I C O L D

COMMITTEE ON CONCRETE DAMS

SELECTION OF MATERIALS FOR CONCRETE IN DAMS

November 2013

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FOREWORD

This Bulletin "Selection of Materials for Concrete in Dams" was initially discussed at the Committee meeting in Antalya in 1999. The final Terms of Reference were approved at the ICOLD Executive Meeting in Beijing in 2000.

The terms of reference stipulated that the Bulletin is to include chapters on selection of: cementitious materials and mineral additions; aggregates; admixtures; and mixing water. The Bulletin addresses both CVC and RCC.

The Bulletin is intended to provide a practical guide to the selection of materials for concrete for dams. A key contribution of the Bulletin is the provision of frameworks to assist in appropriate selection of materials for dams in locations where available sources may be limited.

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Chairman

Committee on Concrete Dams

21 November 2013

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1   Introduction

This Bulletin provides guidelines for selection of materials for concrete dams. It includes chapters on aggregate, cementitious materials, mineral additions, chemical admixtures and mixing water.

ICOLD Bulletin 145, *The Physical Properties of Hardened Conventional Concrete in Dams* discusses briefly the role of the properties of the concrete constituents in the quality of hardened conventionally vibrated concrete (CVC). This bulletin develops these themes and also addresses Roller Compacted Concrete (RCC).

Concrete for dams is in some important respects different from concrete used for other purposes. Very large volumes can be involved with demanding placing schedules. Control of heat of hydration is important in the selection of cementitious materials for mass concrete and to a lesser extent the selection of aggregate. The strength requirements for mass concrete in dams are mostly much lower than those required of structural concrete. The service life of a dam is very long compared to most other structures. For economic reasons, aggregate is normally derived from new sources local to the dam rather than established quarries.

The exterior concrete of the dam must have adequate durability. Durability is defined as ability of the concrete to resist weathering action and abrasion which include frost, rapid temperature fluctuations and running water. This may require the use of high quality aggregate as well as other measures which are set out in this Bulletin.

In most countries there are standards that specify the qualities, components and minimum requirements to be fulfilled in order to obtain an acceptable concrete mix. These standards have been developed for routine use on reinforced or pre-stressed concrete structures which function in different stress ranges to those of a dam. Conformity with these normal standards is intended to ensure that good quality concrete can be produced. Subject to certain safeguards, it may be possible to use constituents of dam concrete which do not conform to such norms, or alternatively, to adapt the dam design to allow the use of poorer materials. For example, hardfill dams and gravity dams with flattened upstream and downstream slopes may be considered. This Bulletin provides guidance on the evaluation of such materials.

For all large dams there must be an extensive sampling, testing and quality control regime in place for aggregates and other materials, see ICOLD Bulletin 136, *The Specification and Quality Control of Concrete for Dams*. This applies particularly when demands of applicable standards and codes of practice are not fully complied with. Deviations may require approval by a supervising authority where test methods and the results are scrutinised.

The purpose of material selection is to obtain a concrete which satisfies the design criteria at lowest possible cost. The cost assumptions underpinning materials evaluations in the design phase may prove to be inaccurate in light of tendered prices and it may be necessary to revise the evaluation. The tenderers may make their own evaluation based on provided or additional test data in order to give the best possible price.

Concrete with well-balanced properties is required which include consideration of strength, workability, heat generation, shrinkage, creep and durability. These properties cannot be optimised independently and mix designs are necessarily compromises linked by the properties of the constituent materials.

Careful evaluation of the available materials should be performed early in project development and continue throughout the design and construction. Laboratory trial mixes should be made in the design phase to determine the interaction of the concrete constituents and suitable mix proportions. These are key activities for the dams engineering team and it

should be led by an engineer of good experience and knowledge of concrete technology as it applies to dams. An experienced geologist will be required to correctly identify the rock types and properties.

Although the design of the concrete mix is not the subject of this Bulletin, material selection must take into account:

- The required fresh properties
- The required hardened properties
- Thermal properties
- Durability
- The potential for expansive chemical reactions, such as AAR, and other long-term deterioration mechanisms
- Finishability of concrete and its surface quality where required for hydraulic surfaces

Here AAR refers to alkali aggregate reactions and includes ASR, alkali silica reaction. The matter of AAR, ASR and other expansive reactions such as ISA, will be addressed in a future ICOLD Bulletin to be entitled *"Expansive Chemical Reactions in Concrete dams"*.

This Bulletin does not provide detailed descriptions of chemical and physical characteristics or processes related to materials or their interactions. These are common to all concrete and good articles covering these aspects are readily available in commonly used reference works and on the internet.

2   Aggregates

2.1   Introduction

Dams are commonly in relatively remote locations, often with no proven sources of concrete aggregate within a reasonable distance. The volumes of concrete can be considerable, mostly in the range of 100,000 m^3 to several million. The quantities of concrete needed for the construction of spillways associated with large embankment dams can also run into several 100,000 m^3. Such quantities and associated production rates demand sources and processing facilities dedicated to the project and commensurate with its size and the duration of construction.

Aggregate will be obtained from rock quarries or excavations in loose sediments within a short distance of the dam or from excavations for the dam and associated works. Haulage costs can be high and there is always a strong incentive to use local materials, even if they do not satisfy usual quality criteria. Only exceptionally will aggregate be hauled long distances, and then only when local rock or loose deposits are unsuitable.

Increased costs of using sub-standard aggregate may arise from additional processing, cementitious materials and chemical additives. Such additions may be required to achieve adequate strengths and fresh concrete properties.

In some measure the geology of each dam site is unique. Some sites have a single rock type and others have a varied geology. Variability in rock types and properties will typically increase with distance from the dam: consideration of increased haul distances may bring more rock types into the picture. In all of this, correct identification of rock types is essential and this should be done by an experienced geologist. This has particular importance in the early project phases when initial assessment of the resources may be based only on field identification.

2.2   Aggregate properties

The properties of aggregate affect the concrete properties and composition in various ways which should be considered in the selection of aggregate sources.

- Concrete strength and modulus: A strong and high modulus aggregate will give a concrete of high strength and modulus. Conversely, a weaker aggregate will give a lower strength concrete and lower modulus. A low modulus concrete is desirable to give higher strain capacity and reduce the cracking potential. A high strength concrete may not be required in the body of dams.

- An optimal aggregate grading curve gives a densely packed aggregate with a higher concrete modulus and allows a reduced cementitious material content.

- Poisson's ratio is normally not significantly influenced by the aggregate.

- Porosity and permeability of aggregate affect frost susceptibility. With high aggregate permeability the concrete permeability may also increase. Related to this is absorption where high values can give problems in producing concrete with consistent water content and workability.

- Thermal parameters including shrinkage are dominated by the aggregate properties.

- Specific gravity: A heavy aggregate is beneficial for the stability of gravity dams.

- Drying shrinkage and creep are dominated by the properties of the cement paste with aggregate properties being less significant.

- Particle shape and texture affect workability and strength or, conversely, the required cementitious content for a given strength. Good particle shape is particularly important for Roller Compacted Concrete. Crushed aggregate typically gives concrete with a water demand which is higher than that for rounded natural aggregate.

Ideal aggregate comprises hard, durable and chemically inert particles of roughly spherical or cubic shape. Table B1 shows typical standard requirements. The further the aggregate is removed from this, the greater the cost of compensating for the deviation. Some rocks are not usable under any circumstances.

Characteristics which may adversely affect aggregate quality are:

Weak particles

Dimensionally unstable material

Propensity to yield flat and elongated particles

Deleterious particles and minerals such as mica

Unsound particles such as clay, organic material, etc.

High and variable water absorption

Amorphous silica and other compounds which might deleteriously react with cement or its hydration products

Water soluble minerals, e.g. salt and gypsum

Some of these can be compensated for by various means such as by proper selection of aggregate crushing and processing equipment. Notably, the deleterious reaction between amorphous silica and the hydration products of cement can be suppressed by using pozzolan as part of the cementitious material. Inclusion of pozzolan commonly also reduces the cost of the concrete and may improve workability, see Chapter 4.

There are other properties related to the mineralogy and surface texture which may affect concrete properties but these are of second order in importance and would not normally affect the selection of aggregate source.

2.3   Aggregate grading curves

The fresh and hardened properties of concrete are also dependent on the grading curve of the aggregate and the maximum size of aggregate (MSA). A bad grading curve or particle shape may adversely affect the workability of the fresh concrete, generate excess bleeding and require a higher cementitious content, increasing the heat of hydration and the temperature rise of mass concrete. These aspects can be controlled to a large extent by suitable processing and are not a primary consideration in material source selection.

The MSA is determined from consideration of:

- the peak strain in tension decreases with increasing MSA

- the shear strength increases with MSA (aggregate interlock)

- workability decreases with increasing MSA

There is a tendency for smaller MSA to be used in mass concrete (say 100 to 120mm instead of 150mm for many older dams) because savings in cement for large MSA are offset by easier mixing and placing, better workability, less segregation and shorter vibration time. For RCC the MSA is commonly restricted to 40 mm to 60 mm for similar reasons but may be 75 mm where workability and segregation are of lesser importance in the interior of dams.

Alluvial sand can on occasion be gap-graded, i.e. some intermediate range of particle sizes or the finer fraction is missing. This may require the addition of other material to compensate for the missing particles or by milling the sand to the required grading. Any additional material may also be milled or crushed. It is not uncommon to use a blend of alluvial and milled or crushed sand to achieve a good grading curve. The inclusion of a milled or crushed product can also provide a missing finer fraction (<75 micron) in the alluvial sand. This can be of particular importance for RCC where the percentage of fines can be high, up to 15% and maybe more. The cost of any such processing must be included in the evaluation of aggregate sources.

2.4 Durability requirements

Weathering of concrete can result in cracking, spalling and loss of material from the concrete surface. Exterior concrete has to be durable and may therefore have to comprise concrete made from resistant materials which are of higher quality than interior concrete. Where frost action is not present, it may be sufficient to specify a minimum strength, maybe as low as 5 to 10 MPa for smaller gravity dams. Concrete for hydraulic surfaces such as spillways may have to have a much higher strength. Frost action will as a minimum demand air entrainment (see Section 5.6). In very harsh climates severe restrictions on absorption values of aggregate, porosity, minimum strengths and maximum water/cementitious ratios may have to be applied. There are various national standards covering requirements for durability and for frost resistance in particular.

2.5 Thermal properties

Thermal expansion is of major significance for dam design as it affects stresses and contraction joint spacings. The coefficient of thermal expansion of the concrete is dominated by the properties of the aggregate. Where there is a choice, it is preferable to select aggregate with a low thermal expansion coefficient. Coefficients vary considerably, even for one rock type, and tests are required to establish the values. Indicative values for concrete with some aggregate rock types are shown in Table 2.1.

Thermal conductivity, diffusivity and specific heat are important properties but are not commonly criteria in the selection of aggregate sources. ICOLD Bulletin 145 *The Physical Properties of Hardened Conventional Concrete in Dams* in its tables 6.4 and 6.5 gives typical values of these parameters and may be referred to if these might be relevant to aggregate source selection.

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Table 2.1 Indicative coefficients of thermal expansion of concrete

Aggregate rock type	Coefficient of linear expansion, 10^{-6} °C
granite and rhyolite	5 to 11
basalt, gabbro, and diabase	4.5 to 8.5
limestone and dolomite	4 to 12
slate	8 to 10
andesite and diorite	5 to 9
sandstone	8 to 12
marble	5 to 9
flint and chert	8 to 12
gneiss, greywacke	4 to 9
quartzite	8 to 13

2.6 Methodology for Selection of Source for Aggregate

The effort required to establish a suitable source for aggregate will vary from the minimal and simple where there is good rock or alluvium close to the dam site, to the extensive and complex where there are no large bodies of obviously suitable material within a reasonable distance. In the latter case aggregate may have to be obtained from sources which will yield material which does not conform to standards referred to in this Bulletin and which may lead to increased cost of the concrete or a change in design to accommodate the available aggregate.

A strategy for determining sources for aggregate has to be developed early in the feasibility stage of project development with refinements following in the tender design phase and into construction. A plan should be developed along the following lines:

- Geological mapping of the area in the vicinity of the dam and more distant promising rock units, to identify the rock types present and with preliminary assessments of suitability as source rock. **Table 2.2** may be used as a guide. If no promising rock is found, the area to be mapped will have to be increased. Obtain surface samples as far as possible from fresh rock for indicative rock strength, petrographic studies (Section 2.7) and chemical testing.

- List the available rock types with their expected properties which will include strength, probable obtainable particle shape (with consideration of processing) and possible deleterious minerals within the rock or liberated during processing. Quarrying (including removal of overburden and access roads), and processing costs (including crushing, screening and washing), transport costs and any possible interference with the rest of the works need to be evaluated. This applies also to foundation and other excavation material where this is to be an aggregate source.

- Make an assessment of which is the most promising source or sources. Develop and implement an investigation programme for these as indicated in Section 2.9.

- Based initially on experience, and later on the results of trial mix programmes, estimate the cost of concrete made with aggregate from alternative sources.

- Evaluate risks associated with each option including adequacy of the size of the source body, risks of undesirable variations in source properties and security of supply.

Consider the technical and cost implications of all factors and make a preliminary determination of the aggregate source. The final determination may have to be made after crushing and screening of rock from trial blasts as only then may issues with particle shape, gradation and processing costs be fully revealed.

2.7 Petrographic microscope examinations

Petrographic microscope examinations should be made early in the investigations to confirm the rock types present and to identify deleterious minerals that might be present. EN 932-3 – *Simplified Petrographic Description of Aggregate* can be used for simplified and preliminary studies for the purpose of general classification. BS 812-104: 1994 – *Petrographic Examination of Aggregates* gives a general method for the detailed examination of samples of coarse or fine aggregates. There is no EN equivalent to this test at time of writing. ASTM C295 – *Petrographic Examination of Aggregates* is similar to the BS but requires each size of processed aggregate to be examined separately. BS 5930 – Petrographic Examination of Rock, includes the requirements of BS 812-104: 1994 and requires the determination of other rock characteristics such as texture, structure, alteration and weathering. RILEM AAR-1 petrographic method includes three separate procedures to identify potentially reactive particles in an aggregate sample. Where hand separation will only work with coarse gravel aggregate, the point counting analysis on a microscopic scale and the whole rock petrography on thin sections are the appropriate procedures for the majority of aggregates used in dam concrete.

2.8 Preliminary Assessment of Suitability of Rock Types

Table 2.2 below provides a summary table of rock types and indicates general suitability and possible issues with applying such rock types as aggregate in dam concrete. It is only to be used to give a preliminary indication of suitability. Extensive testing is required on any new or unproven source of aggregate.

The list of rock type names and their summary descriptions is not exhaustive as there are many variants with different names. An experienced geologist should be able to place most rock types within one of listed rock types. Sand and gravel have been included in the table in the interest of completeness.

The "Comments" column identifies potential problems or suitability and indications of possible expansive chemical reactivity, mostly ASR. The assessed frequency of occurrence of such problems is given in the following columns. These issues are discussed further in Section 2.10.2.

The column "Particle Shape" gives an indication of propensity for a rock type to yield flaky or elongated particles. This may require particular types of crushers in order to achieve a suitable particle shape and processing costs may increase.

The indications in the "Mica" column refer to free mica, not mica bound into the rock (mica as a rock-forming mineral).

Where pozzolanic properties are indicated, this applies to finely ground material, see Section 4. Some highly reactive (ASR) rock types may be pozzolanic if finely ground, e.g. ignimbrite. Some reactive (ASR) rock types may be used as pozzolan either alone or blended with others.

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Table 2.2 Table for Preliminary Assessment of Suitability of Rock Types as Aggregate

See cautionary notes in Section **Erreur ! Source du renvoi introuvable.**.

KEY: ASR: Alkali silica reaction   **ISR**: Internal Sulphate Reaction   **TSA**: Thaumasite Sulphate Reaction

Suitability: 3 = Commonly suitable, 2 = Can be suitable, 1 = May be suitable, 0 = Normally not suitable.

Common or potential problems: XXX = Frequently, XX = Intermediate, X = Occasionally

Rock type	Description	Comments	Suitability	Common or potential problems				
				Chemical reaction	Strength	Particle shape	Mica	Clay
Igneous Volcanic								
Basalt	Fine grained basic rock	May be vesicular and may contain amygdala which may contain reactive mineral	3	X		X		
Andesite	Fine grained intermediate rock	May contain biotite, reactive silica (ASR) and clay minerals	3	XXX				X
Dacite	Felsic to intermediate volcanic rock with high iron content	May contain glass, cristobalite and tridymite	3	XX		X	X	
Trachyte	Fine grained with plagioclase dominating	Normally suitable	3	XX			X	
Rhyolite	Felsic acidic volcanic rock related to granite	Can be suitable, quarries may be complex. May contain glass, cristobalite and tridymite. ASR	3	XXX				
Obsidian	Volcanic glass	Typically reactive (ASR) and brittle, low specific gravity.	0	XXX		XXX		
Ignimbrite	Fragmental or crystalline volcanic rock	Very variable in composition and strength. Has been used as aggregate.	1	XXX	XXX			
Volcanic breccia	Comprises angular fragments of rock in a matrix	Variable composition depending on parent rock(s)	1	XX	X			
Pumice and Scoria	Fine grained and extremely vesicular, scoria denser than pumice	Not suitable as normal weight aggregate, pozzolanic	0	Pozzolanic	XXX			XXX
Tuff	Volcanic ash, may be loose or lithified, may contain montmorillonite	Pozzolanic, may be suitable if lithified	2	Pozzolanic	XX			

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Rock type	Description	Comments	Suitability	Common or potential problems				
				Chemical reaction	Strength	Particle shape	Mica	Clay
Igneous sub-volcanic								
Diabase/ Dolerite	Intrusive mafic rock forming dykes or sills	May contain reactive minerals, ASR	3	X				X
Pegmatite	Mostly rock of granitic composition with very large crystals, mostly in veins. Can be mafic.	May yield aggregate formed of single crystals which may fail on cleavage planes. May contain mica. ASR	1	X	X		XX	
Igneous Plutonic								
Peridotite	Ultramafic rock composed of > 90% olivine	Can contain reactive clays	3					XX
Gabbro	Coarse grained basic plutonic rock related to dolerite	Generally suitable	3					
Norite	Hypersthene bearing gabbro (basic)	Generally suitable	3					
Anorthosite	Ultramafic rock with predominant plagioclase	Generally suitable	3					
Diorite	Coarse grained intermediate rock composed of plagioclase, pyroxene and/or amphibole	ASR may be an issue due to sometimes higher silica content.	3	X				
Granodiorite	Granitic rock with plagioclase > orthoclase	ASR may be an issue due to sometimes higher silica content.	3	X				
Granite	Acidic coarse grained rock composed of orthoclase, plagioclase and quartz	ASR may be an issue due to sometimes higher reactive silica content and feldspars that might release alkalis	3	X			X	
Syenite	Coarse grained rock dominated by orthoclase feldspar	Generally suitable	3					
Aplite (intrusive granite)	Fine grained granite with quartz and feldspar dominant	Generally limited to narrow outcrops (dykes and sills). ASR	3	X				
Clastic sedimentary								
Conglomerate	Large rounded rock fragments in finer matrix	Matrix may be weaker than clasts. ASR	1	X	X			XX
Greywacke	Immature sandstone with quartz, feldspar and rock fragments within a clay matrix	May be suitable, but matrix may be weaker than clasts. ASR	2	XXX	X			XXX
Sandstone	Clastic sedimentary rock defined by its grain size	Often suitable, but can be too weak for aggregate. ASR	3	X	X	XX		
Sand	Un-cemented material mostly finer than 5 mm. Feldspathic sands less suitable than quartzitic sands	Generally suitable, depends on parent rock, may contain clay, shells or mica in deleterious quantities, ASR	3	XX			XXX	X

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Rock type	Description	Comments	Suitability	Common or potential problems				
				Chemical reaction	Strength	Particle shape	Mica	Clay
Gravel and cobbles	Uncemented particles, commonly containing many rock types, mostly coarser than 5 mm	May contain rock types with deleterious properties, depends on parent rock.. ASR	3	XX		XX	X	X
Sedimentary breccia	Composed of angular coarse fragments of other rocks in a finer matrix	May be petrographically heterogeneous with deleterious rock types. ASR	1	XX				
Till (boulder clay)	Broadly graded material formed by glacial action	Can contain much silt and rock flour, expensive to process, may be pozzolanic. ASR	3 [1]	XX		XX		XXX
Tillite	Lithified till	Contains a variety of rock types and each source has to be evaluated. ASR	3	XX				
Claystone	Weakly lithified clay	Generally weak, may slake and yield clay particles. ASR + sulphides	0	X	XXX			XXX
Mudstone	Weakly lithified clay and silt	Generally weak, may slake and yield clay particles. ASR + sulphides	0	X	XXX			XXX
Shale	Weakly lithified fissile claystone and mudstone	Generally weak, may slake and yield clay particles. ASR + sulphides	0	X	XXX			XXX
Siltstone	Weakly lithified siltstone	Generally weak, may slake and yield clay particles. ASR + sulphides	1	X	XXX			XXX
Biochemical and chemical sedimentary								
Chalk	Composed primarily of coccolith fossils	Generally weak and not suitable for aggregate. May be suitable as filler.	0	X	XXX			
Dolomite	Composed of the mineral dolomite + calcite	Normally suitable. ACR	3	X				
Limestone	sedimentary rock composed primarily of carbonate minerals	Normally suitable, but may contain chert. May contain clay. ASR	3	X				X
Marl	Limestone with a considerable proportion of clayey and silty material	Normally not suitable, tends to be weak and clayey	1		XXX			XXX
Travertine	Precipitated calcite and iron oxides	May be vesicular and unsuitable as coarse aggregate	2		X			
Chert and flint	Fine grained chemical composed of silica as part of lithification process	Commonly gives ASR	2	XX		XXX		

[1] After processing

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Rock type	Description	Comments	Suitability	Common or potential problems				
				Chemical reaction	Strength	Particle shape	Mica	Clay
Metamorphic								
Amphibolite	Composed primarily of amphibole	Can be suitable, but may contain a high proportion of biotite	2			X	X	
Hornfels	Formed by heating by an igneous rock	Generally suitable if biotite content is small or remains included in fragments. ASR.	2	XX			X	
Marble	Metamorphosed limestone	Normally suitable	3		X			
Quartzite	metamorphosed sandstone typically composed of >95% quartz	Normally suitable, may contain reactive quartz. ASR.	3	X		X		
Gneiss	Coarse grained banded metamorphic rock, can grade into granite	May yield flaky and elongated aggregate, may contain mica. ASR.	2	X		XXX	XX	
Migmatite	High grade metamorphic rock verging upon melting into a magma	Can contain biotite	3					
Phyllite	Low grade metamorphic rock composed mostly of micaceous minerals	Mica content may make it unsuitable. ASR.	1	XXX			XXX	
Schist	Low to medium grade metamorphic rock	Typically yields flaky and elongated aggregate, may contain mica. ASR.	2	XX		XX	XX	XX
Slate	Low grade metamorphic rock formed from shale or silts	Typically yields flaky and elongated aggregate, may contain mica	1		XX	XXX		XX
Soapstone	Essentially a talc schist	Too weak for aggregate	0		XXX			XXX
Mylonite	Fine grained sheared rock, properties depend on parent rock, ASR if siliceous	Uncommon in large bodies, chemical reactivity affected by parent rock	Depends on parent rock	Depends on parent rock				
Serpentinite	Ultramafic rock dominated by serpentine minerals	Normally unsuitable, contains soft or fibrous minerals including asbestos	0		XXX	XX	XX	
Other								
Mining waste	Highly variable in composition and grain size	Detailed studies required to identify deleterious reactions including degradation mechanisms	1		XXX			
Recycled aggregate	Variable in matrix composition and grain size	Studies required to identify water absorption, strength of matrix and fines content	2		X			

2.9 Quarries and borrow pits

The process described below applies equally to rock quarries and alluvial sources but the methods of investigation may be different.

Having performed the key activities outlined in Section 2.6, the sources have to be investigated by:

- Drilling (and test pits in loose deposits) to demonstrate that a sufficient quantity of suitable rock is available and to reveal complexities in the geology. For feasibility design the estimated quantity should be three times the requirement and for tender design with more holes and good knowledge of the source, the demonstrated quantity should be not less than 1.5 times (and maybe 2 times) the requirement. These ratios may have to be increased if there are known variations which might lead to high wastage. Losses of rock, which might amount to 15% of the nominal requirement, have to be allowed for. These losses are made up mainly of unsuitable rock and shot rock used for other than aggregate production.

- Drilling and test pits may be supplemented with geophysical investigations, such as refraction seismic surveys, to determined overburden depths and thicknesses of alluvial deposits and the like

- Detailed logs of cores to give rock type, fabric and structural elements and to determine complexity of potential quarries

- Petrographic examinations with emphasis on potentially deleterious minerals and features

- Physical investigations, e.g. uniaxial compressive strength (UCS), gradings, clay content, Los Angeles (LA) abrasion, specific gravity, porosity, water absorption, organic content, flakiness and elongation)

- Chemical investigations (e.g. sulphate, chloride, ASR)

A trial blast should be made to obtain fresh rock for laboratory testing of rock properties and to manufacture aggregate for concrete trial mixes. The rock has to be crushed and graded into several size ranges with good particle shape. Sand may have to be milled. Material has to be obtained from potential alluvial or other loose sources. All this should preferably be done at the feasibility stage or early in the tender design stage at the latest, see Chapter 7. The quantities of rock required for concrete testing can be large, maybe 20 tonnes or more, depending on the number of trial mixes required and whether test cylinders or cubes are used. In some practices much larger quantities are obtained, of the order of 200 tonnes, in order to establish a processing methodology and verify the types of crushers required. The trial mixes may include blended natural and manufactured aggregate to overcome deficiencies in the former, e.g. gap grading, missing fines (see Section2.3) or excessive mica (see Section2.10.1.1).

2.10 Deleterious minerals, properties and reactions

The potential source rock may contain deleterious minerals, fabric or structure which might make it unsuitable or complicate its use. Table 2.2 gives a preliminary indication of possible problems but testing is always required for any potential source of aggregate. Problematic materials and reactions, some of which may apply only to specific rock types, are given below.

2.10.1 Minerals

1. Mica

The term mica covers a range of platy minerals and includes muscovite (pale mica) and biotite (dark mica) as the most common forms. It occurs in some metamorphic and igneous rocks and is common in alluvial deposits. Its presence as free mica may reduce concrete strength, in particular tensile strength (although cases are reported where tensile strength was less affected than compressive strength and modulus), and increase water demand (reduce workability). The maximum quantity allowed in fine aggregate (sand) is normally 3 or 5% with the assumption that none will accompany the coarse aggregate. Some micaceous coarse aggregate may yield free mica particles due to abrasion and breakage while handling which might reduce the maximum allowable percentage in the fine aggregate. Alternatively the coarse micaceous aggregate may not be used. Mica as a rock-forming mineral should not exceed 15% of the rock mass. This situation may apply to such rocks as micaceous schist. Of the two most common mica minerals, muscovite and biotite, muscovite may be more deleterious.

If mica contents higher than 3 or 4% of the fine aggregate (sand) are being considered, extensive testing may be required to ensure that the fresh and hardened properties of the concrete are satisfactory.

2. Reactive Silica

Reactive silica occurs in a number of forms, as listed below, and might react with alkali from cement paste, see Section 2.10.1-2 on ASR.

- Quartz, pure silica, SiO_2. The mineral is hard and is widespread in rocks and drift. Some strained, granulated and microcrystalline quartz may be reactive.

- Opal, hydrous silica, $SiO_2.nH_2O$, is found in sedimentary rocks including chert. It occurs also as coatings on alluvium and infilling in voids in volcanic rock.

- Chalcedony is fibrous and porous quartz, typically associated with chert.

- Tridymite and cristobalite are high temperature forms of silica occasionally found in volcanic rocks. These forms of silica are metastable at normal pressures and temperatures.

Generally, the more reactive are the amorphous silicates with low crystallinity or very altered or deformed crystal lattices. Another critical factor of the reactivity is the aggregate's porosity, since the more porous aggregates are, the more easily aggressive ions penetrate and generate expansive products.

Deleterious reaction of silica with cement can be reduced or eliminated by using pozzolans in the concrete mixtures, see Section 4.1.

3. Sulphate minerals: Gypsum, $CaSO_4 \cdot 2H_2O$ and anhydrite, $CaSO_4$

Both gypsum and anhydrite can cause sulphate attack in concrete, see Section 2.10.2.

Gypsum is used in cement to control setting time. The presence of the more soluble forms of gypsum in the aggregate may increase the setting time or prevent the concrete from setting altogether. Natural anhydrite has slower solubility than synthetic anhydrite and can lead to compatibility problems with some chemical additives. If the anhydrite is soluble it will affect the setting time as does gypsum.

The main problem of gypsum in aggregates is not that it reacts with aluminates when the concrete is in a plastic state, but reacts when hardened, which produces internal sulphate

attack, similar to the reaction with oxidation of pyrites and pyrrhotites. Moreover, under certain conditions of temperature and in the presence of carbonates and silicates it can give thaumasite formation, although this is a rare reaction, see Section 2.10.2 - 3.

4.   Iron sulphide minerals

Iron pyrite, FeS_2 is the most common mineral in this group. Through chemical reaction pyrite can create SO_3 and therefore generate internal sulphate attack, see Section 2.10.2 - 2. Iron pyrites and marcasite can react with the hydration products of cement and swell. Not all iron pyrites is harmful (Neville, 1995). There are also cases with iron pyrite inclusions in limestone or granite of a size significantly less than one millimetre generating ettringite formation and deterioration of concrete.

5.   Clay

Clay is mostly harmful to concrete and is normally excluded from aggregate. There are some minerals which might turn to clay through chemical reactions, including weathering. This includes zeolite and laumontite, sometimes present in basaltic rock (amygdales) and some marl, even if initially hard, and some forms of mica. Clay has been added to concrete mixes in a controlled manner as pozzolan (Chapter 4) and to reduce the concrete modulus. Clay may occur as coatings on fine or coarse aggregate which has to be removed by washing. Typically clay content is limited to 1% of the total aggregate for mass concrete.

6.   Salt (NaCl, KCl)

Water soluble salts can occur as a contaminant. Salts may contribute to corrosion of steel reinforcement and embedded items. Typical limits for total water and acid soluble chloride content are 0.5 kg/m^3 for pre-stressed concrete and 0.8 kg/m^3 for reinforced concrete exposed to moisture or chloride in service. There are no particular limitations for unreinforced mass concrete.

Chlorides may react with hydrated and anhydrous compounds of cement, leading to the formation of an expansive compound known "Friedel's salt", which subsequently can also react with the sulphates to form ettringite, c.f. item 4 above.

7.   Periclase, MgO,

This mineral can be found within some dolomitic limestone which changes into $Mg(OH)_2$ and has swelling properties when reacting with cement.

2.10.2   Reactions

1.   ASR

Alkali Silica Reaction (ASR) has been identified in many concrete dams (ICOLD Bulletin 79). ASR normally becomes apparent 20 to 30 years after the dam completion but can manifest itself within only a few years. The alkalis of the cement may react with minerals of the rock containing pseudo-amorphous silica (including cristobalite and tridymite) and strained or granulated quartz, see Section 2.10.1 - 2.

An examination must be carried out in order to check the reactivity of the raw material with reference to the ASR risk. There have been instances where the coarse and fine aggregate was so reactive that it acted as its own pozzolan and no adverse long term reaction took place. Test methods for ASR may be found in ASTM C1260, ASTM C1293, AFNOR P 18-542, AFNOR NF P 18-454, and AFNOR FD P 18-456, AFNOR NF P 18-594 and RILEM Recommended Test Methods. The choice of testing method should be critically considered and testing should

commence as early as possible. Along with the above referred testing methods, targeted petrography is indispensable. Generally the test sequence required to define the the susceptibility of an aggregate is first the petrographic analysis, secondly an accelerated test with aggregate and cement in mortar and, if shown to be reactive, tests with the aggregate and cement in concrete with the addition of pozzolan if used.

2.   Internal Sulphate Attack, ISA

ISA occurs when a source of sulphate is incorporated into the concrete. Examples include the use of sulphate-rich aggregate, excess of added gypsum in the cement or contamination. The reaction causes swelling of the concrete and loss of strength.

The phenomenon is caused by the formation of ettringite as a result of the reaction of calcium aluminate with calcium sulphate. Control of the SO_3 content of the aggregates and concrete temperature are the key factors in avoiding ISA. EN 1744-1 limits the acid soluble SO_3 to a maximum of 0.8 % by mass of the aggregate. The maximum temperature of concrete during hydration should be kept below 60-70 °C.

3.   Alkali-Carbonate Reaction, ACR

ACR is not very frequent. It is a reaction that occurs between the alkalis present in cement and aggregate containing dolomite with the formation of brucite (magnesium oxide) and alkali regeneration to concrete, c.f. Section 2.10.1 - 7. In recent years, some examples of ACR have been reinterpreted as ASR, i.e. reactive silica within a carbonate host rock (Katayama et al, 2008).

2.10.3   Aggregate strength and integrity

1.   Strength

Strength is initially assessed by field inspection and later by testing of uniaxial compressive strength (UCS). The aggregate particles will normally have a higher strength than that indicated by the UCS as the test specimens contain flaws which are obliterated in aggregate crushing. The measurement of abrasion loss will show any material which is too weak to be suitable and this is normally a better guide.

2.   Abrasion loss

Abrasion loss is commonly tested in the Los Angeles abrasion testing machine. Losses can vary from 10% or so for very good igneous rocks to 60 or 70% and even higher for weaker sedimentary rocks. The acceptable maximum value is 50% in ASTM C33 but a maximum of 40% is commonly recommended. The main purpose of the test standard is to ensure that breakage of aggregate during handling remains at a level which do not significantly alter the grading curves. If suitable precautions are taken and control tests carried out, material with a higher abrasion loss than 40% can be used and over 60% has been used successfully at Upper Stillwater dam. In EN 12620 there is no upper limit but aggregates with losses exceeding 40% should be assessed on the basis of experience of use. With high abrasion loss material it may be necessary to eliminate stockpiles (and take the material directly from the screening plant to the batch plant) and transport aggregate by truck rather than conveyor, and provide re-screening aggregate just before it enters the batching plant and wet screening fresh concrete to check on the actual grading curve. Information from this test can be used to adjust the batch weights until an acceptable aggregate grading is achieved in the fresh concrete. Other measures may include using shorter batching times and in RCC applications limiting

equipment passes, adopting more workable mixes and reducing the proportion of coarse aggregate in the mix.

3. Lamination

Lamination is the condition where the rock readily splits into thin slabs or lamina. The splits may occur on bedding or foliation planes and are present in many sedimentary rocks and their metamorphosed equivalents. When put through a crusher the resulting particles tend to be elongated and flaky, both undesirable properties in concrete aggregate. Particle shape can be improved with impact crushers. Excessive flat and elongated particles need not be excluded as aggregate, but their inclusion will give higher cement demands. Concrete made with such aggregate is typically more anisotropic in its properties than concrete made with cubic or well-rounded aggregate. With RCC in particular, tensile strength in the vertical direction may be reduced. Furthermore, the cost of the concrete made with such aggregate will be higher than normal.

4. Slaking

Some rock types, typically marl, shale, siltstone and claystone, deteriorate when exposed to the humidity of the air (water). Such material will not be suitable as a source of aggregate. This property is commonly evident in core boxes where it might occur within days or weeks of the core being exposed.

5. Weathering

Weathering may weaken rock and produce weak and deleterious particles depending on its degree. Rock that is suitable according to the rock type may be unsuitable in its weathered state and will certainly be unsuitable if completely weathered. Rock in weathering class I and II (ISRM classification) can be expected to be suitable from a weathering standpoint.

6. Dimensional stability

Rocks which change volume in response to changing water content are normally not suitable as aggregate. According to EN 12620, the drying shrinkage of aggregate should not exceed 0.075%. If clay minerals are identified, there will be a significant risk of dimensional instability. Such rocks may include shales and other fine-grained sedimentary rocks which are poorly indurated or chemically altered rock. Aggregate with shale, slate, hornblende and greywacke are to varying extents associated with high shrinkage in concrete. Nott *et al.* (2012) report the successful use of aggregate with shrinkage which exceeded the Australian (and European) norms.

ASTM C157 prescribes a method of measuring shrinkage which uses moist cured concrete prisms. These prisms are 100 mm square and 285 mm long which may be too small to give realistic results for dam concrete. Larger specimens may be required, see ICOLD Bulletin 145, p 5-10.

Shrinkage of clay-rich particles is very common although they do not usually form a large proportion of an aggregate. Some clay types are particularly prone to volume change with varying moisture content. The clay can be a contaminant of the aggregate or a natural part of it. Testing with ethylene glycol and the MBV (methyl blue value) test will help identify potentially unsuitable rock (Nott et al, 2012).

7.   Soundness: Freeze-thaw Resistance

Soundness of aggregate is the ability to withstand aggressive action to which concrete might be exposed, particularly that due to weather. Damage due to freezing and thawing is the prime concern where sub-zero temperatures may occur.

Damage potential increases with the number of freeze-thaw cycles and decrease in temperature.

A petrographic examination of the aggregate according to the procedure specified in ASTM C295 or BS 812-104 can give an indication of the presence of weak and highly absorptive particles that can be susceptible to damage from freeze-thaw action. Where the presence of such particles is observed or suspected, a physical test can be used to assess freeze-thaw resistance of the aggregate.

Susceptible aggregates derived from highly weathered rocks and some conglomerates and breccia may include the following deleterious rocks: schist, mica schist, phyllite, limestone with expansive clay laminae, altered dolomite, chalk, marl, shale, porous flint and chert, altered porous basalt, particles containing expansive clays or aggregate loosely cemented by clay minerals.

Freeze-thaw resistance of the aggregate is mainly dependent on type of climatic exposure, type of use and petrography. The frequency of freeze-thaw cycles and the degree of saturation of the aggregates is important. If the aggregates are exposed to sea water or de-icing salts, the risk of freeze-thaw degradation increases markedly. The freeze-thaw resistance is also related to aggregate grain strength, pore size distribution and amount of pores within the aggregates.

A first screening may be done with a water absorption test according to EN 1097-6 where a result below 1% suggests good freeze-thaw resistance of the aggregates irrespective of exposure type. However, many satisfactory aggregates have significantly higher absorption values, so that this criterion may be overly conservative.

For aggregates with water absorptions over 1%, further testing may be carried out according to EN 1367-1 where the weight loss in percent is measured after freezing and thawing in water. If the aggregates (concrete) will be exposed to sea water or de-icing salts a test according to EN 1367-2 should be performed. Acceptable limits depending on exposure type and climatic regions can be found in EN 12620, Table F1, which has to be read in conjunction with Table 18 of the same EN. For the most severe conditions the weight loss should not exceed 1%.

Physical tests may be carried out to ASTM C88 or CRD-C 148-69.

In severe conditions testing of the hardened concrete freeze-thaw durability still has to be done even if the aggregates are considered durable. Testing can be made according to CEN/TS 12390-9 where good durability is proved when scaling is below 0.5 kg/m^2.

Testing of the resistance to the sodium sulphate action can be done according to ASTM C 88 and samples are deemed satisfactory if the average loss by weight, after 5 cycles, is not more than 12% and not more than 18% when magnesium sulphate is used (the limits are 10% and 15% for fine aggregate).

8.   Water absorption

Water absorption can be a significant factor in the choice of aggregate, particularly if the dam will be exposed to freeze-thaw cycles, and is commonly associated with lesser quality aggregates. Water absorption normally is not a significant factor in the choice of aggregate in

frost-free climates. However, there are cases where the high absorption of the aggregate has considerably disturbed the effectiveness of setting time retarding admixtures in RCC. If there is a choice, aggregate with a low absorption is preferred. All aggregate used in concrete should be saturated surface dry (SSD) when it enters the mixers and this has to be ensured by suitable watering systems in the stockpiles. Fine aggregates generally have a higher absorption than the coarse aggregate. Particle strength and resulting strength of concrete is adversely affected as absorption values increase.

In EN 1097-6 the value for water absorption should not exceed 3 to 5 % depending on the type of rock.

2.10.4 Contaminants

1. Shell content

Shell content of coarse and fine aggregate has little effect on compressive strength, but some effect on tensile strength and workability. EN 12620 recommends a maximum limit of 10% for coarse aggregate for the strictest category.

If the shell content exceeds standard or code requirements, tests must be carried out to check that the required compressive and tensile strengths can be achieved economically and that the impact on durability is limited.

2. Organic impurities

Organic matter in aggregate may have a retarding effect on the setting of cementitious material and may result in lower strengths of the hardened material at all ages.

The presence of organic impurities may be tested according to ASTM C40 or EN 1744-1. If the material fails this test, further tests are required using ASTM C87. Here mortar is tested for strength using sand in its natural state and washed and the results compared. There may be time dependence of the effect of impurities. Aggregates and filler aggregates that contain organic or other substances in proportions that alter the rate of setting and hardening of concrete shall be assessed for the effect on stiffening time and compressive strength in accordance with ASTM C87 or EN 1744-1. The proportions of such materials shall be such that, in accordance with EN 1744-1, they do not increase the stiffening time of mortar test specimens by more than 120 min and that they do not decrease the compressive strength of mortar test specimens by more than 20% at 28 days.

3. Unsound particles

Some of the deleterious mineral above may be unsound particles. Others may occur such as wood and coal. Particularly coal can swell and can disrupt hydration. The quantity of all unsound particles is normally limited to 2 to 5%. Up to 0.25% coal is allowable according to EN 12620 and 0.5 to 1% is allowed by ASTM C33.

4. Fines in aggregate

Fines in aggregate, particles less than about 75 micron in size, are normally limited to safeguard workability and overall grading. Common limitations on fines in aggregate are:

Coarse:	2% but up to 4% for all crushed rock
Fine:	4% but up to 16% for all crushed rock
All-in aggregate:	11%

Included fines should be non plastic. Fines adhering firmly to coarse aggregate surfaces can result in reduced tensile strengths, washing may be required.

ASTM 33 gives 3 to 5% for fine aggregate increased to 5 to 7% for manufactured sand and up to 1.5 % of coarse aggregate depending on concrete use.

The sand equivalent test provides a measure of the relative proportions of detrimental fine dust or clay-like material in fine aggregate. The test may be done in accordance with ASTM D2419.

The ASTM requirements can be too restrictive. High percentages of fines may be acceptable, particularly in RCC, subject to satisfactory test results on trial mixes. The percentages should be sensibly constant whatever their value.

3   Cement

3.1   Selection of cement

The selection of cement starts with a survey of manufacturers within a reasonable distance of the dam and the products they produce. A reasonable distance can be very large; haul distances of many hundreds of kilometres are not unusual. The selection is made from the type and quality of the cement, the ability of the manufacturers to deliver adequate quantities, how it performs with pozzolan and its cost delivered to site. Wherever possible all cement should be obtained from a single source.

A source of cement should be selected which gives a product which conforms to an appropriate standard. When deciding on cement suppliers for major dam concrete works it is important to check that the factory is capable of producing a chemically and physically consistent product. It will be necessary to obtain test series, preferably done independently of the manufacturer, covering a long time period (many months or years). It may also be necessary to study the factory process in some detail to verify consistency of raw materials and manufacture as well as quality control procedures.

Test standards for cement are listed in Table B2.

The most common types of cement are manufactured to EN 197 CEM I and ASTM C150 Type I. These are basic cements used for general construction. Cement to ASTM Type II is preferred for mass concrete due to its lower heat of hydration and is used where available. With the use of pozzolan in the concrete the use of low heat and sulphate resistant cements is less imperative. Type I or CEM I would be used in mass concrete normally in conjunction with pozzolan. The worldwide drive to reduce carbon dioxide emissions may lead to changes in the cement sector and may have an impact on the selection of cement, with a possible trend of reduced availability of CEM I and Type I and their replacement with CEM II and similar. CEM II comprises a family of nineteen types of pozzolanic cement containing 6 to 35% pozzolan which may be slag, silica fume, natural pozzolan, fly-ash, burnt shale, limestone powder or a combination of these. For mass concrete (CVC), pozzolanic cements can be used alone or with additional pozzolan. Pozzolanic cements, including slag cements, are mostly not favoured for major RCC dam construction. Pozzolan should preferably be added at site at ratios determined from site specific tests, see Chapter 4. The chemical and physical properties of the pozzolanic cement have to be particularly consistent for this application and have to be assured.

3.2   Conformance to standards and consistency of properties

3.2.1   Chemical composition

The chemical composition of Portland cement is variable and complex. It is manufactured by fusing clay and limestone in a kiln to produce clinker, adding gypsum to control setting time and grinding to a fine powder.

The main chemical constituents are shown in Table 3.1. The conventional way of representing the constituents is shown under the heading CCN, Cement Chemists' Notation.

SELECTION OF MATERIALS FOR CONCRETE IN DAMS

Table 3.1 Principal constituents of Portland cement

Chemical compound	CCN	Mass %
Tricalcium silicate (CaO)$_3$ · SiO$_2$	C$_3$S	45-75%
Dicalcium silicate (CaO)$_2$ · SiO$_2$	C$_2$S	7-32%
Tricalcium aluminate (CaO)$_3$ · Al$_2$O$_3$	C$_3$A	0-13%
Tetracalcium aluminoferrite (CaO)$_4$ · Al$_2$O$_3$ · Fe$_2$O$_3$	C$_4$AF	0-18%
Gypsum, CaSO$_4$ · 2 H$_2$O		2-6 %

The allowable ranges of the main constituents are large. Changes in the ratios can affect the performance of the cement even if all ratios are within ranges allowed by various standards. The amount of tricalcium silicate and tricalcium aluminate affects the early strength and some manufacturers will compensate for a deficiency of this component by milling the cement finer.

Conformance to a standard is necessary but not sufficient.

The standard chemical tests give results for various components which may be critical for cement performance. These are determination of:

- loss on ignition

- insoluble residue

- sulphur trioxide content

- manganese content

- alkali content, required where aggregate is potentially reactive (or its reactivity is unknown)

The standard limits are shown in Table A1, Table A2 and Table A3.

3.2.2   Physical properties

The physical test data are used in the selection process. Conformance to standards is important as is consistency with time during manufacture.

1. Setting time

The setting time for the cement using paste (e.g. ASTM C191 *Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle*) is an indicative test. Tests on cement from a particular manufacturer should be consistent over time. With consistency in other physical properties, this indicates that the cement as supplied is consistent. Inconsistency has to be investigated and corrected.

During both the evaluation and construction phases any risk or occurrence of false setting must be identified and drawn to the attention of the manufacturer. If the producer cannot solve the problem, another source must be found.

2. Compressive strength

The compressive strength and its evolution with time will depend mainly on the compound composition and the fineness of the cement. A common test method is ASTM C 109 *Test*

Method for Compressive Strength of Hydraulic Cement Mortars. In general, cement strengths cannot be used to predict concrete strengths with a great degree of accuracy because of the many variables in aggregate characteristics, concrete mixture and construction procedures.

3. Fineness: Blaine value

Fineness of the cement is usually measured by its specific surface area, i.e. by the total surface area of all grains contained in a unit weight of the cement. For cement the specific surface area is between 250 and 600 m^2/kg (2500 to 6000 cm^2/g). Cement for concrete in dams should preferably be in the range of 300 to 350 m^2/kg for EN CEM I or ASTM Type I and in the range of 350 to 400 m^2/kg for pozzolanic cements.

4. Heat of hydration

The heat of hydration can vary with manufacturer and with changes in chemical composition and fineness. A low heat of hydration is desirable but might not be of overriding importance when pozzolan is used. The heat of hydration for Type I and CEM I cement is typically 350 J/g and 400 J/g at 7 and 28 days respectively. Type II gives slightly lower values and Type IV might be around 2/3 of Type I.

Knowledge of the heat of hydration is required for dam design and it should be measured. The choice of the test method for the heat of hydration is of major importance for the dam concrete. There are three common methods:

- The "dissolution" chemical method as defined by EN 196-8 and ASTM C186,

- The "semi-adiabatic" physical method as defined by EN 196-9.

- Adiabatic temperature rise of concrete USBR 4911

EN 196-9 gives values that are nearer to the conditions in the dam and it should be used to evaluate several cement, pozzolan, and mixture alternatives. USBR 4911 gives the temperature rise and heat of hydration for the full mixture and is particularly useful for final design of mass concrete and RCC which use high percentages of pozzolan.

The "dissolution "method gives consistent results for Portland cement, but may not give realistic results for cements containing pozzolan or slag.

ICOLD Bulletin 145, pages 6-2 to 6-10 provides further detail on heat of hydration and its measurement.

5. Soundness

Soundness refers to the ability of a hardened paste to retain its volume after setting. Lack of soundness or delayed destructive expansion is caused by excessive amounts of hard-burned free lime or magnesia (CaO and MgO). It is measured in the autoclave expansion test (ASTM C151) and provides an index of potential delayed expansion caused by the hydration the compounds, see Table A2.

4 Mineral Admixtures

4.1 Reasons for use

Mineral admixtures may be cementitious (termed 'Supplementary Cementitious Materials' in North America) and react with the hydration products of the cement to form strong compounds or they may be inert fillers designed to increase the amount of paste in the concrete mix. These admixtures may be included for reasons of economy and to enhance the fresh and hardened properties of the concrete.

Pozzolans are man-made or natural materials, which though not cementitious in themselves, contain constituents (e.g. amorphous quartz, aluminium and calcium silicates), which will combine with lime at ordinary temperatures in the presence of water to form compounds possessing cementitious properties. The lime, calcium hydroxide, results from hydration of cement.

The use of pozzolanic materials is now common in concrete for dams because:

- heat of hydration is reduced

- alkali-silica reaction is prevented or the risk substantially reduced

- setting time is increased, which is important for RCC

- costs of the cementitious materials are often reduced as pozzolan may be cheaper than cement

- workability may increase (or lowered water demand), depending on the pozzolan

- resistance to sulphate attack is increased

- permeability may be decreased

The mineral admixture can affect the extent of autogenous shrinkage. Fly-ash lowers shrinkage and slag and silica fume increasing shrinkage compared to the use of cement alone.

Pozzolan can be added to concrete in large ratios and where sufficient can react with all the calcium hydroxide generated by cement hydration and prevent alkali-silica reaction. In this context, low lime fly-ash should be added at a rate of not less than 40% of the total cementitious content and maybe more. Blastfurnace slag may be required at a rate of 50% to achieve the same effect and in France a minimum of 60% is required. Pozzolan contents of up to 90% and more of the cementitious content have been used.

Testing will be required to check that the proposed proportion of pozzolan is effective in eliminating harmful alkali-silica reaction. Various EN and ASTM procedures are available but they may not give realistic results for dam concrete due to the large size and longevity of the structures and the small size of the specimens. One option is to manufacture large concrete cubes with concrete containing the aggregate and cementitious materials to be used in the dam. These cubes might be of the order of 1 m or more in size. They need to be made as early as possible in the development of the project, preferably in the feasibility stage, to give several years of observation of potential expansion.

Inert fillers may be crusher dust, milled rock and minerals (e.g. limestone) or silt.

These materials may be added to the concrete at site to allow variations in the mix proportions in response to changing strength requirements and other factors.

4.2 Methodology for Selection

The source of pozzolan may be man-made, primarily fly-ash and blast furnace slag, or natural such as volcanic ash. Fly-ash is normally chosen if it is available at a reasonable cost as it has good pozzolanic properties and is mostly consistent in properties from any one power station drawing coal from one source. With the increasing use of pozzolanic cement in some regions and countries, or due to the lack of coal fired power plants, fly-ash is sometimes difficult to obtain and often expensive. Natural pozzolans are increasingly coming into use.

Thus the primary choice is between fly-ash or blast furnace slag on the one hand and natural pozzolan on the other. Fly-ash decreases the autogenous shrinkage and blastfurnace slag may increase the shrinkage compared with a cement-only concrete. Blastfurnace slag gives higher heat of hydration than fly-ash. If both types of pozzolan are available, selection of fly-ash will normally give the better technical performance.

Including sustainability considerations, fly-ash may preferentially be selected over a natural pozzolan, if both sources are available at reasonable cost.

The method of identification and selection of a natural pozzolan is presented in Section 4.7. The types of mineral admixtures in common use are illustrated in Figure 4.1. Other materials including meta-kaolin and crop residue ash not normally used in dam concrete are not shown. Silica fume has applications in high strength concrete and is not included primarily for its pozzolanic properties.
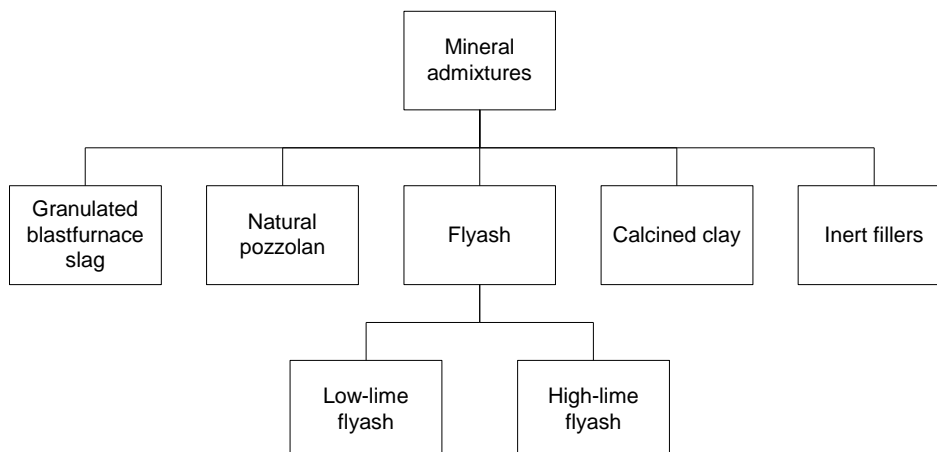
Figure 4.1: Types of mineral admixture used in dams

The efficacy of pozzolan and the amount to use in the concrete has to be determined in tests on trial mixes. Separate test series will be required for each combination of cement and pozzolan. A range of ratios of cement to pozzolan is tested and the optimal mix proportions with respect to strength, workability and cost are selected. Other factors, such as achieving an adequate paste volume, may be important. Paste volume may also be increased by adding inert filler and using air entrainment.

4.3 Strength development

Concrete made with varying proportions of pozzolan and cement develops strength at different rates, see Figure 4.2. The more pozzolan the slower the gain in strength but in the long term there is normally little difference between a mix with 40 % or less pozzolan and

neat cement mixtures. In some mixes with a high percentage of pozzolan the long term strength may even exceed that for neat cement. This applies in principle to all effective pozzolans irrespective of source.

Figure 4.2: Typical strength development of different ratios of pozzolan
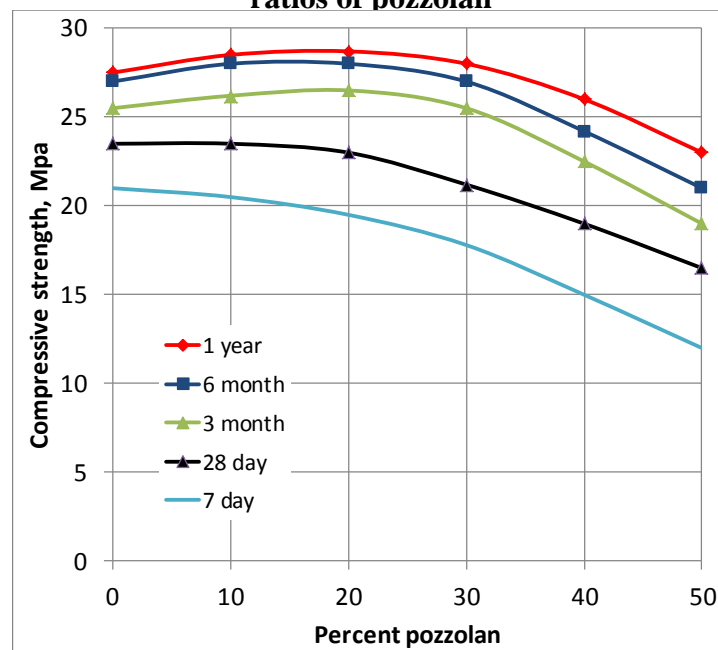
(based on ACI 232.1 R12)

4.4   *Fly-ash*

4.4.1   General description

Fly-ash comprises quartz and amorphous aluminium and calcium silicates, commonly occurring as spherical particles. Table A4 gives required properties according to ASTM 618

and Table A5 gives a comparison of requirements for low lime fly-ash for a range of standards.

The loss on ignition for fly-ash may be higher than the standard requires and loss on ignition values above 12% have been successfully used in some RCC. Higher loss on ignition may increase the water demand and chemical admixture dosages (e.g. retarders and air entraining admixtures), but if it is reasonably constant, a consistent and fully useable concrete may be obtained. A high activity index is desirable but concrete may be made also with fly-ash which fails to meet the criteria subject to satisfactory trial mix test results.

Fly-ash may be low lime fly-ash (ASTM Class F) produced by burning high grade coal in a thermal power station or may be high lime fly-ash (Class C) where low grade (brown) coal is used. If low lime fly-ash is available at reasonable cost, it is the preferred option due to its good properties and consistency. High lime fly-ash may be used but will normally require processing to reduce the free lime content.

4.4.2 Selection of source

Trial mixes are normally carried out in two stages. In the first stage, trial mixes are made for each combination of cements and fly-ash being considered. For each combination, mixes are prepared with a range of cement to fly-ash ratios using standard aggregate. Cubes or cylinders are made for compression testing. When the compression strengths are available, a comparison can be made of the efficacy of the different combinations of material sources. The most cost effective sources are selected. There may be more than one set of sources carried forward to the tender documents to avoid commercial disadvantage. Second stage testing will be on trial mixes using the selected material combinations and aggregate derived from the planned quarry or alluvial source. On occasion more than one source may be under consideration with a corresponding increase in the scope of testing.

4.4.3 Chemical composition

The chemical composition is highly dependent on the type of:

- coal, which governs the CaO content (hard or brown coal),
- furnace, which affects the carbon and amorphous silicate content, and fineness.

For the estimation of the quality of the fly-ash the test should be carried out according either EN or ASTM as shown in Table B3. As well as fineness, the particle size distribution is of interest in assessing the efficacy of the fly-ash.

4.4.4 Heat of hydration

As noted above, most concrete for dams includes pozzolan. Table 4.1 shows an example of the influence on heat of hydration of the addition of fly ash, expressed as temperature rise.

Table 4.1 Illustration of temperature rise with fly-ash blended with cement

Cementitious material	t_{max}, °C	time, h
CEM I 32,5	24.3	20
CEM I 32,5 + 20% PFA	19.1	22
CEM I 32,5 + 30% PFA	18.2	23

4.5   Blastfurnace Slag

Slag is a by-product of metal production and refining. The most common slag comes from iron and steel making. In some areas slag from copper processing is available. The most common material of this group used in concrete is blastfurnace slag from pig iron production. Molten slag can be air-cooled or rapidly quenched to be granulated.

Crushed, milled or ground to very fine cement-sized particles, ground granulated blastfurnace slag (GGBS) has cementitious properties, which make a suitable partial replacement for or admixture to Portland cement.

Ordinary Portland Cement can be replaced by up to 80% slag by mass and the use of up to 90% has been reported.

ASTM C 989 classifies slag by its increasing level of reactivity as Grade 80, 100, or 120. ASTM C 1073 covers a rapid determination of hydraulic activity of GGBS.

Typical properties of slag are given in Table A6.

The quality of GGBS should be tested in accordance with EN or ASTM as shown in Table B4.

The chemical ratios, the ratios between the various active constituents, are important for the GGBS suitability but not sufficient: Al_2O_3 and minor elements could play a significant role in strength development.

4.6   Silica fume

Silica fume is an ultrafine addition composed mostly of amorphous silica made by electric arc furnaces as a by-product of the production of silicon or ferrosilicon alloys. It is available as powder or in slurry form and has a tendency to agglomerate.

Silica fume is used to produce high performance concrete or mortar possessing increased strength, impermeability and durability. It may be used to give concrete improved abrasion resistance, where a very low permeability is required and to improved frost resistance. Silica fume concrete has different shrinkage characteristics compared with plain or fly-ash concrete and enhanced curing procedures should be applied. Silica fume is not normally used in mass concrete for dams due to cost factors, rapid slump loss and drying shrinkage shortly after placing.

The maximum dosage of silica fume is limited to 11% of the cement (EN 206-1). Standard requirements for silica fume are shown in Table A7.

For the estimation of the quality of the silica fume the test should be carried out according either EN or ASTM as shown in Table B5. Silica fume should conform to ASTM 1240 or EN 13263-1.

4.7   Natural Pozzolan

4.7.1   General description

In many regions fly-ash or slag is not available within a reasonable distance or the cost may be very high due to shortage of supply. With the now extensive use of pozzolanic and slag cement in the construction industry, much of the fly-ash and slag produced is so consumed. Natural pozzolans are in many cases a viable alternative.

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Volcanic ash is often a good alternative to fly-ash where it can be found. Other materials can show pozzolanic activity. Such diverse sources as volcanic glass, pumice, scoria, lacustrine sediments, diatomaceous earth, alluvium and glacial till have been used or tested for use. In other cases it has been reported that fines from crushed basalts showed some pozzolanic activity, whereas in other cases milled basalt proved completely inert. Calcined clay, activated by thermal treatment at temperatures of 500 to 800°C, can have good pozzolanic properties.

These materials are processed by crushing, milling, size separation and homogenization. Construction of a project specific processing plant may be viable only for very large dams.

4.7.2   Identification of sources

A wide area around the site should be surveyed for potential sources. This might extend up to 1000 km or more from the dam. The search should include the leading involvement of geologists. In the initial survey a sample of a few kilos should be collected from each source. From these a selection will be made based on their relative likelihood of being pozzolanic, processing costs and transport costs. These selected materials will then be subject to a series of preliminary tests for pozzolanic activity. Testing standards for natural pozzolan are given in Table B6.

Preliminary evaluation, screening, of potential sources of pozzolan should be based on several tests:

Chemical composition: EN 196-2 or ASTM C 114

> These tests will produce a range of chemical test data where the content of oxides of calcium, silicon and aluminium are of special interest. The ratios of these components can only give a rough indication of likely pozzolanic activity. Figure 4.3 shows a tripartite diagram where the ratios of these three oxides can be plotted. The zone containing ratios for natural pozzolans is shown. The ASTM C618 acceptance criterion for natural pozzolan (Class N) is $SiO_2 + Al_2O_3 + Fe_2O_3 \geq 70\%$, see Table A4.

Activity index: EN 196-5 or ASTM C 311

> The activity index is the ratio of strength between mortar cubes made with 20% of cement replaced by pozzolan and cubes with neat cement. A high index indicates possible pozzolanic activity. The standard acceptance criterion is 70%. The test on its own is not reliable. A better indication of pozzolanic activity is the strength activity index of mortar cubes using lime instead of Portland cement.

Insoluble reside: EN 196-2 or ASTM C114

> The IR is measured according to method I of EN 196-2. If the IR is less than 85, the IR is evaluated again by method II.

Hydroxyl and calcium ion content: EN 196-5, the Fratini test

> In this test the two key parameters are plotted on a standard diagram see Figure 4.4 Results of Fratini test (EN 196-5) at 8 and 30 days at 40°C. The diagram has an upper zone where materials are not pozzolanic and a lower pozzolanic zone. The results change with time and the 30 day results should be used on the plot.

Mineralogical analysis

> The minerals present in a sample, including amorphous silica and strained quartz, can be determined using a polarizing petrographic microscope. X-ray diffraction is a useful

ancillary procedure, but cannot directly detect non-crystalline (amorphous) reactive material. Both methods are semi-quantitative and either method can be used to give an indication of likely pozzolanic activity.

The results of these tests are all indicative and do not give a final answer as to whether a material is adequately pozzolanic. All the collected results need to be evaluated and a judgement made on which materials are most likely to be pozzolanic and thus warrant further detailed investigation. Reference should be made to normal requirements, e.g. Table A4. The results should be used to rank the materials in sequence of likely pozzolanic activity. This list, in conjunction with data on likely processing and transport costs, should be used as a basis for selecting materials for further testing. In making such a list, it is prudent to include at least one material which is very promising as insurance, even if its cost at site may be higher than the rest.

As for fly-ash, further investigation should consist of a series of trial mixes using varying ratios of cement to pozzolan and standard aggregate. This will yield a realistic measure of pozzolan effectiveness and thus how much may be required in the dam concrete. At a later stage it will be necessary to refine the testing by using aggregate derived from rock extracted from the intended production quarry.
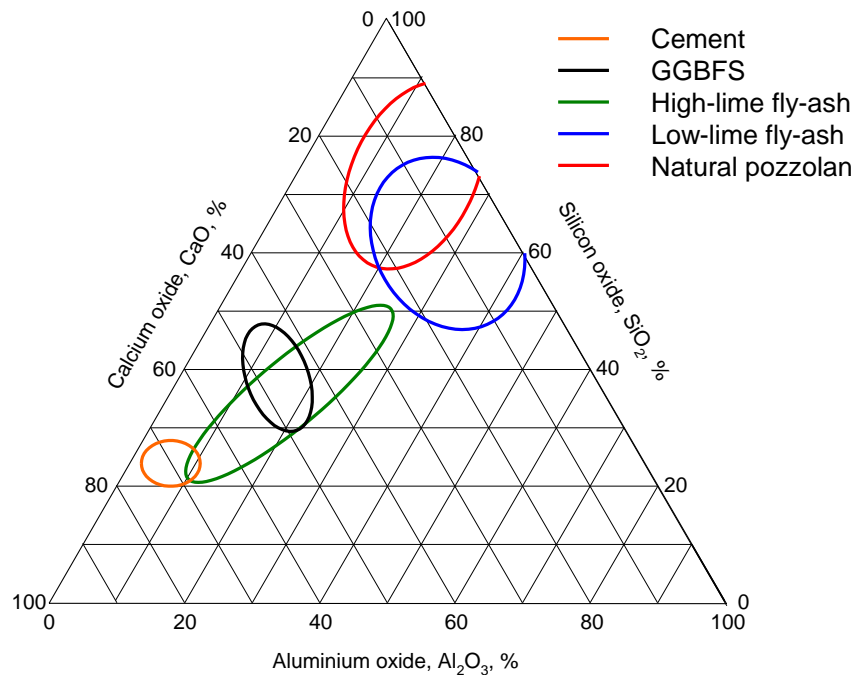
Figure 4.3: Ranges of compositions of cementitious materials
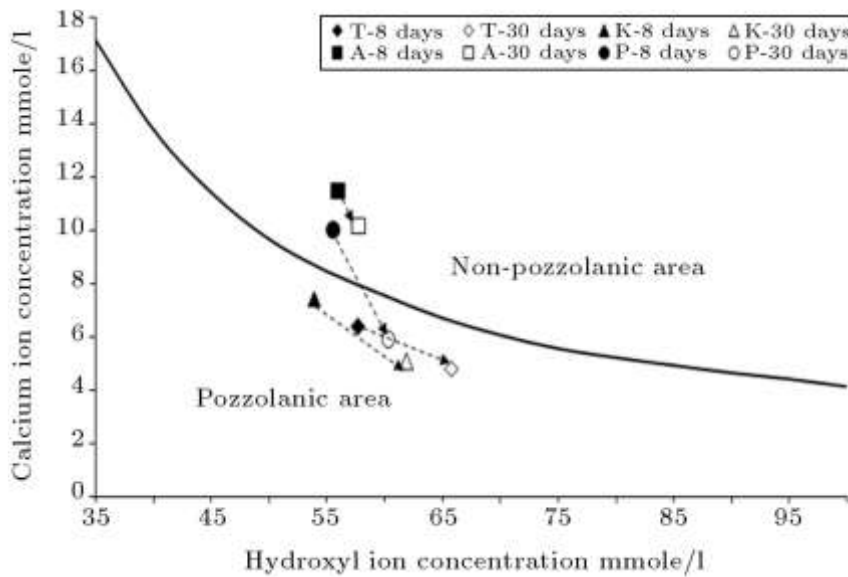
Figure 4.4 Results of Fratini test (EN 196-5) at 8 and 30 days at 40°C.
(From T. Parhizkar, et al 2010)

4.8   Calcined clay: meta-kaolin

Calcined clays are used in general purpose concrete construction much the same as other pozzolans. They can be used as a partial replacement for the cement, typically in the range of 15% to 35%, and to enhance resistance to sulphate attack, control alkali-silica reactivity, and reduce permeability. Calcined clays have a relative density of between 2.40 and 2.61 with Blaine fineness ranging from 650 m^2/kg to 1350 m^2/kg. Calcined shale may contain on the order of 5% to 10% calcium, which results in the material having some cementing or hydraulic properties on its own. Because of the amount of residual calcite that is not fully calcined, and the bound water molecules in the clay minerals, calcined shale will have a loss on ignition (LOI) of perhaps 1% to 5%. The LOI value for calcined shale is not a measure or indication of carbon content as would be the case in fly ash.

Meta-kaolin is an ultrafine addition produced by low temperature calcination of high purity kaolin clay. The product is ground to an average particle size of about 1 to 2 micrometres. Meta-kaolin is used in special applications where very low permeability or very high strength is required. In these applications, meta-kaolin is used more as an additive to the concrete rather than a replacement of cement; typical additions are around 10% of the cement mass.

The estimation of the quality of the material should be carried out according to French standard NF P 18-513 as shown in Table B7: Testing standards for calcined pozzolan. This test gives the amount of lime consumed by the pozzolan. This quantity and the $SiO_2 + Al_2O_3$ content, are the most important parameters in defining material quality.

Meta-kaolin may increase water demand in the concrete mix and may accelerate cement hydration, speeding up strength development. Meta-kaolin may be beneficial in ternary systems in conjunction with fly-ash or GGBS. Although potentially improving concrete durability, meta-kaolin may not be suitable in mass concrete due to a higher hydration heat, increased temperature control efforts, and therefore higher unit cost of the concrete.

4.9   Ash from combustion of crop residues

Rice husk ash (RHA) contains 85 % to 90 % amorphous silica. The physical properties, such as angularity, surface area, and porosity are similar to Portland cement. The type of RHA suitable for pozzolanic activity is amorphous rather than crystalline.

The ash is milled very fine (<35 micron) and is marketed as a substitute for silica fume, To ensure a consistent standard, it requires ash from a controlled combustion environment. However, production tends to be dispersed with many small mills producing 10,000 tonnes per year or less. There are, however, much larger mills in some countries producing more than 100,000 tonnes per year.

Many other crop residues have been investigated and might be suitable, subject to full evaluation.

4.10   Inert fillers

Inert fillers can be used to increase the paste content of concrete. They may be the fines fraction (<75 micron) of the crushed sand or may be added as a separate constituent. Inert fillers may be used with cement alone or with pozzolans. Such materials typically increase the water demand for a given workability which may be undesirable in CVC but does not affect RCC to a significant extent. Inert filler might constitute up to 15% of the fine aggregate (sand).

5 Chemical Admixtures

5.1 Introduction

Chemical admixtures may be used to improve the properties of fresh and hardened concrete.

The most common agents used are:

- Water reducers (plasticisers) to improve workability for a given water content
- Set retarders to give more time for successive concrete lifts to be placed on fresh concrete and delayed set for some slip-formed concrete
- Air entraining admixtures to improve frost resistance, increase paste volume and improve workability

Accelerators that give early set and high early strength are not used in mass concrete and are not common in other concrete for dams.

Admixtures to improve pumpability may be used for some applications.

European Standard EN 934-2 categorises admixtures according to their effect. Other standards dealing with admixtures are ASTM C 260 for air-entrainment and C494 for water-reducing and set-controlling admixtures.

Most admixtures have effects other than their primary objective. Set retarders have some water reducing effect and water reducers affect setting time. Suppliers of these chemicals can offer agents with combined effects beyond those inadvertently present. Air entrainers typically interact weakly with other agents.

Water reducers and set retarders, and to lesser extent air entrainers, reduce segregation problems as the concrete mixes tend to be more cohesive.

Chemical admixtures provided by different suppliers can have different effects depending on the cementitious materials and the aggregate. Some work well for low and moderate dosages but give unpredictable results if these are increased. Changes in the dosage of selected chemicals should give predictable and consistent changes in concrete properties.

The effects achieved are often sensitive to changes in temperature and water content of the mix. Other factors which affect the results are controllable items such as consistency of mixing time and the method and sequence of adding the chemicals. Accuracy of dosing is most important and the batching plant must be set up for this.

Expansion agents have been used to compensate for thermal and other shrinkage. Experience of such use is limited, can be characterised as experimental, is difficult but has been employed in China. The consequences of excessive expansion can be severe. Until the science and practice of use of expansion agents in dam concrete has been further developed, they should be used exceptionally and with great caution. For particular applications, such as limited placements under imbedded items, expansion agents might be considered.

5.2 Applicable standards and tests

Chemical admixtures should conform to the requirements of well-recognised standards such as EN or ASTM. The test standards applicable to chemical admixtures are listed in Chapter 6, References, and their applicability is indicated in Table B8 to Table B12.

If the admixture is certified to EN 934-2, the following properties should be tested; homogeneity and colour (visual), effective component (IR-spectra), density, dry material content, pH-value, total chlorine and water-soluble chlorine contents and alkali content.

Occasional independent chemical testing of products may be prudent.

The manufacturer will perform a series of routine tests to ensure conformity to standards and product specifications. Typically the manufacturer will also have carried out tests of the admixtures on standard concrete. He should also provide case histories and references for its use. Upon request, manufacturers are commonly prepared to make further tests for particular applications and give advice on time and sequence of batching, effect of over-dosage, influence of temperature, side effects, compatibility with other admixtures etc. Such information may be accepted for initial guidance, but all materials to be used have to be tested independently for each specific project.

5.3   The selection process

The first part of the trial mix programme will show if water reducers are required to achieve adequate workability of the design mixes. The method of construction will indicate if the concrete needs to be given a retarded setting time. A requirement for frost resistant concrete will dictate the use of air entrainers, but their use might also arise from a need to increase the paste content to fill the voids in the fine aggregate and to improve workability. Although air entrainment improves workability, this is a consequence of their use and normally not the primary reason for inclusion.

We have the following requirements:

1.   Only water reduction/increased workability

2.   Only set retardation

3.   Water reduction and set retardation

4.   Air entrainment on its own, or with any of the above

Trial mixes have to be made with various types or brands of admixture to establish which materials and dosages give the desired effect. Each concrete mix design has to be tested.

Some practitioners use mortar cubes for testing admixtures prior to construction and trial mixes thereafter. Mortar tests are quicker and cheaper to use than concrete mixes but there may be poor correspondence between tests on mortar and concrete and the tests are best be avoided.

Set retarders affect workability and where used they should be incorporated at the intended dosages in the trial mixes used to define the concrete mix proportions.

The action of admixtures of all kinds is temperature sensitive and the trial mixes should be made at temperatures which will occur at site during mixing and placing. This may mean a reduction of temperature of the trial mixes by using ice or chilled water.

If air entrainment is to be used, the type and amount of admixture required to give the necessary air volume is established first.

The following text applies whether air entrainment is included in the mix or not.

For either water reduction or retardation, the trial mixes are made with suitable types and brands of admixture to find the product which gives the desired effect economically and reliably. With a requirement for both water reduction and set retardation, separate admixtures

may be used or a readymade combined agent may be employed. Where separate admixtures are used, the agent for adjustment of the dominant factor is tested first. The linkage of properties will give some of the subsidiary effect which may or may not be adequate. If not adequate, the second agent has to be tested in combination with the first. The test series needed to establish the correct dosage of each chemical may be extensive. The set retarder and water reducer in any one mix should be from the same manufacturer, who will be required to provide a guarantee of their compatibility, supported by test results and case histories.

Whereas manufacturers may be able to supply combined agents suited to the specific combination of retarding and water reducing requirements, with changing conditions on site the combination of these requirements may change and the combined agent may not work as required. For some applications this may not be critical. An example could be mass concrete where workability may be the prime requirement and where setting time may not be critical: the dosage of admixture would be dictated by the required workability.

The admixture, or combination of admixtures, which reliably gives the required effects should be selected on the basis of unit cost of the treated concrete

The above tests and procedures should be followed prior to tender for the work. Although suitable chemical admixtures and dosages may have been established, the specifications will typically be performance oriented. The pre-tender test data should be provided to the tenderers. The tenderers may wish to pursue other agents for commercial or other reasons. The contractor, when appointed, will be required to repeat tests on the concrete design mixes (be they the Engineer's or Contractor's mix designs or preferred admixtures) using the same materials as will be used in the works, initially on laboratory mixes but finally using the production batch plant and mixers. Change of manufacture and adjustments to the admixture types and dosages may result.

5.4   Water reducers and plasticisers

Water reducing admixtures (WRA) are used to reduce the water content and thus cement and pozzolan contents for a given workability; to improve workability for given water content; and to control setting time.

The savings in cement and pozzolan conferred by the use of these agents can be considerable. The water/cementitious ratio is given primarily by strength or durability requirements and there has to be sufficient paste to give adequate workability. Water reducers are designed to reduce the paste volume required for an acceptable workability. In RCC the paste volume is often set to the minimum required to achieve separation of the aggregate particles. Water reducers will increase the workability if RCC trial mix manufacture shows that this is necessary.

Reductions of water content (and therefore paste content) can be between 5 and 30% depending on the admixture, dosage and original water content, with a significant saving in cementitious content, although there is not a strict pro rata relationship. The admixtures are most effective for concrete containing larger amounts of fine graded material. The water reduction for mass concrete is normally in the 5 to 10% range and higher reductions for structural concrete.

Water reducers typically have a retarding effect, particularly at high dosages. Usually the improvement of the workability is limited in time. Where concrete is transported in transit mixers, admixture can be added when it has reached the site.

Standard water reducers often have an adequate effect and are significantly cheaper than superplasticisers (high range water reducers) but the latter are used to some extent in mass concrete. Some superplasticisers can cause a reduction in the effectiveness of air entrainers and manufacturers' advice should be sought if an air entrainer and a superplasticiser are to be used in combination.

5.5 Set retarders

Delay of the setting time is required where successive concrete lifts are to be placed on fresh concrete. Without set retarders the initial set may be two to three hours after mixing. With retarders the initial set may be delayed to 24 hours or more. Over-dosing or use of an inappropriate chemical may prevent setting altogether.

The heavy retardation sometimes used requires dosages of chemicals higher than the maximum dosages given by the manufacturers. Extensive testing is required to ensure that the retarding admixture will perform as required.

In ASTM C403, setting time is measured by the penetration resistance of concrete in cubes until final set has occurred. The test concrete is screened from complete concrete mixes with the aggregate coarser than 5 mm removed. The initial set is defined by when the concrete attains a penetration resistance of 3.4 MPa (500 psi) and correspondingly the final set at 27.6 MPa (4000 psi).

Extensive testing may be required to identify an agent which gives predictable setting times that can be adjusted by varying the dosage of the chemical. Most marketed products give predictable results at small to moderate dosages for limited set retardation, but not all perform well where heavy retardation is required. Trial mixes using the final mix proportions will be required to establish the relationship between dosage and setting times. The trials may have to be extended to the testing of full batches are there can be differences in performance compared to laboratory mixes.

Air entrainment does not usually affect the setting time.

The setting time depends on the agent, the dosage, the pre-mixing time before adding the agent (increased premixing time gives increased effect), temperature (increased temperature, decreasing effect) and the chemistry of the cement (increased amount of C_3A, gives decreasing effect).

Specialised retarders can delay the setting of the concrete by several days. The longer the delay, the harder it is to control.

A side effect of the delayed setting is that bleeding can continue for a longer period, leading to a greater volume of bleed water and larger plastic shrinkage. This has a deleterious effect on permeability and plastic shrinkage cracking and therefore the durability of the concrete. It may be necessary to re-vibrate and implement more effective protection and curing.

5.6 Air entrainers

Entrained air occurs as very small bubbles evenly distributed in the paste. It is distinct from entrapped air which occurs as macroscopic, even large, air bubbles.

Air entrainers are used to provide frost resistance, increase the paste content and improve workability. Most concrete will have improved cohesion with less bleed and mix segregation. The required air content for frost resistant concrete depends on the exposure and MSA and as placed is likely to be 3 to 4%. There is some air loss between mixing and placement which

may amount to 2% and the target value at the mixer might be 5 to 6%. RCC as well as CVC can be air entrained. For improved cohesion and reduced bleed in concrete, 2 to 3% entrained air is usually sufficient. For freeze thaw resistance the amount of air is dictated by the paste volume in the mix.

EN 934-2:2009 and ASTM C260 / C260M - 10a are in common usage for specifying air entrainment admixtures.

At the tender stage various makes of admixtures may be offered. Acceptance of these will be subject to further testing on trial mixes and evaluation of field performance. This will entail verification of air content at the placement and within the hardened concrete thereafter, especially in surface zones exposed to freeze-thaw conditions. This is particularly important for pumped concrete.

In structural concrete there will be a loss of strength of about 5 or 6% for each percentage of air entrained. This loss will be much reduced in the leaner mass concrete usually used in dams and may be negligible. The extent of strength loss, if any, will become evident in the trial mixes.

Fly-ash usually has residual active carbon which can significantly increase the dosage of air entrainer required. Some types of air entraining admixture are more tolerant of fly-ash than others and the manufacturers' advice should be sought.

The air content in concrete mixes is measured according to EN 12350-7 or ASTM C 231, and to ASTM C457 for hardened concrete.

It is important to verify the effect on the freeze-thaw durability on the hardened concrete via testing according to CEN/TS 12390-9 since not only the amount of entrained air but also the pore size distribution and distance between air pores are of importance.

6   Mixing water

Mixing water should conform to the requirements of EN 1008, ASTM C1602 or equivalent. Table B13 gives a list of required tests and suitable testing standards.

Potable water is considered suitable for use in concrete and needs no testing.

Water from underground sources, natural surface water and industrial wastewater may be suitable for use in concrete, but requires testing for conformance to requirements.

Seawater or brackish water is usually not suitable for concrete with reinforcement because of its high chloride content and even unreinforced concrete might be affected by alkalis and sulphates

Water recovered from processes in the concrete industry is usually suitable but there are restrictions on the amount of solid material and it can influence the aesthetics and concrete exposed to aggressive environments and must be tested for this. Again, such water might contain alkalis and sulphates.

7   Time Schedule for Testing of materials

The testing of material for dams is time-consuming. It is important to obtain samples and start tests as soon as possible in each phase of project development. Some tests can take a year or more to complete, such as certain tests for alkali-silica reaction where very long periods of testing are desirable. Strength tests on concrete trial mixes at 365 days maturity or more may be required. Before such tests can be started, a number of tests on aggregate and cementitious materials have to be made. In some compressed schedules the final test results of the long duration tests may not be complete until after the nominal completion of the particular project phase. Table 7.1, Table 7.2 and Table 7.3 give an indication of key activities and their durations. The sequence of activities is approximate and there will be some overlap. If pozzolans will not be used, the test duration on trial mix specimens will be reduced.

At the start of each project phase a schedule of material investigations and testing should be drawn up, noting the dependency of certain tests and activities on the completion of others. In cases where variations in limits from normal standards are to be considered, sufficient time for extensive testing must be provided. Time may also have to be allowed for approvals of external authorities.

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**Table 7.1: Tests and key activities for pre-feasibility and feasibility studies
Indicative sequence and durations**

	Activity/Tests	Duration Weeks	Conclusion
Pre-feasibility	Quarry identification Petrography	6	
	Aggregate physical properties	9	
	Aggregate chemical properties	9	
	Identification of pozzolan sources Identification of cement sources	2	Potential sources of materials identified
Feasibility	Petrography Quarry location confirmation	9	
	Proving availability of materials incl. aggregate by drilling, sampling and data collection (cement and pozzolan)	13	
	Aggregate physical properties Aggregate chemical properties	4	Confirmation of suitable aggregate sources
	Pozzolan sources Chemical and physical properties Preliminary tests with cement Requirements for processing	13	Confirmation of suitable pozzolan sources
	Collection of manufacturers' data on cement	4	Confirmation of suitable sources
	Tests on mixing water	1	Confirmation of suitability
	Alkali silica reaction, other long term physio-chemical tests	9 to 52 or more	Indication of chemical problems
	Trial mixes to test pozzolan - cement efficacy with standard aggregate or from site quarry	13	Identification of preferred cement and pozzolan sources
	Preliminary concrete mix designs	2	Probable mix proportions

**Table 7.2:   Tests and key activities where concrete mixes are defined in tender
Indicative sequence and durations**

	Activity/Tests	Duration Weeks	Conclusion
Detailed design and Tender Documents	Obtain bulk aggregate sample (many tonnes) Crush, grade and tests for physical properties	4	Identification of aggregate processing requirements
	Alkali silica reaction, other long term physio-chemical tests (conclusion)	52	Confirmation of any chemical problems
	Tests on cement and pozzolan	4	Selection of suitable cements sources

	Activity/Tests	Duration Weeks	Conclusion
Construction	Identify chemical admixture requirements (air entrainment, workability, setting time) Tests in trial mixes	2	Selection of suitable admixtures and dosages
	Trial mixes including chemical admixtures	30 to 56	Determination of mix proportions
	Material and concrete specifications Mix designs	13	Completion of tender documents
	Obtain bulk aggregate samples (many tonnes) from stockpiles, test for physical properties	2	
	Tests on cement and pozzolan	4	
	Test air entrainment, workability and setting time admixtures in trial mixes to establish dosages	2	
	Trial mixes including chemical admixtures. Freeze-thaw testing if exposure conditions require it.	30 to 56	Adjustment of mix proportions
	Mix designs for construction		

Table 7.3: Tests and key activities when concrete mixes defined in contract period: Indicative sequence and durations

	Activity/Tests	Duration Weeks	Conclusion
Detailed design and Tender Documents	Alkali silica reaction, other long term physio-chemical tests (conclusion)	52	Confirmation of any chemical problems
	Tests on cement and pozzolan	4	Selection of suitable cements sources
	Material and concrete specifications Mix designs	13	Tender documents
Construction period Does not include QA/QC testing and control	Obtain bulk aggregate sample (many tonnes) from quarry, crush, grade and tests for physical properties.	4	Identification of aggregate processing requirements
	Tests on cement and pozzolan	4	Confirmation of cement and pozzolan sources
	Identify chemical admixture requirements (air entrainment, workability, setting time) Tests in trial mixes	2	Selection of suitable admixtures and dosages
	Trial mixes including chemical admixtures. Freeze-thaw testing if exposure conditions require it.	30 to 56	Determination of mix proportions
	Mix designs for construction		

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ASTM C 114 Test Methods for Chemical Analysis of Hydraulic Cement

ASTM C 115 Test Method for Fineness of Portland Cement by the Turbidimeter

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ASTM C 151 Test Method for Autoclave Expansion of Portland Cement

ASTM C 186 Test Method for Heat of Hydration of Hydraulic Cement

ASTM C 191 Test Method for Time of Setting of Hydraulic Cement by Vicat Needle

ASTM C 204 Test Method for Fineness of Hydraulic Cement by Air Permeability Apparatus

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Chapter 4   Pozzolans

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ASTM C39 / C39M - 12 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

ASTM C78 / C78M - 10 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)

ASTM C138 / C138M - 12 Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete

ASTM C157 / C157M - 08 Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete

ASTM C143 / C143M - 10a Standard Test Method for Slump of Hydraulic Cement Concrete

ASTM C192 / C192M - 07 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory

ASTM C231 / C231M - 10 Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method

ASTM C232 / C232M - 09 Standard Test Methods for Bleeding of Concrete

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Chapter 6   Mixing water

EN 1008:2002 Mixing water for concrete – specification for sampling, testing and assessing the suitability of water, including water recovered from process in the concrete industry, as mixing water for concrete.

Appendix A – Typical properties of cementitious materials

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Table A1: Cement: Standard Composition Requirements (ASTM C150)

Compound	Applicable Test Method	Cement Type				
		I	**II**	**III**	**IV**	**V**
Silicon dioxide (SiO2), min, %	C 114	...	20.0[B,C]	... .	..	...
Aluminium oxide (Al2O3), max, %	C 114	...	6.0	... ..	. .	..
Ferric oxide (Fe2O3), max, %	C 114	...	6.0[B,C]	...	6.5	...
Magnesium oxide (MgO), max, %	C 114	6.0	6.0	6.0	6.0	6.0
Sulphur trioxide (SO3),D max, %	C 114					
When (C3A)E is 8 % or less		3.0	3.0	3.5	2.3	2.3
When (C3A)E is more than 8 %		3.5	F	4.5	F	F
Loss on ignition, max, %	C 114	3.0	3.0	3.0	2.5	3.0
Insoluble residue, max, %	C 114	0.75	0.75	0.75	0.75	0.75
Tricalcium silicate (C3S), max, %		...	..	. ...	35[B]	...
Dicalcium silicate (C2S), min, %		...	...	...	40[B]	...
Tricalcium aluminate (C3A), max, %		...	8	15	7[B]	5[C]
Tetracalcium aluminoferrite plus twice the tricalcium aluminate						
(C4AF + 2(C3A)), See Annex or solid solution (C4AF + C2F), as applicable, max, %		...	..	.	...	25[C]

[B] Does not apply when the heat of hydration limit in Table 4 is specified (see ASTM C150).

[C] Does not apply when the sulfate resistance limit in Table 4 is specified (see ASTM C150).

[D] There are cases where optimum SO_3 (using Test Method C 563) for a particular cement is close to or in excess of the limit in this specification. In such cases where properties of a cement can be improved by exceeding the SO_3 limits stated in this table, it is permissible to exceed the values in the table, provided it has been demonstrated by Test Method C 1038 that the cement with the increased SO_3 will not develop expansion in water exceeding 0.020 % at 14 days. When the manufacturer supplies cement under this provision, he shall, upon request, supply supporting data to the purchaser.

[F] Not applicable.

Table A2 Cement: Standard Physical Requirements (ASTM C150)

Property	Test Method	Cement Type				
		I	II	III	IV	V
Heat of hydration at 7 days, max, J/g [H]	C186		290		250	
Heat of hydration at 28 days, max, J/g [H]	C186				290	
Air content of mortar, [B] volume %:	C 185					
max		12	12	12	12	12
min		...	...	...	...	...
Fineness, [C] specific surface, m^2/kg						
Turbidimeter test, min	C 115	160	160	...	160	160
Air permeability test, min	C 204	280	280	...	280	280
Autoclave expansion, max, %	C 151	0.80	0.80	0.80	0.80	0.80
Strength, not less than the values shown for the ages indicated as follows: [D]						
≤Compressive strength, MPa (psi):	C 109/ C 109M					
1 day		...	...	12.0	…	…
3 days		12.0	10.0	24.0	…	8.0
			7.0[E]			
7 days		19.0	17.0	…	7.0	15.0
			12.0[E]			
28 days	...	...	.	..	17.0	21.0
Time of setting (alternative methods):[F]						
Gillmore test:	C 266					
Initial set, min, not less than		60	60	60	60	60
Final set, min, not more than		600	600	600	600	600
Vicat test:[G]	C 191					
Time of setting, min, not less than		45	45	45	45	45
Time of setting, min, not more than		375	375	375	375	375

[B] Compliance with the requirements of this specification does not necessarily ensure that the desired air content will be obtained in concrete.

[C] The testing laboratory shall select the fineness method to be used. However, when the sample fails to meet the requirements of the air-permeability test, the turbidimeter test shall be used, and the requirements in this table for the turbidimetric method shall govern.

[D] The strength at any specified test age shall be not less than that attained at any previous specified test age.

[E] When the optional heat of hydration or the chemical limit on the sum of the tricalcium silicate and tricalcium aluminate is specified.

[F] The time-of-setting test required shall be specified by the purchaser. In case he does not so specify, the requirements of the Vicat test only shall govern.

[G] The time of setting is that described as initial setting time in Test Method C 191.

[H] Optional parameters

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Table A3 Cement: European standard for CEM I

EN 197-1 sets out the requirements for 27 types of cement plus 7 sulphate resisting types. Only the requirements for CEM I (basic cement) are given here.

		Cement type CEM I	Reference in EN 197-1	Test standard	Comment
Chemical requirements					
$3CaO \cdot SiO_2 + 2CaO \cdot SiO_2$	%	≥ 66.7	§ 5.2.1	EN 196	In clinker
Clinker content	%	≥ 95	Table 1	EN 196	
CaO / SiO_2		≥ 2	§ 5.2.1	EN 196	
Mineral additives	%	≤ 5	Table 1	EN 196	
Mg O	%	≤ 5	§ 5.2.1	EN 196	
Loss on ignition	%	≤ 5	Table 4	EN 196-2	
Insoluble residue	%	≤ 5	Table 4	EN 196-2	
Sulphate (SO_3)	%	≤ 3.5	Table 4	EN 196-2	For 32.5[1] N[2], 32.5 R[3], 42.5 R
Sulphate (SO_3)	%	≤ 4.0	Table 4	EN 196-2	For 42.5 R, 52.5 N, 52.5 R
Chloride	%	≤ 0.1	Table 4	EN 196-2	
Physical requirements					
Compressive strength @ 2 days	MPa	32.5[1] N[2]: Not req. 32.5 R[3] : ≥ 10 42.5 N: ≥ 10 42.5 R: ≥ 20 52.5 N: ≥ 20 %2.5 R: ≥ 20	Table 3	EN 196	
Compressive strength @ 7 days	MPa	32.5 N: ≥ 12.0	Table 3	EN 196	
Compressive strength @ 28 days	MPa	32.5 N, 32.5 R : 32.5 to 52.5 42.5 N, 42.5 R: 42.5 to 62.5 52.5 N, 52.5 R ≥ 52.5	Table 3	EN 196	
Initial set	min	≥ 60 to 75	Table 3	EN 196	
Soundness (expansion)	mm	≤ 10	Table 3	EN 196	

[1] Strength class given by 28-day strength   [2] Ordinary early strength   [3] High early strength

SELECTION OF MATERIALS FOR CONCRETE IN DAMS

Table A4 ASTM standards for pozzolan

The tables below are taken from ASTM C618, *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.*

Note: N = natural pozzolan, F = low lime fly-ash, C = high lime fly-ash

Standard Chemical Requirements

Class	N	F	C
Silicon dioxide (SiO_2) plus aluminium oxide (Al_2O_3) plus iron oxide (Fe_2O_3), min, %	70.0	70.0	50.0
Sulphur trioxide (SO_3), max, %	4.0	5.0	5.0
Moisture content, max, %	3.0	3.0	3.0
Loss on ignition, max, %	10.0	6.0[A]	6.0

[A] The use of Class F pozzolan containing up to 12.0 % loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available.

Standard Physical Requirements

Class	N	F	C
Fineness:			
Amount retained when wet-sieved on 45 μm (No. 325) sieve, max, %	34	34	34
Strength activity index: A			
With Portland cement, at 7 days, min, per cent of control	75[B]	75[B]	75[B]
With Portland cement, at 28 days, min, per cent of control	75[B]	75[B]	75[B]
Water requirement, max, per cent of control	115	105	105
Soundness: C			
Autoclave expansion or contraction, max, %	0.8	0.8	0.8
Uniformity requirements:			
The density and fineness of individual samples shall not vary from the average established by the ten preceding tests, or by all preceding tests if the number is less than ten, by more than:			
Density, max variation from average, %	5	5	5
Per cent retained on 45-μm (No. 325), max variation in percentage points from average	5	5	5

[A] The *strength* activity index with Portland cement is not to be considered a measure of the compressive strength of concrete containing the fly ash or natural pozzolan. The mass of fly ash or natural pozzolan specified for the test to determine the *strength* activity index with Portland cement is not considered to be the proportion recommended for the concrete to be used in the work. The optimum amount of fly ash or natural pozzolan for any specific project is determined by the required properties of the concrete and other constituents of the concrete and is to be established by testing. *Strength* activity index with Portland cement is a measure of reactivity with a given cement and is subject to variation depending on the source of both the fly ash or natural pozzolan and the cement.

[B] Meeting the 7 day or 28 day *strength* activity index will indicate specification compliance.

[C] If the fly ash or natural pozzolan will constitute more than 20 % by mass of the cementitious material in the project mixture, the test specimens for autoclave expansion shall contain that anticipated percentage. Excessive autoclave expansion is highly significant in cases where water to cementitious material ratios are low, for example, in block or shotcrete mixtures.

Table A5 Comparison of Standards for Use of Low Lime Fly Ash in Concrete

		American	Canadian	European			Russian				Chinese		
		ASTM	CAN3-	EN450-2003[2]			25818-91				DL/T5055-1996		
		C618-98	A23-MB2	A	B	C	I	II	III	IV	I	II	III
Chemical properties:													
$SiO_2 + Al_2O_3 + Fe_2O_3$	(%)	> 70		>65	>65	>65							
CaO	(%)			<11	<11	<11	< 10	< 10	< 10	< 10			
SO_3	(%)	< 5.0	< 5.0	<3.5	<3.5	<3.5	< 3.0	< 5.0	< 3.0	< 3.0	< 3.0	< 3.0	< 3.0
MgO	(%)	< 5.0		<4.5	<4.5	<4.5	< 5.0	< 5.0	none	< 5.0			
Available alkalis	(%)	< 1.5		<5.5	<5.5	<5.5	< 3.0	< 3.0	< 3.0	< 3.0			
Loss-on-ignition	(%)	< 12.0[1]	< 12.0	< 7.0	<9.0	<11	< 20	< 25	< 10	< 10	< 5	< 8	< 15
Physical properties													
Retained 45µm sieve	(%)	< 34	< 34		4)		< 20[5]	< 30[5]	< 20[5]	< 20[5]	< 12	< 20	< 45
Pozzolanic activity	(%)	> 75	> 68	>70[3]	>70[3]	>70[3]					> 75	> 62	
Water demand	(%)	< 105									< 95	< 105	< 115
Autoclave expansion	(%)	< 0.8	< 0.8										
Drying shrinkage	(%)	< 0.03	< 0.03										
Moisture content	(%)	< 3.0	< 3.0								<1.0	<1.0	

Notes: 1. After proving with trial mixes, without trial mixes limit is 6.0%

2. Limit values for single results. Percentages are by mass

3. at 28 days – 80% at 90 days

4. Fineness 45% (Cat. N), 13% (Cat. S)

5. for anthracite coal

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Table A6 Standard requirements for ground blast furnace slag

Standards				American ASTM 989			European EN151 67-1 2005	Canadian CSAcA363 1983	Japanese JIS A 6206 1997		
Moisture %	%			-			≤ 1.0		≥ 2.80		
Glass content %	%			-			≥ 67				
									Class 4000	Class 6000	Class 8000
									300 - 500	500 - 700	700 - 1000
Specific surface	kg/m²			-			≥ 275				
Retained on 45 micron sieve	%			≤ 20			-	≤ 20.0			
Loss on ignition	%						≤ 3.0		≤ 3.0		
MgO	%						≤ 18		≤ 10.0		
S	%			≤ 2.5			≤ 2	≤ 2.5	≤ 2.0		
SO$_3$	%			≤ 4.0			≤ 2.5		≤ 4.0		
Cl	%						≤ 0.1		≤ 0.02		
Na$_2$O-Equ.							On demand				
CaO + MgO + SiO$_2$							≥ 67				
(CaO+MgO)/SiO$_2$							≥ 1.0		≤ 1.4		
Compression strength											
2d								≥ 3.5			
7d								≥ 10.5			
Activity index				G.80	G.10	G.120			Class 4000	Class 6000	Class 8000
7d				-	≥ 75	≥ 95	≥ 45		≥ 55	≥ 75	≥ 95
28d				≥ 75	≥ 95	≥ 115	≥ 70		≥ 75	≥ 95	≥ 105
91d				-	-	-	-		≥ 95	≥ 105	≥ 105
Permitted additions, gen. %	%						≤ 1.0		≤ 1		
SO$_3$	%			Up to max. SO$_3$ content					≤ 4		

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Table A7 Standard requirements for silica fume

Standards		American	European	Canadian	Japanese	Chinese
		ASTM C1240 – 04	EN 13263:2005	CAN/CSA A23.5 - 98	JIS A 6207 2000	GB/T18736-2002
SiO_2	%	> 85,0	> 85.0	> 85.0	> 85.0	> 85.0
SO_3	%		<2.0	<2.0	<2.0	
Cl	%		<0.3		<0.1	<0.2
Free CaO	%		<1.0		<1.0	
MgO	%				<5.0	
Free Si	%		<0.4			
Available alkalis (Na_2O equivalent)	%	Report				
Moisture	%	<3.0			<3.0	<3.0
Loss on Ignition	%	<6.0	<4.0	<6.0	<5.0	<6.0
Specific surface	m^2/kg	>15,000	15,000 to 35,000		>15,000	>15,000
Bulk density, undensified		Report				
Pozzolanic Activity Index	%	> 105 @ 7d, accelerated cure	> 100 @ 28d, standard cure		> 95 @ 7d, <105@28d, standard cure	> 85 @28d, standard cure
Retained on 45 micron sieve	%	<10		<10		
Variation from average on 45 micron sieve	%-points	<5				
Density	kg/m^3	Report				
Autoclave expansion	%			<0.2		
Foaming				No foam		
Dry mass deviation from value declared in slurry	%-points		<2			
Water requirement ratio	%					< 125

Appendix B – Testing Standards

SELECTION OF MATERIALS FOR CONCRETE IN DAMS

Table B1: Test standards for aggregate

Standard	EN	ASTM
Sampling of aggregates	EN 932-1, EN 932-2	ASTM D 75, ASTM D 3665
Petrographic examination	EN 932-3	ASTM C 295
Light-weight Particles	-	ASTM C 123
Resistance to Degradation of small size Coarse Aggregates by Abrasion	EN 1097-2	ASTM C 131
Resistance to Degradation of large size Coarse Aggregates by Abrasion	EN 1097-2	ASTM C 535
Water absorption	EN 1097-6, EN 1097-6/A1	ASTM C 566 ASTM 127
Clay lumps and friable particles	-	ASTM C 142
Flat and elongated particles	EN 933-3, EN 933-4	-
Chert	-	ASTM C 123
Coal and lignite	EN 1744-1	ASTM C 123
Organic impurities	EN 1744-1	ASTM C 40
Effect of organic impurities on strength	EN 12620	ASTM C 87
Soundness	EN 1367-1	ASTM C 88
grading	EN 933-1	ASTM C 136
Fineness modulus	EN 12620	ASTM C 136
Material finer than 0.075 mm (0.063 mm)	EN 933-1	ASTM C 117
Alkali - Silica reaction	-	ASTM C 1260, ASTM C 1293
Bulk density	EN 1097-3	ASTM C 29
Density	EN 1097-6, 1097-6/A1	-
Alteration resistance of basalt	EN 1367-1	-
Acid soluble SO_3	EN 1744-1	-
Total Sulphate content (S)	EN 1744-1	
Cl	EN 1744-5	-
Alkali - Silica reaction	-	ASTM C 1260 ASTM C 1293
Alkali – Carbonate Rock reaction	-	ASTM C 586 ASTM C 1105

Table B2: Test standards for cement

Standard	EN	ASTM
Sampling	EN 196-7	ASTM C 183
Compressive strength	EN 196-1	ASTM C 109
Flexural strength	EN 196-1	ASTM C 348
Setting time	EN 196-3	ASTM C 191
Soundness	EN 196-3	ASTM C 151
Fineness	EN 196-6	ASTM C 204
Heat of hydration	EN 196-9	ASTM C 186
Air content		ASTM C 185
CaO	EN 196-2	ASTM C 114
CaO free	EN 196-2	ASTM C 114
SiO_2	EN 196-2	ASTM C 114
MgO	EN 196-2	ASTM C 114
$Al2O_3$	EN 196-2	ASTM C 114
SO_3	EN 196-2	ASTM C 114
Fe_2O_3	EN 196-2	ASTM C 114
Cl	EN 196-2	ASTM C 114
K_2O	EN 196	ASTM C 114
Na_2O	EN 196	ASTM C 114
Loss on Ignition	EN 196-2	ASTM C 114
Insoluble residue	EN 196-2	ASTM C 114
Sulphate resistance	-	ASTM C 452

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Table B3: Testing standards for fly-ash

Standard	EN	ASTM
Moisture content		ASTM C 311
Activity	EN 196-1	ASTM C111
Fineness	EN 451-2, EN 196-6	ASTM C 311
Water requirement	-	ASTM C 311
Density	ASTM C 188	ASTM C 311
Soundness	EN 196-3	ASTM C 311
Moisture content	-	ASTM C 311
CaO	EN 196-2	ASTM C 114
CaO free	EN 451-1	ASTM C 114
SiO_2	EN 196-2	ASTM C 114
Fe_2O_3	-	ASTM C 311
MgO	EN 196	ASTM C 114
Al_2O_3	EN 196-2	ASTM C 114
SO_3	ÖN B 3309	ASTM C 114
Cl	EN 196-21	ASTM C 114
K_2O	EN 196-21	ASTM C 311
Na_2O	EN 196-21	ASTM C 311
Loss on Ignition	EN 450	ASTM C 114
Rest of carbon (TOC)	EN 13639	-
Sulphate resistance	Koch-Steinegger Procedure	ASTM C 311

Table B4: Test procedures for ground granulated blastfurnace slag

Standard	EN	ASTM
Activity Index	EN 196-1 (mix of 75% cement and 25% fly-ash)	ASTM C 989
Fineness	EN 451-2	ASTM C 430
Specific surface	EN 196-6	ASTM C 204
Density	EN 196-6	ASTM C 188
Soundness	EN 196-3 (50% cement, 50 % fly-ash)	-
Air content	-	ASTM C 185
Autoclave expansion	ASTM C 151	ASTM C 151
Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction	-	ASTM C 441
CaO	EN 196-2	-
SiO_2	EN 196-2	-
MgO	EN 196-2	-
Al_2O_3	EN 196-2	-
SO_3	EN 196-2	C 114
S	EN 196-2	C 114
Cl	EN 196-21	C 114
K_2O	EN 196-21	-
Na_2O	EN 196-21	-
Rest of carbon (TOC)	EN 13639	-
Glass content	EN 197-1	-
Sulphate resistance,	Koch-Steinegger Procedure	ASTM C 452

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Table B5: Testing standards for silica fume

Standard	EN	ASTM
Sampling	EN 196-7	ASTM C 311
Activity Index	EN 13263-1	ASTM C 311
Fineness	-	ASTM C 430
Specific surface	ISO 9277	-
Density	-	ASTM C 188
Dry mass (for suspension)	EN 13263-1	-
Moisture content	-	ASTM C 311
Autoclave expansion	-	ASTM C 151
Sulphate resistance	-	ASTM C 1012
Fe_2O_3	-	ASTM C 114
Si free	ISO 9286	
SiO_2	EN 196-2	ASTM C 114
Al_2O_3	-	ASTM C 114
SO_3	EN 196-2	ASTM C 114
CaO free	EN 451-1	-
CaO	-	ASTM C 114
MgO	-	ASTM C 114
K_2O	EN 196-2	ASTM C 114
Na_2O	EN 196-2	ASTM C 114
Cl	EN 196-2	ASTM C 114
Loss on ignition	EN 196-2	ASTM C 114

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Table B6: Testing standards for natural pozzolan

Standard	ASTM	Standard	ASTM
Sampling	ASTM C 311	SiO_2	ASTM C 114
Activity Index	ASTM C 311	Al_2O_3	ASTM C 114
Fineness	ASTM C 430	SO_3	ASTM C 114
Density	ASTM C 188	CaO	ASTM C 114
Moisture content	ASTM C 311	MgO	ASTM C 114
Autoclave expansion	ASTM C 151	K_2O	ASTM C 311
Sulphate resistance	ASTM C 1012	Na_2O	ASTM C 311
Alkali-Silica Reaction	ASTM C 441	Loss on ignition	ASTM C 114
Fe_2O_3	ASTM C 114		

Table B7: Testing standards for calcined pozzolan

Standard	EN	ASTM
SiO_2	EN 196-2	ASTM C 114
Al_2O_3	EN 196-2	ASTM C 114
Cl	EN 196-2	ASTM C 114
SO_3	EN 196-2	ASTM C 114
Free CaO	EN 451-1	ASTM C 114
Total alkaline content (Na_2O_3 equivalent)	EN 196-2	ASTM C 114
MgO	EN 196-2	ASTM C 114
Loss on ignition	EN 196-2	
Methyl blue test	EN 933-9	
$Ca(OH)_2$	>Annex A NF P 18-513	
density	EN 196-6	ASTM C 188
Fineness	EN 933-1	ASTM C 430
Activity index	EN 196-1 (85% cement, 15% calcined Pozzolan)	ASTM C 311
Water demand	EN 196-3 (85% cement, 15% calcined Pozzolan)	ASTM C 311
Setting time	EN 196-3 (85% cement, 15% calcined Pozzolan)	ASTM C 191
Soundness	EN 196-3 (85% cement, 15% calcined Pozzolan)	ASTM C 151
Dry content	5.3.7 NF P 18-513	

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Table B8: Test procedures for all types of admixtures, general requirements

Standard	EN	ASTM
Homogeneity	Visual	-
Colour	Visual	-
Effective component	EN480-6	-
Relative density (for liquids only)	ISO 758	-
Conventional dry material content (liquid admixtures)	EN 480-8	ASTM C 494
Residue by oven drying (non liquid Admixtures)	-	ASTM C 494
Specific gravity (liquid admixtures)	-	ASTM C 494
pH value	ISO 4316	ASTM E 70
Total chloride	ISO 1158	-
Water soluble chloride	EN 480-10	-
Alkali content	EN 480-12	-
Infrared Analysis	-	ASTM C 494

Table B9: Additional Test procedures for water reducing admixtures

Standard		EN	ASTM
Water reduction	VeBe	EN 12350-3	ASTM C1170
	Slump	EN 12350-2	ASTM C 143
	Flow	EN 12350-5	ASTM C 138
Compressive strength		EN 12390-3	ASTM C 192; ASTM C 39
Flexural strength		-	ASTM C 78
Density		EN 12350-6	ASTM C 138
Air content in fresh mortar		EN 12350-7	ASTM C 231
Shrinkage		-	ASTM C 157
Bleeding of the concrete		EN 480-4	ASTM C 232

Table B10: Additional Test procedures for air entraining admixtures

Standard	EN	ASTM
Air content in fresh concrete	EN 12350-7	ASTM C 231
Air void characteristic in hardened concrete	EN 480-11	ASTM C 457
Density	EN 12350-6	ASTM C 138
Compressive strength	EN 12390-3	ASTM C 192; ASTM C 39
Flexural strength	-	ASTM C 78
Shrinkage	-	ASTM C 157
Bleeding of the concrete	EN 480-4	ASTM C 232

For EN Standard use reference mortar/concrete according to EN 480-1.

Table B11: Additional Test procedures for set retarding admixtures

Standard	EN	ASTM
Setting time	EN 480-2	ASTM C 403
Compressive strength	EN 12390-3	ASTM C 192; ASTM C 39
Flexural strength	-	ASTM C 78
Density	EN 12350-6	ASTM C 138
Air content in fresh concrete	EN 12350-7	ASTM C 231
Shrinkage	-	ASTM C 157
Bleeding of the concrete	EN 480-4	ASTM C 232

For EN Standard use reference mortar/concrete according to EN 480-1

Table B12: Additional Test procedures for water reducing and retarding admixture

Standard		EN	ASTM
Water reduction	slump	12350-2	ASTM C 143
	VeBe	12350-3	ASTM C1170
	Flow	12350-5	ASTM C 138
Compressive strength		12390-3	ASTM C 192
Flexural strength		-	ASTM C 78
Setting time		480-2	ASTM C 403
Density		12350-6	ASTM C 138
Air content in fresh mortar		12350-7	ASTM C 231
Shrinkage		-	ASTM C 157
Bleeding of the concrete		-	ASTM C 232

For EN Standard use reference mortar/concrete according to EN 480-1

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Table B13: Test procedures for mixing water

Standard	EN	ASTM
Sampling	EN 1008	-
Oil and fat	EN 1008	
Colour	EN 1008	
Particulate material	EN 1008	ASTM C 1603
Aroma	EN 1008	
pH	EN 1008	
Humus	EN 1008	
Cl	EN 196-21	ASTM C 114
SO_4	EN 196-2	ASTM C 114
K_2O	EN 196-21	ASTM C 114
Na_2O	EN 196-21	ASTM C 114
Sugar	-	ASTM C 114
P_2O_5	-	ASTM C 114
NO_3	ISO 7890-1	ASTM C 114
Pb^{2+}	-	ASTM C 114
Zn^{2+}	-	ASTM C 114