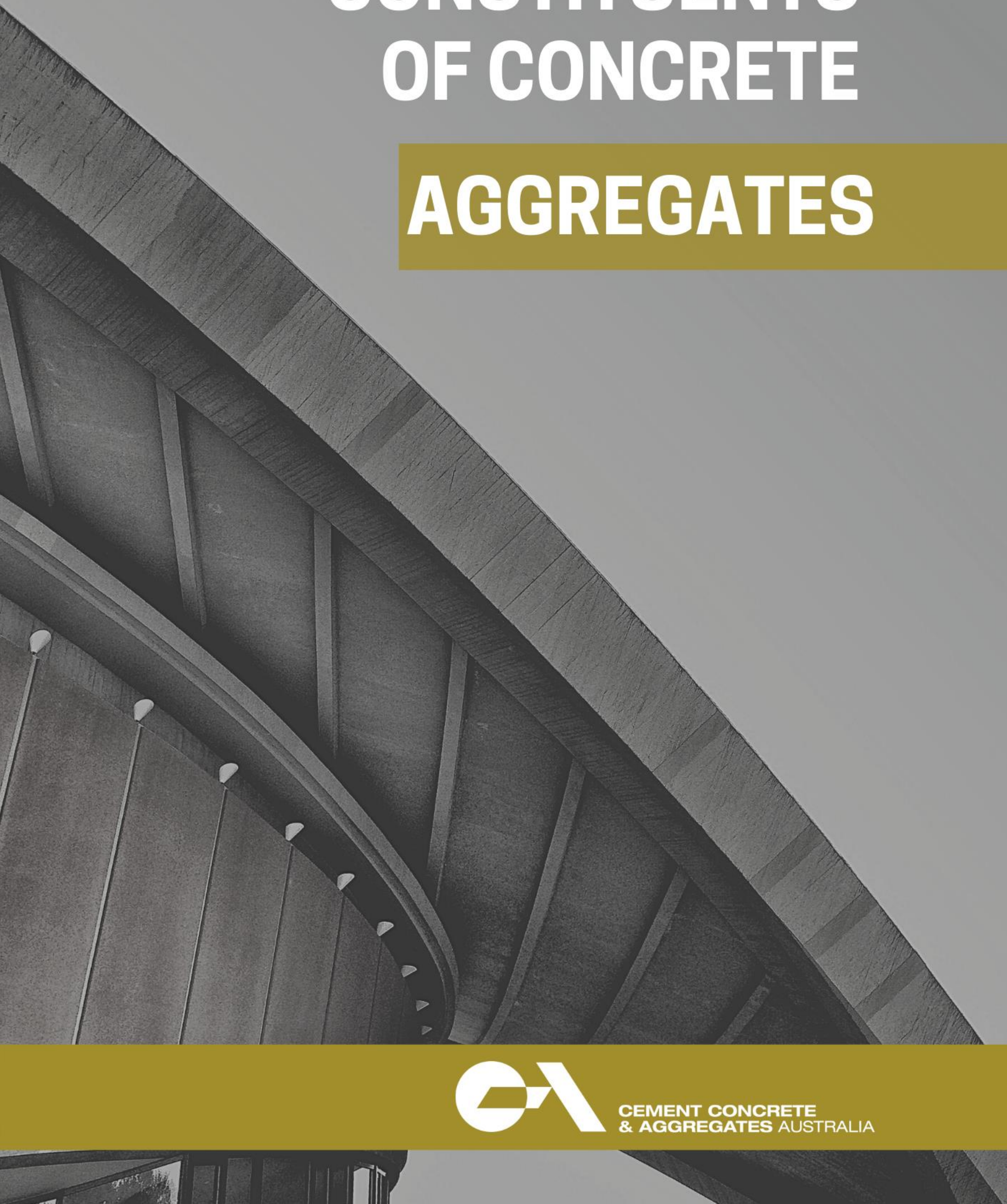
PART II. CONSTITUENTS OF CONCRETE

AGGREGATES



CEMENT CONCRETE
& AGGREGATES AUSTRALIA

CONTENTS

1 OUTLINE

This section summarises information on the properties of aggregates, their sources in Australia, and their classification for use in concrete. It discusses their properties in some detail and their influence on the properties of the concrete. It also outlines methods of testing aggregates.

Aggregates form between 60% and 80% of the volume of concrete and are an important constituent of concrete. At one time they were considered to be inert fillers, but we now know their properties can significantly affect the performance of concrete in both its plastic and hardened conditions.

The physical and chemical test methods for the properties of concrete aggregates are covered by Australian Standards including AS 1141 and AS 1012. The specifications for concrete aggregates are covered by AS 2758.1.

AS 1141 contains methods for the sampling and testing of aggregates used for concrete, asphalt, sprayed bituminous surfacing, pavements, railway ballast and other engineering purposes. In this section reference is made to those methods relating to the use of aggregate in concrete.

2 TYPES AND USES OF AGGREGATES

Concrete aggregates, regardless of their origin, can be divided into four classes: heavyweight aggregates, normal-weight (or dense) aggregates, lightweight aggregates and ultra-lightweight aggregates. The majority of aggregates used to make concrete fall into normal-weight and lightweight classes.

Normal-weight aggregates are sands (fine aggregate), natural gravels and hard rock, crushed or uncrushed (in the case of natural aggregates). There are also certain manufactured aggregates, such as crushed iron blast-furnace slag, which have a particle density of not less than 2,100 kg/m^3. Manufactured aggregates are not a major source of aggregate employed in the production of concrete in Australia and are still required to comply with the requirements of AS 2758.1.

Lightweight aggregates are defined by AS 2758.1 as those having a particle density less than 2,100 kg/m^3 but not less than 500 kg/m^3. They are used to produce concrete of substantially lower unit mass than that made from dense aggregates and include materials such as scoria, a porous rock of volcanic origin, and manufactured materials such as foamed iron blast- furnace slag and expanded shales.

Structural lightweight concrete, with dry density greater than 1,800 kg/m^3 and compressive strength ranging from 20 MPa to 32 MPa, is produced with scoria, foamed slags and expanded shale. Moderate-strength lightweight concrete falls midway between low-density and structural concretes using normal weight aggregate with respect to unit weight and strength, the most common aggregate used in this type of concrete being pumice. Sintered pulverised fuel ash aggregate is also used but rarely in Australia.

Heavyweight aggregates include limonite, barytes, magnetite and steel 'punchings'. These are used principally in the production of concrete for shielding against radiation (nuclear power stations and hospital applications) but also find application where extremely heavy mass concrete is required for other reasons (e.g. to balance floatation in marine structures) but these uses are comparatively rare.

Ultra-lightweight aggregates are defined as those having a particle density of less than 500 kg/m^3. They are used to produce concrete with a very low density. Concretes with densities as low as 400 kg/m^3 can be produced using materials such as vermiculite (a micaceous mineral) and perlite (a volcanic glass). The thermal insulation values of such concretes are high, but their compressive strengths are very low. They are therefore not suited to structural purposes but rather as an insulating backfill.

Information relating to the categorisation of these aggregates, their uses and impact on concrete density is summarised in **Table 3.1**.

Table 3.1 – Types of Aggregate for Concrete

Weight categories	**Types of aggregates**	**Uses**	**Indicative concrete density (kg/m^3)**
Ultra-lightweight *Particle density(*)* *<500 kg/m^3*	Vermiculite; Perlite.	Thermal insulation	500 to 1,000
Lightweight *Particle density(*)* *<2,100 kg/m^3*	Pumice; Sintered pulverised fuel ash.	Lightweight concretes	1,000 to 1,800
	Scoria; Foamed iron blast-furnace slag; Expanded shales; Expanded clays.	Lightweight structural concretes	1,800 to 2,100
Normal-weight *Particle density(*)* *≥2,100 kg/m^3*	Natural sands; Natural gravels; Natural rocks; Air-cooled iron blast-furnace slag.	Normal-weight structural concretes	2,100 to 2,800
Heavyweight *Particle density(*)* *≥3,200 kg/m^3*	Limonite; Barytes; Magnetite; Steel punchings.	Heavyweight mass concretes; Radiation shielding.	2,800 to 5,000

***NOTE:** (*) Particle density on dry basis is determined in accordance with AS 1141.5 for fine aggregates and AS 1141.6.1 or AS 1141.6.2 for coarse aggregates.*

3 SOURCES OF AGGREGATES

3.1 GENERAL

The common types of normal weight aggregate used in practice are:

- Natural sands and gravels;
- Crushed rock aggregate;
- Manufactured aggregate;

The sources of these aggregates are discussed in the following sections.

3.2 NATURAL SANDS AND GRAVELS

Natural sand and gravel sources are widely distributed throughout Australia although urban development and the past exploitation of the remaining deposits are reducing their availability in locations close to the major cities. Such deposits include:

- ***Stream beds*** – particles are normally rounded in shape, clean and strong, most of the weak material having been removed by erosion. The particle sizes existing in a specific location will relate to the volumes and speed of water travelling in the stream bed. In most cases this limits stream beds to finer size particles (typically sands);
- ***Alluvial deposits*** – formed on flood plains and in larger riverbeds. Depending on the original source of the parent rocks as well as the volume and rate of water flow, such deposits may contain rocks and stones of a number of different types and sizes that can be sieved into useful size fractions by screening. Sands from these sources trend towards coarser fractions with particle sizes from 0.4 mm to 5.0 mm;
- ***Marine deposits*** – formed at the edges and bottom of seas and lakes. Note that marine aggregates may introduce unacceptable quantities of chlorides into concrete unless appropriately managed;
- ***Dunes*** – formed by the action of wind. These sands tend to be single-sized and very fine (typically sands with predominate particle sizes less than 0.6 mm).

3.3 CRUSHED ROCK AGGREGATE

Crushed rock is sourced from hard-rock quarries in a systematic process of drilling and blasting rock formations to produce suitably sized material to feed into a crushing and screening process. Crushed rock aggregates have the advantage that they can be produced in any desired size and grading by the installation of suitably designed crushing and screening equipment. Rock types that are suitable as concrete aggregates are grouped into three major classifications according to their geological origin:

Igneous Rocks – Igneous rocks are formed from molten minerals emanating from below the earth's surface. Basalt, diorite and granite are examples of igneous rocks commonly used as concrete aggregates. This rock type suitability for concrete aggregate depends on its mineral composition. Some igneous rocks can be unsatisfactory for use in concrete. For example, 'green basalts' contain secondary clay minerals that cause the aggregate to exhibit large volumetric expansion/contraction with changes in moisture content. If this material is used in concrete subject to wetting and drying, it can expand and either adversely affect the durability of or eventually disrupt the concrete.

Sedimentary Rocks – Sedimentary rocks are formed at the earth's surface by the accumulation and consolidation of the products of weathering and erosion of geologically older rocks and minerals. The sediments usually harden by cementation or compaction over very long periods of time. Limestone, sandstone, shales and chert are examples of sedimentary rocks.

Limestones are probably the most widely used as concrete aggregates in this group. Limestones vary from very hard fine-grained crystalline rocks to very soft and weak materials like chalk. Hard limestone is generally suitable for use in concrete, but soft limestone should be avoided.

Sandstones may be suitable as concrete aggregates if they are composed of quartz grains cemented together with amorphous silica. Sandstones that consist of sand grains bound together by clay are generally unsatisfactory because they are weak and porous and may soften in water.

Shales are generally unsatisfactory because of their soft and absorptive nature. Cherts are hard and dense but, depending on the silica minerals present, may be subject to severe alkali-reactivity in concrete.

Metamorphic Rocks – Metamorphic rocks are formed from pre-existing rocks (both igneous and sedimentary in origin). Actions of changes in the earth's crust including heat and/or pressure lead to change or 'metamorphism' to the original rock. They are dense but may be weak in one plain. Marble, quartzite, Gneiss, phyllite and slate are examples of this type of rock.

The mineral compositions of metamorphic rocks are highly variable, depending in part on the degree of metamorphism and in part on the composition of the parent material. Certain metamorphic rocks may be more prone to alkali-reactivity in concrete as a result of straining of the quartz structure during metamorphism.

3.4 MANUFACTURED AGGREGATE

Manufactured aggregates may be either by-products of an industrial process, such as blast-furnace slag, or products specially manufactured as aggregates (e.g. expanded clays and shales). Expanded clay or shale is now rare in Australia but they were an important source of lightweight aggregate in past years.

Iron Blast-furnace Slag – Iron Blast-furnace Slag is the non-metallic by-product produced in an iron blast furnace (see Part II, Section 2 of this Guide). It consists, essentially, of silicates and calcium alumina-silicates and other bases. By changing the cooling conditions and cooling rates, the molten slag can be made to solidify into a number of different forms with distinctive physical properties. By far the most common slags are those derived from iron blast furnaces, but copper slag has also been used as a concrete aggregate in Australia. Slag aggregates need to undergo a period of weathering in a stockpile before they are used in concrete. Three types of iron blast furnace slag are available commercially:

- Air-cooled slag is a crystalline product produced by allowing the molten slag to cool slowly in pits or bays under atmospheric conditions. This is the usual source of slag aggregates;
- Granulated slag is a glassy, granular product formed when molten slag is quenched rapidly in water. It is sometimes used as a fine aggregate, but is more often ground to provide a material with cementitious properties;
- Foamed slag is the vesicular product formed by the controlled quenching of thin layers of molten slag in shallow pits. Water may or may not be used for quenching.

Granulated and foamed slags are also sources of lightweight aggregate.

Expanded Clays and Shales – When certain types of clay and shale are heated to about 1,200°C, they begin to fuse and melt. At the same time, the gases generated expand the mass rapidly to form a honeycomb of small cells. The resultant material, when cooled, has a low particle density and unit weight (bulk density), but is hard and strong.

Sintered Pulverised Fuel Ash – Fly ash is a material formed during the combustion of pulverised coal in power station steam boilers or similar high-temperature combustion chambers (Part II, Section 2 of this Guide). A lightweight aggregate is formed by mixing fly ash with water and coal slurry, then pelletising and sintering the mixture to 1,400°C. This form of lightweight aggregate is more common in the UK, USA and Europe but rarely imported to Australia.

4 AGGREGATE PROPERTIES IN AS 2758.1

4.1 GENERAL

Aggregate properties that affect the resulting concrete, and the limits placed on those properties in AS 2758.1, are discussed in Clauses 4.2 to 4.6 below and summarised in **Tables 3.6**, **3.7**, **3.8** and **3.9** at the end of this section. Note that (as shown in **Table 3.8**) for the durability properties of coarse aggregates covered in AS 2758.1 clauses 9.3.2 to 9.3.4, only one of the three sets of tests is required to be satisfied.

4.2 GRADING

A concept used to describe any aggregate used in concrete is the 'Nominal size' or maximum size of that aggregate. The maximum nominal size of aggregate used in a concrete mix can influence mix binder content, water demand and ease of compaction of the concrete. Aggregates of standard nominal sizes (coarse and fine aggregates) are noted in AS 2758.1 and include details of their recommended specifications including the grading requirements of each nominal size.

Grading is the distribution of particle sizes in a particular nominal size of an aggregate. It influences the water demand of concrete and its subsequent tendency to bleed and segregate. Hence, it influences the mix proportions for a desired workability and water/cement ratio. The coarser the grading (i.e. the lower the proportion of fine aggregate), the lower the cement content required for a given workability and water/cement ratio. However, this is true within limits only as a sufficient amount of fine material is always required to obtain a cohesive mix that can be transported, placed and compacted without segregation.

Aggregates having a continuous, relatively smooth grading curve will generally produce mixtures with fewer large voids between particles. The amount of cement paste required to fill these voids is thereby reduced. In other words, a larger volume of concrete can be made from a given amount of cement paste, and it is, therefore, a more economical mix.

If an aggregate grading is deficient in fines, (i.e. there is not enough sand to fill the voids between coarse aggregate particles), or if the sand is coarse, the concrete mix will be harsh, difficult to place and finish, and will tend to bleed excessively. On the other hand, aggregate combinations with excessive amounts of sand, or excessively fine sands, may produce uneconomical concretes because of the larger surface area of the finer particles. In consequence, an excessive amount of cement may be required to produce the required strength and workability.

Whilst continuously graded coarse and fine aggregates are normally specified for use in concrete, gap-graded mix design combinations (as required, for example, for exposed-aggregate concrete) can also be used to produce satisfactory mixes. **Figure 3.1** shows typical grading curves for continuous and gap-graded aggregate blends.

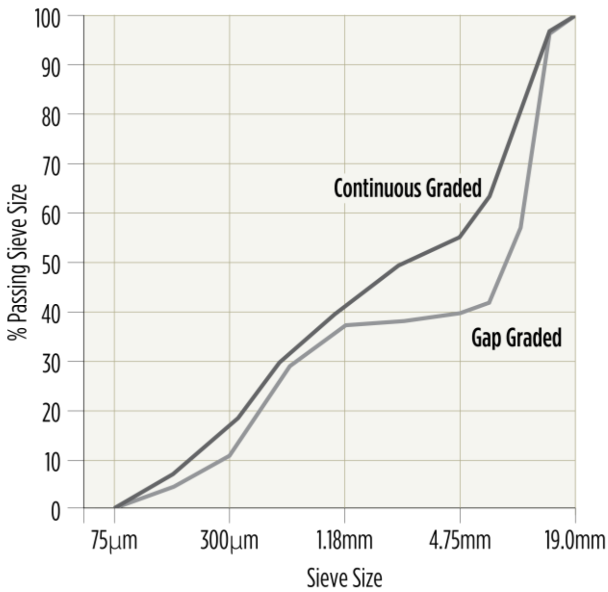


Figure 3.1 – Grading Curves for 20 mm Maximum Size Aggregate Concrete Blend – examples only

While there is a need for aggregates to meet specified grading curves, no ideal grading exists. Good concrete can be produced from blending a range of fine and coarse aggregate gradings and relatively wide ranges of recommended target grading are recommended by AS 2758.1 Appendix B. Some of these recommended ranges in target grading are shown in **Table 3.2** and **Table 3.3**.

The aggregate grading significantly influences the water demand and workability of the concrete, and hence affects concreting operations on the job. Ultimately, it may affect the strength and other properties of the hardened concrete. Hence, it is extremely important that either aggregate gradings be uniform during the currency of a project or that the concrete mix be adjusted when changes occur in the grading.

Even when not necessary for visual reasons (e.g. for exposed aggregate 'architectural' concrete), it is often more economical to maintain uniformity in the aggregates than to adjust the mix proportions for variations in grading. Therefore, limits on variation from the agreed target grading of the submitted sample in the one job are recommended in AS 2758.1. Some of these limits are shown in **Tables 3.4** and **3.5** but others are available in AS 2758.1 including proposed single size aggregate grading as well as other size fractions.

The grading is determined by sieve analysis in accordance with AS 1141.11. In carrying out the sieve analysis, the percentage passing each sieve is determined. The coarse and fine aggregates are sieved separately, each nominal material size, e.g. 20 mm, has its own grading and is usually reported separately.

Table 3.2 – Recommended Grading Limits for Fine Aggregate

Sieve size	Mass of sample passing sieve (%)	
	Uncrushed fine aggregate	**Crushed fine aggregate**
9.50 mm	100	100
4.75 mm	90-100	90-100
2.36 mm	60-100	60-100
1.18 mm	30-100	30-100
600 µm	15-100	15-80
300 µm	5-50	5-40
150 µm	0-20	0-25
75 µm	0-5	0-20

Table 3.3 – Recommended Grading Limits for Nominal Size, Graded Coarse Aggregate

Sieve size	Mass of sample passing (%) – nominal size of graded aggregate			
	40 mm	**28 mm**	**20 mm**	**14/7 mm**
75.0 mm	100	-	-	-
37.5 mm	85-100	100	-	-
26.5 mm	-	85-100	100	-
19.0 mm	30-70	-	85-100	100
13.2 mm	-	25-60	-	85-100
9.5 mm	10-35	-	25-55	-
6.7 mm	-	-	-	25-55
4.75 mm	0-5	0-10	0-10	-
2.36 mm	-	0.5	0.5	0-10
75 µm	0-2	0-2	0-2	0-2

Table 3.4 – AS 2758.1 Uniformity Requirements for Fine Aggregate

Sieve size	Maximum deviation (%)	
	Uncrushed fine aggregate	**Crushed fine aggregate**
9.50 mm	-	-
4.75 mm	±5	±5
2.36 mm	±5	±10
1.18 mm	±10	±15
600 µm	±15	±15
300 µm	±10	±10
150 µm	±5	±5
75 µm	-	±5

Table 3.5 – AS 2758.1 Uniformity Requirements for Graded Coarse Aggregate

Sieve size	Maximum deviation (%) – nominal size of graded aggregate			
	40 mm	28 mm	20 mm	14 mm
75.0 mm	-	-	-	-
37.5 mm	±10	-	-	-
26.5 mm	±15	±10	-	-
19.0 mm	±15	±15	±10	-
13.2 mm	±10	±15	±15	±10
9.5 mm	±10	±10	±15	±15
6.7 mm	±5	±10	±10	±15
4.75 mm	-	±5	±5	±5
2.36 mm	-	-	-	-
75 µm	-	-	-	-

4.3 PARTICLE SHAPE AND SURFACE TEXTURE

The shape and texture of aggregate particles has an important influence on the workability of freshly mixed concrete, and hence may affect both the water demand and the water/cement ratio (**Figure 3.2**). Smooth, rounded aggregate particles will produce a concrete with a lower water demand than one made from angular crushed aggregates all other things being equal. However, this is seldom the only criterion in the choice of aggregate.

The strength of concrete is affected by the bond between coarse aggregate particles and the cement paste and by the interlocking characteristics of the aggregate. For optimum strength, a rough-textured, cubical-shaped aggregate will generally give higher strength at the same water/cement ratio.

Figure 3.3 provides guidance on the classification of aggregates according to their particle shape and surface texture. Particle shape is described as rounded, irregular, angular, flaky, elongated, or flaky and elongated. These fairly broad descriptions are normally sufficient to categorise aggregate particles visually.

Similarly, surface texture can be classified as glassy, smooth, granular, rough, crystalline or honeycombed.

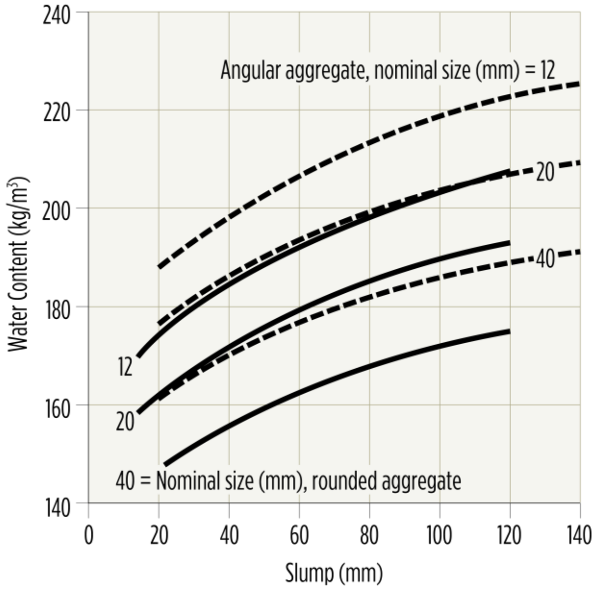


Figure 3.2 – Water Requirement for Concrete using Aggregates of Different Shapes and Nominal Sizes

Because flat, flaky or elongated particles not only reduce workability but may also affect adversely the strength of concrete by their tendency to selective orientation and bridging (thus forming pockets or honeycombs), aggregate specifications generally limit the allowable percentage of such misshapen particles. AS 2758.1 limits the proportion of misshapen particles in the fraction of a coarse aggregate retained on the 9.50 mm test sieve to 10%, when determined in accordance with AS 1141.14 for an aspect ratio of 3:1.

The flakiness index, determined in accordance with AS 1141.15, may also be used to describe the shape of an aggregate particle. This method uses a slotted thickness gauge to determine the percentage, by mass, of flaky particles, where a flaky particle is defined as one with its least dimension (thickness) less than 0.6 of its mean dimension. The mean dimension is defined as the mean of the smallest square sieve size through which the particle passes and the largest sieve on which it is retained. AS 2758.1 limits the proportion of misshapen particles in the fraction of a coarse aggregate retained on the 9.5 mm sieve, assessed by flakiness index, to a maximum of 35%.

The angularity number is another index of the shape of a particle and is determined in accordance with AS 1141.16. It is a measure of relative angularity based on the percentage voids in an aggregate after compaction in a prescribed manner. The most rounded aggregates have about 33% voids. The angularity number is defined as the amount by which the percentage of voids in a compacted aggregate sample exceeds 33%. In practice, it ranges from 0, for a spherical aggregate, to about 12 for very angular aggregates.

Figure 3.3 – Categorisation of Aggregate Particles by Shape and Surface Texture

4.4 PARTICLE DENSITY AND WATER ABSORPTION

Aggregate water absorption and density are linked through the test methods. The determination of aggregate density and water absorption is carried out in accordance with either AS 1141.5, AS 1141.6.1 or AS 1141.6.2. The bulk density of an aggregate is determined in accordance with AS 1141.4. The principles of these tests are discussed in the following.

Aggregate Density

AS 2578.1 provides three different ways of describing aggregate density:

- *Particle density:* Particle density is defined as the mass of a quantity of aggregate particles divided by their saturated surface-dried volume, i.e. the mass of a solid cubic metre of aggregate. The value is calculated and reported for either aggregate in SSD condition or aggregate in oven dry condition;
- *Bulk density:* Bulk density is defined as the mass of a unit volume of oven-dried aggregate, i.e. the mass per cubic metre of aggregate, as it fills a large container of known volume (including voids between aggregate particles). Bulk density is reported for both loose filled aggregates and for compacted aggregates.

Density is one of the parameters used to classify aggregates. For example, AS 2758.1 defines lightweight aggregates as having a particle density less than 2.1 t/m^3 and a compacted bulk density less than 1.2 t/m^3.

The density of an aggregate is not a measure of its quality, although density is normally related to porosity which, in turn, is related to strength. The SSD aggregate density is used in proportioning concrete mixes. Substituting one aggregate in a concrete for another of different density will influence the yield and the unit mass of the concrete as well as a number of other properties.

Aggregate Water Absorption

All aggregates contain minute pores which can become filled with moisture when saturated. The amount of moisture absorbed in these pores may be quite small, as is the case with dense fine-grained rocks, or quite large, as with lightweight and other porous materials. The amount of moisture absorbed is known as the water absorption of coarse and fine aggregate and may be determined by the methods set out in AS 1141.5, AS 1141.6.1 and AS 1141.6.2.

Surface moisture may also be present in aggregates giving them a damp or wet appearance. The total moisture content of an aggregate is the sum of the absorbed and the surface moisture present.

It is an important parameter because it can affect the amount of water which should be used in a concrete mix to achieve the given water/cement ratio. Variations in the moisture content of stock-piled aggregates are possibly the most common cause of variations in slump and concrete strengths. The surface moisture contents of sands, in particular, are significant.

In preparing a mix design for concrete using a particular aggregate, it is normal to determine first the moisture content of the aggregate in a saturated surface-dry condition (i.e. with the pores filled with water but without free moisture on the surface of the particles). If the aggregates used in the subsequent manufacture of the concrete have moisture contents less than this figure, additional water will need to be added to avoid a loss of workability as the aggregates absorb moisture. If greater than this figure, free moisture will be present on the surface of the aggregates and less water should be added.

4.5 AGGREGATE STRENGTH AND DURABILITY

The strength and physical durability of an aggregate can be assessed using test methods such as the '10% Fines' test better known as 'Wet/Dry Strength Variation' and Los-Angeles Abrasion test. The presence of weak aggregate particles in some aggregates and methods of assessing and limiting these are important to maintaining overall concrete strength and durability. The principles of these tests are discussed in the following.

Wet/Dry Strength Variation and Wet Strength

Dimensional stability and strength under changing moisture conditions is an important property of aggregates intended for use in concrete. Aggregates that weaken, swell or shrink as they take up or lose water contribute to concrete shrinkage and durability. In extreme cases, the concrete may deteriorate with cycles of wetting and drying because of the expansion and contraction of the aggregate. Dimensional instability occurs in an aggregate when the minerals comprising the rock include unstable clays (e.g. volcanic breccia).

The wet/dry strength variation test set out in AS 1141.22 provides an overall guide as to the dimensional stability of a coarse aggregate. It compares the two crushing forces required to produce fines through breakdown that amount to 10% of a fixed mass of the aggregate being tested. When crushed in the oven-dry and saturated surface-dry conditions the two crushing forces are compared. The result is expressed as the variation in crushing strength as a percentage of the dry crushing strength of the aggregate. The higher the wet/dry strength variation, the less stable is the aggregate.

Clause 9.3.2 in AS 2758.1 sets limits on the maximum wet/dry strength variation between 25% and 45%, depending on the concrete exposure conditions set out in AS 3600 and also provided in AS 2758.1 – Appendix A (also see **Table 3.8** for limits). The high values apply to aggregates to be used in an indoor or protected position and the lower values to aggregates exposed to adverse climatic and service conditions (e.g. cycles of wetting and drying, cycles of freezing and thawing, marine environments, heavy industrial pollution etc.).

The wet strength of an aggregate will influence the strength of concrete made from it. High-strength concrete requires aggregates of high strength. However, weaker aggregates may be satisfactory if the strength of concrete is not expected to exceed that of the aggregate. The strength of aggregates is likely to vary considerably with their structure and mineral composition.

Aggregates influence the drying shrinkage of the concrete by restraining the shrinkage of the cement paste. The rigidity of the aggregate will influence its restraining effect. Thus, the higher the modulus of elasticity of the aggregate, the more effective it will be in reducing the shrinkage of the concrete.

Aggregate strength is generally gauged by the wet/dry variation test in accordance with AS 1141.22 (particularly the wet strength value*).* Clause 9.3.2 in AS 2758.1 specifies minimum limits for the wet strength of aggregate. The minimum wet strength ranges from 50 kN to 100 kN depending on the concrete exposure condition from AS 3600. The lower value is for aggregates to be used in concrete of lower strengths and used in protected conditions. Higher wet strengths are required for aggregates to be used in more adverse conditions.

Abrasion Resistance

The abrasion resistance of an aggregate is its ability to resist being worn away by friction with other materials. Abrasion resistance is required in an aggregate to avoid degradation during handling, stockpiling and mixing. Breaking down, or grinding of the aggregate during concrete production, generates fines which increase mixing-water demand. This, in turn, may cause some difficulty in producing high-quality concrete.

Except for concrete with an exposed-aggregate finish, the abrasion resistance of the aggregate bears no direct relationship to the abrasion resistance of concrete made from it. The abrasion resistance of concrete is found to be indirectly related to concrete strength.

At the same time, weak, soft, or friable aggregates are obviously unsuitable for concrete exposed to wear, whilst strong abrasion-resistant materials do improve concrete performance in the longer term.

The 'Los Angeles value' test is used to determine an aggregates abrasion resistance and is specified as an option in AS 2758.1. The test method is carried out in accordance with AS 1141.23 and is the most common method of testing the abrasion resistance of coarse aggregate particles. This test combines the effects of impact and abrasion by tumbling aggregate particles together with steel balls in a slowly revolving steel drum that has 'shelves' causing the aggregate and steel ball mixture to drop from a consistent height during drum rotation. A specified quantity of aggregate is placed in the drum with a charge of standard-size steel balls. The percentage of the aggregate worn away is determined by sieving and weighing. The maximum acceptable percentage loss is set by Clause 9.3.3 in AS 2758.1 for various types of aggregate and for various concrete exposure conditions.

Maximum values are 30%, 35% and 40% depending on the stone type and the exposure classification of the project. The higher the Los Angeles value, the more prone the aggregate to degradation, and the less suitable it is to produce an abrasion resistant concrete.

Unsound and Marginal Stone Content

Aggregate particles that are abnormally weak or low on density or have some other undesirable property must be minimised in a concrete aggregate. The unsound stone content test is covered by AS 1141.30.1. In this test a sample of coarse aggregate retained on a 4.75-mm sieve is soaked in water and then dried. After pressing each particle against the bottom of a dish (using finger pressure) the broken-down particle material passing a 4.75-mm sieve is regarded as unsound. Clause 9.3.4 in AS 2758.1 specifies maximum of 5% by mass for unsound stone content. In addition to this there may be aggregate particles that are not unsound by this measure but are weaker than acceptable to the user of the aggregate. AS 2758.0 Appendix C defines how such 'marginal stone' is assessed and limits defined into the aggregate supply agreement. AS 2758.1 specifies a combined maximum of 10% for the total of unsound and marginal stone (this assessment method is largely targeted at basic igneous rocks that may contain unacceptable levels of decomposed and weak materials).

4.6 AGGREGATE CHEMICAL RESISTANCE AND DURABILITY

Aggregates that are maintained in a benign environment can appear to be quite sound and durable. Two key tests are specified by AS 2758.1 to determine the durability of aggregate in environments where the presence of moisture and chemicals in concrete or from the environment surrounding the concrete may lead to degradation of the aggregate and so the concrete containing this aggregate.

Sulfate Soundness

The soundness of an aggregate is its ability to withstand the aggressive actions to which concrete containing it might be exposed, particularly those due to weather and chemical attack.

If aggregate from a particular source has given satisfactory service in the past, it may be considered sound. The soundness of aggregates not having a service record can be assessed by tests as discussed below.

The sodium sulfate soundness test (AS 1141.24) determines the resistance of the aggregate to disintegration when subjected to a number of cycles of immersion in a sodium sulfate solution, of specified concentration, followed by oven drying. The higher the percentage loss of parent material suffered by the sample, the less sound is the aggregate. Clause 9.3.3 in AS 2758.1 relates the maximum percentage loss to the exposure conditions of the concrete. The limits set maximum values of loss in a range from 6% to 12%, the higher figure being for use in concrete in a protected environment and the lower for concrete in severe exposure conditions.

Fine Aggregate Degradation Factor

The degradation factor is an alternative durability test used to assess the fine aggregate portion of an aggregate blend or sand. It is better suited to evaluate manufactured sand.

The degradation factor test determines the clay and fine silts generated by vigorously agitating clean aggregate in the presence of water. A sample of washed fine aggregate is sized to form a combined test sample of 50 g each of four size fractions between 4.75 mm and 425 µm. The combined sample is agitated in water in a Sand Equivalent Test cylinder using the power-operated shaking. The agitation is continued for 20 minutes. Following the attrition by agitation of the aggregate particles, the water, carrying the attrition products, is recovered and the aggregate is cleaned with further water. The water sample is transferred to a test cylinder and the clay and silt is treated with a flocculent. The sample is allowed to settle for 20 minutes, the height of the flocculated column is then used in a calculation that reflects the percentage of non-flocculent material (sand) compared to the original material before abrasion in water. The test method is described in AS 1141.25.3 and AS 2758.1 recommends a minimum value of 60%.

Alkali-Aggregate Reactivity (AAR)

Aggregates that are chemically stable will neither react chemically with cement in a harmful manner nor be affected chemically by normal external influences.

Reactive aggregates may result in serious damage to the concrete by causing abnormal expansion, cracking and loss of strength.

Alkali-aggregate reaction (AAR) is the reaction between the alkalis from the cement and other sources and certain mineral phases present in the coarse or fine aggregates. Under certain conditions, deleterious expansion and consequent cracking of the concrete may result (e.g. map cracking) **Figure 3.4**. The two major types of AAR are:

- Alkali-silica reaction (ASR);
- Alkali-carbonate reaction (ACR).

Figure 3.4 – Typical Map Cracking caused by Alkali-Aggregate Reactions

Alkali-carbonate reaction is the reaction between certain dolomitic limestone and alkalis in the pore solution of the concrete. It is rare in Australia.

Alkali-silica reaction is the reaction of the alkalis in the pore solution of the concrete with aggregates containing certain forms of reactive silica such as strained quartz, amorphous silica, opaline material, cryptocrystalline quartz, chalcedony and cristobalite.

A small proportion of concrete throughout the world has suffered from deterioration due to AAR. In Australia, reports of problems in a relatively small, but significant number of structures identified in recent years has increased interest in AAR. A set of national guidelines on minimising the risk of damage due to AAR in concrete structures in Australia (AS HB 79) along with associated changes to AS 2758.1 have been produced to assist designers, specifiers, suppliers and contractors.

Field service records, when available, provide the useful information on the reactivity of aggregates. Apart from the length of time to gather such service records, the information could be either scarce or inconclusive. It is therefore often necessary to use laboratory test procedures to determine the potential reactivity of the aggregates.

With the exception of petrographic analysis (ASTM C 295), previous methods of assessing the likely reactivity of aggregates were considered to be imprecise. The two test methods have been developed into Australian Standards. These test methods are AS 1141.60.1 (Accelerated Mortar Bar Test), and AS 1141.60.2 (Concrete Prism Test).

These test methods take approximately a month for the Accelerated Mortar Bar Test and between a year and two years for the Concrete Prism Test. In view of this, suppliers of aggregates need to build up a number of tests during production of aggregates to be able to provide assurance to a user that the aggregate is suitable for concrete.

Current best practice on how to recognise and mitigate the potential for alkali-silica reactivity can be obtained from the joint publication of the CCAA and Standards Australia called *'AS HB 79, Alkali-Aggregate Reaction – Guidelines on Minimising the Risk of Damage to Concrete Structures in Australia'*.

The key methods proposed for controlling the risk of ASR in concrete include:

- Use of low alkali cement;
- Limiting the total alkali content of the concrete;
- Using supplementary cementitious materials (e.g. using suitable fly ash, GGBFS and silica fume);
- Preventing moisture ingress to the concrete (to slow reactions and to minimise the introduction of alkalis from salt water) by various means including water repellent sealers;
- Using lithium salts in the concrete mix.

Other Chemical Reactions

Other damaging chemical reactions involving aggregates include oxidation or hydration of certain unstable minerals. Pyrites (ferrous sulfide), for example, can oxidise and hydrate to form brown iron hydroxide which in turn may cause unsightly stains on the surface of concrete. The presence of magnesia (MgO) or lime (CaO) in the aggregate may also cause pop-outs or cracking due to their hydration and expansion.

Impurities and Other Harmful Materials

Besides reactive minerals, aggregates may contain other impurities, such as organic matter, which are harmful to concrete.

Organic matter, such as that derived from decaying vegetation, is capable of delaying setting and hardening of concrete. It is more likely to be found in fine than in coarse aggregate and may be detected by the test set out in AS 1141.34. In this test, sand is placed into a bottle containing a sodium hydroxide solution and allowed to stand for 24 hours. The colour of the liquid above the sample is then compared with the colour of a standard reference solution or standard glass slide. If the colour of the liquid is lighter than that of the reference solution or slide, the amount of organic impurities present in the aggregate is not significant. If the colour of the liquid is darker than that of the reference solution, the aggregate contains organic compounds and further tests should be made to determine if these are harmful. Normally, the strength, setting time and air content of concrete made with the sand are used as a gauge of the harmful effects of the impurities.

Sugar has a strong retarding effect on the setting and hardening of concrete. In severe cases of contamination, the resulting concrete may not set or may fail to gain appreciable strength. AS 2758.1 specifies a negative result on the presence of sugar in aggregate when determined in accordance with AS 1141.35.

Silt, clay and dust may form a coating on aggregate particles, resulting in weakened bond between the aggregate and the cement paste. Excessive amounts of these fine materials may also increase the water demand of the concrete, resulting in loss of concrete strength and an increase in its permeability.

The amount of fine material is determined by washing a sample of the aggregate over a 75-micron sieve. AS 1141.11 and AS 1141.12 describe the relevant test procedures. The clay content of fine aggregate is assessed using the proportion of 2-micron material as per AS 1141.13. AS 2758.1 requires that all coarse and fine aggregate have a 2-micron proportion of 1% or less of the total mass of the individual aggregate.

For manufactured fine aggregates, AS 2758.1 requires an assessment of the presence of deleterious fines. This assessment determines a Deleterious Fines Index by multiplying the percentage passing the 75-micron sieve for the sand (determined by the methods in AS 1141.11 and AS 1141.12) with the methylene blue adsorption value (also referred to as 'MBV', determined by the method in AS 1141.66). MBV is a test to determine the 'activity' of clays in the fine aggregate. The multiple of these tests is not to exceed 150, however it is noted that manufactured sands with higher values up to 200 have been successfully used in concrete at lower proportions in the concrete aggregate blend.

Coal, wood and other lightweight materials tend to rise to the surface during vibration of concrete, especially in pavements and floors, and produce a very poor surface finish. They also cause pop-outs and staining on vertical surfaces. The percentage of light particles can be determined using the test set out in AS 1141.31. AS 2758.1 specifies a maximum limit on light particles of 1% by mass of aggregate (3% for slag aggregate).

Where surface appearance of the concrete is important, the amount of coal, wood and charcoal should preferably be even less than 1%.

Aggregates, particularly those dredged from the sea, or those quenched and washed with sea water, may be contaminated by sea salt which contains a high proportion of chloride ions. The amount of chlorides in concrete is of major concern because of its influence on the corrosion of embedded steel. They also increase shrinkage and reduce the sulfate resistance of concrete. AS 2758.1 clauses 14.3.2 and 14.3.3 and AS 1379 clauses 2.7.2 and 2.7.3 specify (in different ways) maximum chloride and sulfate contents for aggregates and for concrete as produced. Adoption of the limits specified in AS 1379 is recommended for assessing suitable limits for aggregate as these may be under those required by AS 2758.1.

Testing of the chloride content and sulfate content of aggregates is performed using the method in AS 1012.20.1 (acid extraction method) but the chloride content may also be assessed using the water extraction method using AS 1012.20.2. The water solubility method has different limits set in AS 2758.1 but is most applicable where an aggregate has chlorides locked within its mineral components that are not available to impact on the chloride level in concrete's pore solution.

5 OTHER PROPERTIES

5.1 GENERAL

There are other properties of aggregate that may impact on the performance of certain types of concrete, but these are not specified in AS 2758.1. Some of them are discussed in the following sections.

5.2 THERMAL EXPANSION

The coefficient of thermal expansion of aggregates varies from rock type to rock type and even within one type. In general, it increases with increases in the silica content of the aggregate.

The main effect of this property is to cause differential stresses between the aggregate and the cement paste (when the concrete is heated or cooled) that tend to break up the bond between the aggregate and the paste.

Concretes made with different aggregates may therefore perform very differently when subjected to high or low temperatures. When exposed to fire, for example, concrete made with siliceous materials is likely to spall and crack (resulting in loss of strength) to a much greater extent than concrete made with calcareous aggregates, e.g. limestone **Figure 3.5**.

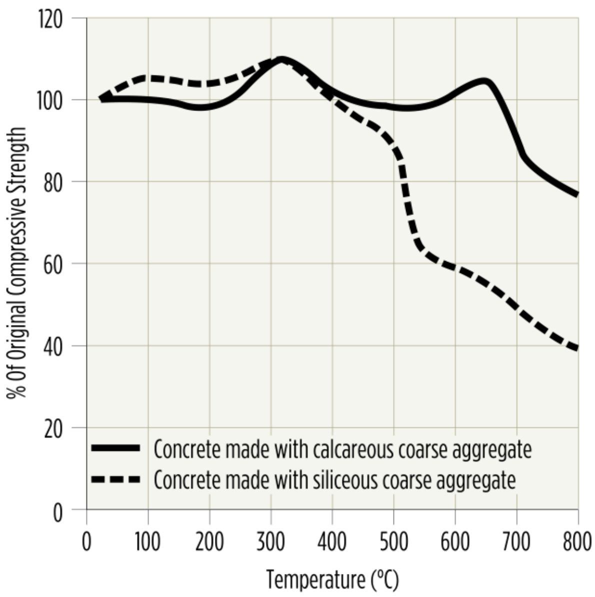


Figure 3.5 – Effect of Coefficient of Expansion of Aggregate on Performance of Concrete in Fire

5.3 COLOUR

The colour of aggregate is an important property in the production of architectural concrete, or that exposed to public scrutiny. There is considerable scope to control concrete colour through the choice of aggregates.

There is a wide variety of colours available in aggregates, ranging from white (e.g. limestone and quartz aggregate) to brown and red (e.g. river gravel) and to very dark coloured aggregates (e.g. basalt, dolerite).

The colour of the fine aggregate normally has the major influence on the colour of the concrete. It is, therefore, important that the supply does not vary during the course of the work and stockpiling of special aggregate may be necessary.

6 SUMMARY OF AGGREGATE SPECIFICATIONS

The specified properties of concrete aggregates and related test methods are best summarised in the Tables on the following pages.

Table 3.6 – Specification of Dimensional Properties of Aggregates

Aggregate Property	Test Methods	AS 2758.1 Specification
Grading	AS 1141.11.1	Fine aggregates: – Shall be in accordance with the submitted tender grading (a guide to acceptable target grading is given in **Table 3.2**); – To vary by not more than permissible deviations given in **Table 3.4**. Coarse aggregates: – Shall be in accordance with the submitted tender grading (a guide to acceptable target grading is given in **Table 3.3** with more details in AS 2758.1 Appendix B); – To vary by not more than permissible deviations given in **Table 3.5**.
	AS 1141.12	All aggregates: – The passing 75-micron proportion shall not exceed 2% for coarse aggregates, 5% for natural fine aggregates and 20% for manufactured fine aggregate.
Particle shape and surface texture	AS 1141.14	Unless otherwise specified, the proportion of misshapen particles in the fraction of coarse aggregate retained on a 9.50-mm sieve, using 3:1 ratio, not to exceed 10%.
	AS 1141.15	Flakiness index: not to exceed 35%.

Table 3.7 – Specification of Density and Water Absorption of Aggregates

Aggregate Property	Test Methods	AS 2758.1 Specification
Density	AS 1141.4 AS 1141.5 AS 1141.6.1 AS 1141.6.2	Particle density on a dry basis: – For heavyweight aggregate not less than 3.2 t/m^3; – For normal weight aggregate, less than 3.2 t/m^3 and greater than or equal to 2.1 t/m^3; – For lightweight aggregate, less than 2.1 t/m^3 and greater than or equal to 0.5 t/m^3; – For ultra-lightweight aggregate less than 0.5 t/m^3. Bulk density (compacted): – For all aggregates other than lightweight, not less than 1.2 t/m^3. For lightweight aggregate, less than 1.2 t/m^3; – For all coarse lightweight aggregates, the bulk density shall not vary by more than 10% from the tender sample test value.
Water Absorption	AS 1141.5 AS 1141.6.1 AS 1141.6.2	The maximum permissible water absorption should be nominated in the project specification. As a guide (not in AS 2758.1), water absorption figures of normal weight aggregate: – $\leq$5% for an individual fine aggregate; – $\leq$3% for an individual coarse aggregate; – Water absorption limit of $\leq$3% for the combined coarse and fine aggregate in a concrete aggregate mixture would be suitable.

Table 3.8 – Specification of Durability Properties of Aggregates

Aggregate Property	Test Methods
Wet Strength Dimensional Stability	AS 1141.22
Abrasion Resistance	AS 1141.23
Soundness	AS 1141.24
Unsound/Marginal Stone Content	AS 1141.30.1
Degradation Factor	AS 1141.25.3

AS 2758.1 Specification

Fine aggregates: Satisfactory when conforming to the following conditions.

Aggregate type	Concrete exposure classification	Conditions
Uncrushed	A1, A2 and B1	No specific durability requirements.
Uncrushed	B2 & C (C1 and C2)	Weighted average loss not greater than 6% when tested in accordance with AS 1141.24.
Crushed	For all exposure classes	Weighted average loss not greater than 6% when tested in accordance with AS 1141.24. Degradation Factor less than 60 when tested in accordance with AS 1141.25.3.

Coarse aggregates: Satisfactory when conforming to the limits specified for one of the following three sets of tests.

1. Wet strength and wet/dry strength variation

Concrete exposure classification	Minimum wet strength (kN)	Maximum wet/dry strength variation (%)
C (C1 & C2)	100	25
B1, B2	80	35
A1, A2	50	45

2. Los Angeles value and sodium sulfate soundness

Concrete exposure classification	Maximum Los Angeles value (% loss)		Maximum value sodium sulfate soundness (% weighted average loss)
	Coarse-grained rock	All other rock	
C (C1 & C2)	35	30	6
B1, B2	35	30	9
A1, A2	40	35	12

3. Los Angeles value and marginal stone content

Concrete exposure classification	Maximum Los Angeles value (%)		Maximum unsound stone content (% loss)	Total unsound and marginal stone (%)
	Coarse-grained rock	All other rock		
C (C1 & C2)	35	30	5	10
B1, B2	35	30	5	10
A1, A2	40	35	5	10

Table 3.9 – Specification of Deleterious Materials in Aggregates

Aggregate Property	Test Methods	AS 2758.1, AS HB 79 or AS 1379 Specification
Alkali-reactive materials	AS 1141.60.1 AS 1141.60.2 AS HB 79 AS 2758.1 – Appendix C	The supplier shall provide appropriate documentation to allow the assessment of the reactivity classification of the aggregate. AS HB 79 provides details of the classification and appropriate measures of mitigation if required.
Impurities and other harmful materials	AS 1141.34	Colour obtained from test not to be darker than the standard colour of the reference solution.
	AS 1141.35	The aggregate shall test negative to presence of sugar.
	AS 1141.13	Material finer than 2 µm not to exceed 1% for each of the coarse and fine aggregates.
	AS 1141.31	Except for lightweight and ultra-lightweight aggregates – materials, with particle density less than 2.0 t/m^3, not to exceed 1% by mass in the total of fine and coarse aggregates. For vesicular materials, 3% by mass is permissible.
	AS 1141.32	Weak particles are limited to a maximum of 0.5% by weight in normal weight aggregates and to 2% by weight of coarse lightweight aggregate.
	AS 1379 AS 1012.20.1 AS 1012.20.2	– Aggregates tested to AS 1012.20.1 containing sulfide or sulfate salts shall not exceed 0.01% by weight of aggregate. In addition, the combined aggregate used for a concrete mix shall not result in the concrete sulfate content exceeding 5% by mass of Portland Cement; – The combined aggregate tested to AS 1012.20.1 containing chloride salts (expressed as Cl-) exceeding 0.04% should not be used in reinforced concrete and should be reported if exceeding 0.01% (or 0.008% if tested in accordance with AS 1012.20.2). A combination of aggregates and tested to AS 1012.20.1 containing chloride salts which exceed 0.15% should not be used in plain concrete.
Deleterious fines in manufactured fine aggregate	AS 2758.1 – Clause 8.4 AS 1141.11 AS 1141.12 AS 1141.66	– Deleterious Fines Index (DFI) is assessed by multiplying the Percentage Passing 75 µm for the aggregate by the Methylene Blue Absorption Value (e.g. 7% passing 75 µm × MBV of 11 = DFI of 77); – DFI must not exceed a value of 150 without further assessment of the sand's performance in concrete.

7 REFERENCES

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4) AS HB 79 – *Alkali Reactivity – Guidelines on Minimising the Risk of Damage to Concrete Structures in Australia* (2015)
5) AS 1012.20.1 – *Methods of testing concrete – Determination of chloride and sulfate in hardened concrete and aggregates – Nitric acid extraction method* (2016)
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7) AS 1141.4 – *Methods for sampling and testing aggregates – Bulk density of aggregate* (R2013)
8) AS 1141.5 – *Methods for sampling and testing aggregates – Particle density and water absorption of fine aggregate* (R2016)
9) AS 1141.6.1 – *Methods for sampling and testing aggregates – Particle density and water absorption of coarse aggregate – Weighing in water method* (R2016)
10) AS 1141.6.2 – *Methods for sampling and testing aggregates – Particle density and water absorption of coarse aggregate – Pycnometer method* (R2016)
11) AS 1141.11.1 – *Methods for sampling and testing aggregates – Particle size distribution – Sieving method* (2009)
12) AS 1141.12 – *Methods for sampling and testing aggregates – Materials finer than 75μm by washing* (2015)
13) AS 1141.13 – *Methods for sampling and testing aggregates – Materials finer than 2 μm* (R2018)
14) AS 1141.14 – *Methods for sampling and testing aggregates – Particle shape, by proportional calliper* (R2018)
15) AS 1141.15 – *Methods for sampling and testing aggregates – Flakiness index* (R2018)
16) AS 1141.16 – *Methods for sampling and testing aggregates – Angularity number* (R2016)
17) AS 1141.22 – *Methods for sampling and testing aggregates – Wet/dry strength variation* (2019)
18) AS 1141.23 – *Methods for sampling and testing aggregates – Los Angeles value* (2009)
19) AS 1141.24 – *Methods for sampling and testing aggregates – Aggregate soundness – Evaluation by sodium sulfate solution* (2013)
20) AS 1141.25.3 – *Methods for sampling and testing aggregates – Degradation factor – Fine aggregate* (R2013)
21) AS 1141.30.1 – *Methods for sampling and testing aggregates – Coarse aggregate quality by visual inspection* (2009)
22) AS 1141.31 – *Methods for sampling and testing aggregates – Light Particles* (2015)
23) AS 1141.32 – *Methods for sampling and testing aggregates – Weak particles (including clay lumps, soft and friable particles) in coarse aggregates* (2008)
24) AS 1141.34 – *Methods for sampling and testing aggregates – Organic impurities other than sugar* (2018)
25) AS 1141.35 – *Methods for sampling and testing aggregates – Sugar* (2007)
26) AS 1141.60.1 – *Methods for sampling and testing aggregates – Potential alkali-silica reactivity – Accelerated mortar bar method* (2014)
27) AS 1141.60.2 – *Methods for sampling and testing aggregates – Potential alkali-silica reactivity – Concrete prism method* (2014)
28) AS 1141.66 – *Methods for sampling and testing aggregates – Methylene blue adsorption value of fine aggregate and mineral fillers* (2012)

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