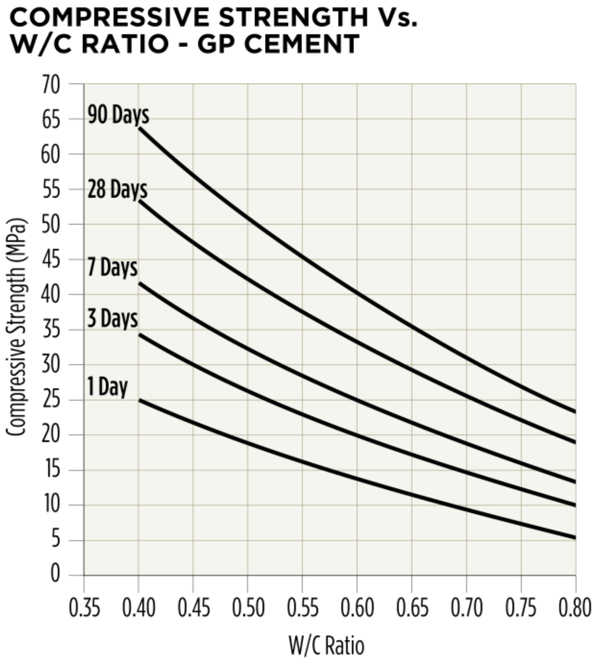


*Figure III.1 – W/C Vs. Strength Curves for GP Cement*

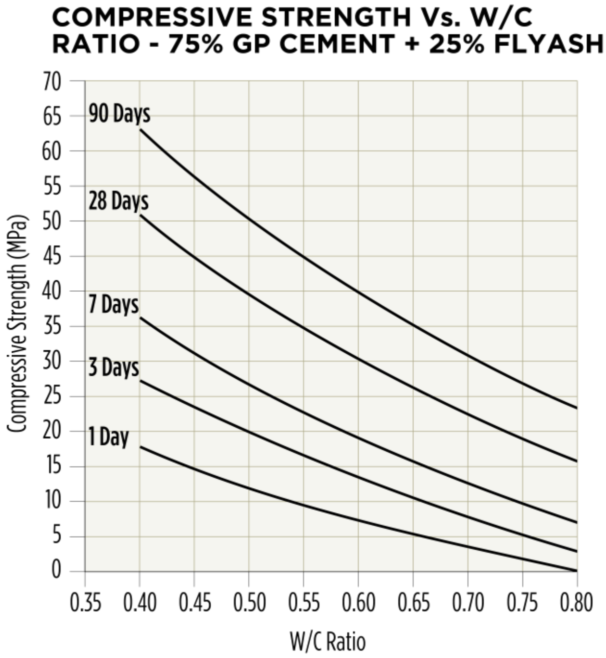


*Figure III.2 – W/C Vs. Strength Curves for a Blend of 75% GP Cement with 25% Fly Ash*

## 2.6 ESTIMATING WATER DEMAND

The total water content of any concrete mix is affected by any (or all) of the following factors:

- Consistency or slump of concrete;
- The maximum aggregate size of the concrete mix;
- The properties of the coarse and fine aggregate that affect the packing of aggregate (e.g. shape and surface texture);
- Silt and clay fines in the fine and coarse aggregate;
- Admixtures used in the concrete;
- The type of cement and SCM used;
- The air content of the concrete mix;
- The volume of cement plus SCM's in the mix;
- The ambient and concrete temperature as well as the time of the concrete delivery from mixing to delivery on site.

When designing a concrete mix, it is necessary to take account of all of these factors.

The 'water content' in concrete is normally calculated as the volume of water added to the concrete plus the water contained in the coarse and fine aggregates in excess of that required to produce a saturated surface dry (SSD) condition plus the water content in the admixtures used. This quantity of water is more correctly referred to as 'Total Mix Water' and is the volume of water used to calculate W/C ratio.

ACI 211.1 [4] provides some useful approximate estimates of the total water content of concrete for differing maximum aggregate sizes and slumps. A selection of this information is reprinted in **Table III.3**.

As can be seen in **Table III.3**, the total water content of concrete is significantly reduced by increasing the maximum aggregate size or reducing the concrete slump. While ACI 211.1 does consider the impact of air entrainment on the total water content it does assume a mix design in accordance with this Standard but does not allow for the effects of admixtures, significant variance in cement content or the properties of the aggregates.

Air entrained in concrete can partially replace some of the volume of total water at the same consistency. ACI 211.1 does discuss this impact and it is discussed further in sub-section 2.7.

*Table III.3 – Estimate of Water Content of Concrete Mixes with Different Maximum Aggregate Size & Slump (based on ACI 211.1)*

| **Max. aggregate size (mm)** | **Water content of non-air entrained concrete** | | |
|---|---|---|---|
| | **Average slump (mm)** | | |
| | **40 mm** | **90 mm** | **160 mm** |
| 9.5 | 207 | 228 | 243 |
| 12.5 | 199 | 216 | 228 |
| 19 | 190 | 205 | 216 |
| 25 | 179 | 181 | 202 |
| 37.5 | 166 | 169 | 190 |
| 50 | 154 | 160 | 178 |
| 75 | 130 | 145 | 160 |

Admixtures used in concrete may have a significant effect on the mix design total water content. Admixtures are discussed in detail in Part II, Section 5 of this Guide. In the case of water-reducing, mid-range water-reducing and high-range water-reducing admixtures the mix total water content can be reduced by between 5% and 25% depending on the specific admixture or admixture combination used. Admixture suppliers can provide data on the effectiveness of their products.

For example, a mix design using 19 mm maximum sized aggregate and a 90 mm target slump will have a design water content of approximately 205 Litres/$m^3$ without admixtures of any type (refer to **Table III.3**). If a mid-range water reducing admixture with a demonstrated water reducing ability of 10% is used in the mix, then approximately 20 Litre/$m^3$ of water can be taken out of this mix giving a revised water content of 185 Litres/$m^3$.

## 2.7 ESTIMATING AIR CONTENT

Air occurs in concrete in two forms:

- Naturally entrapped air (typically ranging from 0.2% to 3.0% in general);
- Specifically, entrained air produced by the actions of admixtures including air entraining admixtures (AEA).

Both forms of air are part of concrete mix volume but may have differing impacts on the concrete workability and consistency as well as having different air bubble sizes.

Entrained air will generally have the following properties in a plastic concrete mix:

- It may improve the workability of concrete at the same consistency;
- It can replace an amount of the design water in the plastic concrete mix at the same consistency;
- It increases the volume (yield) of the concrete mix.

In the concrete hardened state entrained air is most useful in protecting against freeze-thaw damage in exposed concrete structures. AS 3600 specifies entrained air contents (that vary with maximum sized aggregates used) that are necessary to provide a level of freeze-thaw durability. These percentages of entrained air are:

- For 10 mm to 20 mm maximum sized aggregate – use between 4% and 8% entrained air;
- For 40 mm maximum sized aggregate – use between 3% and 6% entrained air.

ACI 211.1 also gives similar advice for freeze-thaw protection but notes that the design air content, for what AS 1379 describes as Normal-Class concrete, can benefit workability by adding some air entrainment over the naturally entrapped air content. This gives the mix designer the ability to selectively design for extra air to a mix where lower cement contents are used. The ACI 211.1 recommendations are summarised in **Table III.4**.

The effectiveness of air entrainment on reducing the total water content of concrete varies with the amount of air entrained (as opposed to entrapped air). In the design air contents suggested by ACI 211.1 in **Table III.4**, it can be seen that for each maximum aggregate size the added entrained air for improved workability is around 1.5% air. In **Table III.5** the likely water reduction for 1.5% and 3.0% added entrained air is estimated for a range of W/C ratio concrete mixes.

*Table II.4 – Design Air Contents for Normal Concrete*

| **ACI 211.1 Recommended total Air Content** | | |
|---|---|---|
| **Maximum Aggregate Size (mm)** | **Design Entrapped Air (%)** | **Total Air Content for improved Workability (%)** |
| 9.5 | 3.0 | 4.5 |
| 12.5 | 2.5 | 4.0 |
| 19 | 2.0 | 3.5 |
| 25 | 1.5 | 3.0 |
| 37.5 | 1.0 | 2.5 |
| 50 | 0.5 | 2.0 |
| 75 | 0.3 | 1.5 |

From **Table III.5** the estimate for the design total water reduction due to entraining 3.0% air in a mix with a calculated design W/C ratio of 0.50 would be 9 litres per $m^3$ less than that estimated in using **Table III.3** and before the impacts of any other admixtures on total water content reduction are accounted for.

*Table III.5 – Impact of Entrained Air on Mix Total Water*

| **Water Reduction for Design Air Content** | | |
|---|---|---|
| **Concrete W/C Ratio** | **1.5% Entrained Air (Litre/m$^3$)** | **3.0% Entrained Air (Litre/m$^3$)** |
| 0.80 | 15 | 25 |
| 0.70 | 12 | 20 |
| 0.60 | 9 | 15 |
| 0.50 | 5 | 9 |
| 0.40 | 2 | 4 |

## 2.8 ESTIMATING THE VOLUME OF A CONCRETE MIX CONSTITUENTS

A key principle in mix design is that the aim of combining a set of concrete ingredients is to produce a total volume of concrete equal to 1.000 $m^3$ as noted in sub-section 2.3. The addition of the volume of all constituents added to concrete in a concrete mix design should equal 1.000 $m^3$ if correctly designed. The calculation of the volume of each constituent group in the concrete mix is normally estimated by slightly varying rules. In terms of calculation method, the groups of constituents with common methods of estimating their volume are:

- Cement and SCMs;
- Coarse and fine aggregates;
- Water and liquid admixtures;
- Dry additives including fibres.

The method for calculating the volume of each of these four groups is discussed in the following sub-sections.

***Cement and SCM Volumes***

Cement and SCM's are normally produced in the form of essentially dry powders. Their solid volume in the concrete mix is estimated by dividing their proposed dry mass (normally in kg) by the tested value of the individual cement or SCM particle density (in kg/m$^3$).

The particle density of this group of materials is commonly provided by the supplier in the form of a 'specific gravity' or SG which is the particle density relative to water. For example, GP cement in Australia will typically have an SG of between 3.12 and 3.16 and a value of 3.15 is used in mix design. To convert the SG to kg/m$^3$ is simply multiply the SG by 1,000 (the density of water at 23ºC). In this case the particle density of the GP Cement becomes 3,150 kg/m$^3$. So, where a mix contains (for example) 350 kg of GP Cement, its volume in the concrete mix equals 350/3,150 = 0.111 m$^3$.

SCM's such as fly ash, ground granulated blast furnace slag or silica fume generally have lower particle densities than cement and the supplier will be able to provide the mix designer with the SG or particle density values specific to each particular product.

***Coarse and Fine Aggregate Volumes***

Aggregates are generally separated into the specific sizes supplied. A concrete mix may, for example, contain 20 mm aggregate, 10 mm aggregate, manufactured coarse sand and fine natural sand. Each of these four aggregate constituents have in common the fact that that they will absorb water and are generally designed in the concrete mix in saturated surface dry ('SSD') condition. When estimating each constituent's volume in the concrete mix the mass of the aggregate is estimated in SSD condition and the volume estimated by dividing the SSD Mass of aggregate by the SSD Particle Density of the aggregate.

For example, consider a concrete mix contains 750 kg of SSD 20 mm Limestone aggregate. This limestone aggregate has an SSD particle density of 2,700 kg/m$^3$ so the volume of 20 mm Limestone in the mix equals 750/2,700 = 0.278 m$^3$.

***Water and Liquid Admixture Volumes***

Water is generally measured into concrete in litres or kg (1 litre of water has a mass of approximately 1 kg) depending on the method of batching in a concrete plant. One cubic metre of water is 1,000 litres so if 200 litres of water is added to a concrete mix then its volume is 200/100 = 0.200 m$^3$. Water in concrete includes water contained in aggregates in excess of SSD condition. When carrying out batching of concrete aggregates that are not SSD condition, then the net excess water above or below SSD condition needs to be added into the total water and its volume estimated.

Liquid admixtures are either weighed into concrete or more commonly measured by volume. Admixtures are commonly batched as a proportion of the concrete mix cement and SCM mass (mL per 100 kg of binder) or by volume per cubic metre of concrete (mL or litres per m$^3$ of concrete). Admixture suppliers provide information on the density or SG of specific admixtures so their volume is simply calculated if batched by mass (e.g. if an admixture is batched as 400 gm per 100 kg of cement and its SG is 1.12 then simply dividing 400 by 1.12 = 357 mL per 100 kg of cement).

Admixtures are generally (but not always) a relatively small volume in the concrete mix but should not be ignored in calculations.

***Dry Additives and Fibre Volumes***

The suppliers of these products generally pre-package these products into pre-weighed packages suitable for batching and can provide details of the SG or particle density of the specific products.

The same procedure will be followed for estimating their volume as is used for cement and SCM materials (i.e. the materials are assumed to be essentially dry and their dry particle density is used to calculate the volume for a specific mass of product dosed).

## 2.9 BLENDING AGGREGATES

The stage in mix design where aggregates are blended to provide an optimal proportioning is where there are real differences in the many manual mix design methods used. In this section the ACI 211.1 method and the British method developed by the Road Research Laboratory (Road Note No. 4 *'Design of concrete mixes'*) [5] are discussed as they take differing but workable methods to produce a preliminary mix design.

In the previous sections methods for calculating the paste content of a concrete mix design have been discussed along with some methods of estimating the mass and volume of the individual components of a concrete paste. If the total volume of paste plus any additional solid additives was, for example, 0.300 $m^3$ then the remaining volume in a 1.000 $m^3$ concrete mix will be composed of aggregates with a volume of 0.700 $m^3$ (i.e. 1.000 – 0.300).

Both methods for blending coarse and fine aggregates discussed in this section are aimed at producing a preliminary concrete mix design with suitable workability, which requires an understanding of three of the standard aggregate tests:

- The particle size distribution or 'grading' of each individual coarse and fine aggregate as well as the 'combined grading' of the blends of coarse and fine aggregates;
- The particle density and water absorption of each of the individual coarse and fine aggregates;
- The bulk density of oven dry aggregate for each of the individual coarse and fine aggregate used as well as for blends of coarse or fine aggregates.

These three aggregate properties have been discussed in Part II, Section 3 of this Guide.

The two methods of blending aggregates are discussed in the following sub sections.

***The ACI 211.1 Method***

In this method, the ACI have recognised two aspects that are apparent from particle packing analysis. The first aspect is that the larger the maximum size aggregate used, the lower the proportion of fine aggregate that will be needed to produce an optimal blend in terms of particle packing. The second aspect is that the finer the fine aggregate is, the greater the portion of coarse aggregate will be needed to produce a similar workability as it reduces the spacing required between coarse aggregate particles in the concrete mix.

As provided in **Table III.6**, the basis of this design is to firstly select a maximum size of aggregate used, and (a) if the aggregate needs to be blended with a smaller size aggregate then an optimal blended grading of the aggregates is determined by achieving a blend that complies with the 'maximum aggregate size to 4.75 mm' sieve grading in ASTM C33 [8] which is similar to those for Nominal size 'graded aggregates' in AS 2758.1 (and repeated in Part II, Section 3 of this Guide), and (b) the blended aggregate should be assessed for oven dry, compacted bulk density ('dry rodded' as per ASTM C29 [7], which is similar to Australian Standard AS 1141.4 [6] in oven dry and compacted condition).

*Table III.6 – Volume of Coarse Aggregate per Unit Volume of Concrete (SI units) (replication of ACI 211.1 – Table A1.5.3.3)*

| **Nominal maximum size of aggregate (mm)** | **Volume of dry-rodded coarse aggregate* per unit volume of concrete for different Fineness Moduli** of fine aggregate** | | | |
|---|---|---|---|---|
| | **2.40** | **2.60** | **2.80** | **3.00** |
| 9.5 | 0.50 | 0.48 | 0.46 | 0.44 |
| 12.5 | 0.59 | 0.57 | 0.55 | 0.53 |
| 19 | 0.66 | 0.64 | 0.62 | 0.60 |
| 25 | 0.71 | 0.69 | 0.67 | 0.65 |
| 37.5 | 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 |

***NOTE****:*

**Volumes are based on aggregates in dry-rodded condition as described in ASTM C 29. These volumes are selected from empirical relationships to produce concrete with a degree of workability suitable for usual reinforced construction. For less workable concrete such as required for concrete pavement construction they may be increased about 10%. For more workable concrete, such as may sometimes be required when placement is to be by pumping, they may be reduced up to 10%.*

***See ASTM Method 136 for calculation of Fineness Modulus.*

If more than one fine aggregate is being used then either (a) a suitable blend of fine aggregates is selected to achieve a Fineness Modulus between 2.4 and 3.0 or (b) a combined grading is selected to meet the grading requirements of ASTM C33 [8].

*[**NOTE**: The Fineness Modulus of sand is simply the percentage retained on consecutive sieve sizes (0.150 mm, 0.300 mm, 0.600 mm, 1.18 mm, 2.36 mm and 4.75 mm) added together and divided by 100 (see **Table III.7** for an example)].*

*Table III.7 – Fineness Modulus Calculation Example*

| **Calculating Fineness Modulus of Sand** | | | |
|---|---|---|---|
| **Sieve Size (mm)** | **Passing Sieve Size (%)** | **Retained Sieve Size (%)** | **Fineness Modulus Calculation** |
| 9.5 | 100 | 0 | 0 |
| 4.75 | 100 | 0 | 0 |
| 2.36 | 95 | 5 | 0.05 |
| 1.18 | 75 | 25 | 0.25 |
| 0.600 | 45 | 55 | 0.55 |
| 0.300 | 30 | 70 | 0.70 |
| 0.150 | 8 | 92 | 0.92 |
| 0.075 | 4.5 | 95.5 | N.A. |
| **TOTAL FINENESS MODULUS** | | | 2.47 |

It should be noted that the range of ASTM C33 particle sizes and related Fineness Moduli of sands in concrete for the USA are generally slightly coarser than those generally available in Australia for reasons of different climate and geology, but in most cases a blend of sands with a fineness modulus greater than 2.40 can be achieved.

When calculating the effect of blending two or more aggregates to assess the grading of the blend it is simply done by multiplying each aggregates grading percentage passing for each individual sieve size by the percentage of that aggregate in the blend. This calculation is best demonstrated in **Table III.8**. For example (from **Table III.8**) at the 13.2 mm sieve:

- 60% of 35% = 21% contribution to the blend for Aggregate A;
- 40% of 100% = 40% contribution to the blend for Aggregate B;
- The total of these two contributions is 61% passing the 13.2 mm sieve for the 60% A + 40% B blend.

*Table III.8 – Theoretical Grading of the Blend of Two Aggregates*

| **Calculating Blended Aggregate Grading** | | | |
|---|---|---|---|
| **Sieve Size (mm)** | **Grading Aggregate A (%)** | **Grading Aggregate B (%)** | **60% A + 40% B Calculation** |
| 26.5 | 100 | 100 | 100 |
| 19.0 | 95 | 100 | 97 |
| 13.2 | 35 | 100 | 61 |
| 9.5 | 10 | 85 | 40 |
| 4.75 | 2 | 8 | 4 |
| 2.36 | 1 | 2 | 1 |
| 1.18 | 0 | 0 | 0 |

Using **Table III.6** is best demonstrated with an example:

- Assuming that aggregate A and B in the **Table III.8** example are to be used in a concrete mix design and that the 60% Aggregate A + 40% Aggregate B blend has been assessed as having the following properties:
  – Particle size distribution of the blend as noted in **Table III.8**;
  – SSD Particle density of 2,700 kg/m$^3$ and water absorption of 1.0%;
  – Oven Dry compacted bulk density of 1,520 kg/m$^3$.

- In addition, it is to be blended into a concrete mix design with the sand used as an example in **Table III.7** which has the following properties:
  – Particle size distribution and Fineness Modulus as noted in **Table III.7**;
  – SSD Particle density of 2,550 kg/m$^3$ and water absorption of 2.0%.

- Then from **Table III.6** it can be estimated that the quantity of coarse aggregate blend in the concrete mix for a 19 mm nominal size aggregate with sand of FM = 2.47 is approximately 0.65 m$^3$ of compacted, oven dry aggregate per m$^3$ of concrete;
- So, the oven dry coarse aggregate blend is calculated by multiplying the bulk density (1,520 kg/m$^3$) by 0.65 = 988 kg of dry blended coarse aggregate per m$^3$ of concrete;
- This is converted to SSD condition by adding in the water absorbed (i.e. 1% of 988 kg = 10 kg), so the mass of SSD coarse aggregate in the concrete mix is equal to 988 kg + 10 kg = 998 kg of blended coarse aggregate;
- Based on the blend ratio nominated in **Table III.8** this calculates out at 60% of SSD Aggregate A = 599 kg and 40% of SSD Aggregate B = 399 kg;
- The remaining calculation is to calculate the fine aggregate content. As noted in the second paragraph of this section, the calculated total aggregate solid volume in this concrete mix was 0.700 m$^3$ per m$^3$ of concrete. The volume of blended coarse aggregate is simply the SSD mass divided by the SSD particle density = 998 kg / 2,700 kg/m$^3$ = 0.370 m$^3$;
- The fine aggregate volume is equal to 0.700 m$^3$ – 0.370 m$^3$ = 0.330 m$^3$. The SSD fine aggregate mass is calculated from this volume of fine aggregate by multiplying it by the SSD particle density of the fine aggregate = 0.330 m$^3$ × 2,550 kg/m$^3$ = 842 kg/m$^3$;
- The final Aggregate blend for this mix is:

  SSD Coarse Aggregate A: 599 kg;
  SSD Coarse Aggregate B: 399 kg;
  SSD Fine Aggregate: 842 kg.

***The British 'Road Note No. 4' Method***

This method blends the solid volume of aggregates to achieve a target grading of the combined coarse and fine aggregates based on a series of four 'preferred grading curves'. An example of these curves is given for a 20 mm maximum aggregate size concrete in **Figure III.3**.

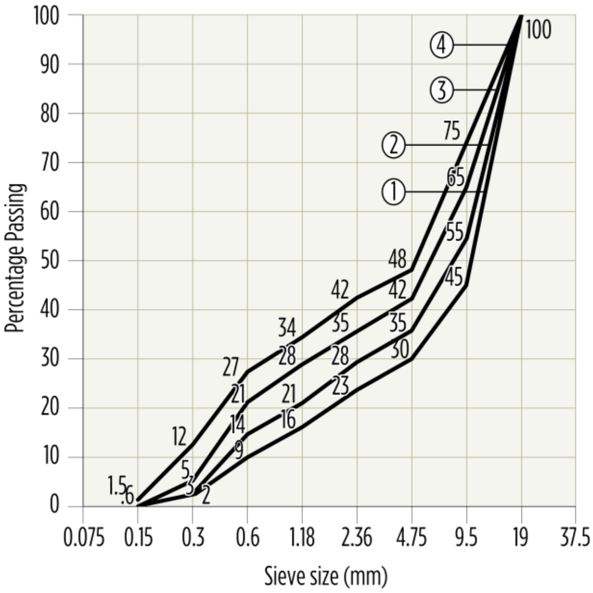


*Figure III.3 – Road Note No. 4 [5] – Target Grading for 20 mm Maximum Size Aggregate*

The four curves in **Figure III.3** numbered 1, 2, 3 and 4 need some care when applying them to general concrete. In the worked mix design example used in this section the volume of paste has been noted as being 0.300 m$^3$ per m$^3$ of concrete. This volume of paste reflects a concrete mix with approximate W/C ratio of 0.75 and associated lower cement content. Generally, it would be recommended to use grading curve number 4 (in **Figure III.3**). As the W/C ratio is reduced the most suitable target grading moves progressively to curves numbered 3 then 2 and finally to curve 1 as the W/C ratio drops to approximately 0.40 or below.

A worked example is carried out to demonstrate this method using the same aggregates as those nominated in the previous ACI 211.1 method worked example.

The method uses a volumetric grading and it is assumed that coarse aggregates A and B have identical SSD particle density as they are from the same source of aggregate. The blended coarse aggregate SSD particle density will therefore apply to both components.

To determine the blended coarse and fine aggregate grading a simple process, as demonstrated in the ACI 211.1 method (also **Table III.8**), is used except that three aggregates are blended in this case. The aim of the blending is to produce a combined grading with a 'best fit' to the target grading from **Figure III.3**.

The blending process is best demonstrated in a table form (see **Table III.9**). The values in **Table III.9** are the result of numerous iterations to achieve the best fit from the materials used, which in this case is 22.5% by volume of 'coarse aggregate A' + 31.9% by volume of 'coarse aggregate B' + 45.6% by volume of 'fine aggregate'. The total of the combined aggregate percentages must be 100.0%. It should be noted that the best fit is rarely a perfect fit and depends on the grading of individual component aggregates.

The result of this curve fitting can also be demonstrated in a graph form (**Figure III.4**).

**ACTUAL GRADING Vs. TARGET GRADING**

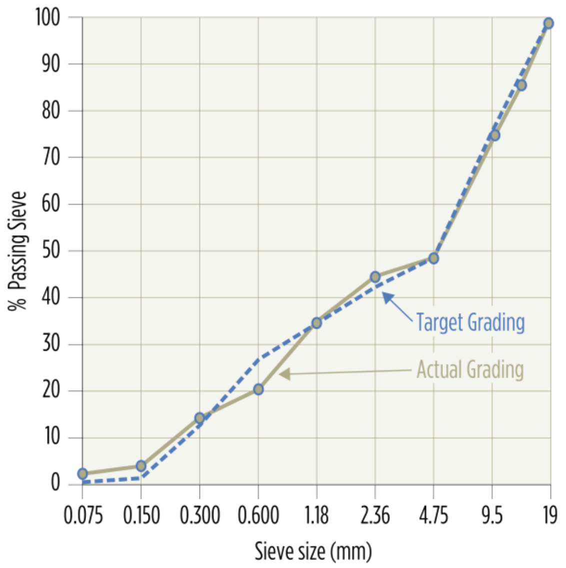


*Figure III.4 – Graph of Combined Aggregate Best Fit Grading versus Target Grading*

Having determined previously that the total volume of coarse and fine aggregates is equal to 0.700 m$^3$, it is a simple process to calculate the solid volume of each individual aggregate by multiplying the percentage of that aggregate in the 'best fit' blend by the total volume.

The solid volumes of each aggregate are calculated:

- Coarse Aggregate A: 0.700 m$^3$ × 22.5% = 0.158 m$^3$;
- Coarse Aggregate B: 0.700 m$^3$ × 31.9% = 0.223 m$^3$;
- Fine Aggregate: 0.700 m$^3$ × 45.6% = 0.319 m$^3$.

From these solid volumes the total SSD mass of each aggregate in a cubic metre of concrete can be estimated by multiplying the solid volume by the particular aggregate SSD particle density:

- Coarse Aggregate A: 0.158 m$^3$ × 2,700 kg/m$^3$ = 425 kg;
- Coarse Aggregate B: 0.223 m$^3$ × 2,700 kg/m$^3$ = 603 kg;
- Fine Aggregate: 0.31 m$^3$ × 2,550 kg/m$^3$ = 814 kg.

The final Aggregate blend for this mix is:

SSD Coarse Aggregate A: 425 kg;
SSD Coarse Aggregate B: 603 kg;
SSD Fine Aggregate: 814 kg.

It can be seen that these batch masses are slightly different to those estimated by the ACI 211.1. They have a greater quantity of coarse aggregate and less fine aggregate although the total mass of aggregate is almost the same.

Neither of the methods is 'right' or 'wrong' but in sub-section 3 the next steps taken from this theoretical mix design are explored.

# 3. ASSESSMENT OF A THEORETICAL MIX DESIGN

## 3.1 GENERAL

Steps 6 and 7 in sub-section 2.3 noted that the theoretical mix design must be assessed by laboratory trial mix and ultimately in a full-scale field trial before the mix is accepted for general supply.

The key properties of concrete that need to be assessed are split into two parts:

- Plastic properties of concrete;
- Hardened properties of concrete.

The final mix design accepted for supply will generally be adjusted from the original theoretical design mix through the trial mix program. This step is critical in the overall mix design process.

*Table III.9 – Combined Aggregate Best Fit Grading*

| Sieve size (mm) | Concrete aggregate grading | | | Blend grading | Target grading (Curve 4) |
|---|---|---|---|---|---|
| | Coarse aggregate A | Coarse aggregate B | Fine aggregate | 22.5% A + 31.9% B + 45.6% FA | |
| 26.5 | 100 | 100 | 100 | 100 | 100 |
| 19 | 95 | 100 | 100 | 98.9 | 100 |
| 13.2 | 35 | 100 | 100 | 85.4 | 87 |
| 9.5 | 10 | 85 | 100 | 75.0 | 75 |
| 4.75 | 2 | 8 | 100 | 48.6 | 48 |
| 2.36 | 1 | 2 | 95 | 44.2 | 42 |
| 1.18 | 0 | 0 | 75 | 34.2 | 34 |
| 0.6 | 0 | 0 | 45 | 20.5 | 27 |
| 0.3 | 0 | 0 | 30 | 13.7 | 12 |
| 0.15 | 0 | 0 | 8 | 3.6 | 1.5 |
| 0.075 | 0 | 0 | 4.5 | 2.1 | 0.5 |

***Plastic Properties of the Concrete Mix Design***

The trial batch of concrete is most commonly assessed for:

(a) Slump;
(b) Air Content;
(c) Wet Density;
(d) Yield;
(e) The Appearance of Concrete is also assessed visually for acceptable workability, potential for segregation and ease of finishing.

Tests for these plastic properties will need to meet the specified or acceptable requirements before longer term hardened properties are assessed. If any of the properties (particularly slump, air content and yield) are not as specified or as expected then mix design correction may need to be made based on the common relationships of mix design to these properties.

***Hardened Properties of the Concrete Mix Design***

Having satisfied the requirements for plastic properties of the (adjusted) mix, the trial batch of concrete is assessed for its hardened properties. These may vary with specification but commonly include:

(a) Compressive strength at various ages;
(b) Flexural Tensile strength at various ages;
(c) Drying Shrinkage up to 56 days;
(d) Various specified durability tests.

If any of these tests do not conform to the specified or expected values, then adjustments may need to be made based on the common relationships of mix design to these properties.

## 3.2 MIX DESIGN ADJUSTMENTS FOR PLASTIC PROPERTIES

Common adjustments are discussed based on correcting the concrete mix to achieve the required plastic properties.

### *Slump Adjustment*

The concrete slump can be most simply adjusted through varying an admixture dosage, but care must be taken to ensure that side effects (e.g. on set time) are accounted for. Increased water reducing admixture will generally increase the slump and decreasing the admixture dose will decrease the slump.

An alternative to adjusting admixture dosage is to adjust the mix total water. The relationship between slump and the total water content of a mix is noted in **Table III.3** and can guide a change in water content. For example, if a trial mix slump was measured as 40 mm but the required target slump for a 20 mm maximum size aggregate mix was 80 mm, then an increase of approximately 12 Litres/m$^3$ of water could be used to correct the slump. Unfortunately, this will have a side effect on the W/C ratio and may significantly impact on other hardened properties. In order to avoid such a side effect then the cement (or Cement + SCM) content could be increased in proportion with the water content. In this case, assuming a target W/C ratio for the mix is 0.50, the increase in cement content (or SCM + cement content) will need to be 12 Litres/m$^3$ / 0.50 = 24 kg/m$^3$. By maintaining the W/C ratio the strength and related properties may be maintained.

### *Air Content Adjustment*

The concrete air content is normally adjusted by raising or lowering the dose rate of air entraining agent.

### *Wet Density and Yield Adjustment*

The wet density variation in concrete generally relates to impacts of varying constituent material quantities and their variation in density. If the theoretical mix design has been batched at the correct slump and air content, then it is expected that the wet density will be the same as that calculated for 1.000 m$^3$ of that concrete mix design. In some cases, the measured density is higher or lower than the design value. For example, total mass of batched materials for a mix design is 2,350 kg/m$^3$. When tested the plastic density is found to be 2,320 kg/m$^3$. This means that the concrete mix yield is equal to 2,350/2,320 = 1.013 (i.e. it is 'over-yielding' by 1.3% in this case). The simple mix correction is to divide the mix design batch masses by the yield (1.013) to correct the mix design. This method works in the opposite case where the batch mass is less than the measured plastic concrete density ('under-yield') except that in this case the mix ingredients will be proportionally increased.

### *Adjustment for General Appearance and Workability*

The most common cases in which this occurs are where the mix appears to have too much coarse aggregate and looks harsh and has poor workability or the opposite where the mix appears to have too much sand and may be segregating. Corrections to these are generally made by adjusting the ratio of sand to coarse aggregate but in some cases, may require a complete change of aggregate if that is possible.

Concrete that is pumped into position will most likely need an adjustment of the coarse aggregate to fine aggregate ratio from that of a mix being directly deposited from the truck into a 'kibble' or into forms. In some cases, concrete pump manufacturers do provide target grading curves and specifications for concrete mix design used in their own pumps.

## 3.3 MIX DESIGN ADJUSTMENTS FOR HARDENED CONCRETE PROPERTIES

Common adjustments are discussed based on correcting the concrete mix to achieve the required hardened concrete properties.

***Adjustments for Strength and Durability***

The reason for grouping the strength tests and durability test impact on mix design is that in most cases the various types of strength tests are related to concrete compressive strength. Most of the commonly specified durability tests are also related to compressive strength as a result of its relationship to mix W/C ratio.

In all of these tests the correction to mix design will most likely require an adjustment to the mix W/C ratio or less commonly a complete change to cement type, aggregate type or admixture combination.

As seen in sub-section 2.5 there is a direct relationship between W/C ratio and compressive strength at various ages. A smaller adjustment in compressive strength generally requires modification of the W/C ratio. For example, a GP Cement mix designed with a target 28-day strength of 37.5 MPa is trial batched and only achieves 33.0 MPa. A review of **Figure III.1** would suggest that a reduction in W/C ratio by approximately 8% will be required to achieve the necessary change in strength. This can be achieved by increasing the cement content by 8% or reducing the water by 8% (or a combination of water and cement contents to reduce W/C by 8%). If the existing mix cement content was designed as 280 kg/m$^3$ and it was decided to correct this, then it would require a cement content increase of 20 kg/m$^3$ to increase strength as well as an adjustment of the mix design aggregate contents to maintain yield due to the increased paste content created by increasing the cement.

***Adjustment for Drying Shrinkage***

The drying shrinkage of concrete is partly related to the total water content of concrete and to the type of cement, properties of the coarse aggregate and the ratio of coarse aggregate to fine aggregate in the mix design. A reduction in drying shrinkage of 100 micro-strain at 56 days can be achieved by some of the following adjustments to an existing mix:

- A reduction of total water of 30 Litre/m$^3$. This may be achievable with a high range water reducing admixture, but care is needed in selection of the HRWRA as some do increase drying shrinkage at the same water content;
- An increase in coarse aggregate content of the concrete mix by 100 kg/m$^3$ by reducing the fine aggregate content to compensate yield. This may be possible if the concrete is not being pumped;
- Addition of a shrinkage reducing admixture at the required design dosage to the mix.

## 4. REFERENCES


1) AS 3600 – *Concrete structures*
2) AS 1379 – *Specification and supply of concrete* (R2017)
3) AS 2758.1 – *Aggregates and rock for engineering purposes – Concrete aggregate* (2014)
4) ACI 211.1 – *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete* (R2002)
5) UK Road Research Laboratory, *'Road Note No. 4 – Design of Concrete Mixes',* London (1950)
6) AS 1141.4 – *Methods for sampling and testing aggregates – Bulk density of aggregate* (R2013)
7) ASTM C29 – *Standard Test Method for Bulk Density ('Unit Weight') and Voids in Aggregate* (2017)
8) ASTM C33 – *Standard Specification for Concrete Aggregates* (2018)


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