Industrial Minerals Laboratory Manual

CONSTRUCTION MATERIALS

D J Harrison and A J Bloodworth
British Geological Survey

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Industrial Minerals Laboratory Manual

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D J Harrison and A J Bloodworth

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Cover illustration:
Close-up of roadstone specimens located on the 'road wheel'
in an accelerated polishing machine used to determine
polished stone value (PSV). Photo courtesy of ELE International Ltd.

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Preface

Industrial mineral raw materials are essential for economic development. Infrastructure improvement and growth of the manufacturing sector requires a reliable supply of good quality construction minerals and a wide range of other industrial mineral raw materials.

Although many less developed countries have significant potential industrial mineral resources, some continue to import these materials to supply their industries. Indigenous resources may not be exploited (or are exploited ineffectively) because they do not meet industrial specifications, and facilities and expertise to carry out the necessary evaluation and testwork are unavailable. Unlike metallic and energy minerals, the suitability of industrial minerals generally depends on physical behaviour, as well as on chemical and mineralogical properties. Laboratory evaluation often involves determination of a wide range of inter-related properties and must be carried out with knowledge of the requirements of consuming industries. Evaluation may also include investigation of likely processing required to enable the commodity to meet industry specifications.

Over the last 10 years, funding from the Overseas Development Administration has enabled the British Geological Survey to provide assistance to less developed countries in the evaluation of their industrial mineral resources. This series of laboratory manuals sets out experience gained during this period. The manuals are intended to be practical bench-top guides for use by organisations such as Geological Surveys and Mines Departments and are not exhaustive in their coverage of every test and specification. The following manuals have been published to date:

- Limestone
- Flake Graphite
- Diatomite
- Kaolin
- Bentonite
- Construction Materials

A complementary series of Exploration Guides is also being produced. These are intended to provide ideas and advice for geoscientists involved in the identification and field evaluation of industrial minerals in the developing world. The following guide has been published to date:

Biogenic Sedimentary Rocks

A J Bloodworth
Series Editor

D J Morgan
Project Manager
1. INTRODUCTION

Stone, brick and cement have been used for construction since ancient times, although the relative importance of these resources has changed with time. Many ancient civilisations developed the use of natural stone to a fine art, and dimension stone still occupies an important place in architecture, particularly in the construction of prestigious buildings.

The Greeks and Romans discovered that a relatively strong and durable mortar could be made by mixing certain types of volcanic ash or calcined clay with lime. Although ‘Roman’ or ‘pozzolanic’ cement was widely-used as mortar for dimension stone and bricks, it was not until the development of Portland Cement in 1824 that concretes could be manufactured with sufficient strength to allow the construction of roads, bridges and buildings of all sizes. Concrete is produced by the incorporation of stone particles (aggregate) in a cement matrix, and demand for concreting aggregates (crushed rock, sand and gravel) continues to rise throughout the world. Aggregates are also widely used in road construction. Roads are usually built with a sub-base of coarse aggregate and surfaced by concrete or asphalt (sand/bitumen mixture). A surface ‘wearing course’ is often added by rolling crushed rock chippings into the asphalt. The demand for aggregates to be used in modern road systems is enormous; in most countries large volumes of crushed rock, as well as naturally-occurring sand and gravel, are used in road construction and concrete production.

Fired clay bricks are amongst the most important materials used for construction in less developed countries. The durability, dimensional consistency and relatively low finished-value of bricks ensures that they are utilised for an extremely wide variety of construction purposes. Clay raw materials for brick making come from a wide variety of sources. This is reflected in considerable variation in the mineralogy and chemistry of brick clays. In this respect, clay for the manufacture of bricks and other structural clay products such as tiles, hollow blocks and sewer pipes differs from most industrial minerals. Provided the finished product can be manufactured economically to meet certain specifications, the mineralogy and chemistry of the material are only relevant insofar as they influence forming and firing behaviour.

The construction industry worldwide has a basic need for rocks and minerals and, if society continues to ask for higher standards of housing, roads and infrastructure development, then the demands for
Construction materials will continue to increase. Figure 1 shows a summary of the main natural resources used in construction.

This manual is concerned with the necessary procedures and techniques which are required to evaluate the properties of raw materials for potential constructional end-uses. Emphasis is given to the preferred laboratory procedures for evaluating specific properties and the manual also outlines the major constructional uses of industrial rocks and minerals. The manual is structured to include separate sections on aggregates, dimension stone and brick clays.
Construction materials

Figure 1. Summary of the main natural resources used in construction

Mineralogy and Petrology Group, British Geological Survey © NERC 1994
2. AGGREGATES

The term "aggregates" describes a wide variety of materials. These are predominantly crushed rocks or natural sands and gravels (primary aggregates), although industrial byproducts (such as slag, colliery wastes, fly ash) and recycled waste materials (such as brick, concrete, asphalt) may be used as substitutes (secondary aggregates) for quarried materials.

There is no single accepted system for the classification of aggregate materials based on particle size limits, but it is convenient to follow usual industrial usage in separating coarse aggregate (rock particles >5 mm diameter) from fine (Table 1).

Table 1. Classification of aggregates by particle size.

<table>
<thead>
<tr>
<th>Size limits</th>
<th>Grain size</th>
<th>Qualification</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>64mm</td>
<td>Cobble</td>
<td></td>
<td>Coarse aggregate</td>
</tr>
<tr>
<td>16mm</td>
<td>Pebble</td>
<td>Coarse</td>
<td>Coarse aggregate (gravel)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fine</td>
<td></td>
</tr>
<tr>
<td>5mm</td>
<td></td>
<td></td>
<td>Coarse aggregate</td>
</tr>
<tr>
<td>1mm</td>
<td>Sand</td>
<td>Medium</td>
<td>Fine aggregate (sand)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fine</td>
<td></td>
</tr>
<tr>
<td>0.25mm</td>
<td></td>
<td>Fines (silt and clay)</td>
<td>Fines</td>
</tr>
<tr>
<td>0.063mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Both coarse and fine aggregates are used in mass concrete or in road construction, although fine aggregate is also used as building sand, asphalt sand and cable sand.
Construction materials

2.1 Geological occurrence

There are two principal sources of aggregate materials: hard consolidated rocks which must be blasted, crushed and processed to aggregates, and natural sand and gravel deposits which are unconsolidated deposits and require minimal processing.

2.1.1 Sand and gravel

Sand and gravel (Thurrell, 1971; Merrit, 1992) are naturally occurring particulate deposits. They are mostly relatively young, unconsolidated superficial deposits derived from the redistribution of rock weathering products by water, ice or wind. They are usually alluvial deposits (river channel, terrace or fan deposits) or glacial deposits (morainic, fluvioglacial outwash, periglacial material), although modern marine sands and gravels occur widely on the seafloor of many continental shelf areas (Harrison, 1992a). Sand and gravels may also occur in older consolidated or partially consolidated bedded deposits as conglomerates or pebbly sandstones (Piper, 1982).

2.1.2 Crushed rock aggregates

Most hard (‘solid’) rocks are potentially suitable for coarse aggregates. However, demanding specifications of aggregate materials used in road pavements and concrete require that ‘high-quality’ crushed rock aggregates are used. These are commonly derived from indurated and cemented sedimentary rocks and the tougher, crystalline igneous or metamorphic rocks.

Sedimentary rocks: Most limestones and dolomites are hard and durable and useful for aggregate. They are common rock types and usually occur in thick beds which are structurally simple and easy to quarry. As a consequence, they are widely extracted for aggregate materials, as well as for cement manufacture (limestone only), and for industrial processes which utilise the chemical properties of the stone (Harrison, 1992b).

Sandstones, gritstones, arkoses (feldspathic sandstones) and greywackes (‘impure’ sandstones) are all commonly used as aggregate materials, although their strength and durability directly depends on the degree of cementation. An example of an assessment survey of sandstone resources is provided by Adlam et al. (1984).
Igneous rocks

Igneous rocks are widely quarried for crushed rock aggregates. The finer-grained varieties (such as dolerite, basalt or porphry) are often preferred due to their high strength, although large amounts of aggregates are also produced from coarse-grained rocks (such as granites and diorites). The suitability of these rocks for aggregate depends on mineralogy, texture, and degree of alteration.

Metamorphic rocks

The wide range of metamorphic rock types is reflected in their variable usefulness as aggregate. Coarse or medium grained, massive, granular rocks such as gneisses, quartzites and marbles generally provide high quality aggregates, whereas foliated and platy rocks such as schists and phyllites are usually weaker and may be less durable.

2.1.3 Weathering

Weathering processes operating in the tropics and in arid regions may result in discoloration, decomposition, or disintegration of the rock material. Ideally, only fresh, or faintly weathered rock material should be used for aggregate. A classification of weathering grades for rock masses is given in a Geological Society Report (1977).

In tropical regions, intense chemical weathering results in clay-rich mantles up to 100m thick (Fookes et al., 1971), restricting access to unweathered bedrock. Upward migration of salts in arid areas may cause mechanical disintegration of porous sedimentary rocks. Duricrusts (composed of salts transported via pore fluids) may develop in the upper few metres of a sedimentary rock mass. In desert regions, the development of duricrusts (calcrete or silcrete material) within the sand deposits may themselves form potential aggregate materials, although they are generally extremely variable in composition. In general, the best prospective aggregate sources in arid regions are igneous and metamorphic rocks.
2.2 Uses and specifications

A brief summary of the major uses of aggregates with an indication of typical specification requirements is given below. More detailed descriptions can be found in Smith and Collis (1993) and Pike (1990).

2.2.1 Roadstone

Crushed rock aggregates and natural gravels and sands are commonly used in road pavement construction. In the UK, the USA and many other countries, roadstone is the largest single end-use of construction aggregates. Modern flexible road pavements consist of a series of discrete layers (Figure 2).

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wearing course</td>
<td>10-40 mm</td>
</tr>
<tr>
<td>Basecourse</td>
<td>40-75 mm</td>
</tr>
<tr>
<td>Roadbase</td>
<td>100-200 mm</td>
</tr>
<tr>
<td>Sub-base</td>
<td>(varies in thickness)</td>
</tr>
<tr>
<td>Capping layer</td>
<td>(if required)</td>
</tr>
<tr>
<td>Bedrock</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Road pavement construction layers.

The 'sub-base' distributes the load onto the subsoil and forms a working platform for construction. It is overlain by the 'roadbase' which is the main load-bearing layer. The surfacing layers consist of a 'basecourse' and a thin 'wearing course'.

Aggregates used in road pavement construction may be unbound, or bound by cementitious or bituminous binders. Unbound layers are usually used for sub-bases but may be used for bases or, in the case of
minor roads, the whole structure. Unbound aggregates generally perform less well than bound aggregates as pavements (Croney & Croney, 1991) but they have the important advantage of comparatively low cost.

The performance of an aggregate layer in a pavement depends on the mineralogical, physical and mechanical properties of the stone, particle shape and grading (which may be affected by processing) and the method of laying the pavement. Aggregates which are used in the load-bearing layers should be resistant to crushing and impact loads, as well as chemical and physical weathering. Good pavement drainage is also essential, a characteristic which is affected both by the aggregate grading, and by the pore size distribution within the aggregate. Aggregates which are used in pavement surfacing are also required to be sound, strong and durable. In addition, they must also be resistant to polishing (for skid resistance) and show resistance to stripping (the aggregate must maintain adhesion with the binder).

A wide range of crushed rock types, as well as natural gravels and sands and certain secondary aggregates, are used as roadstone aggregates. Well-cemented sandstones and limestones are generally of high strength, as are most igneous rocks. Foliated metamorphic rocks are generally of low durability, but non-foliated varieties are extremely hard and tough. Road surfacing aggregates are required to be hard wearing and skid resistant; sandstone or igneous rock aggregates are generally preferred for this purpose.

Specifications for materials used in road making in the UK are given in Department of Transport (1991) and in relevant British Standards (such as BS 812, 882, 594, 4987, 6543). Guidelines in the USA are provided by the American Society for Testing and Materials (ASTM). Other countries such as Australia (AS 2758,1141) and New Zealand (NZS 3121) have developed their own national and local standards for roadstone aggregates. These reflect the materials, climatic and economic constraints of the locality. There are no international standards (ISO) for aggregates, although draft European standards are in preparation by the Committee for European Standardisation (CEN). Some typical specification requirements for roadstone aggregates are given in Table 2.
Table 2. Typical specification requirements for roadstone aggregates.

<table>
<thead>
<tr>
<th>Test Description</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle density (specific gravity)</td>
<td>Generally &gt;2.65</td>
</tr>
<tr>
<td>Water absorption (an indicator of porosity)</td>
<td>&lt;2%</td>
</tr>
<tr>
<td>Flakiness index (shape factor)</td>
<td>&lt;25 (for wearing course) &lt;35 (for general purposes)</td>
</tr>
<tr>
<td>Aggregate impact value (AIV strength test)</td>
<td>Generally &lt;25</td>
</tr>
<tr>
<td>Aggregate crushing value (ACV strength test)</td>
<td>Generally &lt;24 or &lt;30</td>
</tr>
<tr>
<td>10% fines value (strength test)</td>
<td>&gt;160 kN</td>
</tr>
<tr>
<td>Los Angeles abrasion value (LAAV attrition test)</td>
<td>&lt;40 (for wearing course) &lt;50 (for base course)</td>
</tr>
<tr>
<td>Aggregate abrasion value (AAV surface wear test)</td>
<td>&lt;14 for lightly trafficked sites or &lt;10 for potentially dangerous sites</td>
</tr>
<tr>
<td>Polished stone value (PSV skid resistance test)</td>
<td>&gt;60 for potentially dangerous sites &gt;45 for low risk sites</td>
</tr>
<tr>
<td>Sulphate soundness test (disintegration by weathering test)</td>
<td>&lt;18% magnesium sulphate loss</td>
</tr>
</tbody>
</table>

Note: This table shows specifications relating to British and American standards. Where test value limits are not specified, then guideline values are shown.
2.2.2 Concrete aggregates

Concrete is usually made from a mixture of water, cement, and both coarse and fine aggregate. The water and cement form the paste, whilst the aggregate forms an inert filler. Aggregate is the major constituent of concrete (60% - 80% by volume) and the type of aggregate influences the mix proportions and the performance of the concrete. The properties of the aggregate affect concrete characteristics such as density, strength, durability, thermal conductivity, shrinkage and creep. The shape and surface textures of the aggregate particles and their grading (distribution of particle sizes) are important factors influencing the workability and strength of concrete. Aggregates should not be of a type, nor contain sufficient impurities, that would have an adverse effect on the setting properties of the cement or the durability of the concrete.

The aggregate particles must be sufficiently strong that they do not reduce the bulk shear strength of the concrete. The porosity (water absorption) of aggregate particles is important. Particles with a high porosity have a high surface area and therefore an excessively high water requirement in concrete. Physical and mechanical properties for concreting aggregates are given in Table 3. In general these are similar to those given for roadstone aggregates. Some special requirements for coarse aggregate in concrete are given in Table 4. Table 5 shows limits for clay, silt and dust in aggregates for concrete.
Table 3. Physical and mechanical properties of concrete aggregates.

<table>
<thead>
<tr>
<th>Property</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size and grading</td>
<td>BS 882 gives grading limits</td>
</tr>
<tr>
<td>Particle shape (flakiness index)</td>
<td>&lt;50 (gravel) and &lt;40 (crushed rock) - BS 882</td>
</tr>
<tr>
<td>Particle density</td>
<td>Not usually limited, except for concrete used in dams, marine protection etc.</td>
</tr>
<tr>
<td>Water absorption (porosity)</td>
<td>Not usually limited, but a recommended max. value of 2.5% is sometimes specified</td>
</tr>
<tr>
<td>Strength</td>
<td>BS 812, 882, ASTM C131 (see Tables 2 and 4)</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>BS 812, 882, ASTM C131 (see Tables 2 and 4)</td>
</tr>
<tr>
<td>Cleanliness</td>
<td>See Table 5</td>
</tr>
<tr>
<td>Soundness (magnesium sulphate)</td>
<td>&lt;18 for coarse aggregate and &lt;15 for fine aggregate - ASTM C33</td>
</tr>
</tbody>
</table>

Table 4. Some mechanical property requirements for coarse aggregate in concrete (BS 882).

<table>
<thead>
<tr>
<th>Type of concrete</th>
<th>10% fines value (kN)</th>
<th>AIV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy duty concrete floors</td>
<td>&gt;150</td>
<td>25</td>
</tr>
<tr>
<td>Road pavement wearing surfaces</td>
<td>&gt;100</td>
<td>30</td>
</tr>
<tr>
<td>Others</td>
<td>&gt;50</td>
<td>45</td>
</tr>
</tbody>
</table>
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Table 5. Limits upon fines content in concrete aggregates (BS 882).

<table>
<thead>
<tr>
<th>Aggregate type</th>
<th>Quantity of clay, silt, dust (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>2</td>
</tr>
<tr>
<td>Crushed rock</td>
<td>4</td>
</tr>
<tr>
<td>Sand</td>
<td>4</td>
</tr>
<tr>
<td>Crushed rock sand</td>
<td>16</td>
</tr>
</tbody>
</table>

In addition to being hard, durable, clean and free of clay, concrete aggregates should contain only small amounts of coal, organic material, pyrite and soluble sulphates. A list of undesirable constituents is given in Table 6. Concrete aggregates should also be resistant to attack by alkaline cement pore fluids. The alkali-silica reaction (ASR) may induce expansion and cracking in concrete. ASR is a chemical reaction between disordered forms of silica, which may occur in aggregates, and hydroxyl ions formed by the release of alkali compounds from the cement. The reaction forms a swelling gel which may induce stress, resulting in expansion and cracking which over time can threaten structural integrity.

A combination of the following may lead to ASR-induced cracking:

- a significant quantity of reactive silica (low reactive silica contents will not induce expansion) in the aggregate;
- available alkalis (generally from the cement) above a critical level;
- moisture from an external source.

The reactivity of silica depends on the amount of order in the crystal structure. Opal is highly disordered and is the most reactive form of silica. In contrast, well ordered unstrained quartz is usually unreactive (see Tables 6 and 7). There are a number of tests for assessing the reactivity of aggregates, such as the ASTM C289 quick test, the ASTM C227 mortar bar expansion test and the gel pat test (Jones & Tarleton, 1958). Petrographic examination of aggregates is also an important assessment procedure (ASTM C295). There are guidelines for minimising ASR in new constructions by using aggregates that contain less than 2%, or more than 60% reactive silica (Concrete Society, 1987; Department of Transport, 1991). Any quartz in the aggregate should...
Construction materials

not be in the form of 'quartzite' and should contain less than 30% highly strained quartz. More detailed summaries of ASR are given by Hobbs (1988) and British Cement Association (1988).

A further type of alkali-aggregate reactivity is the alkali-carbonate reaction (ACR), which occurs when certain carbonates react with alkalis to cause expansion and cracking (Gillot & Swenson, 1969). Potentially deleterious carbonates are dolomitic, especially those with a high clay content.

Table 6. Deleterious minerals in concreting aggregates.

<table>
<thead>
<tr>
<th>ASR minerals</th>
<th>Opal (vein material, vug fillings, cementing materials)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tridymite and cristobalite (minor constituent of some acid and intermediate volcanic rocks)</td>
</tr>
<tr>
<td></td>
<td>Chalcedony (some cherts and flints, vein material, cementing material etc.)</td>
</tr>
<tr>
<td></td>
<td>Microcrystalline quartz (chert and flint, groundmass of some igneous and metamorphic rocks, cementing material etc.)</td>
</tr>
<tr>
<td></td>
<td>Strained quartz (metamorphic rocks)</td>
</tr>
<tr>
<td></td>
<td>Volcanic glass (some acid to basic volcanic rocks)</td>
</tr>
<tr>
<td></td>
<td>Zeolites (particularly natrolite and heulandite)</td>
</tr>
<tr>
<td>ACR minerals</td>
<td>Dolomitic carbonates</td>
</tr>
<tr>
<td>‘Swelling’ minerals</td>
<td>Smectite, mixed-layer clays, kaolinite, zeolites</td>
</tr>
<tr>
<td>Iron minerals and metallic oxides</td>
<td>Pyrite, lead and zinc oxides</td>
</tr>
<tr>
<td>Chlorides</td>
<td>Common salt</td>
</tr>
<tr>
<td>Sulphates</td>
<td>Gypsum, magnesium and sodium sulphates</td>
</tr>
<tr>
<td>Organic matter</td>
<td>Coal, lignite, sugars, humus</td>
</tr>
<tr>
<td>Mica</td>
<td>Can be present in granites, gneisses and sandstones</td>
</tr>
</tbody>
</table>
Construction materials

Table 7. Rock types which may contain potentially reactive silica

<table>
<thead>
<tr>
<th>Rock types</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volcanic rocks</td>
<td>Rhyolites, dacites and their tuffs; some andesites</td>
</tr>
<tr>
<td>Sedimentary rocks</td>
<td>Rocks containing cherts and flints (some limestones); rocks with reactive particles</td>
</tr>
<tr>
<td>Metamorphic rocks</td>
<td>Some quartzites and some phyllites</td>
</tr>
<tr>
<td>Hydrothermal rocks</td>
<td>Those with opal and chalcedony</td>
</tr>
</tbody>
</table>

Aggregates selected for use in concrete should comply with British Standard specifications (BS 882) or other national standards. When the use of materials not complying with such specifications is unavoidable, it should be demonstrated that sufficiently strong and durable concrete can be made with them.

Most concretes have a density of around 2400 kg/m³. By using lightweight aggregates the density can be reduced to less than 2000 kg/m³. Densities of over 3000 kg/m³ can be attained by the use of heavyweight aggregates. Pumice is used in the manufacture of lightweight concrete blocks, and artificial lightweight aggregates used in concrete structures include expanded clays and shale, as well as pulverised fuel ash. Heavyweight aggregates used in high-density concretes include baryte, hematite and magnetite.

2.2.3 Aggregates for mortar

Mortar is a mix of natural sand (or other fine aggregate) and a lime/cement or gypsum-based binder, used in bonding masonry or as a surface plastering and rendering material. Sand is the major constituent and the quality of the mortar is dependent on the particle size and shape of the sand, as well as on any impurities within the sand.
Construction materials

Specifications for mortar sands indicate that sands should be hard, durable, clean and free from adherent coatings such as clay, and free from clay in pellet form. Most specifications (including BS 1199 and 1200) emphasize particle-size distribution. Some typical grading requirements for mortar sand used in bricklaying are given in Table 8. Grading specifications for sands used in plastering and rendering are given in Table 9.

Table 8. Grading specifications for mortar sands for laying bricks.

<table>
<thead>
<tr>
<th>Sieve sizes</th>
<th>UK (type S)</th>
<th>Japan</th>
<th>USA</th>
<th>Belgium</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.00 mm</td>
<td>98-100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>2.36 mm</td>
<td>90-100</td>
<td>90-100</td>
<td>95-100</td>
<td>100</td>
</tr>
<tr>
<td>1.18 mm</td>
<td>70-100</td>
<td>70-100</td>
<td>70-100</td>
<td>100</td>
</tr>
<tr>
<td>600 μm</td>
<td>40-100</td>
<td>40-100</td>
<td>40-75</td>
<td>80-100</td>
</tr>
<tr>
<td>300 μm</td>
<td>7-70</td>
<td>5-75</td>
<td>10-35</td>
<td>40-85</td>
</tr>
<tr>
<td>150 μm</td>
<td>0-15</td>
<td>0-25</td>
<td>2-35</td>
<td>10-25</td>
</tr>
<tr>
<td>75 μm</td>
<td>0-5</td>
<td>0-10</td>
<td>--</td>
<td>0-7</td>
</tr>
</tbody>
</table>

Table 9. Grading requirements for mortar sands for plastering and rendering (BS 1199).

<table>
<thead>
<tr>
<th>Sieve size</th>
<th>Type A</th>
<th>Type B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.00 mm</td>
<td>95-100</td>
<td>95-100</td>
</tr>
<tr>
<td>2.36 mm</td>
<td>60-100</td>
<td>80-100</td>
</tr>
<tr>
<td>1.18 mm</td>
<td>30-100</td>
<td>70-100</td>
</tr>
<tr>
<td>600 μm</td>
<td>15-100</td>
<td>55-100</td>
</tr>
<tr>
<td>300 μm</td>
<td>5-50</td>
<td>5-75</td>
</tr>
<tr>
<td>150 μm</td>
<td>0-15</td>
<td>0-20</td>
</tr>
<tr>
<td>75 μm</td>
<td>0-15</td>
<td>0-5</td>
</tr>
</tbody>
</table>

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There are many different national standards for mortar sands. European Standards are being drafted and in 1994 these new standards (CEN) will supersede all current European national standards. In view of the divergence of specifications, then the practical criteria for specifying an acceptable mortar sand should be its ability to perform satisfactorily in a variety of mortar mixes.

Although most sands used in mortar are composed of quartz, carbonate sands may comprise the only locally available source of sand for mortar in some arid and tropical climates areas. The closely-sized nature of these beach sands may cause problems of moisture control when used in mortar.

2.2.4 Railway track ballast

Substantial amounts of coarse aggregate are used as railway track ballast, where the ballast layer supports and maintains alignment of the railway track, and provides a free draining base. This requires a strong, angular aggregate with a high resistance to abrasion. Limestone aggregates are generally not used because of their low resistance to abrasion. Igneous rocks (rhyolites, granites, dolerites, basalts) are generally preferred. The material is usually expected to lie within a specified size range (often between 70-20 mm) and should be free of organic impurities, marl and clay. A Los Angeles value of 23 or less is often specified, although in the UK the main quality requirement is a Wet attrition value (BS 812:1951) of less than 4%. In common with many aggregate specifications, the selection of suitable materials for railway ballast is often based on experience and judgement rather than on experimental data.

2.2.5 Aggregates for filters

Aggregates are widely used as drainage filters in earthworks, in water filtration and in effluent treatment. Although the total volume of filter aggregate is relatively small, they are used in a wide range of applications (Table 10), and high quality aggregates are required in certain application.
Construction materials

Table 10. Aggregates for filter applications.

<table>
<thead>
<tr>
<th>Application</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water supply</td>
<td>Well filters and envelopes</td>
</tr>
<tr>
<td>Purification works</td>
<td>Fine and coarse filter beds</td>
</tr>
<tr>
<td>Land drainage</td>
<td>Trench fills, soakaway fills, pipe envelopes</td>
</tr>
<tr>
<td>Structural drainage</td>
<td>Foundation drainage, roadbed drainage, dam and slope drainage</td>
</tr>
<tr>
<td>Stabilization works</td>
<td>Pressure relief, saturation control</td>
</tr>
</tbody>
</table>

Aggregates used as filters are required to be strong and durable, with a specified grading and particle shape. The filler layer will need to be structurally stable, highly permeable and durable with a low susceptibility to physical and chemical decay. Specifications of aggregates for filters and drains are not usually stringently applied, but guideline requirements for acceptable materials are given in Table 11.

Table 11. Typical specification requirements for filter aggregates.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grading</td>
<td>less than 10% fines</td>
</tr>
<tr>
<td>Flakiness index</td>
<td>&lt;30</td>
</tr>
<tr>
<td>Relative density</td>
<td>&gt;2.5</td>
</tr>
<tr>
<td>Water absorption</td>
<td>&lt;3%</td>
</tr>
<tr>
<td>Aggregate impact value</td>
<td>&lt;30</td>
</tr>
<tr>
<td>Los Angeles value</td>
<td>&lt;40</td>
</tr>
<tr>
<td>Soundness (MgSO4)</td>
<td>&lt;12% loss</td>
</tr>
</tbody>
</table>
2.3 Laboratory assessment of aggregates

Evaluation of aggregate deposits involves study of the geological setting and determination of the mineralogical, physical and, in certain cases, the chemical properties of the stone. Aggregate assessment should therefore begin with a desk study to collate available geological data, followed by field reconnaissance and evaluation of prospects involving mapping, section measuring and sampling. This will enable the general lithology to be described, as well as interpretation of stratigraphical relationships and geological structure. The main factors which need to be assessed at the field stage of investigations include:

- Stratigraphical position
- Bulk composition, degree of lithological variability
- Structure of the deposit, structural discontinuities, degree of fracturing
- Thickness of the deposit
- Type and thickness of overburden
- Degree of weathering
- Presence of deleterious horizons, alteration zones etc.
- Hydrogeological parameters
- Field strength testing (Schmidt Hammer, Franklin point load test)
- Sample collection (from exposures or drilling, pitting, trenching)

More detailed guidelines on appropriate field survey techniques are given in Mathers (1993).

After the identification of a deposit with economic potential, further detailed laboratory investigations of physical and mechanical properties are required to prove its aggregate qualities. Some of the laboratory techniques and procedures are sophisticated and require expensively equipped laboratories; others are relatively simple and may be carried out in more basic laboratories or even in the field setting. Figure 3 illustrates a comprehensive laboratory assessment scheme for aggregate materials. A simplified assessment scheme which is recommended for reconnaissance investigations is given in Figure 4.

A wide range of tests (Table 12) has been devised to describe aggregate materials and to assess their value and potential ‘in-service’ performance. Most are performed on the finished aggregate product. The tests outlined in the following text are standard in Britain and the USA; similar standards apply in most other countries.
Construction materials

Field survey

Field sampling

Cored boreholes

Minimum 74 mm diameter

Samples from quarries/exposures

Minimum 25 kg sample

Petrographic examination

Sample preparation (crushing/sieving)

Chippings of preferred size fractions (usually 10-14 mm)

Physical tests

Grading, particle shape, relative density, water absorption

Mechanical tests

AIV, ACV, 10% fines, AAV, LAAV, PSV, soundness

Chemical tests

Chloride, organics, sulphate, alkali reactivity

Geological data

Petrographic data

Aggregate test data

Assessment report and maps

Figure 3. Laboratory assessment scheme for aggregate materials.
Figure 4. Simplified laboratory assessment scheme for reconnaissance investigation of aggregate materials.

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Table 12. Standard tests for evaluating aggregates.

<table>
<thead>
<tr>
<th>Petrographic examination</th>
<th>ASTM C295</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical tests</td>
<td></td>
</tr>
<tr>
<td>1. Aggregate grading and particle shape</td>
<td></td>
</tr>
<tr>
<td>2. Relative density</td>
<td></td>
</tr>
<tr>
<td>3. Water absorption</td>
<td></td>
</tr>
<tr>
<td>Mechanical tests: strength</td>
<td></td>
</tr>
<tr>
<td>1. Aggregate impact value (AIV)</td>
<td>Measures resistance to granulation under impact stresses. BS 812.</td>
</tr>
<tr>
<td>2. Aggregate crushing value (ACV)</td>
<td>Measures resistance to crushing under a gradually applied load. BS 812.</td>
</tr>
<tr>
<td>3. Ten per cent fines value</td>
<td>Measures resistance to crushing by the application of a gradually applied load. BS 812.</td>
</tr>
<tr>
<td>Mechanical tests: durability</td>
<td></td>
</tr>
<tr>
<td>1. Aggregate abrasion value (AAV)</td>
<td>Measures surface wear following abrasion. BS 812.</td>
</tr>
<tr>
<td>2. Los Angeles abrasion value (LAAV)</td>
<td>Measures resistance to attrition by impact and abrasion forces. ASTM C131.</td>
</tr>
<tr>
<td>4. Sulphate soundness</td>
<td>Measures resistance to disintegration by weathering action or salt crystallisation. ASTM C88.</td>
</tr>
<tr>
<td>Chemical tests</td>
<td></td>
</tr>
<tr>
<td>1. Chloride content</td>
<td>BS 812.</td>
</tr>
<tr>
<td>2. Organic content</td>
<td>BS 1377.</td>
</tr>
<tr>
<td>3. Sulphate content</td>
<td>BS 812.</td>
</tr>
</tbody>
</table>
2.3.1 Petrographic techniques

Petrographic examination is required to determine composition of an aggregate and to assist in the assessment of potential suitability for end-use. It is particularly important to identify the relative amounts of constituents which may have a bearing on the quality of the aggregate (such as clay minerals, coal, strained quartz, chalcedony, opal, iron oxides, bitumen, zeolites).

There is no British Standard for procedures for petrographic examination of aggregates, although a draft method has been prepared for future incorporation in BS 812: Part 104. ASTM C295-85 gives standard procedures for petrographical examination of aggregate materials. The following text aims to provide simplified practical guidelines for the qualitative and quantitative examination of aggregate petrography. The examination must be undertaken by a person experienced in petrography and with access to a suitably equipped laboratory.

Rock names used in the descriptions should generally be restricted to those recommended in BS 812: Part 102 (Table 13), although it may also be necessary to include more detailed petrographic data.

The examination can be undertaken on either processed (such as crushed rock aggregate) or unprocessed materials (rock samples), and consideration should be given to the required sampling procedures and minimum sample size (see BS 812). The method involves visual recognition and quantification or semi-quantification of rock and mineral constituents. A qualitative examination of the aggregate sample (coarse, fine or mixed) is used to determine aggregate type and its general character and petrography. A representative sub-sample is then taken which is subject to a more detailed, quantitative examination. Detailed methods for petrographic description are given in Appendix 1.
Construction materials

Table 13. Recommended rock names for petrographic descriptions of aggregates (BS 812)

<table>
<thead>
<tr>
<th>Petrological term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andesite</td>
<td>Fine-grained, usually volcanic, variety of diorite</td>
</tr>
<tr>
<td>Arkose</td>
<td>Sandstone containing over 25% feldspar</td>
</tr>
<tr>
<td>Basalt</td>
<td>Fine-grained basic volcanic rock, similar in composition to gabbro</td>
</tr>
<tr>
<td>Breccia</td>
<td>Rock consisting of cemented angular rock fragments</td>
</tr>
<tr>
<td>Chalk</td>
<td>Very fine-grained, soft, white limestone</td>
</tr>
<tr>
<td>Chert</td>
<td>Cryptocrystalline silica</td>
</tr>
<tr>
<td>Conglomerate</td>
<td>Rock consisting of cemented rounded pebbles</td>
</tr>
<tr>
<td>Diorite</td>
<td>Intermediate plutonic rock consisting mainly of plagioclase, with hornblende, augite or biotite</td>
</tr>
<tr>
<td>Dolerite</td>
<td>Basic rock, with grain size intermediate between that of gabbro and basalt</td>
</tr>
<tr>
<td>Dolomite</td>
<td>Rock composed of calcium magnesium carbonate</td>
</tr>
<tr>
<td>Flint</td>
<td>Cryptocrystalline silica originating as nodules or layers in chalk</td>
</tr>
<tr>
<td>Gabbro</td>
<td>Coarse grained, basic plutonic rock consisting essentially of calcic plagioclase and pyroxene, sometimes with olivine</td>
</tr>
<tr>
<td>Gneiss</td>
<td>Banded rock, produced by intense metamorphism</td>
</tr>
<tr>
<td>Granite</td>
<td>Acidic plutonic rock, consisting essentially of alkali feldspars and quartz</td>
</tr>
<tr>
<td>Granulite</td>
<td>Metamorphic rock with granular texture and no preferred orientation of the minerals</td>
</tr>
<tr>
<td>Greywacke</td>
<td>Impure sandstone, composed of quartz, other minerals and rock fragments</td>
</tr>
<tr>
<td>Gritstone</td>
<td>Sandstone, with coarse and usually angular grains</td>
</tr>
<tr>
<td>Hornfels</td>
<td>Thermally-metamorphosed rock consisting predominantly of silicates</td>
</tr>
<tr>
<td>Limestone</td>
<td>Sedimentary rock, consisting predominantly of calcium carbonate</td>
</tr>
<tr>
<td>Marble</td>
<td>Metamorphosed limestone</td>
</tr>
<tr>
<td>Microgranite</td>
<td>Acidic rock with grain-size intermediate between that of granite and rhyolite</td>
</tr>
<tr>
<td>Quartzite</td>
<td>Metamorphic or sedimentary rock, composed essentially of quartz grains</td>
</tr>
<tr>
<td>Rhyolite</td>
<td>Fine-grained or glassy acidic rock, usually volcanic</td>
</tr>
<tr>
<td>Sandstone</td>
<td>Sedimentary rock, composed of cemented sand grains</td>
</tr>
<tr>
<td>Schist</td>
<td>Fissile metamorphic rock in which the minerals are arranged in layers</td>
</tr>
<tr>
<td>Slate</td>
<td>Metamorphic rock derived from argillaceous sediments or volcanic ash, characterised by cleavage</td>
</tr>
<tr>
<td>Syenite</td>
<td>Intermediate plutonic rock consisting mainly of alkali feldspar with plagioclase, hornblende, biotite, or augite</td>
</tr>
<tr>
<td>Trachyte</td>
<td>Fine-grained, usually volcanic, variety of syenite</td>
</tr>
<tr>
<td>Tuff</td>
<td>Consolidated volcanic ash</td>
</tr>
</tbody>
</table>
Procedure for rock samples This should involve a general description of the macroscopic features of the lump or core sample, with additional information on mineral composition provided by thin section examination. The petrographic description should include details of rock type, structure, fracturing, texture, weathering, alteration, and relative proportions of major and minor components.

Unsatisfactory components It is recommended that the petrographic report should include specific notes relating to the presence, absence and relative proportions of deleterious impurities in the aggregate. A list of these potentially unsatisfactory components is given in Table 6. X-ray diffraction analysis is a useful supplement to petrographic examination, particularly in the identification of deleterious minerals such as clays.

2.3.2 Physical tests

Grading (particle-size distribution) An aggregate containing a range of particle sizes from fine to coarse is known as 'well-graded'. When the particles are more or less uniform in size the aggregate is classified as 'poorly-graded'. Grading affects the compaction capacity, permeability and strength of roadbase and concrete aggregates.

The grading of an aggregate sample is determined in the laboratory using a standard group of sieves (such as those specified by BS 812) on a wet or dry sieving basis (Figure 5). Grading data (percentage passing versus particle size) are generally plotted on semi-logarithmic charts to give a 'grading curve'. Most national standards for aggregates specify grading requirements; an example of the British Standard specification of fine aggregate for concrete is given in Table 14.
Table 14. Grading of fine aggregates for concrete (BS 882).

<table>
<thead>
<tr>
<th>BS sieve size</th>
<th>Overall limits</th>
<th>Additional limits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Coarse</td>
</tr>
<tr>
<td>10 mm</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>5 mm</td>
<td>89 - 100</td>
<td></td>
</tr>
<tr>
<td>2.36 mm</td>
<td>60 - 100</td>
<td>60 - 100</td>
</tr>
<tr>
<td>1.18 mm</td>
<td>30 - 100</td>
<td>30 - 90</td>
</tr>
<tr>
<td>600 µm</td>
<td>15 - 100</td>
<td>15 - 54</td>
</tr>
<tr>
<td>300 µm</td>
<td>5 - 70</td>
<td>5 - 40</td>
</tr>
<tr>
<td>150 µm</td>
<td>0 - 15</td>
<td></td>
</tr>
</tbody>
</table>

Particle shape  The shape of aggregate particles reflects the petrology of the rock, depositional environment (natural gravels), or the quarrying and aggregate production process (crushed rock aggregates). Shape is predominantly a function of processing and largely reflects the type of crushing plant used. However, hard, tough or brittle rocks tend to generate more flakes than weaker rocks in crushing, although the latter produce more fines.

Particle shape affects the performance of an aggregate during both construction and service. Angular, cuboidal aggregates are generally preferred. Very flaky and elongated particles are relatively weak and also have a high bitumen or binder demand due to their relatively large surface area. BS 812 classifies aggregate shapes into six categories; rounded, irregular, angular, flaky, elongated and flaky, and elongated. The first three listed are equidimensional and may be referred to as 'cuboidal' (Ramsey, 1965). In the appraisal of aggregate shape it is recommended that reference is made to this classification by visual inspection of the sample and comparison with the descriptions and photographs given in BS 812.

Estimations of shape factor are also provided in BS 812 in the indices of flakiness and elongation.

Flakiness index  This test measures the weight-percentage of particles whose least dimension is less than 0.6 times the mean dimension. Test
Construction materials

procedure for a selected size fraction (such as 10-14 mm) involves the use of a specially designed slotted sieve or thickness gauge.

Flakiness index ($I_f$) = \frac{\text{mass of particles passing sieve/gauge}}{\text{total mass tested}} \times 100\%

In this test a higher numerical value indicates a more flaky aggregate. A limit of 35% is specified (BS 63) for 10 mm aggregate for general purposes, but a maximum flakiness index of 25% is given for aggregates used in surface dressings.

Different countries tend to use different sieve sizes in their aggregate specifications but the general principle of testing and limiting particle shape is widely accepted.

Elongation index An aggregate particle is elongated when it has one dimension greater than the other two dimensions. The elongation index is the weight-percentage of particles whose long dimension is more than 1.8 times the mean dimension. Once again, a British Standard gauge is used and, for each size fraction, the elongation index ($L_e$) is defined as:

\text{Elongation index} = \frac{\text{mass of particles refused by gauge}}{\text{total mass of particles tested}} \times 100\%

The elongation index is not usually specified in construction contracts as shape factor can be determined more quickly by determination of flakiness index. Elongate particles are usually also flaky. Other terms which also are sometimes used for describing particle shape are angularity number (BS 812), sphericity and roundness (Wadell, 1933).

Surface texture The surface texture of aggregates considerably influences the adhesion between aggregate and binders or cement. In general, a rough surface texture gives good adhesion, whereas a glassy surface results in poor adhesion.

BS 812: 1975 gives six categories for describing the surface texture of aggregate particles. These are:

- glassy (such as flint or vitreous slag)
- smooth (such as natural gravels, slate, marble)
- granular (such as sandstone, oolitic limestone)
- rough (such as some limestones, dolerite, porphyry)
- crystalline (such as granite, gneiss)
- honeycombed (such as pumice, some slags)
Construction materials

Figure 5. Sieving to determine aggregate grading.

Figure 6. Aggregate impact test (AIV) apparatus.
Construction materials

Figure 7. Aggregate crushing test (ACV) apparatus.
Construction materials

Figure 8. Apparatus for determination of Los Angeles abrasion value (LAAV).
Construction materials

Figure 9. Limestone chippings before and after testing for aggregate abrasion value (AAV).
Figure 10. Apparatus for determination of aggregate abrasion value (AAV).
Construction materials

Figure 11. Accelerated polishing machine for determination of polished stone value (PSV). Photo courtesy of ELE International Ltd.

Figure 12. Close-up of specimens located on the 'road wheel' in the accelerated polishing machine (PSV). Photo courtesy of ELE International Ltd.
Ten per cent fines value This test is a variation of the ACV test and also gives a measure of the resistance of an aggregate to crushing under a gradually applied compressive load. It is, however, applicable to relatively weak as well as strong aggregates. The ten per cent fines value is the load required to produce 10% fines rather than the amount of crush for a specific load. It is recommended that the ten per cent fines value is used in preference to the ACV test, particularly in situations where relatively weak or variable quality aggregates are to be assessed. A detailed procedure for the determination of the ten per cent fines value is given in Appendix 5.

Strength testing of core or lump samples (field testing) Two methods of field rock quality measurements are sometimes used in aggregate exploration projects. These are the ‘Point Load Test’ and the ‘Schmidt Rebound Hammer Test’. Both methods use simple, portable devices which are easy to operate.

The point load test obtains an indirect measure of the compressive strength of rock cores and can also be used on lump rock. A load is diametrically applied through conical plattens, the ram being driven by a hand-operated hydraulic pump. A gauge measures the load at failure, giving a measure of the tensile rock strength. It is claimed that these values correlate with laboratory uniaxial compression tests (Broch & Franklin, 1972), and that an estimated value of rock strength is easily and rapidly obtained. However, our experience has shown that test values have a low reproducibility (Harrison, 1983) and it is recommended that this test is used with caution.

The Schmidt rebound hammer test also measures rock strength and gives results which have been shown to correlate with uniaxial compressive strength (Deere & Miller, 1966). The instrument is held tightly against the rock surface and a spring-loaded piston applies a blow of constant force to the rock. The amount of rebound of the piston, which is influenced by the elasticity of the rock, is recorded on a scale. Results are, however, strongly influenced by rock discontinuities, degree of weathering and by the nature of the rock surface. Our experience is that this method gives poor reproducibility (Harrison, 1983) and we would not recommend its use in exploration of aggregate deposits.

2.3.4 Mechanical tests: durability

A number of tests have been devised to assess the resistance to wear or decay (the durability) of an aggregate material. These include the Los
Construction materials

Los Angeles abrasion value (LAAV) The LAAV test is described in ASTM C131 and C535, although the former method is normally preferred for roadstone and concrete aggregates. The test is not included in British Standards, but will be included in new European Standards. It measures the resistance of an aggregate to attrition by impact and abrasion forces.

The test machine comprises a hollow steel cylinder of specified dimensions which is loaded with the aggregate sample (5000g) and a charge of steel balls (Figure 8). The cylinder is rotated at 33 rpm and this causes attrition through tumbling and impact of the particles and the steel balls.

For strong and moderately strong aggregates the results of the test are numerically similar to the ACV and AIV, although for weaker aggregates the LAAV is higher. A detailed procedure for the determination of the LAAV is given in Appendix 6.

The LAAV test method is simple, although noisy, and gives precise results. The only drawback is the large sample charge (5 kg of graded aggregate). Nevertheless, the LAAV test is a preferred method for evaluating aggregates and may replace the AIV, ACV and AAV in certain testing programmes.

Aggregate abrasion value (AAV) This test provides an estimation of surface wear and is used in the selection of wearing-course aggregates (Department of Transport, 1991). AAV reflects the textural strength of the aggregate and the hardness and brittleness of the constituent minerals. Low resistance to abrasion in road surfacing aggregates causes an early loss of road texture resulting in poor skid resistance. A detailed procedure for the determination of AAV is given in Appendix 7.

The test is fairly complex involving the mounting of aggregate particles in a resin backing (Figure 9) and abrading the specimens in a specially designed (BS 812 : Part 113 : 1990) abrasion machine (Figure 10). The test is carried out on non-flaky, washed and surface dry 10-14 mm aggregate, of measured relative density.

Polished stone value (PSV) The polished stone value is designed to provide a relative measure of the resistance of aggregate to the polishing action of tyres when used in the wearing surface of a road (BS 812 : Part 114 : 1989). The test procedure is complex, involving the
preparation of test specimens similar to those in the AAV test, and polishing these specimens in an accelerated polishing machine (Figures 11 and 12). The polish of the specimens is then measured using a pendulum-type friction tester. The coefficient of friction, expressed as a percentage, is the polished stone value. A higher value signifies greater resistance to polishing. Values over 65 indicate a highly polish-resistant rock especially suitable for road wearing courses in high risk areas. Some typical PSVs for a range of rock types are given in Table 15. A detailed procedure for the determination of PSV is given in Appendix 8.

The test is carried out on washed and surface dry, non-elongate aggregate which has passed a 10 mm sieve but is retained on a 10-14 mm flake sorting sieve. A PSV control stone is used for calibration of the friction tester.

2.3.5 Aggregate soundness

Climate has a major influence on weathering and, hence, also on the degree of disintegration and decomposition (soundness) of aggregates. Rainfall and temperature are the major factors. Various tests have been devised to assess the resistance of aggregates to the effects of weathering caused by factors such as freezing and thawing, wetting and drying and elevated temperatures. The rocks most susceptible to physico-chemical changes include dolerite, shales and any rocks with expansive clay minerals (such as illite or montmorillonite).

Petrological examination can give a valuable indication of probable soundness by determining mineralogy and the nature and distribution of pores and fissures. The soundness of aggregates, however, is usually judged by the use of tests such as the sulphate soundness test, the methylene blue adsorption test and the slake durability test.

**Sulphate soundness test** This test (ASTM C88, BS 812:Part 121:1989) measures the resistance of aggregate to accelerated physical weathering by salt crystallisation. This is accomplished by repeated cycles of immersion in saturated solutions of sodium or magnesium sulphate followed by oven drying. The internal expansive force caused by the growth of sulphate crystals in the pores of the aggregate simulates the expansion of water on freezing.

The most widely applied procedure is that given in ASTM C88 in which coarse or fine aggregate of specified size and mass is placed in perforated containers and immersed in prepared solutions of magnesium or sodium sulphate of specified density at a temperature of 20 to 22°C.
for a period of 16 to 18 hours. The samples are then removed from the solution, drained for 10 to 20 minutes, dried to constant weight in an oven at 105 to 115°C and cooled. This cycle of immersion and drying is repeated five times. After removing all traces of salt by washing the samples are dried at 105 to 115°C and sieved (see ASTM C88 for specified sieve sizes). The weight retained is recorded and the loss is expressed as a percentage of the initial weight. This is the sulphate soundness loss.

The method for determining soundness specified in BS 812 is similar to that in ASTM C88. However, the test is carried out on 10 to 14 mm sized aggregate and uses a saturated solution of magnesium sulphate. The period of immersion is 17 hours ± 30 minutes and draining takes place for 2 hours ±15 minutes. Oven drying is carried out for at least 24 hours and each specimen is cooled for 5 hours ±15 minutes. The duration of one cycle is therefore around 48 hours. After five cycles the sample is sieved on a 10 mm sieve and the mass of material retained is expressed as a percentage of the original mass to give the soundness value.

Criticism of the test (by either test procedure) is the time taken to complete the test and its poor precision. There are therefore reservations about this test although it is capable of distinguishing between aggregates of superior soundness and those which are unsound. A maximum limit of 18% loss is set for magnesium sulphate soundness by ASTM D692 for coarse aggregates used in bituminous surfacings.

Methylene blue adsorption test (the clay index) Rock aggregates which contain swelling clay minerals (mainly those of the smectite group) such as basic igneous rocks and greywackes are prone to degradation by the pressures caused by the expansion of these secondary minerals. Although X-ray diffraction can be used to identify the type of clay, a soundness test using methylene blue has been developed to give an assessment of the quantity of these clays in the aggregate. Methylene blue is an organic dye which is adsorbed by clay minerals. The amount of dye adsorption is proportional to the clay content of the rock. A detailed procedure for the methylene blue adsorption test is given in Appendix 9.

The test has some advantages, including rapid procedure and simple laboratory equipment. It is now a standard test in many countries (e.g. France, New Zealand). The Department of Environment of Northern Ireland specifies a MBV limit of 1% for basalt aggregates and 0.7% for gritstone aggregates.
Slake durability test  Alternate wetting and drying (slaking) causes some rocks, particularly compacted shales and weathered rocks, to degrade. The slake durability index (Franklin, 1970) is a measure of the resistance of a rock to slaking. The procedure is relatively simple, involving immersion of the aggregate sample placed in a wire mesh drum in water and rotation of the drum at fixed speed for 10 minutes. After drying and weighing, the loss in weight of the aggregate is expressed as a percentage of the initial weight. This is the slake durability index. This test is particularly relevant for weak, low-grade materials which need to be assessed for their suitability as roadstone aggregates.

2.3.5 Chemical tests

Chloride content  The presence of chlorides in concreting aggregates can cause problems by increasing the risk of corrosion of embedded metals, reduction of sulphate resistance in sulphate resisting cements, and by contributing to alkali-silica reactions. Sea-dredged aggregates may contain high chloride concentrations, although this is readily reduced by washing. There are several relatively simple and rapid test methods for determining chloride, including conductivity meters and the use of test strips (Figg & Lees, 1975). However, the best known is the Volhard test (BS 812: Part 117, 1988) which is based on a silver nitrate titration and requires analytical laboratory facilities. The method involves the addition of an excess of standard silver nitrate solution to the chloride sample solution which has been acidified with nitric acid. The excess silver nitrate is then back-titrated with potassium thiocyanate using ferric ammonium sulphate as an indicator.

Maximum chloride contents for concreting aggregates are specified in BS 882.

Organic content  Organic impurities such as coal and lignite in concrete aggregates may retard or inhibit the setting and hardening of Portland cement and may also result in an unacceptable surface appearance of the concrete. It is therefore necessary to limit the amount of deleterious organic materials in concrete aggregates (see BS 812, ASTM C33). Most organic impurities can be removed from aggregate materials by floating in a liquid of density of just below 2.0. Many organic materials which occur in aggregates can also be detected by their ability to give a brown colouration in a solution of sodium hydroxide. This latter test method (ASTM C40) gives a rapid indication of the presence of organic retarders in aggregate.
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Sulphate content The presence of soluble sulphates such as gypsum in concreting aggregates may result in swelling reactions in the hardened concrete and cracking and disintegration. Limits are therefore often specified for the sulphate content of aggregates for concrete. This is usually expressed as %SO₃, acid-soluble sulphate content. The test methods developed to enable determination of sulphate content (such as BS 812: Part 118, 1988) involve extraction of the sulphates in the aggregate by hydrochloric acid and gravimetric determination of the sulphate ions by precipitation with barium chloride. Artificial aggregates (such as colliery waste, slag and PFA) also usually contain sulphides which may oxidise to sulphates in certain conditions. Methods for determining sulphide and total sulphur contents are given in BS 1047: Part 2, 1974.

Alkali-aggregate reactivity Reactions between certain minerals in aggregates and alkalis (sodium and potassium) in cements can induce expansion and cracking in concrete. The most widely known is the alkali-silica reaction (ASR) and less common are alkali-carbonate reactions.

The potential reactivity of aggregates in concrete are best assessed using the procedures set out in national standards or regulations valid in the place of use. However, the three basic methods of determining potential reactivity are as follows:

- Petrographic analysis: involving the identification and quantification of potentially reactive minerals in the aggregate. This procedure (ASTM C295 and BS 812: Part 104) is recommended for the initial evaluation of aggregate reactivity.

- Direct measurements of expansion: involving such tests as the mortar bar test (ASTM C227) and concrete prism expansion tests as used in Canada, South Africa and the UK (BS 812: Part 123 - draft). These tests are thought to be the most reliable methods of measuring reactivity, but are very time consuming. It is necessary to continue expansion measurements for up to 12 months.

- Chemical tests: involving treatment of the aggregate with an alkaline solution (sodium hydroxide) to reveal any reactivity. Test methods such as the gel pat test (Jones & Tarleton, 1958) and the ASTM quick test are used in the USA and Germany. The potential reactivity of carbonate aggregates is assessed by the ASTM C586 test. Chemical tests, however, are not always reliable and it is recommended that any positive results are confirmed by petrographic examination and mortar bar tests.
It should be noted that even if reactive minerals are present in the aggregate, significant expansion will not occur if the total alkali content of the cement is less than 0.6%. In other words, if low alkali cements are used in concrete, then disruptive expansion caused by alkali-aggregate reaction is unlikely to occur regardless of the presence of potentially reactive minerals in the aggregate.
### Table 15. Aggregate test data for a range of rock types from Britain, Fiji and the Kingdom of Tonga.

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Location</th>
<th>RD</th>
<th>WA</th>
<th>AIV</th>
<th>ACV</th>
<th>10%F</th>
<th>LAAV</th>
<th>AAV</th>
<th>PSV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>Derbyshire</td>
<td>2.65</td>
<td>1.5</td>
<td>25</td>
<td>26</td>
<td>160</td>
<td></td>
<td></td>
<td>12.7</td>
</tr>
<tr>
<td>Limestone</td>
<td>Derbyshire</td>
<td>2.69</td>
<td>0.5</td>
<td>18</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>10.3</td>
</tr>
<tr>
<td>Dolomite</td>
<td>Derbyshire</td>
<td>2.70</td>
<td>2.6</td>
<td>30</td>
<td>--</td>
<td>--</td>
<td>18.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>Mendips</td>
<td>2.67</td>
<td>0.5</td>
<td>22</td>
<td>23</td>
<td>--</td>
<td>26</td>
<td>9.1</td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>Mendips</td>
<td>2.66</td>
<td>0.8</td>
<td>19</td>
<td>21</td>
<td>180</td>
<td>23</td>
<td>7.6</td>
<td>39</td>
</tr>
<tr>
<td>Limestone</td>
<td>Cotswolds</td>
<td>2.24</td>
<td>6.5</td>
<td>50</td>
<td>--</td>
<td>--</td>
<td>62.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dolomitic Lst.</td>
<td>Durham</td>
<td>2.68</td>
<td>1.1</td>
<td>26</td>
<td>26</td>
<td>170</td>
<td>--</td>
<td>10.8</td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>Tonga</td>
<td>2.44</td>
<td>2.6</td>
<td>27</td>
<td>31</td>
<td>--</td>
<td>26</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>Tonga</td>
<td>2.14</td>
<td>8.1</td>
<td>42</td>
<td>--</td>
<td>39</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td>S.Wales</td>
<td>2.66</td>
<td>0.9</td>
<td>25</td>
<td>20</td>
<td>--</td>
<td>--</td>
<td>8.3</td>
<td>72</td>
</tr>
<tr>
<td>Sandstone</td>
<td>Mendips</td>
<td>2.45</td>
<td>2.0</td>
<td>26</td>
<td>21</td>
<td>--</td>
<td>--</td>
<td>6.7</td>
<td>60</td>
</tr>
<tr>
<td>Greywacke</td>
<td>S.Wales</td>
<td>2.67</td>
<td>0.8</td>
<td>24</td>
<td>19</td>
<td>--</td>
<td>--</td>
<td>9.1</td>
<td>72</td>
</tr>
<tr>
<td>Greywacke</td>
<td>N. Yorkshire</td>
<td>2.69</td>
<td>0.4</td>
<td>10</td>
<td>11</td>
<td>330</td>
<td>--</td>
<td>7.2</td>
<td>62</td>
</tr>
<tr>
<td>Granite</td>
<td>Cornwall</td>
<td>2.81</td>
<td>0.2</td>
<td>15</td>
<td>15</td>
<td>270</td>
<td>14</td>
<td>3.3</td>
<td>51</td>
</tr>
<tr>
<td>Granite</td>
<td>Cornwall</td>
<td>2.78</td>
<td>0.3</td>
<td>19</td>
<td>18</td>
<td>220</td>
<td>16</td>
<td>3.0</td>
<td>52</td>
</tr>
<tr>
<td>Granite</td>
<td>Cumbria</td>
<td>2.75</td>
<td>0.5</td>
<td>23</td>
<td>25</td>
<td>--</td>
<td>--</td>
<td>3.4</td>
<td>54</td>
</tr>
<tr>
<td>Diorite</td>
<td>Leicestershire</td>
<td>2.58</td>
<td>1.2</td>
<td>20</td>
<td>19</td>
<td>190</td>
<td>21</td>
<td>5.4</td>
<td>54</td>
</tr>
<tr>
<td>Dolerite</td>
<td>Cornwall</td>
<td>2.72</td>
<td>0.5</td>
<td>14</td>
<td>14</td>
<td>290</td>
<td>12</td>
<td>6.3</td>
<td>57</td>
</tr>
<tr>
<td>Basalt</td>
<td>Fiji</td>
<td>2.50</td>
<td>1.2</td>
<td>21</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Basalt</td>
<td>Northumbs.</td>
<td>2.55</td>
<td>1.1</td>
<td>12</td>
<td>13</td>
<td>280</td>
<td>--</td>
<td>5.1</td>
<td>--</td>
</tr>
<tr>
<td>Andesite</td>
<td>Fiji</td>
<td>2.60</td>
<td>2.2</td>
<td>15</td>
<td>16</td>
<td>--</td>
<td>17</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Andesite</td>
<td>Mendips</td>
<td>2.69</td>
<td>1.2</td>
<td>13</td>
<td>12</td>
<td>360</td>
<td>16</td>
<td>2.8</td>
<td>55</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RD</th>
<th>Relative density (on an oven dried basis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WA</td>
<td>Water absorption (%)</td>
</tr>
<tr>
<td>AIV</td>
<td>Aggregate impact value</td>
</tr>
<tr>
<td>ACV</td>
<td>Aggregate crushing value</td>
</tr>
<tr>
<td>10% F</td>
<td>Ten percent fines value</td>
</tr>
<tr>
<td>LAAV</td>
<td>Los Angeles abrasion value</td>
</tr>
<tr>
<td>AAV</td>
<td>Aggregate abrasion value</td>
</tr>
<tr>
<td>PSV</td>
<td>Polished stone value</td>
</tr>
</tbody>
</table>

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3. DIMENSION STONE

Natural stone which can be cut and dressed into regular shapes or sizes for use in construction is known as dimension stone. A wide range of rock materials can be used as dimension stones and include granite, marble, limestone, sandstone, slate, soapstone, serpentine, gneiss and many other rocks. There is often confusion of terminology, as the dimension stone industry uses commercial definitions for rock types rather than geological definitions. Thus, the commercial use of the term 'granite' usually refers to any igneous rock which can be cut and polished. This includes not only true granite, but also rocks such as gneiss, granodiorite and gabbro. Similarly, the commercial term 'marble' covers any recrystallised calcareous rock that can take a polish. This may be limestone, dolomite, serpentine or a true metamorphosed marble.

3.1 Uses and specifications

Dimension stone is used primarily in the building and construction industry, in urban landscaping industries, and in tombstones, monuments and ornamental objects. Within the construction industry natural stone is used for both interior and exterior applications. For example, granite is often used for exterior cladding of buildings due to its high resistance to weathering, particularly in polluted urban environments. Marble and other calcareous rocks, on the other hand, are today mainly used for interior work except in favourable climates, due to their lower durability.

The desirable properties of a good dimension stone are:

- Attractive appearance (colour, texture)
- Durability (physical and chemical stability)
- Strength (structural loading)
- Consistency of quality

Other factors which may affect the selection of dimension stone include the costs of quarrying, processing and transportation, and the availability of alternative sources of supply. Stone selection is generally dominated by aesthetic appeal and the preferences of architects and design engineers. The physical properties of the stone are generally of secondary consideration.
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The ASTM, however, publishes specifications for dimension stones (ASTM C503, C568, C615, C616 and C629) which cover physical properties of the stone such as density, strength and abrasion resistance. A summary of the required physical properties of granite, limestone, sandstone, slate and marble for building stones is given in Table 16. There are few British Standard specifications for natural stone in building, other than slates for roofing (BS 680) and stone for kerbs (BS 435) or sills (BS 5642). The UK Building Research Establishment (BRE) provides some further guidance on stone selection (BRE Digest 269) and durability criteria.

Table 16. ASTM specifications for some natural stone used in building

<table>
<thead>
<tr>
<th>Test requirement</th>
<th>Granite LD</th>
<th>Granite MD</th>
<th>Granite HD</th>
<th>Limestone</th>
<th>Sandstone</th>
<th>Slate</th>
<th>Marble</th>
</tr>
</thead>
<tbody>
<tr>
<td>C 97 Specific gravity (lbs/ft²)</td>
<td>&gt;160</td>
<td>&gt;110</td>
<td>&gt;136</td>
<td>&gt;161</td>
<td>&gt;140</td>
<td>&gt;170</td>
<td>&gt;140</td>
</tr>
<tr>
<td>C 97 Water absorption (%)</td>
<td>&lt;0.4</td>
<td>&lt;12</td>
<td>&lt;7.5</td>
<td>&lt;3.0</td>
<td>&lt;3.0</td>
<td>&lt;0.25</td>
<td>&lt;0.75</td>
</tr>
<tr>
<td>C 99 Modulus of rupture (KSI)</td>
<td>&gt;1.5</td>
<td>&gt;0.4</td>
<td>&gt;0.5</td>
<td>&gt;1.0</td>
<td>&gt;1.0</td>
<td>&gt;7.2</td>
<td>&gt;1.0</td>
</tr>
<tr>
<td>C170 Comp. strength (KSI)</td>
<td>&gt;19</td>
<td>&gt;1.8</td>
<td>&gt;4.0</td>
<td>&gt;8.0</td>
<td>&gt;10</td>
<td>----</td>
<td>&gt;7.5</td>
</tr>
<tr>
<td>C 241 Abrasion resistance</td>
<td>--</td>
<td>&gt;10</td>
<td>&gt;10</td>
<td>&gt;10</td>
<td>&gt;8</td>
<td>&gt;8</td>
<td>&gt;8</td>
</tr>
</tbody>
</table>

LD - Low density  MD - Medium density  HD - High density

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3.2 Assessment of dimension stones

3.2.1 Field exploration

The exploration for dimension stones varies from regional reconnaissance of potential sources of a wide variety of rock types through to evaluation of specific deposits or site development investigations. Whatever scale of approach is applicable, it should include a desk appraisal of available geological data and regional mapping studies to determine the stratigraphy, general lithology and structure of the rock units. Site specific studies should include detailed geological mapping supported by core drilling. Together, these should aim to evaluate the lithology, thickness, degree of jointing and fracturing and the overall geological consistency of the deposit. Samples should be obtained from rock exposures and drill cores to represent the geological variations within the deposit, such as colour, texture, bedding and soundness. The samples can then be sawn into blocks for polishing and finishing and also for laboratory testing to ASTM or similar standards. At the quarry development stage or production stage, large, orientated quarry blocks will need to be extracted from the potential production area. Each specimen block is then subject to a job specific laboratory testing programme.

3.2.2 Laboratory testing of dimension stones

Dimension stones used in construction should be durable enough to withstand prevailing climatic and environmental conditions, and be strong enough to resist structural loading without crumpling or failing. The stone must also resist staining. Evaluation procedures for dimension stones should therefore include means of assessing durability, strength and the amount of water absorption.

Durability is principally determined by the physical structure of the stone, particularly pore structure (Ross & Butlin, 1989), although mineralogical composition may also influence this property. Coarse-textured rocks are generally more durable than fine-textured materials. Stone with a high proportion of very fine pores tends to be less durable than stone with a coarser pore size distribution. Petrographical examination of the stone (see previous section on aggregates) can give extremely valuable information on mineralogy and microporosity (Sedman & Barlow, 1989). It is recommended that all studies of dimension stones should include the preparation and examination of thin sections. They are inexpensive and quick to prepare, and their detailed
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description provides information on the parameters controlling durability.

The pore structure of a potential dimension stone may also be assessed by determination of the porosity and saturation coefficient (the extent to which the pores fill with water with time). These two parameters indicate the amount of water a stone will absorb under natural conditions. The decay of many porous building stones (chiefly limestones and sandstones) is mainly caused by gypsum crystallisation resulting from reaction between air, water and the stone. The expansion which takes place during the precipitation of gypsum causes the stone to break down. The saturation coefficient and porosity can be calculated from the same set of data.

**Porosity** The porosity is the volume of the pores within a stone expressed as a percentage of the stone’s total volume. It is measured by vacuum saturation with water (Price, 1975).

Porosity may be as high as 40 per cent or less than 1 per cent. The value of porosity, however, does not provide information on pore size or on how the pores are distributed within the stone. Petrological observations are therefore required for this input, although the determination of saturation coefficient provides indirect information on pore size.

**Saturation coefficient** The saturation coefficient is a measure of the extent to which the pores are filled when a stone absorbs water for a standard time.

Values range between about 0.4 to 0.95. A high value (>0.8) indicates a stone with a high proportion of fine pores (i.e. low durability).

A detailed procedure for the determination of porosity and saturation coefficient is given in Appendix 10.

**Crystallisation test** The Building Research Establishment (BRE) crystallisation test (Honeyborne, 1982) gives a direct measure of degradation by aggressive accelerated weathering causing crystallisation of salts in pores of the stone. A similar test is specified for aggregates in ASTM C88.

In brief, the test involves immersion of dry stone cubes in a solution of sodium sulphate decahydrate for two hours at a constant temperature. This is followed by oven drying at controlled humidity for 16 hours. After cooling, the process is repeated for a total of 15 cycles. The
results are presented as a percentage weight loss and have been used to divide limestones into six classes of durability. These classes are summarised in Table 17 and range from grade A (best) to grade F (worst). A detailed procedure is given in Appendix 11.

Table 17. Durability grades of limestone building stones (after Honeyborne, 1982)

<table>
<thead>
<tr>
<th>Limestone durability grade (crystallisation test)</th>
<th>% weight loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>&lt;1</td>
</tr>
<tr>
<td>B</td>
<td>1 - 5</td>
</tr>
<tr>
<td>C</td>
<td>5 - 15</td>
</tr>
<tr>
<td>D</td>
<td>15 - 35</td>
</tr>
<tr>
<td>E</td>
<td>35 - 100</td>
</tr>
<tr>
<td>F</td>
<td>&gt;100</td>
</tr>
</tbody>
</table>

The BRE crystallisation test requires relatively sophisticated laboratory facilities and is expensive and time-consuming. The results cannot always be interpreted with confidence since the test can prove unreliable. Indeed, the Stone Federation of Great Britain has recently called for the test to be abandoned. However, it is the most widely accepted test for the durability of porous building stones. Current research in the UK is considering procedures to modify the test method in order to improve repeatability. At the moment it is recommended that additional indirect studies of pore structure be carried out to evaluate durability.

Many sandstones are liable to decay when exposed to polluted (acidic) atmospheres. BRE recommend an acid immersion test for assessment of sandstone durability. This is a very simple test involving the immersion of the stone in a sulphuric acid solution, followed by an examination of the sample for signs of decay. A detailed procedure is given in Appendix 12.

American standards A wide range of test methods for characterising the physical properties of dimension stones has been developed by the American Society for Testing and Materials (ASTM) and are widely
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used on an international basis. The tests include bulk specific gravity / water absorption ASTM C97, modulus of rupture ASTM C99 and compressive strength ASTM C170. Other tests include the determination of flexural strength ASTM C880 and the abrasion resistance of stone for flooring ASTM C241. Detailed procedures for these tests are given in the relevant ASTM Standards.

In strength testing the anisotropy of the stone and the orientation of the natural bedding are important factors. The strength of the stone may also vary greatly when it is wet. The ASTM tests include procedures to quantify these variations.

The selection of a dimension stone is therefore a combination of aesthetic appeal, which is to some extent a function of fashion, and physical specifications. The evaluation of stone is only reliable if the samples available for inspection and testing are representative. Although natural stone is a variable product it is important the variability is kept within limits which are known and understood.
4. BRICK CLAYS

Fired clay bricks are amongst the most important materials used for construction in developing countries. The durability, dimensional consistency and relatively low finished-value of bricks ensures that they are utilized for an extremely wide variety of construction purposes - from low-cost housing and lining of pit latrines to industrial buildings and high-rise office blocks. Brick clays and (to a lesser extent) bricks are low-value materials and it is generally considered uneconomic to transport them over long distances (they are said to have a high 'place-value'). Any assessment of their economic potential must therefore take this overriding factor into account. A deposit of high-quality brick clay raw material has little commercial value if it is remote from a market for construction materials.

Clay raw material for brick making comes from a wide variety of sources including bedded mudrock formations, hydrothermally-altered volcanic rocks, river alluvium and colluvial soils. This is reflected in considerable variation in the mineralogy and chemistry of brick clays. In this respect, clays for the manufacture of bricks and other structural clay products such as tiles, hollow-blocks and sewer pipes differ from most industrial minerals. Provided the finished product can be manufactured economically to meet certain specifications, the mineralogy and chemistry of the raw material are only relevant insofar as they influence forming and firing behaviour.

4.1 Structural clay products

4.1.1 Bricks

Relatively low-strength bricks suitable for the construction of low-rise housing and similar buildings are known as common bricks or, where used on the outside of a building, facing bricks. These bricks must normally comply to a minimum compressive strength (Table 18). High-strength/low-porosity engineering bricks are normally used in load-bearing applications. Standards specified for bricks (such as BS 3921: 1985) generally include a 'durability' requirement expressed as frost resistance and soluble salt content. Whilst frost resistance is not relevant in tropical countries, soluble salt content and related specifications for efflorescence will reflect the durability and appearance of bricks in any climate. Soluble salts (such as gypsum) can cause unsightly efflorescence on the surface of bricks and can cause powdering or flaking of the brick in severe cases. Soluble salts from
bricks can also react with alkaline components in mortar to cause disruption of brickwork over time.

Table 18. Classification of bricks by compressive strength and water absorption (from BS 3921:1985).

<table>
<thead>
<tr>
<th>Class</th>
<th>Compressive strength (N/mm²)</th>
<th>Water absorption % by mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering A</td>
<td>&gt;70</td>
<td>&lt;4.5</td>
</tr>
<tr>
<td>Engineering B</td>
<td>&gt;50</td>
<td>&lt;7.0</td>
</tr>
<tr>
<td>Damp-proof course 1</td>
<td>&gt;5</td>
<td>&lt;4.5</td>
</tr>
<tr>
<td>Damp-proof course 2</td>
<td>&gt;5</td>
<td>&lt;7.0</td>
</tr>
<tr>
<td>All others</td>
<td>&gt;5</td>
<td>no limits</td>
</tr>
</tbody>
</table>

4.1.2 Hollow blocks

These products are used as a lightweight alternative to bricks in the construction of walls, floors and ceilings, though they do require rendering when used externally. Clay feed used in the manufacture of blocks is generally ground to a finer particle size than equivalent material used in the manufacture of bricks. Hollow blocks are extruded through a complex die and then wire-cut to size. Drying and firing of hollow blocks must be carefully controlled to avoid cracking of the large surface area body (Ridgway, 1982).

4.1.3 Sewer pipes

These are used for sewage, cable-ducting and land-drainage purposes. Sewage pipes are either salt-glazed or the clay body is vitrified to render them impervious to water.

Where technology is restricted to relatively unsophisticated low-pressure extrusion, kaolinitic clays are generally preferred for production of sewer pipes because these plastic materials are more easily formed using this equipment. These clays also have long vitrification ranges which
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are able to tolerate the wide temperature variation found in simple downdraught kilns without too much variation in the physical properties of the final product. However, the refractory nature of these clays results in relatively weak, porous fired bodies which need to be thick-walled to provide sufficient strength, and salt-glazed to render them impermeable. Salt-glazing requires high firing temperatures (around 1200°C) in order to volatilise the salt and react with the clay to form a glaze. Problems associated with the salt-glazing process include air pollution and degradation of kiln lining from chlorine volatilised during firing. The introduction of high-pressure vacuum extrusion equipment has reduced the need for plastic clays in the manufacture of pipes. Relatively fast-firing tunnel kilns enable thin-walled pipes to be produced which are impermeable through vitrification of the clay body. The clays used in this process tend to be much less refractory than those used in salt-glazed pipes, with lower maturing temperatures and shorter vitrification ranges. These factors enable a much wider range of clay assemblages to be used in this process, although the quality of the final product is very dependent on careful characterisation, selection and quality control of the raw material. Clay feeds with predictable and consistent firing characteristics are required to feed an automated continuous manufacturing process (Highley, 1982).

4.1.4 Roof tiles

Fired clay roof tiles are used as durable roofing material in many parts of the world. Clay feed used in the manufacture of blocks is generally ground to a finer particle size than equivalent material used in the manufacture of bricks. They must normally conform to a maximum porosity value to ensure weather resistance. In the UK, standards for clay roofing tiles are covered by BS 402 (1970).
4.2 Laboratory investigation

Laboratory investigation of clays for brickmaking in developing countries generally involves determination of physical properties and mineralogical components directly relevant to the manufacturing process (forming and firing). Because of place-value considerations, it is usually more important to compare unknown clays with local materials of proven commercial value rather than raw materials used by highly-mechanised brick manufacturers in developed countries. The laboratory investigation must also take into account factors such as manufacturing technology and specifications required for the finished product.

4.2.1 Mineralogy and chemistry

Though not fundamental to the assessment of the economic potential of brick clays, mineralogical analysis remains useful in identifying components which may affect the forming and/or firing process, and the overall quality and appearance of the finished product.

Variation in clay mineralogy may strongly influence forming behaviour. Halloysites (common in many tropical red soils) are very non-plastic and may cause problems in some moulding processes. Smectite-group clays confer very high plasticity, but may lead to excessive shrinkage and cracking on drying.

The firing behaviour and finished quality of bricks may be strongly influenced by components such as carbonates, sulphides and organic matter which evolve volatiles on heating (see Section 4.2.3). The presence of minerals such as pyrite, gypsum and halite in brick clay raw materials will strongly influence the soluble salt content of the fired clay brick. As stated above, soluble salts may affect the final appearance and/or the durability of bricks and brickwork. High soluble salt content in the raw material (particularly halite and other chlorides) may cause considerable damage to plant and to the environment through the evolution of chlorine gas during the firing process. Brick clay resource surveys in arid areas should take particular account of the nature and quantity of soluble salts present in clay samples. Atmospheric pollution from brickmaking plants may also result from evolution of sulphur dioxide (mainly from the oxidation of pyrite) and fluorine (from certain micas) during the firing process. Raw material evaluation prior to establishment of large-scale plant for brick production should take possible emissions from these sources into account.
4.2.2 Forming properties

Plasticity, dry shrinkage and dry strength are interlinked properties which contribute to the forming behaviour of brick clay. Plasticity may be quantified using a ‘plasticity index’ derived from Atterberg liquid and plastic limits. The plasticity index acts as a guide to the workability of the clay when mixed with water; low values are generally considered acceptable for mechanised stiff extrusion processes, whilst higher values indicate suitability for slop-moulding of bricks by hand (Bain & Highley, 1979). The plastic limit gives an indication of likely shrinkage on drying.

Plasticity data from different clay samples can be compared using a clay ‘workability’ chart (Figure 13). Detailed procedures for the determination of Atterberg plastic and liquid limits are given in Appendices 13 and 14. ‘Green-to-dry’ shrinkage may be measured accurately using kerosene/mercury volume displacement. A detailed method for the determination of dry shrinkage (along with water of plasticity and dry porosity) is given in Appendix 15. Although high shrinkage clays invariably show high dry strength, they may also exhibit a tendency to crack and distort.

4.2.3 Firing properties

Perhaps the most relevant technique for the evaluation of brick clays is the investigation of fired properties.

Reactions occurring on firing brick clays Initially, at temperatures up to 200°C, any moisture remaining in the ware after drying will be driven off. Between 450-600°C the clay minerals lose their structural water (dehydroxylation). This results in a weakening of the body, since the dehydroxylated clay has little or no plasticity or binding power. Any organic matter present may burn off at any temperature between 300° and 700°C, the temperature and ease of removal depending on the type of organic matter present and the rate of heating. In most firing processes, it is important that the kiln atmosphere is strongly oxidizing to enable oxidation of carbon to carbon dioxide to take place as early as possible. The carbon must be burnt off before the surface of the ware vitrifies, since this can prevent oxygen reaching carbon within the body, with the result that this carbon will remain unburnt even at higher temperatures. Lack of an effective oxidizing atmosphere surrounding -
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and within - the ceramic body may also suppress oxidation of any sulphide minerals present to sulphur dioxide and ferric oxide, a reaction that normally occurs between 400-500°C. Failure to burn off carbon and sulphide minerals results in ‘blue cores’ due to the presence of reduced (ferrous) iron compounds in the body. Ferrous iron is an aggressive flux which tends to lower the melting point of the aluminosilicates in the body. CO₂ and CO produced by the reaction between organic matter and iron compounds may be trapped by this melt, resulting in distortion of the ware (‘bloating’). Some manufacturing processes utilise the effects of iron reduction to improve the performance of the finished ware. Vitrified clay sewer pipes are generally manufactured with blue core to reduce permeability and increase strength. ‘Blue’ engineering bricks are produced by reducing iron on the surface of the ware by decreasing the oxygen content of the kiln atmosphere. However, these processes require rigid control of raw materials and firing conditions and, in general, clays containing relatively large amounts of organic matter (>3%) are best avoided as raw materials for bricks and other structural clay products.

Quartz undergoes a phase change at 573°C (the alpha-beta inversion). Since this change involves an expansion, the rate of temperature increase in most manufacturing processes is slowed near this temperature for bodies containing substantial quartz, as rapid heating could cause cracking. Any carbonate minerals present will decompose to the oxide and carbon dioxide between 600-900°C. Release of carbon dioxide may cause an increase in porosity of the body.

All the reactions described above occur below the conventional firing range of ceramic bodies. Vitrification, or glass formation, may start at any temperature above 900°C, depending on the composition of the body. Fluxing materials react with other body constituents with which they are in contact to form liquid, and the proportion of liquid increases as the temperature increases. The body contracts due to the formation of liquid (firing shrinkage) and the porosity is reduced. If vitrification is allowed to go too far, so much liquid may be formed that the body loses shape.

Reaction can occur between particles on heating without formation of a liquid. Such solid-phase reactions are the first step towards densification, even in cases where solid-phase reaction is followed by the formation of a liquid. The process is one of mutual diffusion between atoms of touching particles and is known as sintering. As a result of sintering, particles become fewer and larger and pores are eliminated. Strength is developed through interlocking of particles.
A common crystalline constituent of fired bricks and other clay-based ceramics is the mineral mullite. This forms by solid-phase reaction in alumino-silicates above 800°C along with cristobalite (Grimshaw, 1971). In bricks made from calcium (carbonate)-bearing clays, high-temperature calcium silicates such as wollastonite and gehlenite may form (Dunham & Mwakaruka, 1984).

Vitrification, sintering, and the formation of new crystalline phases are time-temperature dependant. Additional melting, together with the formation of further crystalline components, is encouraged by a 'soak' period at maximum temperature. Optimum soak temperatures and times for clays of a given composition can be determined using time-temperature-transformation (TTT) diagrams. A review of the application of TTT diagrams to the firing of brick clays and other heavy clay products is given in DoE (1993). On cooling, the liquid solidifies to a glass which cements together the unmelted particles and crystals formed during heating, thus giving strength to the fired body. Figure 14 illustrates typical changes in mineralogy in a brick clay during the firing cycle. This 'cartoon' is taken from Dunham (1992) which provides a useful review of the mineralogy of brickmaking.
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Figure 13. Clay 'workability' chart (from Bain & Highley, 1979). Plasticity index is used to indicate the forming properties of a particular clay. 'Optimum' and 'acceptable' properties are defined on the chart; lower values are acceptable for stiff extrusion, whilst soft-mud or hand-throwing requires higher plasticity index values. Plastic limit defines the position on the chart which indicates likely shrinkage on drying.

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Figure 14. Changes in mineralogy of brickclay on firing (from Dunham, 1992). The firing cycle comprises a 24 hour ramp up to the soak temperature which is followed by 12 hours at 1050°C and completed by a 24 hour cooling period. Numbered stages comprise (1) dehydration of clay minerals, gypsum and iron hydroxides; (2) loss of CO₂, S and hydrocarbons; (3) alpha/beta-quartz transition; (4) solid-state mineral reactions; (5) melt production; (6) reactions on cooling.
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*Vitrification curves* Although laboratory firing can in no way reproduce the conditions of an industrial kiln, this method does represent a simple method of identifying potential firing problems such as 'bloating', melting and excessive refractoriness. Broad classifications of clays can be drawn by comparing the fired properties of 'unknowns' with those of brick clays of proven commercial value. Fired properties are assessed by heating identical clay test pieces over a temperature gradient which broadly corresponds to that likely to be encountered in an industrial kiln. Changes in physical properties such as shrinkage, bulk density, porosity and specific gravity are then plotted against temperature to form a series of 'vitrification curves'.

Test pieces for brick and other structural clays may be formed by extrusion or hand moulding, either in the form of rods or miniature bricks (briquettes). Where large numbers of clay samples are being processed - e.g. in a regional survey of clay resources - there is a need for uniformity of approach and, for efficiency, sample preparation time needs to be kept to a minimum. Under these circumstances, small-diameter extruded test pieces are probably the best (Figure 15). These can be formed using a very simple hand-operated extruder (Figure 16). Changes in the physical properties of test pieces are determined by mercury displacement (Figure 17) and water absorption. Detailed methods for the determination of fired properties are given in Appendix 15.

Firing of test pieces is preferably carried out in a temperature-gradient furnace; a normal muffle furnace can be used but this procedure is much less efficient as the furnace has to be heated separately for each temperature required. Temperature-gradient furnaces may be of two basic types. (1) A chamber where the temperature changes in a linear manner from one end to another (the test piece is then usually a long rod or brick and individual smaller test pieces are cut from this at the end of the firing cycle to correspond to the range of temperatures required). (2) A number of separate cells with temperature differences of the order of 30-50°C (Figure 18). This is the most convenient arrangement as it allows firing of a range of test pieces from a number of samples in one operation.

Caution must be exercised when attempting to extrapolate results from the small-scale testing of the firing behaviour of a clay to its likely behaviour in commercial practice. Firing of a clay body is a dynamic process and the extent of the various reactions occurring at a particular temperature is a function of the heating rate, the size of the body and the grain size of its components. Of necessity, heating rates used in laboratory firing trials are much faster than those used in commercial...
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practice, so reactions may not reach equilibrium in the laboratory test pieces. However, test pieces used in laboratory trials are appreciably smaller than commercial ceramic bodies and—compared to clays used in structural ceramics—the grain size is usually much finer; reactions may therefore proceed faster in these smaller test pieces. To some extent the differences in heating rate and size/fineness between test pieces and commercial clay bodies may balance each other but the fact still remains that laboratory-derived vitrification curves should only be used as an indication of the behaviour of a clay in a commercial process. Whatever methodology is chosen for laboratory temperature-gradient firing, it is advisable to submit clays used in existing commercial processes to the same preparation and firing procedures, in this way building up a ‘library’ of vitrification curves of clays used for known processes. This approach is especially valuable where regional surveys of clay resources are being conducted as it enables a preliminary assessment to be made of likely uses.

The shape of the curves reflect physical changes within the clay as vitrification reactions (such as point melting and sintering) proceed with increasing temperature. If available manufacturing technology is relatively unsophisticated, clays which show a long vitrification range are generally more valued as raw material for bricks and other structural clayware. These are more able to tolerate temperature variations likely to be encountered in a traditional intermittent-firing industrial kiln whilst still producing bricks which fall within a given range of physical properties. More advanced technology (such as continuous-process tunnel kilns) may be able to tolerate clays with a much narrower vitrification range by close control over kiln temperature and atmosphere, although consistency and quality-control of the feed material are of paramount importance (see Section 4.1.3). A series of vitrification curves derived from brick clays which show a range of fired properties is shown in Figures 19 to 22.
Figure 15. Test pieces formed from a series of brick clays from Fiji. Temperature gradient increases from left to right (from $900^\circ$ to $1250^\circ$C).
Figure 16. Hand-operated extruder used to form brick clay test pieces.
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Figure 18. Mercury displacement apparatus used to determine volume changes on firing in brick clay test pieces.
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Figure 19. An eight-cell temperature-gradient furnace.
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Figure 20. Vitrification curve from a Lower Cretaceous brick clay from southern England. The relatively narrow vitrification range shown by this material is typical of a mixed-assemblage clay. The rapid increase in porosity and reversal of shrinkage above 1050°C indicates expansion or 'bloating' of the clay body, probably due to the presence of organic matter.

Figure 21. Vitrification curve from an Upper Carboniferous brick clay from the English Midlands. The relatively slow changes in porosity and shrinkage in this material are typical of the broad vitrification range shown by kaolinitic clays.

Figure 22. The vitrification curve taken from a potential brick clay from Fiji indicates a relatively refractory clay which shows little change in shrinkage or porosity below 1100°C. This siliceous clay is likely to produce an under-vitrified, relatively low-strength brick when fired to temperatures employed in most brick manufacturing operations (between 1000°C and 1100°C).
References


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Standards

British Standards


BS 435 (1975). Dressed natural stone kerbs, channels, quadrants and setts.

BS 594 (1985). Hot rolled asphalt for roads and other paved areas.


BS 1199 (1976). Sands for external renderings, internal plastering with lime and Portland cement, and floor screeds.


BS 3921 (1985) Specifications for clay bricks

BS 4987 (1988). Coated macadam for roads and other paved areas.


American Standards


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Australian Standards


New Zealand Standards


Appendix 1: Petrographic examination of aggregates

Procedure for qualitative examination

1. Record general characteristics of the aggregate sample including the maximum particle size and distinguish between natural and processed aggregate. Describe the grading, texture and shape of the aggregate particles.

2. Using a binocular microscope and/or hand lens identify the main rock types and estimate the relative proportions of the constituents. Record colour, grain size, degree of weathering, alteration etc.

Procedure for quantitative examination

Coarse aggregates (>5 mm)

1. Sieve the sample into separate size fractions using 50 mm, 37.5 mm, 20 mm, 10 mm and 5 mm sieves.

2. Determine the mass of each size fraction.

3. Examine each size fraction and determine petrological composition by hand separation and weighing. This will usually require the preparation of thin sections of selected particles and their examination using a petrographical microscope. Thin sections are particularly valuable for investigation of fine grained rocks and alteration products. Sufficient thin sections should be examined to understand the nature of the aggregate and to identify any impurities.

4. Calculate the overall composition of the test sample.

NOTE: In certain circumstances a simplified (and more rapid) examination may be appropriate, involving the single assessment of the >5 mm size fraction.
Fine aggregates (<5 mm)

1. Sieve the sample into separate size fractions using 5 mm, 2.36 mm and 1.18 mm sieves.

2. Determine the mass of each size fraction.

3. Examine each size fraction using a binocular microscope and determine petrological composition by hand sorting. Thin sections may be required for detailed identification. <1.18 mm material should be assessed by point counting of a thin section where the material is embedded in resin.

4. Calculate the overall composition of the test sample.

The method (in common with most test methods) requires two representative portions to be tested, and the result is the mean of the two determinations.
Appendix 2: Relative density and water absorption

Procedure for coarse aggregate (40 mm to 5 mm)

1. Wash the test portions (1 kg sample size) to remove all traces of undersize material.

2. Immerse each portion in water (in a gas jar) for 24 hours at 15° to 25°C and weigh (mass B).

3. Empty the gas jar, refill with water and weigh (mass C).

4. Place aggregate on a dry cloth and allow to surface dry until visible water films are removed. This is the saturated and surface dried (SSD) condition. Weigh the aggregate (mass A).

5. Place the SSD aggregate in an oven at 100° to 110°C for 24 hours. Cool and weigh (mass D).

Relative density (oven-dried) = \( \frac{D}{A - (B - C)} \)

Relative density (saturated and surface dried) = \( \frac{A}{A - (B - C)} \)

Apparent relative density = \( \frac{D}{D - (B - C)} \)

Water absorption (%) = \( \frac{(A - D)}{D} \times 100 \)
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Procedure for fine aggregate (<5 mm size)

1. Wash the test portions (c. 500 g sample size) to remove all traces of undersize (<75 μm) material using a 75 μm BS test sieve.

2. Immerse each portion in water (in a gas jar) for 24 hours at 15° to 25 °C and weigh (mass B).

3. Empty the gas jar, refill with water and weigh (mass C).

4. Dry the sample on the 75 μm sieve using a gentle current of warm air from a hair dryer. Stir to ensure uniform drying until the fine aggregate attains a 'free running' (or SSD) condition. Weigh the aggregate (mass A).

5. Place the aggregate on a tray in an oven at 100 - 110 °C and dry for 24 hours. Cool and weigh.

The calculations are the same as those given for the coarse aggregate method.
Appendix 3: Aggregate impact value (AIV)

An impact testing machine, as specified in BS 812, is required for this test and should be fixed to a concrete block or floor at least 450 mm thick. The test is carried out on 10 - 14 mm sized aggregate in a surface dry condition.

1. Place sample portion (mass A) in the 102 mm diameter x 50 mm deep hardened steel cup and tamp to a single horizontal layer.

2. Fix cup firmly to base of impact testing machine.

3. Subject the sample to 15 blows from the hammer, which has a 100 mm diameter cylindrical head and a total mass of 13.5 - 14.1 kg, falling through 381± 6.5 mm.

4. Remove the crushed aggregate from the cup and determine the mass of material (mass B) passing a 2.36 mm sieve.

\[
\text{AIV} = \frac{B}{A} \times 100
\]

5. The test result is the mean of two determinations and is reported to the nearest whole number. A lower numerical value indicates a more resistant rock.
Appendix 4: Aggregate crushing value (ACV)

The test is carried out on 10-14 mm sized surface dry aggregate and requires a sample size of about 2 kg.

1. Place the weighed sample (mass A) in three tamped layers in the 150 mm diameter hardened steel cylinder and level the surface of the aggregate.

2. Load the sample (through the ram apparatus) with a force that is increased at a uniform rate from 0 to 400 kN in 10 minutes.

3. Release the load and remove the crushed material from the cylinder.

4. Sieve the material on a 2.36 mm test sieve and weigh the fraction passing the sieve (mass B).

5. Repeat the test, using a second sample of the same mass as the first sample.

\[ \text{ACV} = \frac{B}{A} \times 100 \]

6. The mean of the two results, to the nearest whole number, is the test result. Once again, a lower value indicates a more resistant rock.

NOTE: The shape of aggregate particles affects both the AIV and ACV. Flakiness can introduce differences in AIV and ACV of over 30%. The flakiness index (\(I_F\)) should always be quoted when comparing particular AIV's or ACV's.
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Appendix 5: Ten per cent fines test

The ten per cent fines test is made on 10 - 14 mm sized, surface dry aggregate which is loaded in the standard ACV apparatus.

1. The weighed aggregate sample is placed in the steel cylinder to form a 100 mm thick horizontal bed (similar to the ACV test).

2. Apply a uniform loading rate to cause total penetration of the plunger (in 10 minutes) of approximately 15 mm (gravels), 20 mm (crushed rocks) or 24 mm (honeycombed aggregates).

   If an AIV is available the required loading can be estimated by using the following formula:

   Required force (kN) = \frac{4000}{AIV}

3. Record the maximum force \( x \) to produce the required penetration.

4. Release the load and remove the crushed material from the cylinder.

5. Sieve the material on a 2.36 mm sieve and weigh the fraction passing the sieve. Express this mass as a percentage of the mass of the test sample. The percentage fines must fall within the range of 7.5 to 12.5. If it does not, repeat and adjust the loading until the percentage fines fall within this range.

6. Make a repeat test at the same force (to produce percentage fines within the required range).

7. The Ten percent fines value = \frac{14 \times x}{y + 4} kN

   where \( x \) is the maximum force (kN) and \( y \) is the mean percentage fines from two tests at \( x \) kN.

8. Report the result to the nearest 10 kN for forces of 100 kN or more, or to 5 kN for loads of less than 100 kN.
Appendix 6: Los Angeles abrasion value (LAAV)

Test procedure (for 10-14 mm sized aggregate)

1. Wash the aggregate and dry in an oven at 110 °C.
2. Weigh the test sample (5000 g) - mass $M_1$ - and place in test machine.
3. Place 11 balls weighing 4800 g (+20 -150 g) in the machine.
4. Replace the cover and rotate for 500 revolutions.
5. Remove the crushed material from the cylinder and wet sieve using a 1.6 mm sieve.
6. Dry the aggregate retained on the sieve in an oven at 110 °C.
7. Weigh this oversize material ($M_2$).

The $\text{LAAV} = \frac{M_1 - M_2}{M_1} \times 100$

where $M_1$ is the mass of the test portion, and $M_2$ is the mass of aggregate retained on the 1.6 mm sieve.

9. The result is quoted to the nearest whole number.
Appendix 7: Aggregate abrasion value (AAV)

The test is carried out on non-flaky, washed and surface dry 10-14 mm aggregate, of measured relative density.

1. Two specimens are made for each test. Each specimen consists of at least 24 aggregate particles, placed shoulder to shoulder in a single layer in a metal mould of specified dimensions. The flattest surface of the particles should lie on the bottom of the mould.

2. Fill the interstices between the aggregate particles with fine sand to three quarters of their depth.

3. Mix resin and hardener and fill the mould to overflowing. Cover with flat plate and clamp.

4. When the resin has hardened, remove the specimens from the moulds, clean, trim and weigh (mass A).

5. Fit each specimen into the backing trays and place on the grinding lap in the abrasion machine. Place weights on the specimen to give a total load of 2 kg.

6. Rotate the lap through 500 revolutions at a speed of 28 to 30 rpm, feeding abrasive silica sand across the specimens.

7. Remove the specimens from the machine and backing trays and weigh (mass B).

\[ AAV = \frac{3(A - B)}{d} \]

where A is the mass of the specimen before abrasion, B is the mass of specimen after abrasion, and \( d \) is the SSD relative density of the aggregate.

8. The mean of the two tests is calculated to two significant figures. In this test a lower numerical value indicates a more resistant rock. Some typical AAVs for a range of rock types are given in Table 15. Values in excess of 15 indicate inadequate abrasion resistance and such aggregates would be considered unsuitable for road surfacing (Hawkes and Hosking, 1972).
Appendix 8: Polished stone value (PSV)

The test is carried out on washed and surface dry, non-elongate aggregate which has passed a 10 mm sieve but is retained on a 10-14 mm flake sorting sieve. A PSV control stone is used for calibration of the friction tester.

1. Four specimens are prepared for each sample, as well as four specimens of the control stone. Each specimen consists of 35 to 50 particles, placed shoulder to shoulder in a single layer with their flattest surfaces lying on the bottom of the mould.

2. Fill the interstices between the particles to three quarters of their depth with fine sand.

3. Mix the hardener with the resin and fill the mould with the mixed resin.

4. When the resin has hardened, remove the specimen from the mould, clean and trim.

5. Fourteen specimens are polished on the polishing machine during each run. Clamp the fourteen specimens round the periphery of the road wheel of the polishing machine.

6. Rotate the road wheel at 315-325 rpm and bring the specified solid rubber tyre to bear on the surface of the aggregate with a force of 715-735 N. Continuously feed the tyre with corn emery and water for a period of 3 hours.

7. Remove the specimens from the machine, and thoroughly clean. Store the specimens in water at 18° to 20°C for a period of 30 minutes to 2 hours.

8. Measure the state of the polish of the wet specimen by using the friction test apparatus in a room kept at 18° to 22°C.

9. Rigidly locate the test specimen in the friction tester and release the pendulum from the horizontal position. Measure the height of the upward swing of the pendulum, after it has traversed the specimen, by the friction pointer. Note the reading of the pointer to the nearest whole number.
10. The test specimens and control stone specimens are tested in this manner five times, and the mean of the last three readings is recorded for each.

11. The mean (S) is calculated for each group of four specimens and recorded to the nearest 0.1 unit. Calculate the mean value (C) of the four control specimens and record to 0.1 unit. Calculate the PSV from the following equation:

\[
PSV = S + 52.5 - C
\]

12. Report the PSV to the nearest whole number.
Appendix 9: Methylene blue dye adsorption

The test procedure is derived from Hills and Pettifer (1985) and is carried out on small (1 g) representative samples passing a 75 µm sieve.

1. Disperse the sample portion in 30 ml of water and titrate by adding 0.5 ml increments of methylene blue solution that has been prepared by dissolving 0.1 g of methylene blue in 100 ml of distilled water.

2. After each addition, agitate the suspension for one minute.

3. Using a glass rod remove a drop of suspension on to a filter paper. The drop consists of a dark blue centre and a colourless rim.

4. Repeat the procedure at intervals until the end point is reached. This is evident by the appearance of a light blue halo of unadsorbed dye between the dark blue centre and the colourless rim. It indicates that the sample is no longer capable of further adsorption.

5. The methylene blue value (MBV) is:

\[ \text{MBV} = \frac{0.1V}{M} \]

where \( V(\text{ml}) \) is the volume of methylene blue solution to reach the end point, and \( M(\text{g}) \) is the mass of the test portion.
Appendix 10: Porosity and saturation coefficient

1. Dry four small (4-5 mm) samples of dimension stone at 103°C (±3°C).
2. Cool to 20°C and place in a vacuum desiccator fitted with a funnel to admit water.
3. Evacuate the desiccator and maintain the vacuum for two hours.
4. Saturate the samples with water and admit air to restore atmospheric pressure.
5. Weigh the samples in water (W₁) and in air (W₂).
6. Dry at 103°C (±3°C) for 16 hours, cool and weigh (W₀).
7. Immerse the samples in water at 15-20°C for 24 hours, remove and weigh (W₃).
8. Porosity (P) is calculated from:
   \[ P = \frac{W₂-W₀}{W₂-W₁} \times 100\% \]
9. The saturation coefficient (S) is calculated from:
   \[ S = \frac{W₃-W₀}{W₂-W₀} \]

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Appendix 11: BRE crystallisation test

1. Make up sodium sulphate solution (dissolve 1400 g sodium sulphate decahydrate [Na$_2$SO$_4$.10H$_2$O] in 8.6 litres deionised water at 20°C ±0.5°C).

2. Prepare four to six 4 cm cubes of stone using a suitable saw.

3. Wash and dry at 103°C (±2°C).

4. Allow to cool in a desiccator to 20°C (±2°C).

5. Weigh cubes to ±0.01 g (W$_0$).

6. Label and weigh again (W$_1$).

7. Place each cube in a 250 ml beaker and cover with sodium sulphate solution to a depth of 8 mm. Leave for two hours, maintaining temperature at 20°C (±0.5°C).

8. Remove cubes from solution and place in an oven at 103°C (±2°C). The initial humidity of the oven should be increased by placing a shallow tray containing 300 ml of water in the oven 30 minutes before adding the test cubes. Dry for 16 hours.

9. Remove cubes and allow to cool to 20°C (±2°C).

10. Repeat steps 7 to 9 until 15 cycles have been completed.

11. Weigh the cubes (W$_f$) and calculate the percentage weight loss:

\[
\text{% weight loss} = \frac{100(W_0 - W_f)}{W_0}
\]

12. Calculate mean percentage loss.
Appendix 12: Acid immersion test

1. Prepare a 20\% (w/w) sulphuric acid solution.
2. Prepare six 50 x 50 x 15 mm test pieces from each sandstone.
3. Immerse the samples in 200 ml of sulphuric acid solution and leave for ten days.
4. Remove the samples and examine for surface changes. If there is any sign of decay, the sample has failed the test.
Appendix 13: Laboratory procedure for the determination of clay liquid limits

Equipment & reagents

Pestle and mortar
125 μm sieve
2 large palette knives
1 small palette knife
Wash bottle
500 ml beakers
Large watch glass
Casagrande apparatus/Cone penetrometer
Glass weighing bottles
Analytical balance, 0.01 g readability, 1 kg capacity
Drying oven (110°C)
Large square glass plate (400 by 400 mm approx.)

Distilled/deionised water

Preparation of clay pastes

1. Gently grind 100 g dry clay to pass 125 μm screen.

2. Mix <125 μm dry clay thoroughly with a small amount of distilled water on the glass plate using the palette knives for at least 15 minutes to obtain a stiff paste. DO NOT add an excessive amount of distilled water as the resulting paste must be not be too fluid.

3. Place clay paste in a beaker, cover with a watch glass to prevent evaporation and allow to ‘age’ overnight.

Determination of liquid limit: Cone penetrometer method

1. Remove the clay paste from the beaker and work the clay on the glass plate with the palette knives for about 10 minutes.

2. Place a portion of the clay into the cup with a palette knife taking care not to trap any air. Strike-off excess clay with the straight edge of palette knife to obtain a smooth level surface.
Construction materials

3. Position the cup in the centre of penetrometer base plate. Lower the penetration cone until the tip of the cone just touches the surface of the clay: if the cone is correctly positioned a slight movement of the cup will just mark the surface of the clay. Gently lower the dial gauge stem until it contacts the top of the cone shaft by using the INNER knob at the centre of the gauge. Set the dial gauge reading to zero by adjusting the OUTER knob at the centre of the gauge.

4. Release the cone for a period of 5 seconds using either the automatic or manual release (if using manual release, avoid jarring the instrument during this action). After locking the cone in position, gently lower the dial gauge stem until it contacts the top of cone shaft by using the INNER knob at the centre of the gauge. Record the gauge dial reading (penetration depth) to the nearest 0.1 mm.

5. If penetration depth is less than 15 mm, add more water to the clay and repeat steps 2-4. If the penetration depth is greater than 15 mm proceed to step 6.

6. Repeat steps 2-4 until two subsequent dial readings are within ±1 mm. This ensures consistent results.

7. If the conditions in step 6 are satisfied remove a small amount of clay paste (10 g approx.) from the area penetrated by the cone and place in a weighing bottle (mass M1) and replace airtight lid. Weigh the bottle containing the wet clay (mass M2). Open the lid and place overnight in an 105°C oven. The bottle plus dried clay is then weighed the following morning (mass M3). Moisture content is then calculated as percentage of the dry mass of sample (see worksheet).

8. Repeat steps 1-7 at least three more times adding additional increments of distilled water. Mix very thoroughly each time more water is added. Amounts of water added should be such that penetration values in the range 15 mm to 25 mm are obtained. Moisture content/penetration depth co-ordinates are plotted on the graph paper on the worksheet and are then connected by a straight line ‘best fit’ (the flow curve).

9. The liquid limit is reported as the moisture content, expressed to the nearest whole-number, corresponding to a penetration depth of 20 mm on the flow curve.
Construction materials

*Determination of liquid limit: Casagrande method.*

1. Remove the clay paste from the beaker and work the clay on the glass plate with the palette knives for about 10 minutes.

2. Place a portion of the remixed clay in the cup of the Casagrande apparatus and level-off parallel to the base of the apparatus, ensuring that there are no entrapped air bubbles. Carefully draw the grooving tool supplied through the paste, keeping it normal to the surface of the cup with the chamfered edge facing the direction of movement.

3. Having first ensured that the counter is set to zero, steadily turn the crank at the rate of two revolutions per second until the paste at the bottom of the groove closes up over a length of 13 mm. This distance may be measured with a ruler or the end of the grooving tool. Record the number of bumps at which this occurs.

4. If the number of bumps is greater than 50, add more water to the clay and repeat steps 2 and 3. If the number is less than 50 proceed to step 6.

5. If the conditions in step 4 are satisfied remove a small amount of clay paste (10 g approx.) from the area of the groove and place in a weighing bottle (mass M1) and replace airtight lid. Weigh the bottle containing the wet clay (mass M2). Open the lid and place overnight in an 105°C oven. The bottle plus dried clay is then weighed the following morning (mass M3). Moisture content is then calculated as percentage of the dry mass of sample (see worksheet).

6. Repeat steps 1-5 at least three more times adding additional increments of distilled water. Mix very thoroughly each time more water is added. Amounts of water added should be such that bump values are evenly scattered above and below 25. Bump values of less than 10 are discounted. Moisture content/bump value co-ordinates are plotted on the semi-logarithmic graph paper on the worksheet and are then connected by a straight-line ‘best fit’ (the flow curve).

7. The liquid limit is reported as the moisture content, expressed to the nearest whole-number, corresponding to 25 bumps on the flow curve.
Construction materials

NOTES
The results obtained by using the two methods do differ (see Section 5.2.2). Where the liquid limit is less than 100 differences are not considered significant as they are within the normal variation typically obtained using the Casagrande method. However, for liquid limit values above 100 the cone penetrometer method is known to give LOWER values in comparison to the Casagrande test.
# Liquid Limit Worksheet (Cone Penetrometer Method)

**LIQUID LIMIT: CONE PENETROMETER METHOD**

<table>
<thead>
<tr>
<th>Determination No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottle No.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1... Mass empty bottle (g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2... Mass bottle + wet clay (g)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M3... Mass bottle + dry clay (g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass water (g) = M2-M3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass dry clay (g) = M3-M1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture content (%) = ( \frac{(M2-M3)}{(M3-M1)} \times 100 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Penetration depth (mm)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Diagram**

![Diagram of moisture content vs. penetration depth](image)

**Liquid limit worksheet (Cone penetrometer method)**
Construction materials

LIQUID LIMIT: CASAGRANDE METHOD

<table>
<thead>
<tr>
<th>Sample</th>
<th>Operator</th>
<th>Remarks</th>
<th>Date</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Determination No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottle No.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1... Mass empty bottle (g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2... Mass bottle + wet clay (g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M3... Mass bottle + dry clay (g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass water (g) + M2-M3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass dry clay (g) = M3-M1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture content (%) = (M2-M3)/(M3-M1)*100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of blows</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Liquid limit worksheet (Casagrande method)
Appendix 14: Determination of plastic limit and plasticity index

Equipment & reagents

Pestle and mortar
125 μm sieve
Wash bottle
Glass weighing bottles
Analytical balance, 0.01 g readability, 1 kg capacity
Drying oven (110°C)
Large square glass mixing plate (400 by 400 mm approx.)
Polished glass test plate
Metal or glass rod, 3 mm diameter, approx. 100 mm length
Distilled/deionised water

Method

1. Gently grind approximately 25 g dry clay to pass 125 μm screen and place on mixing plate. Using your hands mix water with the sample until a plastic ball can be formed.

2. Mould the ball between the fingers and roll it between the palm of the hands until the heat of the hands has dried the clay sufficiently for slight cracks to appear on the surface.

3. Divide the ball into two sub-samples and set one of these aside.

4. Divide the remaining sub-sample into four equal parts and carry out steps 5-8 separately on each part

5. Mould the clay using the fingers to equalize the moisture distribution. Form the clay into a thread of about 6 mm diameter between the first finger and thumb of each hand.

6. Roll the thread between the fingers of one hand (from the fingertips to the second joint) and the surface of the glass test plate. Use enough pressure to reduce the diameter of the thread from 6 mm to 3 mm in five to 10 complete forward-and-back hand movements. Use the rod to gauge the thickness of the thread. All clays tend to harden near the plastic limit; some "heavy" clays may require 10-15 movements. It is important to maintain uniform rolling pressure: do not change hand pressure as the thread diameter approaches 3 mm.

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Construction materials

7. On completing the operation in step 6, pick up the clay thread and mould using fingers to dry the clay further. Gradual drying is carried out by alternately rolling on the test plate and moulding with the fingers. Continuous rolling should not be attempted as this only dries the surface of the clay. Reform the clay into a ball as described in step 5.

8. Repeat steps 6 and 7 until the thread shears (cracks) both longitudinally and transversely when it has been rolled to about 3 mm diameter. Gather the cracked portions of clay and transfer to an airtight bottle (mass M1) and replace the lid immediately.

9. Carry out steps 5-8 on each of the four portions of the clay, placing all the cracked pieces of clay obtained into the same airtight bottle. The bottle and its moist clay contents is then weighed (mass M2). After opening lid of bottle, place overnight in an 105°C oven. The bottle and dry clay is then weighed the following morning (mass M3). Results can be recorded on the liquid limit worksheets and the moisture content then calculated.

10. Carry out steps 4-9 on the remaining material.

11. Calculate the average of the two moisture contents obtained and express to the nearest whole number. This is the plastic limit.

12. The plastic index (PI) can be calculated by subtracting the plastic limit (PL) from the liquid limit (LL).

NOTES

(i) Test should be carried out on a polished glass surface. If possible use separate plates for mixing and testing as discrepancies will result from use of a textured or scratched glass surface.

(ii) If moisture content of each sub-sample differs by more than ±1% repeat the test.
Appendix 15: Determination of green-to-dry and fired properties

In BGS laboratories, fired properties of brick clays are determined using small extruded test pieces. These test pieces can also be used to determine green-to-dry properties (including shrinkage). Where large numbers of clay samples are being processed - e.g. in a regional survey of clay resources - extruded test pieces provide a means of providing a uniform test pieces relatively rapidly. Test pieces can also be made by hand moulding briquettes. A small hand-operated extruder will provide approximately 10 test pieces 50 mm long by 6.3 mm in diameter from about 100 g of dry clay.

Test piece extrusion and determination of green-to-dry properties

Apparatus

- Pestle and mortar
- 125 μm sieve
- Hand-operated extruder fitted with 6.3 mm die
- Glass plate
- Hand-operated plant sprayer filled with distilled water
- Large pallet knife
- Steel rod (or similar) about 300 mm long by 10 mm in diameter
- Mounted needle
- 4-figure analytical balance with capability to weigh a suspended object
- 50 ml beaker filled with kerosene
- Oven set at 110°C
- Top-loading two-figure balance
- Mercury displacement apparatus (rack and cradle assembly)
- Beaker filled with sufficient mercury to allow test piece to be completely covered to a known depth

Method

1. Gently grind 100g dry clay to pass 125 μm screen.
2. Spread the dry clay on a glass plate and spray with water whilst mixing the clay with the pallet knife.
Construction materials

3. Continue adding water and mixing until the clay just begins to change colour, develops a 'crumbly' texture, and/or just smears when squeezed between finger and thumb.

4. Tip moistened clay into the barrel of the extruder and tamp down using steel rod to remove as much air as possible from the clay.

5. Assemble plunger mechanism and rotate handle until 30 or 40 mm of extruded clay appears through die. Cut this material off and discard.

6. Whilst attempting to maintain an even rotation of the extruder handle, cut about 10 test pieces from the clay extrusion as it appears. Discard any bent or cracked pieces.

7. Number each test piece using a mounted needle and carefully set down on a flat glass or ceramic tile or tray.

8. Select one test piece immediately for weighing in air using four figure balance. Record weight of green test piece in air on green-to-dry properties worksheet.

9. Suspend green test piece from balance (use nylon monofilament or similar) and submerge in kerosene. Ensure that the test piece is not touching the sides of the beaker. Record weight of the green test piece in kerosene on worksheet.

10. Oven dry all test pieces overnight at 110°C.

11. Weigh previously selected test piece in air and record.

12. Record weight under mercury of empty rack and cradle assembly.

13. Record weight of selected test piece under mercury.

14. Calculate water of plasticity, porosity of fired body and green-to-dry shrinkage using formulae provided on the green-to-dry properties worksheet.
Determination of fired properties

**Apparatus**

- Top-loading two-figure balance
- Mercury displacement apparatus (rack and cradle assembly)
- Beaker filled with sufficient mercury to allow test piece to be completely covered to a known depth
- Temperature-gradient kiln or programmable muffle furnace (max. temp. 1250°C)
- Vacuum desiccator
- Vacuum pump

**Method**

1. Weigh in air eight of the remaining oven-dry test pieces. Record these and other weighing data on the fired properties worksheet given below against individual test piece number.

2. Record weight under mercury of empty rack and cradle assembly.

3. Record weight of each oven dry test piece under mercury.

4. Place each test piece in one of the eight cells in the temperature-gradient kiln. The maximum temperature of each cell ranges from 900°C (cell 8) to 1250°C (cell 1). The heating rate is about 4°C/minute; this allows the firing cycle (including a 30 minute isotherm or 'soak' at maximum temperature) to take place within the working day. If a kiln of this type is unavailable, then a suitable laboratory muffle furnace can be programmed to heat individual test pieces to the same range of temperatures. This is more time consuming although different samples can be batched together to be fired simultaneously.

5. Allow the kiln to cool overnight. Repeat steps 1 to 3 with fired test pieces.

6. Submerge test pieces in a dish filled with distilled water. Place the dish in the vacuum desiccator and evacuate for 3 hours.

7. Remove individual test pieces from water, dry off any excess and immediately weigh.
8. Calculation of fired properties is carried out as follows (see also worksheets 1 and 2 below):

Before firing
\[ c = \text{weight of test piece} \]
\[ d = \text{weight of test piece under mercury} \]
\[ h = \text{weight of empty assembly under mercury} \]

After firing
\[ e = \text{weight of test piece} \]
\[ f = \text{weight of test piece under mercury} \]
\[ hf = \text{weight of empty assembly under mercury} \]
\[ g = \text{weight of test piece after water absorption} \]

\[ ab \text{ (water absorption)} = 100 \times \frac{(g-e)}{e} \]
\[ vf = \frac{100}{c} \times \frac{(f-hf)}{13.557} \]
\[ v = \frac{100}{c} \times \frac{(d-h)}{13.557} \]

Porosity (vol. %) = \[ 100 \times \frac{ab}{vf} \]

Shrinkage (vol. %) = \[ 100 \times \frac{(v-vf)}{v} \]

Bulk density = \[ \frac{100}{vf} \]

Specific gravity = \[ \frac{100}{(vf-ab)} \]

Note: Mercury weighings should be carried out in a suitable fume cupboard.
Construction materials

Sample No ........

a: weight green test piece in air
b: weight green test piece in kerosene
c: weight dry test piece in air
d: weight dry test piece in mercury
h: weight empty assembly in mercury

\[
\text{WATER OF PLASTICITY} = \frac{(a-c) \times 100}{c}
\]

volume green body (\(gv\)) = \(\frac{(a-b)}{0.789}\)
volume dry body (\(dv\)) = \(\frac{(d-h)}{13.557}\)
volume dry solids (\(ds\)) = \(gv + c - a\)
pore volume of dry body (\(pv\)) = \(dv - ds\)

\[
\text{POROSITY OF DRY BODY} = \frac{pv}{dv} \times 100
\]

\[
PV = \frac{pv \times 100}{c}
\]

\[
DS = \frac{ds \times 100}{c}
\]

\[
\text{DRY SHRINKAGE FROM WATER OF PLASTICITY} = \frac{W\text{ of } P - PV \times 100}{W\text{ of } P + DS}
\]

Green-to-dry properties worksheet

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## Results of ceramic tests

<table>
<thead>
<tr>
<th>Sample code &amp; firing temp</th>
<th>Before firing</th>
<th>After firing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>c</td>
<td>d</td>
</tr>
<tr>
<td>Wt of testpiece assembly</td>
<td>Wt of testpiece under mercury</td>
<td>Wt empty assembly under mercury</td>
</tr>
</tbody>
</table>

Fired properties worksheet 1.
### Calculation of firing properties

<table>
<thead>
<tr>
<th>Sample:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(Water adsorption)</th>
<th>ab</th>
<th>vl</th>
<th>v</th>
<th>Porosity</th>
<th>Shrinkage</th>
<th>Bulk density</th>
<th>Specific gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>ab = 100 (g.e)</td>
<td>e</td>
<td>c</td>
<td>13.557</td>
<td>v = 100</td>
<td>= 100 ab</td>
<td>= 100 (v-vl)</td>
<td>= 100 (vl-ab)</td>
</tr>
</tbody>
</table>

Fired properties worksheet 2.

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