2

Aggregates

Contents

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Summary

This chapter provides an introduction to aggregates, which are the most consumed natural resource after water. The chapter begins with the main definitions of the term, including those from ASTM, EN, and ISO standards. Next heading establishes the main types of aggregates according to the production method: natural, manufactured, or recycled. Natural aggregates can be further subdivided into sand and gravel, and crushed stone. Geological occurrences of natural aggregates (different possibilities since natural aggregates are generated by a great variety of geologic processes) are then discussed as well as the main extraction methods used in sand and gravel and crushed stone exploitation. The principal processing techniques used in aggregate production (crushing, screening, and washing) are described. Then, this chapter describes the properties of aggregates and their associated tests, organized them into five main groups: general, geometrical, mechanical and physical, thermal and weathering, and chemical properties and tests. A heading devoted to aggregate for use as railway ballast is included whereas other important applications of aggregates such as concrete, mortar, and roads are taken into account in the corresponding chapters. The environmental considerations of aggregate quarrying are finally kept in mind because aggregate is extracted close to major centers of demand (e.g., big cities) to minimize cost of transport.

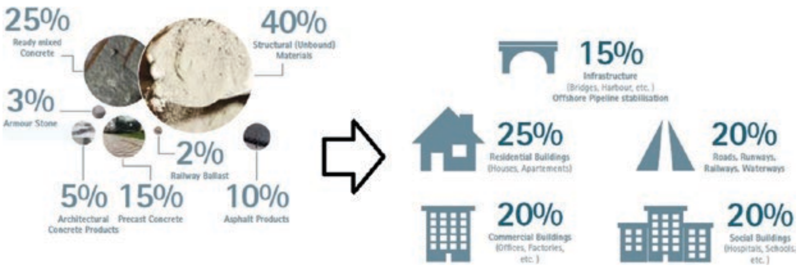
2.1 Introduction

Aggregates (a collective term for mineral materials consisting of grains or fragments of rock) are one of the most common natural resources used in everyday life, having fundamentally enhanced the quality of life. Aggregates are essential for use in construction; they are used in nearly all residential, commercial, and industrial building construction and in most public work projects such as roads, highways and bridges, railroad beds (▣ Fig. 2.1), dams, airports, tunnels, and many others. According to the European Aggregates Association (UEPG), the main applications of aggregates in construction during 2018 and their relative percentages are shown in ▣ Fig. 2.2.

▣ **Fig. 2.1** Aggregate used as railway ballast

Today, aggregate production accounts for more than half of the nonfuel mining volume in the United States. Moreover, in the future, rebuilding of deteriorated roads, highways, bridges, airports, seaports, and private and public buildings will require huge amounts of aggregate to be mined. Although it is almost impossible to know exactly the quantity of aggregates extracted every year in the world, it can be roughly estimated that annual production of aggregate worldwide totals about 25 billion tons. It is clear that both developed countries and developing nations require an extensive use of aggregates.

Some facts to outline the importance of aggregates are the following: (a) after water, aggregates are the most consumed natural resource, (b) it is estimated that 30,000 tons of aggregates are required to construct 1 km of highway and every new 1 km of high-speed railway typically requires 9000 tons of aggregates, (c) about 90% of most paved roads are made of aggregate, either as a base for the road or mixed with asphalt or cement, (d) one cubic meter of concrete incorporates approximately two tons of aggregates (they occupy at least three quarters of volume), (e) the production of aggregates in the United States shifted from about 200 million tons in 1940 to



◘ **Fig. 2.2** Main applications of aggregates in construction during 2018 and their relative percentages (UEPG)

◘ **Fig. 2.3** Aggregate quarry. (Image courtesy of Benito Arnó e Hijos, S.A.U)

approximately 2.50 billion tons in 2018, and (f) actually the European aggregate demand is 2.7 billion tons per year, representing an average demand of 5 tons per capita per year.

Aggregates are generally open-pit mined (◘ Fig. 2.3) and used either in their natural state or after crushing, washing, and sizing. They are generally combined with binding components to form concrete, mortar, and asphalt although they can be used on their own nature to provide the base that underlies paved roads, railroad ballast, surfaces on unpaved roads, and filtering material in water treatment. Unlike metals, e.g., gold or copper, aggregates are a high bulk, low unit value commodity. This type of raw material derives much of its value from their location close to the market. As a consequence, it is said to have a high place value. The transport of aggregates long distances substantially increases its price and can render distant deposits uneconomical. For this reason, the aggregate operations usually are located close to population centers and other market areas.

The most important application of aggregates deals with construction but many other uses are envisaged. They have numerous industrial uses such as the manufacture of pharmaceuticals, sugar, glass, paper, plastics, floor coverings, rubber, synthetic fabrics, cosmetics, toothpaste, and many more. Consequently, it can be said that aggregates in one form or another are used in practically everything that human touch during the day, being obviously vital to the maintenance and development of the society.

2.2 Definitions

There are many definitions for the term *aggregate*, although most of them are very similar. The *Encyclopaedia Britannica* defines aggregate (in building and construction) as "material used for mixing with cement, bitumen, lime, gypsum, or other adhesive to form concrete or mortar." The British Geological Survey (BGS) points out that "aggregates are normally defined as being hard, granular, materials that are suitable for use either on their own or with the addition of cement, lime or a bituminous binder in construction." The Portland Cement Association (PCA) states that "aggregates are inert granular materials such as sand, gravel, or crushed stone that, along with water and Portland cement, are an essential ingredient in concrete."

In ASTM standards, aggregate has a number of definitions depending primarily on their uses. Considering the most important applications of aggregates, aggregate related to concrete (ASTM C125 standard) is "a granular material, such as sand, gravel, crushed stone, or iron blast-furnace slag, used with a cementing medium to form hydraulic-cement concrete or mortar." If aggregates are used in roads and pavements (ASTM D8 standard), they are "a granular material used as a construction material, meeting the requirements of road and paving applications." In aggregates for mortar and grout for unit masonry (C1180 standard), aggregate is "a granular mineral material such as natural sand, manufactured sand, gravel, crushed stone, and air cooled blast furnace slag." Consequently, aggregate embraces a large range of naturally occurring and man-made materials of a broad variety of sizes and physical properties.

Regarding European standards, all EN documents, leaving aside the final application, include the same definition of aggregate: "granular material used in construction." Moreover, the definition of ISO is also extremely short: aggregate is an "inert granular material" (ISO 6707-1 standard for buildings and civil engineering works).

Summarizing the most important aspects exposed in all the previously mentioned definitions of aggregate, it is clear that aggregate is a granular, inert material basically used in construction, the main applications in this sector being the manufacture of concrete and mortar, and for roads and pavements.

2.3 Aggregate Types

Aggregates can be classified based on several criteria. They can be separated into light, heavy, or normal aggregates if their unit weights are taken into account. Aggregates are also classified in fine aggregate (sand) or coarse aggregate (gravel) when particle size is considered. The geological origin can be another feature to classify the types of aggregates: sedimentary, igneous, and metamorphic. Nevertheless, the most common and used system to group the different aggregate types is considering the production method to be used. Thus, aggregates are separated in natural, manufactured, or recycled. EN 12620 standard uses this classification and points out the following definitions: "natural aggregate is aggregate from mineral sources that has been subject to nothing more than physical processing (crushing and sizing); manufactured aggregate is aggregate of mineral origin resulting from an industrial process involving thermal or other modification (e.g. slag); and recycled aggregate (◘ Fig. 2.4) is aggregate resulting from the processing of inorganic materials previously used in construction (e.g., construction and demolition waste – CDW-)." In other words, aggregates are sand and gravel (including marine sediments), crushed rock (e.g., limestone), and recycled (e.g., reprocessed concrete) and manufactured aggregates.

◘ **Fig. 2.4** Recycled aggregate. (Image courtesy of Salmedina S.L.)

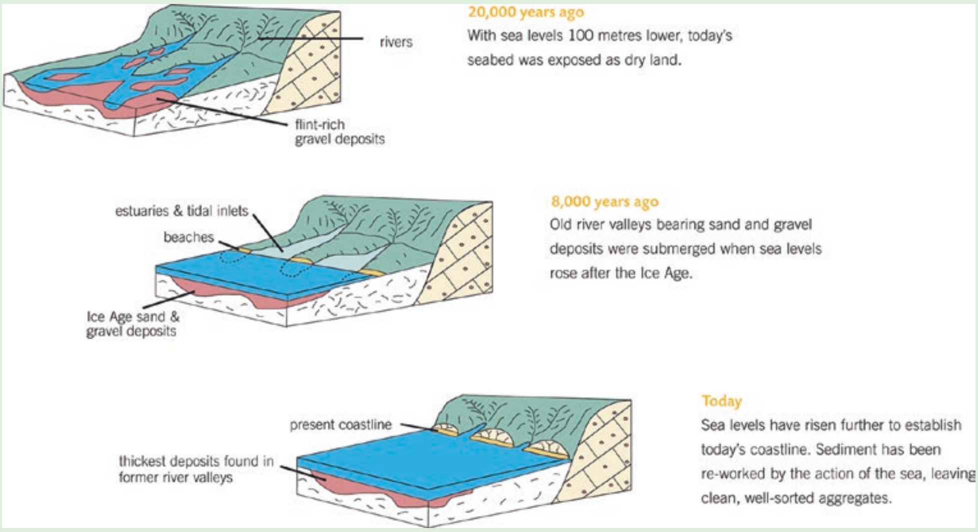
Natural aggregates (sand and gravel, and crushed stone) are extracted mainly from quarries (in some countries also from sea-dredged materials, that is, marine aggregates—▶ Box 2.1: Marine Aggregates) and they constitute by far the most important type of aggregates: 90% of global aggregate production in Europe according to UEPG. Recycled aggregates provide only 8% of production in European countries although they are essential for instance in the Netherlands. Construction and demolition waste is the biggest waste stream in this country and most of it—the inert fraction—is processed and used in concrete, asphalt, or mixed aggregate. Finally, manufactured aggregates represent only 2% of European consumption. Natural aggregates are described in detail in this chapter while recycled aggregates are taken into account in ▶ Chap. 19, specifically devoted to construction and demolition waste. Manufactured aggregates are not contemplated in this book because their impact in world aggregate production is negligible.

Box 2.1

Marine Aggregates

According to the British Marine Aggregate Producers Association (BMAPA), "the marine aggregate industry is one of the UK's key suppliers of sand and gravel. In a typical year (e.g., 2018), around 19 million tons of marine aggregate are dredged from an area of c.90 km^2 – equivalent to 0.01% of the UK seabed. Marine supplies provide around 25% of sand and gravel sales in England and 48% of sales in Wales." Another example of the importance of marine aggregates production is that some 16% of total production from UK waters is exported to France, the Netherlands, and Belgium for use as construction aggregate. This is because that export market exists as a consequence of increasingly constrains of locally won terrestrial aggregates of these countries. Russell (com. pers.) points out that "The Netherlands and Belgium are heavily reliant upon imports of construction aggregate from adjacent nations, especially Germany and France, along with crushed rock by sea from Scandinavia; while both countries have significant volumes of fine-medium marine sand which are widely exploited for beach nourishment, land reclamation and construction, neither has any significant resource of the coarse sand or gravel required for concrete production on their continental shelves."

The distribution of marine sand and gravels that can be used by the aggregate industry is limited to discrete geological deposits that reflect the physical processes that have formed them (◘ Fig. 2.5). Most represent relict deposits generated as a result of ancient glacial and fluvial processes coupled with associated variations in sea level relative to land. In the Quaternary period, several glacial episodes took place from about 26 million years before present to about 11,000 years before present. Thus, fluctuating sea levels over the past two million years have led to the deposition of sands and gravels on the modern seabed. Although these sand and gravels are now submerged, they were originally deposited by large river systems that flowed across the seafloor, when it was exposed as dry land during glacial stages, which in turn corresponded to periods of sea-level lowering. The sands and gravels were deposited by fast-flowing rivers fed by snow and ice melt, which poured out across the



◘ **Fig. 2.5** Genesis of marine aggregates in UK. (Illustration courtesy of BMAPA) dry shelf. In turn, these deposits were subsequently reworked by wave and tidal processes as sea levels rose during warmer interglacial stages. This warm-cold cycle was repeated many times producing sand and gravel deposits that are essentially immobile and locked in ancient river terraces and channels. The availability of suitable resources for commercial dredging is not only defined by the presence of ancient paleovallies, but also by the extent to which more recent marine processes have reworked these deposits.

Extraction of marine aggregates involves the use of purpose-built dredging vessels. To locate the dredging area, vessels use satellite navigation systems. The dredge pipe is then lowered to the seafloor and powerful pumps remove a mixture of sand, gravel, and seawater into the ship's cargo hold (◘ Fig. 2.6). Typically, a dry cargo will be discharged using bucket wheels, scrapers (◘ Fig. 2.7), or wire-hoisted grabs that place the aggregate onto a conveyor system for delivery to the wharf or processing plant. Alternatively, hydraulic discharge can be used to discharge a wet cargo. Powerful pumps on large vessels are capable of drawing up to 2600 tons per hour of sand and gravel raw materials from depths of up to 50 meters. It is important to note that the ability of dredging vessels to access sand and gravel resources will be influenced by the water depth, with most aggregate dredgers unable to dredge beyond water depths of 60 m.

◘ **Fig. 2.6** Dredged material being transferred into the hold of the vessel. (Image courtesy of BMAPA)

◘ **Fig. 2.7** Dredger unloading its cargo of marine aggregates close to the center of London with the use of scraper buckets. (Image courtesy of Mark Russel—BMAPA)

In some countries, e.g., United Kingdom, the term *secondary aggregate* is also used. Secondary aggregates are commonly defined as: "(a) aggregates obtained as a by-product of other quarrying and mining operations (e.g. natural stone waste), or (b) aggregates obtained as a by-product of other industrial processes (e.g. blast furnace/steel slag or coal-fired power station ash)" (BGS 2013). In European specifications, the first type is classified as a natural aggregate whereas the second type is classed as manufactured aggregate.

2.4 Geological Occurrence

Natural aggregates can be subdivided in two types: (a) exposed or near-surface sedimentary, metamorphic, and igneous rocks that are capable of being crushed, and (b) sand and gravel deposits that may be used directly or crushed and sized to meet specifications. Naturally occurring aggregate deposits, whether sand and gravel or source rock for crushed stone, can be present in a great variety of geological environments. Volcanoes, earthquakes, glaciers, rivers and streams, and marine processes have contributed to the formation of materials used as aggregate. In any world region, the availability of bedrock appropriate to crush depends on the geological history of the region, in other words, the processes that formed, eroded, and exposed the bedrock. To locate suitable deposits and to assess the potential for new aggregate sources, the key is to understand the geological processes that form them and the geological settings in which they occur.

In general, sand and gravel were the principal source of natural aggregate until the 1980s but its importance declined since then. In many countries, the relative proportions of crushed stone and sand and gravel production usually are a reflection of the presence and accessibility of sand and gravel deposits, which commonly need fewest methods of processing and are correspondingly cheaper to produce, although they generate important environmental issues. Both types of aggregates are commonly used in construction, according to the specification standards as well as economic considerations. For example, in the manufacturing of Portland cement concrete, alluvial sand and gravel are generally preferred while crushed stone is selected in asphaltic mixtures because asphalt adheres better to rough surfaces.

2.4.1 Crushed Stone

Crushed stone is "the product resulting from the artificial crushing of rock, boulders, or large cobblestones, substantially all faces of which have resulted from the crushing operation" (ASTM C125 standard). It is generally produced by drilling (◘ Fig. 2.8), blasting, loading (◘ Fig. 2.9), and crushing bedrock, although it can involve crushing large boulders or cobblestones. Crushed stone tends to have angular edges, and substantially, all of its surfaces have resulted from the crushing operation. In addition to the size and shape of the particles, this type of aggregate is also classified based on the type of rock from which it was produced: sedimentary, igneous, and metamorphic.

◘ **Fig. 2.8** Drilling in a crushed stone (andesite) quarry. (Image courtesy of Benito Arnó e Hijos, S.A.U)

◘ **Fig. 2.9** Loading aggregates in a crushed stone (andesite) quarry for aggregates. (Image courtesy of Benito Arnó e Hijos, S.A.U.)

Obviously, a great variety of rocks is suitable for utilization as aggregates when crushed. The technical suitability of crushed stones for different aggregate applications is based on their physical characteristics. High-quality aggregate is required for applications such as ballast whereas lower quality aggregates may be acceptable for applications such as concrete or mortar. Most hard rocks are potentially suitable for coarse aggregate but high-quality crushed rock aggregates are usually obtained from very hard, dense igneous rocks.

2.4.1.1 Sedimentary Rocks

There are two main types of sedimentary rocks: (a) those that have been chemically or biochemically formed (calcareous and evaporate rocks), and (b) those that have been mechanically deposited (clastic rocks). Sedimentary rocks show a varied range of properties, from heavy to light, strong to weak, hard to soft, and dense to porous. For this reason, the suitability for their use as crushed stone for aggregates changes accordingly.

Limestone is a sedimentary rock constituted basically by calcium carbonate ($CaCO_3$). Increasing the magnesium carbonate ($MgCO_3$) content, limestone grades into dolomite ($CaMg(CO_3)_2$). The vast majority of limestone and dolomite rocks are hard, durable, and therefore useful for producing aggregates, being common rock types and consequently broadly mined for this application (◘ Fig. 2.10). However, in some cases limestone may be friable, soft, and absorptive when it contains significant amount of clay.

In general, limestone and other carbonates cover about half to three quarters of the rocks used for crushed stone, with granite and other igneous rocks making up the bulk of the remainder. Limestone is also extensively used for cement (see ▶ Chap. 6) and lime (see ▶ Chap. 7) manufacture. Limestone deposits are usually thickly bedded and consistent, which allow them to be quarried thoroughly and economically. This type of sedimentary deposits generally produces durable aggregates suitable for road stone (sub-base and base layers) and concrete. The quality of the limestone deposits may vary based on different geological factors (e.g., waste content, dolomitization processes, or degree of faulting and folding).

Within the group of clastic (mechanically deposited) sedimentary rocks, sandstones, when hard and dense, are generally the only type used for aggregate production. They are a major source of aggregate in some regions. However, sandstones commonly are friable or excessively porous materials due to imperfect cementation of the constituent grains. On the other hand, sandstones can contain clay that renders the rock friable, soft, and absorptive. To a much lesser amount, siltstone and conglomerate are used as crushed stone for aggregates.

2.4.1.2 Igneous Rocks

Igneous rocks form from cooled magma, being classified according to their origin and composition. Where the rock formed by slow cooling at relatively high depth, it shows coarse crystals and includes the general rock types of granite, diorite, and gabbro. Volcanic igneous rocks were extruded onto the earth's surface where they cooled and solidified relatively quickly, promoting the formation of small or microscopic crystals. Examples include rhyolite, andesite (◘ Fig. 2.11), and basalt. Many igneous rocks such as those mentioned are hard, tough, and dense, being excellent crushed stone aggregates.

Although igneous rocks exhibit a wide range of chemical compositions and their

◘ **Fig. 2.10** Aggregate limestone quarry. (Image courtesy of Calcinor)

◘ **Fig. 2.11** Andesite aggregate (object about 10 cm) suitability for aggregate depends on their mineral composition and crystalline fabric and texture, they generally tend to produce hard aggregates with a high degree of skid resistance, being thus very appropriate in road surfacing applications and for utilization in the lower parts of the road pavement. Nevertheless, there are some exceptions: certain extrusive rocks, especially those with a high silica content, are too porous to make good aggregate, and other igneous rocks with a very high content of silica tend to react chemically with alkali when used as aggregate in cement concrete. Some coarse-grained rocks can be less attractive in some applications because of their low crushing strength. Substantial quantities of coarse aggregate are used as railway track ballast (◘ Fig. 2.1). Because ballast requires to be hard, clean, and angular with a very high resistance to abrasion, most of this type of aggregate application is produced from igneous rocks (e.g., andesite or basalt).

2.4.1.3 Metamorphic Rocks

Metamorphic rocks are derived from preexisting rocks (sedimentary, igneous, and metamorphic) through alteration by heat, pressure, and chemical activity, thus comprising a complex range of rock types with different physical characteristics. Vast tracts of the major continents worldwide consist of exposed regional metamorphic rocks that give a choice of aggregate sources. Metamorphic rocks that are hard, tough, and dense can be used as aggregate (e.g., mylonite—◘ Fig. 2.3). These mainly include gneiss (a banded crystalline rock), marble (metamorphosed limestone), and quartzite (metamorphosed sandstone—◘ Fig. 2.12). Some metamorphic rocks, such as highly foliated schist, have planar foliation that produces undesirable planes of weakness, not being therefore suitable for crushed stone (Langer 2006a). On the other hand, some metamorphic rocks such as quartzite can cause excessive wear on crushing equipment.

◘ **Fig. 2.12** Quartzite aggregates. (Image courtesy of Cuminer S.A.)

◘ **Fig. 2.13** Aggregates located in a river terrace near Madrid (Spain)

2.4.2 Sand and Gravel

Sand and gravel deposits are formed by erosion, transportation, and deposition of fragments. They are accumulations of the more durable rock fragments and mineral grains (e.g., quartz), being mainly Pleistocene or younger in age (older deposits may not be sufficiently unconsolidated to be regarded as sand and gravel). Sand and gravel deposits are most common in glaciated areas, alluvial basins, or as deposits accumulated in rivers and streams. Consequently, these materials are found in alluvial fans, river terraces (◘ Fig. 2.13), flood plain materials, alluvial deltas, moraines, tills, and others. Windblown aggregates (e.g., sand dunes) are, in general, of little importance as natural aggregate, excepting as blending sands; this is because they are confined to fine-grained materials. The availability of sand and gravel deposits is intimately linked to the regional geologic history of every region. In the geological assessment of any deposit of sand and gravel, aspects such as size and location, groundwater conditions, and deleterious constituents, among others, are essential.

Sand and gravel aggregate is defined based on particle size rather than composition. For instance, according to European standards, e.g., EN 12620 standard, the term gravel (or coarse aggregate) is commonly used for applications to define "particles between 4 and 80 mm," and the term sand (or fine aggregate) for fragments that are "finer than 4 mm, but coarser than 0.063 mm." The properties of gravel, and to a lesser extent sand, largely depend on the rock properties from which they were derived. Nevertheless, where transporting distances are short, for instance in glaciofluvial environments and alluvial fans, deleterious components can remain and diminish the importance of the deposit.

Most sand and gravel are used as construction aggregate. In many cases, it is preferred over crushed stone to manufacture Portland cement concrete because its smooth, rounded shape allows for easy mixing without addition of excess water and cement. Sand and gravel aggregates have also numerous applications in an unbound state.

2.4.2.1 Fluvial Deposits

They mainly comprise river sands and gravels that take the form of extensive spreads occurring along the floors of major river valleys, commonly beneath alluvium, and as river terraces flanking the valley sides. River terraces are the dissected or eroded remnants of earlier abandoned river floodplains. Deposit thickness varies from less than 1 m to maximum values of 10 m. Sand to gravel ratios are variable, but river deposits typically are relatively clean with lower fines content (silt and clay) than glacial deposits.

In mountainous arid and semiarid regions, rock fragments are eroded and transported during storms down steep-gradient streams to the adjacent basins, resulting in alluvial fans. Alluvial fans are most common in regions of arid and semiarid climate, but some alluvial fan deposits occur in more humid environments. The deposits commonly contain thick unconsolidated material ranging from large boulders to clay-size particles. The coarsest particles are commonly deposited adjacent to the mountains and become progressively finer toward the downstream edge of the deposits. Sand and gravel in alluvial fans may be suitable for aggregate but fan deposits usually include lenticular beds or poorly sorted material interbedded with different amounts of silt and clay. In older fans, gravel may be highly weathered and not suitable for aggregate. In addition, fan gravels may be cemented with caliche, a calcium carbonate precipitate in the soil, making them difficult to extract and process.

Alluvial (river) sand and gravel, either in the channels or floodplains of rivers and streams, or in terraces (lying above the level of the present flood plain), found alongside the rivers or streams, are the principal sources of sand and gravel aggregate. In general, terrace deposits can be more desirable than stream channel deposits because they are above the stream level. The availability and quality of the gravel are strongly dependent on occurrence and properties of nearby bedrock sources. Less resistant minerals are dissolved and/or altered into clays; the more resistant minerals stand as rock particles. Materials in these deposits are desirable as aggregate for many reasons. The most important is that the natural abrasive action of stream transport has removed most of the soft weak rocks, leaving only the harder particles. As a consequence, the latter components have undergone certain degree of rounding, being thus subrounded to well-rounded (▣ Fig. 2.14) an essential factor for the utilization of aggregates in pumping concrete. Moreover, most of this type of deposits contain sand and gravel in the size gradations required for concrete production.

Fluvial sediments can range in composition from nearly all clay, through mixtures of

Fig. 2.14 Well-rounded coarse aggregate

clay, silt, sand, and gravel, to nearly all sand and gravel. If a river or stream changes gradient and downcuts its channel, the older channel and floodplain deposits can be preserved as river terraces. Repeated downcutting can result in a series of terraces or terrace remnants above the level of the modern stream base, which can be important sources of sand and gravel. Older terraces can be exposed to prolonged weathering, thus weakening the material and reducing its suitability as aggregate.

2.4.2.2 Glacial Deposits

Glacial deposits are commonly much less predictable than alluvial deposits in almost every respect. Particle size distribution, particle shape and composition, and thickness and extent of glacial and glaciofluvial deposits vary widely. Glacial deposits subjected to stream action are called *glaciofluvial deposits*. Likewise, the landforms linked to the accumulation of these deposits and from erosion by glacial ice are clearly distinct. Glacial materials are conditioned by the type of bedrock over which the glacier passed. From a geological point of view, genuine glacial deposits are termed *till*, which can be defined as a material deposited directly by the ice. In general, till is a poorly sorted mixture of clay-size to boulder-size particles.

Glaciofluvial deposits show a better level of sorting and include less clay than the glacial ones. As a rule, they have high enough quality to yield satisfactory aggregate in comparison with stream sand and gravel. As glacier ice melts, rock particles that had been crushed, abraded, and carried by the ice are further transported, abraded, and rounded by meltwater. These deposits are potential sources of sand and gravel that are of great importance for use as aggregate. The particle size in the glacial meltwater deposits ranges from boulder to sand, silt, and clay, and can change abruptly, both with depth and laterally, especially where the material was deposited under the ice, e.g., eskers, or on or near the ice, e.g., moraines or kames. Glaciofluvial deposits are commonly thinner than stream deposits in regions of considerable topographic relief.

2.4.2.3 Marine Deposits

Marine deposits on continental shelves are large potential sources of sand and gravel, although surface materials on continental shelves are commonly sand-size and finer-grained. Marine sand and gravel deposits are a significant input to total supply of aggregates in some countries, for instance in Great Britain and Japan. Although marine deposits currently provide a very small proportion of sand and gravel production worldwide, they could become more significant as other sources are depleted, and if economic, regulatory, and environmental concerns can be adequately addressed.

In general, marine sand and gravel resources are unevenly distributed on the continental shelf but are very similar to their land-based equivalents, occurring as small patches separated or covered by extensive areas of uneconomic deposits. They vary in thickness, composition, and grading, and in proximity to the shore. The mineralogy of these deposits varies depending on the source of the material. The origin of gravel-bearing sediments offshore is directly comparable to that of terrestrial deposits (▶ Box 2.1). An advantageous feature of many marine sands is the low silt content while presence of salt is a disadvantageous feature.

2.4.2.4 Beach Deposits

Sand and gravel generated by currents and waves on a beach can result in a good aggregate because the gravel and sand particles are commonly well-rounded and hard. Gravel tends to be swept high onto the coast (backshore) and the sand and finer particles out to sea. Beach gravels are thus strongly localized vertically but laterally extensive along the shore. The sands are generally composed mainly of resistant quartz and feldspar. Thus, beach deposits can all be used as aggregate if they meet the required specifications; however, many beach deposits are thin and lack proper size gradation since a stable beach will rarely contain material finer than medium sand (around 0.2 mm). In any case, exploitation of beach deposits as aggregates commonly generates intense and severe environmental impacts.

2.5 Extraction Methods

While aggregate sources can be widely variable, methods of extraction are similar throughout the world and near all the aggregates are obtained in quarries by surface mining, that is, "the extraction of aggregates from the ground in mines open to the surface" (Bustillo 2018). Nevertheless, the mining system and excavating equipment are different depending on the type of aggregate: sand and gravel or crushed rock. Sand and gravel show usually a low degree of consolidation, so they can be extracted by means of normal earthmoving machinery (◘ Fig. 2.15), and explosives are not required whereas crushed stone is commonly hard rocks and blasting is indispensable (◘ Fig. 2.9). One notable difference between crushed stone quarries and sand and gravel quarries is that the latter commonly requires a higher rate of land use. This is because the sand and gravel deposits tend to be shallow in nature and bigger areas of land require disturbance for a similar amount of production.

◘ **Fig. 2.15** Earthmoving machinery extracting sand and gravel aggregate

2.5.1 Sand and Gravel

Typically, "sand and gravel operations have outputs in the range 10,000 up to 1 million tons per year (t/y); however, sites larger than 500,000 t/y are rare, and most fall in the range 100,000 to 300,000 t/y" (Langer 2006b). Sand and gravel extraction initially involves the removal of overburden that is commonly formed by soil, peat and clay, and weathered material. Overburden thicknesses range from practically nothing to over 10 m, being the thickness of the overburden essential because it controls the economic viability of the quarry. Other factors that can influence the economic viability are the following: (a) geologic characteristics of the deposit, (b) its quality, that is, sand and gravel content, (c) whether the deposit can be worked dry or needs dewatering, (d) whether the quarry is a new site or an extension, and (e) the location of the quarry with respect to markets. The last factor is essential from an economic viewpoint because is almost impossible to extract aggregates when the further transport distance to the market is greater than 30–50 km. Careful removal of overburden is necessary since soil (topsoil and subsoil) must be separated for further restoration (◘ Fig. 2.16). Soil and/or overburden should not be stockpiled over parts of the deposit where future exploitation is expected.

◘ **Fig. 2.16** Overburden (topsoil) stockpiled (in the center of the image) for further restoration. (Image courtesy of CEMEX)

◘ **Fig. 2.17** Sand and gravel quarry with required dewatering processes since dry mining is selected by environmental regulations. (Image courtesy of CEMEX)

From an extraction perspective, different machines and techniques are adopted to suit the particular situation. Thus, sand and gravel deposits are subdivided into two groups: dry mining or wet mining; the latter means that water table is very near the surface and thus almost the entire exploitation is under water. In this case, again two options are also presented: (a) dewatering the site by pumping (◘ Fig. 2.17) or (b) to work the site wet. The final decision to dewater or not depends mainly on deposit thickness, permeability of the materials, and restoration requirements. In general, dry working is preferred because it allows a more selective extraction and is generally more cost-effective.

◘ **Fig. 2.18** Pumping water to draw down the water table. (Image courtesy of CEMEX)

Where sand and gravel mining does not penetrate the water table, that is, whether the aggregates are naturally dry or as a result of dewatering processes, the aggregates can be extracted by employing conventional earth-moving equipment. Thus, shovels, loaders, bulldozers, or similar equipment load the material into trucks (◘ Fig. 2.15) or onto conveyor belts for transfer to the processing plant. Where sand and gravel pits penetrate the water table, such as floodplains or low terraces, another possibility is to fill the pit with water. Thus, the operator may extract the material by using wet mining techniques. In deposits mined below the water table (e.g., low terraces or glaciofluvial deposits), mobile pumps are installed in the initial exploitation for pumping in order to draw down the water table and hold the level below the required digging level (◘ Fig. 2.18). Draglines (◘ Fig. 2.19) are further commonly used to extract the aggregate although other equipment such as floating

Fig. 2.19 Dragline. (Image courtesy of Aggregates Manager)

Fig. 2.20 Floating suction dredge. (Image courtesy of Tronox)

suction dredges (Fig. 2.20), bucket ladders, or slackline excavators can be used. The excavated material is generally stockpiled to drain, taking as much 12 hours for this process, being later rehandled to the processing plant. This rehandling using excavators or shovels obviously increases the final operational costs of the quarry.

2.5.2 Crushed Stone

Mining hard rock quarries is usually more complicated than quarrying sand and gravel. Thus, crushed rocks are obtained from much larger and deeper quarries than sand and gravel ones. They commonly "have outputs ranging from 100,000 t/y to up about 5 Mt/y" (Langer 2006a). As a consequence, the investment in plant and equipment must be very large.

Fig. 2.21 Loading operation of ANFO nylon bags. (Image courtesy of Octavio de Lera)

Fig. 2.22 Ripping dozer

Overburden thicknesses in the quarry can change considerably from almost nil to over 30 m in some operations. It is removed using a combination of hydraulic excavators, ripping, and blasting using explosives (e.g., gelatin dynamite and ANFO—Fig. 2.21). Ripping or mechanical breakage, using a dozer fitted with a tooth at the rear (Fig. 2.22), is possible where the rock mass is already fractured extensively. Likewise, the extraction of sand and gravel aggregate, in the phase of preparation of the rock mass, the works related to the cleaning of all the quarry area from the vegetation and other materials detrimental to the final quality of the aggregates are included. Obviously, topsoil must be separated from the overburden and stockpiled for reclamation activities. In general, hard rock quarries have very little waste in form of overburden because generally all the rock is crushed.

Blasting is usually necessary to extract the required rock and this is carried out in one or more benches (quarrying commonly progresses downward on several different levels or benches, being bench height and width determined principally by geotechnical factors). This primary fragmentation is necessary to reduce the size to the rock mass. In blasting, a line of shot holes is drilled at a distance back from the quarry face, and explosives charged and detonated. The top portion of the hole is filled with nonexplosive material, usually sand or crushed stone, which is referred to as stemming. The explosive in each hole is initiated with detonators or blasting caps. The overall blast usually lasts less than a second and is constituted by many smaller individual blasts. In turn, these individual blasts are separated by delays of a few thousandths of a second.

The pattern of blast-holes, the amount of charge used, and the timing of the blast must be carefully defined "to ensure the maximum efficiency of the explosive, the production of appropriate-sized blocks, and the creation of a new, stable quarry face" (Bustillo 2018). After blasting, if very large pieces of rock blocks are obtained, it is necessary to reduce them in order to obtain smaller blocks compatible with the crusher dimension. This process can take place using either a secondary blasting or through a hydraulic hammer (◘ Fig. 2.23). Finally, an excavator loads the rocks into dump trucks for transporting to either a fixed primary crusher commonly located in the processing plant or a mobile crusher on the quarry floor (◘ Fig. 2.24). Unlike sand and gravel deposits, where particle size distributions are relatively narrow, the crushed rock in the quarry tends to have a broad variety of particle sizes, which precludes utilization of conveyors as the primary transporting system.

◘ **Fig. 2.23** Hydraulic hammer for crushing large pieces of rocks. (Image courtesy of Benito Arnó e Hijos, S.A.U.)

◘ **Fig. 2.24** Mobile crusher on the quarry floor. (Image courtesy of Octavio de Lera)

2.6 Processing Techniques

Depending on the characteristics of the aggregate deposit, some processing is necessary before the product is suitable for use. The objective of a processing plant is thus to prepare the materials in an appropriate form for their utilization as aggregates. It is generally established in terms of particle size and size distribution, particle shape, and mechanical properties. Aggregate can be processed at remote locations using mobile or temporary devices for crushing and screening or can be processed at a fixed plant. The latter is constituted by a large amount of equipment connected by a network of belt conveyors (◘ Fig. 2.10). Fixed plants tend to be associ-

▣ **Fig. 2.25** Storage of different aggregate fractions. (Image courtesy of Benito Arnó e Hijos, S.A.U.)

ated with relatively larger deposits supplying a great variety of markets. In modern processing plants, the stationary equipment is managed by a computer located in a centrally situated control tower and operated by one person. The plant must be provided with monitoring instrumentation, sampling points, and control measures to assure the quality requirements of the aggregate utilization. All aggregate fractions produced in the processing plant stay commonly in storage until needed (▣ Fig. 2.25).

Because aggregate has a very low-cost margin, the processing methods require efficiency since additional cost is added to the final product each time aggregate is handled and/or processed. Processing techniques basically involve crushing and screening in crushed stone aggregates while screening and washing are needed in sand and gravel aggregates. Some of these processes, e.g., washing and sometimes screening, require substantial amounts of water that must be available on site. The use of water and wet processing techniques facilitates the classification of particles and the rejection of fine particles, e.g., clays. Thus, the processing plant must commonly incorporate pumping and slurry handling equipment as well as solid-liquid separation and final dewatering equipment. In addition, it is important to note that land must be available near the site to accommodate the complete processing plant. The description of the processing plant can be carried out according to the processed aggregate, that is, sand and gravel or crushed stone.

2.6.1 Sand and Gravel

After extraction, material to be processed in the plant generally is transported from the quarry by conveyor or haul truck. The material is further stored in a stockpile and a gate at the bottom of the stockpile releases a controlled amount of sand and gravel to a screen where sand is separated from gravel. There are a great number of ways to configure the plant design based on the characteristics of the sand and gravel deposit and its final application, but sand and gravel processing plants are mainly based on screening and washing processes. Most plants are departmentalized to produce different products such as sand and gravel for use in concrete or gravel for utilization as road base or bituminous aggregate.

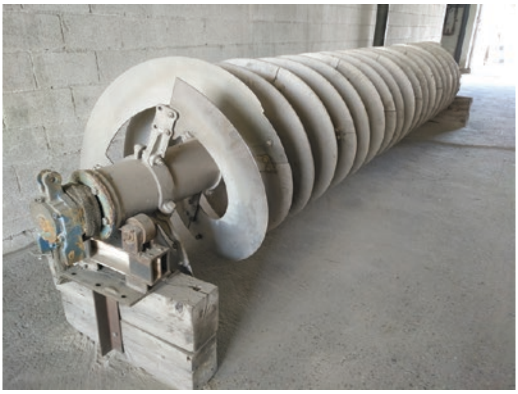
Processing of sand and gravel for most applications is carried out through washing for removing clay, separation of the sand fraction, grading the gravel into different sizes, sand classification and dewatering, and in some cases also crushing of oversize gravel to produce smaller more saleable material. Processing provides scope for adjusting the grain size distribution to match market requirements for the final saleable product. It is also common to blend materials from the same and different sites with the aim to adjust grain size to meet user requirements and to maximize the utilization of resources. Although the final application controls the size of the aggregate to use, the greatest demand is generally concentrated in the following sizes: 4/10 mm, 10/20 mm, and 20/40 mm.

The material usually must be processed to remove lumps of clay, which can plug processing equipment and contaminate the final product (some aggregate applications request a very low content of clay). The principal objective of washing is the elimination of undesirable components (e.g., clay, soft stone, roots, organic matter, and etcetera). For those situations, washing is generally carried out in coarse material through the direct washing on vibrating screens, as commented below. The washing process removes mainly fines (silt and clay) defined as <0.63 mm adhering to the particles or present as clay bound agglomerates that need breaking down. Most sand wash-

■ **Fig. 2.26** Hydrocyclone for separation of fines

ing plants involve the dispersion of sand in water and the separation of fines in a hydrocyclone, which delivers a partially dewatered coarser product. Hydrocyclone (■ Fig. 2.26) has grown into one of the most interesting and broadly used classifiers, being capable of sizing particles as fine as 0.005 mm. It is usually applied in closed circuit within crushing systems and is used to return coarse material back for further crushing and/or grinding. The main advantage of hydrocyclone is that it has big capacities in comparison with their size and can split at finer sizes than most other screening and classification devices.

Spiral classifiers (■ Fig. 2.27) and dewatering bucket wheels (■ Fig. 2.28) can be used in sand and gravel processing plants for dewatering. For fine-grained material (coarse-grained material is already cleaned during the screening process), washing and dewatering bucket wheel are typically used. In this device, a suction dredger or a compressed-air dredger feeds the feeding mixture of sand, gravel, and water. The solids are deposited in the bucket wheel tub and are excavated by the bucket wheel. Depending on the performance, the bucket wheel rotates only with 0.5–2 rpm.



■ **Fig. 2.27** Spiral classifier. (Image courtesy of SAMCA)

■ **Fig. 2.28** Dewatering bucket wheel

The unwanted fines are allowed to settle out in a pond, from which process water is recirculated, or may be further dewatered using nonmechanical sedimentation classifiers (■ Fig. 2.29) or thickeners and different types of pressure filters (e.g., vertical plate filter—■ Fig. 2.30). In a vertical plate filter, the slurry is situated between two plates captured together by an exterior driver screw system. The filtering medium is located against the sides of the plates and the slurry is pumped between them. The slurry pressure presses the pulp against the medium, obliging the liquid to pass across the cloth and leaving the solids as a cake on both surfaces of the frame.

Deposits containing boulders may be fed through a grizzly screen (■ Fig. 2.31) to remove large boulders; sometimes, these boulders go to the crusher to produce crushed aggregates. Thus, crushing is now a common

Fig. 2.29 Nonmechanical sedimentation classifier. (Image courtesy of TEFSA)

Fig. 2.30 Pressure filters for dewatering in an aggregate plant

Fig. 2.31 Grizzly screen used to remove large boulders

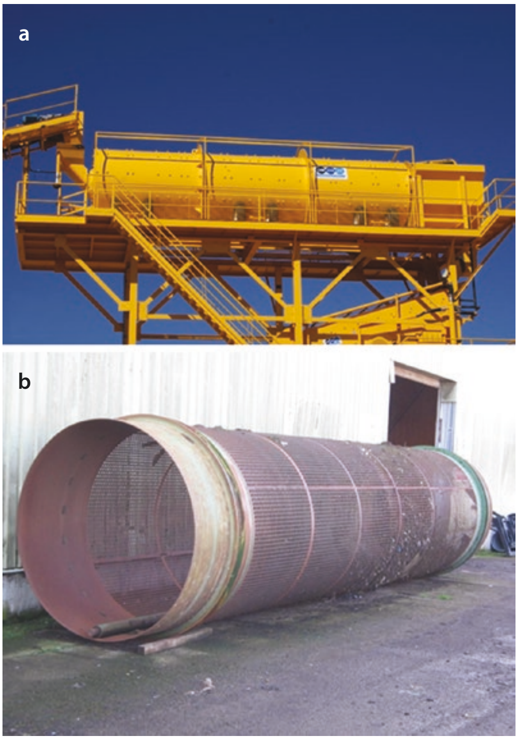


Fig. 2.32 Trommel (**a**) and the screen inside the device (**b**)

feature at many sand and gravel processing plants, being very necessary to maximize saleable product. The material is crushed and screened to separate properly crushed particles that go through the screen from those that go over the screen and back into the crusher.

Trommels and vibrating screens are commonly used to separate the particles into the necessary sizes. A trommel is a horizontal or slightly tilted, in the direction of the material flow, rotating cylindrical screen (Fig. 2.32). They can operate fragments from 6 to 55 mm, and even smaller sizes can be incorporated under wet conditions. A trommel can separate different products by utilizing a series of screens with the coarsest to finest apertures and operating both dry and wet feed material Vibrating screens are undoubtedly the most famous screening devices for separation of particles. In these machines, the perforated surface (Fig. 2.33) is set into a frame that is agitated vigorously. They perform size separations from 250 mm down to 80 μm. One, two, or three screening surfaces can be set into a single frame in single-, double-, or triple-deck configurations. The rapid relative movement engineered between the particles and the screening surface facilitates

Fig. 2.33 Different types of screening surfaces and apertures

Fig. 2.34 Polyurethane nozzles for washing placed cross-sectionally to the material flow in a vibrating screen. (Image courtesy of SAMCA)

Fig. 2.35 Hydraulic classifier. (Image courtesy of SAMCA)

rapid rates of screening. Sometimes, water is used to enhance the separation and washing processes. Washing is performed by applying water jets through spray nozzles directed as a water curtain and under pressure at the material being classified, aiming to remove the impure particles adhering to the material (Fig. 2.34). The nozzles are commonly manufactured in polyurethane because it is economical and abrasion and corrosion resistant. They are installed in metallic pipes placed cross-sectionally in relation to the material flow.

In a number of plants, hydraulic classifiers or hydraulic settling tanks (Fig. 2.35) can be used to separate the sand into various sizes. In these devices, the slurried particles are introduced to a separating chamber that has a base consisting of several pockets. The particles are separated by contrast between the velocity of the particles and the velocity of water.

Upon sale, the stockpiled aggregates may be sold as a single-size product or, as commented previously, two or more materials may be blended to make a new, graded product. For example, sand and properly sized gravel may be mixed in a defined proportion to be used with cement to produce concrete.

Procedures must be followed carefully when stockpiling and handling the final product. It is important to bear in mind that when aggregate falls too far from conveyors onto coned stockpile (◘ Fig. 2.25) or when it is dumped from trucks down a slope, the material can be separated from a well-blended product into individual size fractions, originating thus an inadequate product. Improper handling can also result in contamination of the aggregate with foreign material from underneath the stockpile.

2.6.2 Crushed Stone

After blasting in the quarry, trucks or conveyors move material from the quarry to the processing plant (► Box 2.2: La Soriana Crushed Stone Processing Plant).

Box 2.2

La Soriana Crushed Stone Processing Plant: Courtesy of Benito Arnó e Hijos, S.A.U.

La Soriana crushed stone quarry and processing plant (◘ Fig. 2.36) is located in Huesca (Spain), being the main purpose of this installation the production of railway ballast. In the quarry, the igneous rock (subvolcanic) is extracted by drilling and blasting and then loaded with a front-end loader into a large haul truck fleet that transports the material to the processing operations. These can include crushing, screening, material handling, and storage operations. Crushing is done in three stages: primary (first stage), secondary (second stage), and tertiary (third stage). In general, crushed rock is transported along the process line on conveyor belts.

◘ **Fig. 2.36** Aerial view of La Soriana Crushed Stone Processing Plant. (Courtesy of Benito Arnó e Hijos, S.A.U.)

The run of mine from the quarry is dumped in a hopper and a vibrating feeder sending the material to a grizzly, which carry out the first classification of crushed elements at 100 mm size. The undersize is then separated into 0/30 mm and 30/100 mm fractions, the latter being mixed with the material obtained in the

◘ **Fig. 2.37** Cone crusher. (Image courtesy of Benito Arnó e Hijos, S.A.U.)

jaw crusher. The oversize, including particles ranging from 100 to 900 mm, is send to a jaw crusher (primary crusher) with a feed opening of 3645 mm × 2890 mm to produce size particles ranging from 0 to 200 mm. The output from the primary crusher is conveyed onto the primary stockpile together with the 30/100 mm fraction obtained with the undersize material. This primary stockpile feeds the secondary crusher, a cone crusher (◘ Fig. 2.37) that reduces the size of the crushed stone up to 100 mm. The material is then classified using two vibrating screens, each of one with three mesh units. Thus, four size fractions are produced: 0/6 mm, 6/25 mm, 25/63 mm, and 63/100 mm, being the third fraction (25/63 mm) used as railway ballast.

The 0/6 mm fraction is directly stockpiled whereas the 6/25 mm fraction is then sending to a tertiary crusher (another cone crusher) that produces a 0/25 mm material. This material is finally also separated with a vibrating screen in three fractions: 0/6 mm, 6/12 mm, and 12/25 mm, which can be used for different applications (e.g., concrete or road).

◘ **Fig. 2.38** Primary gyratory crusher. (Image courtesy of Metso)

Crushing involves the continuous process of size reduction of the block rocks, which usually is a dry operation. It is carried out in several stages, e.g., primary and secondary crushing in quarrying aggregates. The main reason for several stages of crushing is the limited reduction ratio available with a single crusher. In crushing terminology, this parameter can be commonly defined as "the ratio of maximum particle size entering to maximum particle size leaving the crusher."

The type of crusher influences the size and the shape of the aggregate result. In the primary crushing stage, pieces of rocks can be as large as 1.5 m, being reduced to a range between 10 and 20 cm by using heavy-duty machines. For this purpose, jaw and gyratory type (◘ Fig. 2.38) crushers are the most used devices. They are defined by a wide input and a narrow discharge and can operate large tonnage of material. "Jaw crushers (◘ Fig. 2.39) generate a reduction ratio between 4:1 and 9:1 whereas gyratory crushers originate a somewhat larger range between 3:1 and 10:1. In general, gyratory crushers can generally process larger rock pieces and more tonnage per hour than jaw crushers can, but they are usually more expensive" (Bustillo 2018).

The crushed rock normally goes to the secondary crushing via a belt conveyor after it leaves the primary crusher. In other cases, it can pass through a screen or other size classifier with oversized material circulated back into the crusher(s) for further reduction. Once the pieces of rock are reduced to smaller components by using the primary crushing units, the secondary machines are used to obtain a further decrease in size (commonly the final product). These secondary units are usually much lighter and smaller than the heavy-duty and big rugged primary units are. Since they use the primary crushed rock as feed, the maximum feed size will commonly be less than 15 cm in diameter. They work always with dry elements and examples of these devices are cone crusher (◘ Fig. 2.37) and impact mills (◘ Fig. 2.40). "Cone crushers generate reduction ratios ranging from 5:1 to 8:1. Very high reduction ratios, for example, from 20:1 to 40:1, can only be obtained utilizing impact crushers" (Bustillo 2018).

◘ **Fig. 2.39** Primary jaw crusher. (Image courtesy of Benito Arnó e Hijos, S.A.U.)

◘ **Fig. 2.40** Impact mill. (Image courtesy of Luis Fueyo)

Regarding screening, the devices used in crushed stone plants are similar to those used in sand and gravel plants, that is, grizzlies, trommels, and mainly vibrating screens are used to separate the particles into the necessary sizes. After screening, truck or conveyors move the material to stockpiles.

2.7 Properties and Testing

Properties of natural aggregates can change depending on the source of the material. Thus, the properties of sand and gravel aggregates are the result of the petrology of the source rocks, transport, and deposition methods, and further weathering of the aggregate particles. Some properties in sand and gravel particles are inherent, e.g., mineralogy, density, and porosity, while other properties such as size, shape, and sorting are defined by the processing methods. With respect to crushed stone, its properties result from the origin and mineralogy of the source rock, the subsequent alteration and weathering processes, and obviously the processing operations. The suitability of an aggregate for a particular application depends mainly on its physical and mechanical properties, but mineralogical and chemical properties are also important in some uses.

The assessment of aggregate properties is carried out by using a range of standard test methods. Laboratory testing is a means of scientifically evaluating the properties and suitability of aggregate material. Because aggregates have many applications, a broad group of tests are devised to describe the material and evaluate its potential value. A general overview of the most important properties of aggregates and their corresponding tests is described in this heading whereas considerations that are more specific are taken into account in each specific aggregate application, e.g., concrete, road pavement, rail ballast.

As a method of organization, the description of properties and tests is carried out in this chapter using the following European classification of tests: "(a) for general properties of aggregates, (b) for geometrical properties of aggregates, (c) for mechanical and physical properties of aggregates, (d) for thermal and weathering properties of aggregates, and (e) for chemical properties of aggregates."

2.7.1 General Properties and Tests

European test methods include the following parts regarding general properties of aggregates: methods for sampling (EN 932-1 standard) and for reducing laboratory samples (EN 932-2 standard), procedure and terminology for simplified petrographic description (EN 932-3 standard), common equipment and calibration (EN 932-5 standard), and definitions of repeatability and reproducibility (EN 932-6 standard). Most of them are related to sampling while EN 932-2 standard is devoted to petrographic description of aggregates. Some corresponding ASTM standards are D75 standard for methods of sampling, C702 standard for reducing samples of aggregate to testing size, and C295/295M standard for petrographic examination of aggregates (for concrete). In addition, ISO 5725 standards series covers the accuracy (trueness and precision) of measurement methods and results.

Proper and careful sampling is essential to obtain reliable results. Information generated from samples is only as representative of the material as the samples on which they are performed. Representative sampling is probably the most difficult of the control operations to perform satisfactorily. Regarding sampling, EN 932-1 standard states: "the aim of sampling is to obtain a bulk sample that is representative of the average properties of the batch… this European Standard specifies methods for obtaining samples of aggregates from deliveries, preparation, and processing plants including stocks… the methods are based on manual procedures; mechanical or automatic sampling and sample reduction may also be used." ASTM D75 standard is also devoted to sampling aggregates and points out: "the preliminary investigation and sampling of potential aggregate sources and types occupies a very important place in determining the availability and suitability of the largest single constituent entering into the construction. It influences the type of construction from the standpoint of economics and governs the necessary material control to ensure durability of the resulting structure, from the aggregate standpoint… Sampling is equally as important as the testing, and the sampler shall use every precaution to obtain samples that will show the nature and condition of the materials which they represent." The most classical methods of sampling are coning and quartering or using a riffle box (▣ Fig. 2.41).

EN 932-1 recommends the following minimum mass of a bulk sample:

$$M = 6 \times \sqrt{D} \times \rho_{\mathrm{b}}$$

where

- M is the mass of the sample, in kilograms,
- D is the maximum grain size, in millimeters,
- ρ_{b} is the loose bulk density, in mega grams per cubic meter.

As commented above, the petrographic description of aggregates is covered by EN 932-3 and C295/C295M standards. The latter states the main purposes of petrographic description: "to determine the physical and chemical characteristics of the material that may be observed by petrographic methods and that have a bearing on the performance

Fig. 2.41 Riffle box for sampling. (Image courtesy of SAMCA)

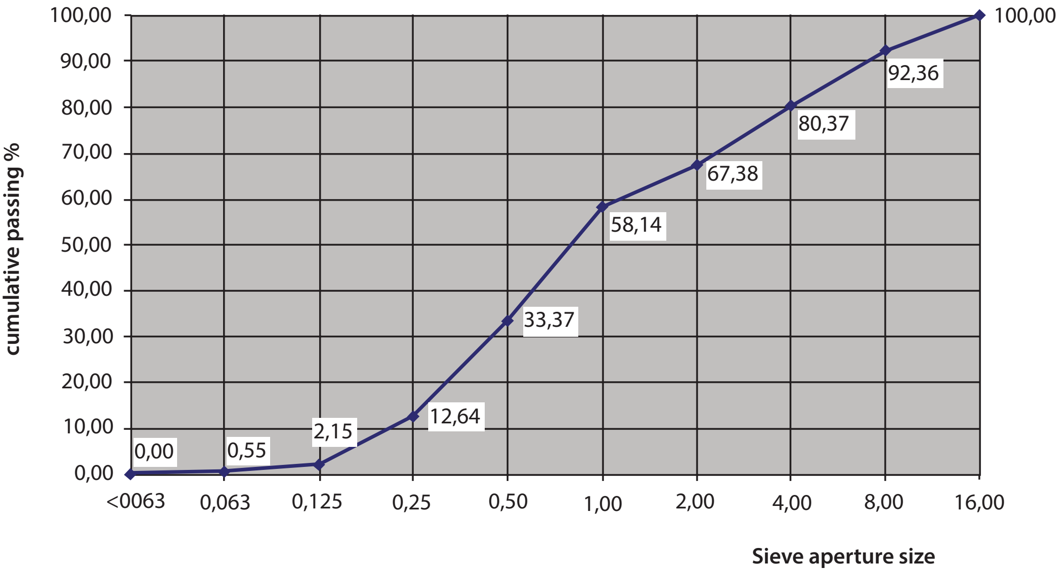
of the material in its intended use, to describe and classify the constituents of the sample, to determine the relative amounts of the constituents of the sample that are essential for proper evaluation of the sample when the constituents differ significantly in properties that have a bearing on the performance of the material in its intended use, and to compare samples of aggregate from new sources with samples of aggregate from one or more sources, for which test data or performance records are available."

EN 932-3 standard, covering procedure and terminology for simplified petrographic description, states that "the sample shall be first subjected to a visual examination to determine the constituent rock or mineral types. It may be appropriate to wash the sample. Each rock type shall then be carefully inspected using a hand lens or a stereoscopic microscope and other appropriate means. If necessary, where appropriate, thin sections should be examined using a polarizing microscope." For an aggregate sample, "the description of the sample (or grain size fraction) shall include: (a) brief information about the shape, surface conditions (roughness etc.) and roundness of particles, (b) a petrographic identification based on counting a sufficiently representative number of particles."

2.7.2 Geometrical Properties and Tests

In European specifications, geometrical properties and tests of aggregates include determination of particle size distribution (sieving method) (EN 933-1 standard), determination of particle size distribution (test sieves); nominal size of apertures (EN 933-2 standard), determination of particle shape (flakiness index) (EN 933-3 standard), determination of particle shape (shape index) (EN 933-4 standard), determination of percentage of crushed and broken surfaces in coarse aggregate particles (EN 933-5 standard), assessment of surface characteristics (flow coefficient of aggregates) (EN 933-6 standard), determination of shell content (percentage of shells in coarse aggregates) (EN 933-7 standard), assessment of fines (sand equivalent test) (EN 933-8 standard), assessment of fines (methylene blue test) (EN 933-9 standard), assessment of fines (grading of filler aggregates) (air jet sieving) (EN 933-10 standard), and classification test for the constituents of coarse-recycled aggregate (EN 933-11 standard).

Some corresponding ASTM standards are the following: C1777 for rapid determination of the methylene blue value for fine aggregate or mineral filler using a colorimeter, C136/C136M for sieve analysis of fine and coarse aggregates, C117 for materials finer than 75-μm sieve in mineral aggregates by washing, D3398 for index of aggregate particle shape and texture, D 4791 for flat particles, elongated particles, or flat and elongated particles in coarse aggregate, D2419 for sand equivalent, C142/142M for clay lumps and friable particles, and D5821 for determining the percentage of fractured particles in coarse aggregate. Finally, ISO 6274 standard specifies a



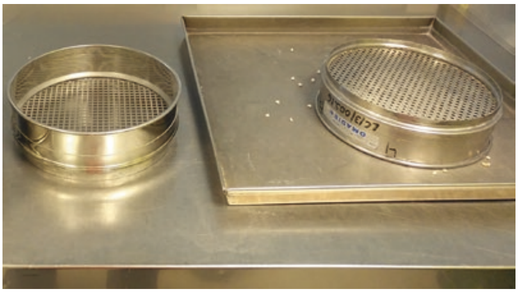
◘ **Fig. 2.42** Example of a particle size distribution

method, using test sieves, for the determination of the particle size distribution of normal weight aggregates for concrete.

Particle size distribution (◘ Fig. 2.42), shape/surface texture, and deleterious fines are key features of sands that control their utilization in many aggregate applications. A property of great significance in the utilization of aggregates is particle size distribution (grading). The production of size grades depends upon the size distribution present in the raw material for sand and gravel aggregates or the efficacy of the crushing process for crushed aggregates. In general, the larger the gravel-to-sand ratio, the better the deposit because aggregate for most construction applications requires a broad range of particle sizes although silt-sized or smaller fine particles are undesirable. Therefore, grain size analysis is one of the most important test procedures, mainly using mechanical sieving techniques (◘ Fig. 2.43). In a sieve analysis, a sample of dry aggregate of known weight is separated through a series of sieves (◘ Fig. 2.44) with progressively smaller openings. Particle size distribution is then expressed as a percent retained by weight on each sieve size. The sieves commonly cover sizes from 0.063 mm to 32 mm or more.

◘ **Fig. 2.43** Mechanical sieving device

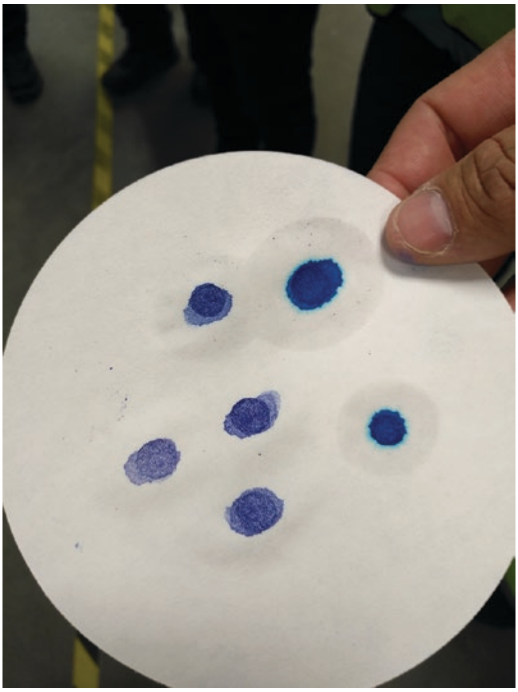
A measure derived from grain size analysis is the sand equivalent value, which estimates the quantity of finest grain size (common clay) (e.g., ASTM D2419 standard). The finest content, for instance, shall be declared in



■ **Fig. 2.44** Sieves used in grain size analysis

■ **Fig. 2.45** Settling in a graduated cylinder. (Image courtesy of LafargeHolcim)

accordance with the relevant category specified in an EN 12620 standard table for concrete aggregates. Sand equivalent is carried out by shaking fine aggregate in a clear graduated cylinder containing a flocculant and preservative solution. After shaking, the particles are allowed to settle (■ Fig. 2.45) and the sand equivalent value is calculated as the ratio of the height of the sand column to the height of the sand and flocculated clay; higher percentages indicate low clay contents. The clay content in the fines fraction of the aggregates can be also determined through methylene blue test, which is a well-established method to determine the presence of clay minerals in aggregates. The method includes the reaction of deleterious clay fines with a blue dye and measuring dye uptake, as a color change, to estimate clay contamination (■ Fig. 2.46).



■ **Fig. 2.46** Example of a color change in methylene blue test. (Image courtesy of LafargeHolcim)

In both types of natural aggregates, the constituent particles within a particular size fraction can display a wide range of shapes. On crushing, rocks break into fragments that are elongated and flattened rather than cuboidal. Quantification of this phenomenon is carried out by measuring the three dimensions of a number of particles and calculating the so-called *flakiness index* and/or *shape index*. The flakiness index is calculated as the mass of particles that pass the bar sieves with parallel slots (■ Fig. 2.47) and the shape index as ratio thickness/length, for example using a caliper. Other shape estimations include sphericity (the nearness of a grain to a sphere) and roundness (degree of angularity of a grain).

Particle shapes are beneficial if the predominant shape is equidimensional and detrimental when the predominant shape is disk or

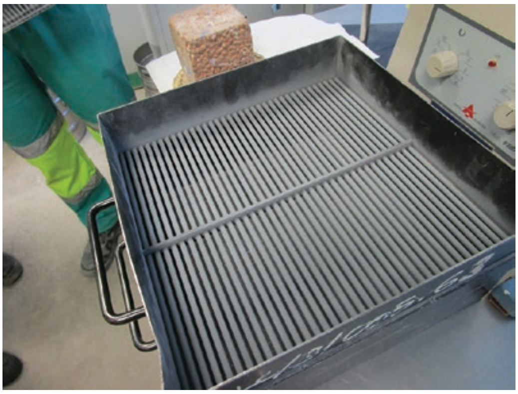


Fig. 2.47 Bar sieve with parallel slots for estimating flakiness index. (Image courtesy of LafargeHolcim)

blade (Langer and Knepper 1998). For example, particle shape influences the workability of concrete; thus, flat or angular particles generated through crushing have an adverse result on workability. Moreover, angular sands may not be workable enough for applications including pumping of concrete.

2.7.3 Mechanical and Physical Properties and Tests

In terms of the mechanical and physical properties of aggregates, the following parts of the test methods are available in European regulation: determination of the resistance to wear (micro-Deval) (EN 1097-1 standard), methods for the determination of resistance to fragmentation (EN 1097-2 standard), determination of loose bulk density and voids (EN 1097-3 standard), determination of the voids of the dry compacted filler (EN 1097-4 standard), determination of the water content by drying in a ventilated oven (EN 1097-5 standard), determination of particle density and water absorption (EN 1097-6 standard), determination of the particle density of filler (Pycnometer method) (EN 1097-7 standard), determination of the polished stone value (PSV) (EN 1097-8 standard), determination of the resistance to wear by abrasion from studded tires (Nordic test) (EN 1097-9), determination of water suction height (EN 1097-10 standard), and determination of compressibility and confined compressive strength of lightweight aggregates (EN 1097-11 standard).

Corresponding or similar ASTM standards are D7428 and D6928 for micro-Deval test, C131/131M, C535, and D3744 for resistance to fragmentation and durability, including the Los Angeles test, C29/29M for bulk density and voids, D7698 for water content and density, C127 and C128 for water absorption and relative density (specific gravity), D1217 for density and relative density using a Pycnometer, D3319 for polishing of aggregates, C566 for total evaporable moisture content of aggregate by drying, and C1252 for uncompacted void content of fine aggregate. With respect to ISO standards, the following test methods are considered: ISO 6782 standard for bulk density (in aggregates for concrete), ISO 6783 standard for particle density and water absorption (in aggregates for concrete), and ISO 7033 standard for the determination of the particle mass-per-volume and the water absorption (in fine and coarse aggregates for concrete) using a pycnometer.

Specific gravity is the ratio of the mass of a given volume of aggregate to the mass of an equal volume of water. Low values of this physical property commonly indicate aggregate that is porous, weak, or absorptive; high-specific gravity values frequently indicate high-quality aggregate. Bulk-specific gravity is the ratio of the weight of a given volume of material, including all voids, to the weight of an equal volume of water. It is an important characteristic of a fine aggregate since the closeness by which the grains are packed is the most important feature to be measured; a sand that has no voids would have a bulk density equal to the specific gravity of the mineral. Specific gravity of aggregate is of significance when design or structural considerations require a concrete with a maximum or minimum weight.

In terms of oven-dried particle density, the aggregates may be classified as: (a) lightweight aggregate (aggregate with oven-dried particle density $\leq$2000 kg/m^3), (b) normal aggregate (aggregate with oven-dried particle density higher than 2000 kg/m^3 and lower than 3000 kg/m^3), and (c) heavyweight aggregate (aggregate with oven-dried particle density ≥3000 kg/m^3).

According to Langer (2006a), “when crushed, the stone particles should be strong, which means they should resist abrasion; hard, which means they should resist loads; tough, which means they should resist impact; and sound, which means they should be able to withstand stresses caused by repeated freezing and thawing or wetting and drying.” Therefore, compressive strength, resistance to impact, and soundness are essential features in crushed stone aggregates. For instance, materials that contain weak, cleavable, absorptive, or swelling particles such as some shales, clayey rocks, very coarse crystalline rocks are low-quality aggregates. Hardness and strength characteristics of aggregates determine their ability to resist mechanical breakdown.

Abrasion resistance, abrasiveness, and polishing are also properties of great importance. The abrasion resistance of an aggregate is commonly used as a general index of its quality. For instance, it is essential where the aggregate is to be used in rail ballast. An aggregate with a low abrasion resistance can increase the quantity of fines in the concrete during mixing, which increments the water requirement of the mix. The most common test for abrasion resistance in coarse aggregate is the Los Angeles abrasion test (▶ Box 2.3: Los Angeles Abrasion Test).

Box 2.3

Los Angeles Abrasion Test

In Los Angeles Abrasion Test, a specified amount of aggregate is placed in a steel drum (◘ Fig. 2.48) that contains steel balls (◘ Fig. 2.49), the drum then is rotated, and the percentage of material worn away is measured.

◘ **Fig. 2.48** Steel drum in Los Angeles abrasion test

◘ **Fig. 2.49** Steel balls in Los Angeles abrasion test

The difference between the original weight and the final weight (sieved through a specified size) is expressed as percentage of the original weight of the sample aggregate. This value is termed Los Angeles abrasion value.

In EN 1097-2 standard, the “testing machine consists of a hollow steel cylinder, closed at both ends, with an inside diameter of 711 mm ± 5 mm and an inside length of 508 mm ± 5 mm. The steel cylinder must be mounted on stub shafts attached to the ends of the cylinder but not entering it, and must be mounted in such a manner that it may be rotated about its axis in a horizontal position. An opening in the cylinder (150 mm ± 3 mm) must be provided for the introduction of the test sample. The opening must be closed with a dust-tight cover that is easily removed.”

The abrasive charge consists of 11 solid, steel spheres having each one a weight between 400 g and 445 g and 45–49 mm diameter. Thus, final weight of abrasive charge ranges between 4690 g and 4860 g. The test sample is formed by at least 15 kg of sample sizing between 10 mm and 14 mm and a final sample weight of 5000 g.

The test procedure includes the main following steps (EN 1097-2 standard): “(1) place the test specimen and abrasive charge in the Los Angeles abrasive testing machine; (2) start the testing machine and run it for 500 revolutions at a rate of 31 rpm to 33 rpm, (3) when the testing machine has completed the required number of revolutions, empty the entire contents into a pan and remove the abrasive charge from the pan, (4) separate the test specimen on the 1.6 mm sieve and weigh and record this value, and (5) calculate the Los Angeles abrasion value using the following equation”:

$$\text{Percent wear} = \frac{(A-B)}{A} \times 100$$

where

- A = Weight of original test specimen to the nearest 1 g (5000 g)
- B = Weight retained on the 1.6 mm sieve to the nearest 1 g

Thus, a Los Angeles abrasion value of 30 means that 30% of the original sample weight passed through the specified size (e.g., 1.6 mm in European standard—EN 1097-2-). For instance, the resistance to fragmentation of coarse aggregates in European regulations for aggregates in concrete (EN 12620 standard) shall be determined in terms of Los Angeles coefficient. This value shall be declared in accordance with the relevant category specified in ◘ Table 2.1 according to the particular application or end use.

◘ **Table 2.1** Categories for maximum values of Los Angeles coefficients in coarse aggregates in concrete (EN 12620 standard)

Los Angeles coefficient	Category *LA*
≤15	LA_{15}
≤20	LA_{20}
≤25	LA_{25}
≤30	LA_{30}
≤35	LA_{35}
≤40	LA_{40}
≤50	LA_{50}
>50	LA_{Declared}
No requirement	LA_{NR}

An alternative to the Los Angeles abrasion test is the micro-Deval test, which is commonly used as an abrasion test for fine and coarse aggregate. The main goal is to determine the abrasion loss in the presence of water and an abrasive charge. Many aggregates are more susceptible to abrasion when wet than dry, and the use of water in this test checks the reduction in resistance to degradation. Materials yielding a low loss in micro-Deval test are unlikely to show significant degradation during handling, mixing, or placing, and they will allow better long-term performance of pavements. The micro-Deval test also uses a rotating drum with steel spheres but the drum is much smaller as are the spheres (◘ Fig. 2.50).

◘ **Fig. 2.50** Machine for micro-Deval test. (Image courtesy of LafargeHolcim)

The polished stone value of an aggregate provides a measure of resistance to the polishing action of vehicle tires under conditions similar to those occurring on the surface of a road.The action of road vehicle tires on road surfaces results in polishing of the top, exposed aggregate surface, and its state of polish is one of the main factors affecting the resistance to skidding. This is related to the ability of the aggregates to lose their initial, rough surface, and develop a polish. Thus, this test is the most important test that an aggregate can undergo if it is to be used as a road surface course. The polish stone value is carried out in two steps: (a) accelerated polishing of test specimens, and (b) measurement of their state of polish by a friction test. As a general rule, it has been found that rock types consisting of a variety of mineral grains of different hardness or size, or of harder grains in a softer cementing matrix, give higher PSV values compared to rocks composed of uniform grains of uniform hardness in a similarly hard matrix.

2.7.4 Thermal and Weathering Properties and Tests

Thermal and weathering properties of aggregates are determined by the following parts of the test methods: determination of resistance to freezing and thawing (EN 1367-1 standard), magnesium sulfate test (EN 1367-2 standard), boiling test *for Sonnenbrand basalt* (EN 1367-3 standard), determination of drying shrinkage (EN 1367-4 standard), determination of resistance to thermal shock (EN 1367-5 standard), determination of resistance to freezing and thawing in the presence of salt (NaCl) (EN 1367-6 standard), determination of resistance to freezing and thawing of lightweight aggregates (EN 1367-7 standard), and determination of resistance to disintegration of lightweight aggregates (EN 1367-8 standard).

Similar or comparable ASTM standards for these tests are C666/666M for resistance of concrete to rapid freezing and thawing, C671 for critical dilation of concrete specimens subjected to freezing, C672 for scaling resistance of concrete surfaces exposed to deicing chemicals, and C88 for soundness of aggregates by use of sodium sulfate or magnesium sulfate.

Physical soundness is generally considered the ability of an aggregate to resist weathering, particularly freezing-thawing and wetting-drying cycles. Properties of rock particles affecting soundness are size, abundance, and continuity of pores, channels, and fractures, together with the degree of water saturation. The size of the pores has a great influence in freezing-thawing behavior of the aggregates because when water turns to ice it increases in volume by about 9%, thus creating pressure within the pores of the stone. Therefore, aggregates that become critically saturated and then freeze cannot accommodate the expansion of the frozen water.

In general, data show that the coarse aggregates, with higher porosity values and medium-size pores, and not the fine ones, cause freeze-thaw deterioration. Large pores do not generally become saturated and water in very fine pores may not freeze readily. The performance of aggregates to freezing and thawing can be evaluated following two criteria: (a) past performance, and (b) laboratory freeze-thaw tests of samples. If aggregates from the same source have previously given satisfactory results when used, they can be considered suitable.

The magnesium sulfate soundness test measures how resistant an aggregate is to chemical weathering and can be carried out on different aggregate sizes. For the test, a weighed sample of aggregate is placed in a wire mesh basket, which is suspended in a saturated magnesium sulfate solution for a period. The magnesium sulfate solution penetrates into the surface of the aggregate particles through any pores that exist, crystallizing in the aggregate pores and generating a very high pressure on the surrounding rock matrix. If weak, the aggregate matrix will disintegrate and fall through the mesh of the enclosing wire basket. When all the soaking/drying cycles have been carried out, the remaining aggregate is washed, dried, and reweighed. The result is expressed as a percentage of the weight of aggregate lost against the original weight. Very weak rocks will disintegrate completely in a small number of test cycles. Results tend to be worse for smaller aggregate sizes.

Weathering due to wetting and drying can also affect the durability of aggregates. Weathering is most commonly developed on a geological time scale but sometimes can take place in service over a period of months or years in some freshly exposed rock surfaces. The expansion and contraction coefficients of rocks change with temperature and moisture content. Thus, severe stress can take place in some aggregates when alternate wetting and drying occurs, causing a permanent increase in volume. Clay lumps and other friable particles can degrade quickly with repeated wetting and drying (ASTM C142/142M standard evaluates clay lumps and friable particles in aggregates). A detailed petrographic study can also help in determining this potential for distress.

2.7.5 Chemical Properties and Tests

Chemical properties of aggregate are important in many applications such as the production of concrete or bituminous mixtures. Thus, some types of aggregates contain minerals that chemically are reactive and can affect the final suitability of the mix. Alkali-silica reaction in concrete (see ► Chap. 9) is probably the most outstanding chemical reaction related to aggregate mineral composition.

The main test methods for chemical properties of aggregates are described in the following parts of European EN 1744 standards series: chemical analysis (EN 1744-1 standard, preparation of eluates by leaching of aggregates (EN 1744-3 standard), determination of water susceptibility of fillers for bituminous mixtures (EN 1744-4 standard), and determination of acid-soluble chloride salts (EN 1744-5 standard). ASTM standards for alkali-silica reaction are C289 for potential alkali-silica reactivity of aggregates (chemical method) and C1260 for potential alkali reactivity of aggregates (mortar-bar method).

2.8 Applications

Aggregates can be used as a construction material in two big types of applications: unbound applications (the aggregate is not bound) and bound applications (mixes containing binding agents such as cements or bitumen). The characteristics of aggregates in bound applications will be considered in the corresponding chapter (► Chap. 9 for concrete, ► Chap. 11 for mortar, and ► Chap. 14 for bituminous mixtures) while the following heading includes the characteristics of aggregates in railway ballast, which is the main unbound application of aggregates (other unbound applications of aggregates are as armourstone (◘ Fig. 2.51)—EN 13383-1 standard—in filter media, and even in ornamental decoration—◘ Fig. 2.52).

2.8.1 Railway Ballast

One of the most demanding applications for crushed aggregate is railway ballast (◘ Fig. 2.1). Railway ballast is a selected crushed and graded aggregate placed upon the railroad roadbed to provide drainage, track stability, flexibility, and uniform support for the rail and ties. Moreover, this type of aggregate also provides distribution of the track loadings to the subgrade as well as facilitating maintenance. In addition, it deters the

◘ **Fig. 2.51** Aggregate used as armourstone (Santander, Spain)

Fig. 2.52 Aggregates used in ornamental decoration

growth of vegetation that might interfere with the track structure. Two types of ballast are usually recognized: top ballast and bottom ballast. Top ballast is the top section of the ballast structure that is commonly exposed to tamping whereas bottom ballast is the bottom and lower part of the structure that supports the overall structure. Moreover, the term sub-ballast (or blanket) is also used. It is a layer of specified coarse-grained material interposed between ballast and formation. The main objectives of sub-ballast are to distribute the load on formation, to eliminate mud pumping, and to contain the seasonal moisture content variations in subgrade.

According to Selig and Waters (1994) and Mundrey (2009), the most important functions of ballast structure are the following: "(a) support the actions coming from the sleepers to the substructure and retain the track in its correct position; those actions can be grouped as uplift, lateral and longitudinal forces, (b) pressure reducing ballast structure to the allowable stress for the underlying structure just below the sleeper, (c) act as resiliency and energy absorbent for the track structure, namely in what concerns to noise and vibrations, especially in high speed lines, (d) the voids between the aggregates provide space for movement and accumulation of crushed aggregates due to fouling, (e) provide quick rainwater drainage system down to the structure and contribute to the elasticity of the railway, and (f) facilitate lining operations and correction of geometry defects by the possibility of rearrange ballast particles with tamping; this eases and speeds up the maintenance operations."

The ballast is required to perform these tasks without exceeding permissible limits of degradation produced by the load and the environment to which it is exposed. It must also resist the entrance of fine particles because the mechanical degradation of ballast particles generates fine particles of varying sizes. Ballast degradation is generally referred to change in particle size distribution of the ballast layer as the result of particle breakage and abrasion, and migration of fine-grained soil from the subgrade. It is important to note that increased levels of degradation can lead to ballast differential settlement, thus altering the track geometry. In general, ballast cleaning is a common practice over time to assure extended life for the ballast and minimize load concentration on rail, sleepers, and tack structures.

The properties of railway ballast aggregate are essential to the effective load-carrying capacity of the rail structure. Thus, strict standards must be established for railway track ballast to provide a high-quality track structure. It is important to bear in mind that the importance of ballast has grown exponentially by means of the increasing of axle loads and train speeds. The different types of materials are used according to the applied requirements, availability, and cost of making ballast. In this sense, one particular material can possess most of the desirable features for good ballast while a deposit of apparently similar material located on the same geographical region will not meet the applicable specification requirements for railway ballast.

Substantial amounts of coarse aggregate are used as railway track ballast since it is typically made of crushed rock with sizes ranging approximately between 20 and 60 mm (◘ Fig. 2.11). In fact, the term *ballast* comes from a nautical term for the stones used to stabilize a ship during loading and transportation. As a rule, track ballast is required to be strong, clean, and angular with a high resistance to abrasion, e.g., Los Angeles abrasion test value of 15–20 at most. Therefore, the majority of railway ballast is sourced from igneous rocks. In common with many aggregate specifications, the selection of suitable materials for railway ballast is often based on experience and judgment as well as on experimental test data.

For aggregates for railway ballast, the European standard is EN 13450. This standard specifies the properties of aggregates obtained by processing natural or manufactured materials or recycled crushed unbound aggregates for use in construction of railway track. There are many other types of national specifications worldwide. Examples of national specifications are American Railway Engineering Maintenance-of-Way Association in the United States (AREMA), Australian Standard for Railway Ballast Specifications, or Canadian National Railways Specification of Crushed Ballast. These specifications cover the types, characteristics, property requirements, and manufacture of mineral aggregates for processed ballast. The type or types of processed ballast material as covered in these specifications and testing requirements such as grading, resistance to wear and to fragmentation, shape and length of the material, durability shall govern the acceptance or rejection of ballast material.

European standardization also considers the presence of the so-called *Sun-burn* or *Sonnenbrand alteration*, which is a type of defect often found in basalt rock that has been affected by atmospheric conditions. It begins with the appearance of grey/white spots, typically capillary cracks that extend outwards from the spots and connecting them with one another. The phenomenon weakens the rock's mineral structure, and as a result, the rock breaks down into smaller particles.

2.9 Environmental Considerations

As already noted, primary aggregates are, where possible, extracted close to major centers of demand to minimize costs. Moreover, since aggregates are probably the lowest value materials that are transported, the cost of transport is an essential factor of the final delivered cost of the aggregate. The increasing number and extent of landscape, nature conservation, and other designations in conjunction with constraints related to factors such as groundwater or location has significantly diminished the number of potential sites for the extraction of aggregates. However, it is essential to remember that aggregates can only be extracted where the geological resources exist.

An aggregate operation is a temporary land use, and when mining is completed, the site is likely to be converted into another beneficial use. Consequently, the overall environmental impact of aggregate extraction is usually relatively small over the long term. In this sense, aggregates are environmentally inert materials and their processing commonly requires only crushing, screening, and washing. Modern technology and scientific investigation methods have made it possible to reduce the environmental impacts from aggregate mining and to manage those impacts at acceptable levels.

Urban growth often threatens established aggregate operations. Some residents near quarries object to the noise, dust, and truck traffic associated with the aggregate operation. As a consequence, many citizens do not support mining and prefer that stone and sand and gravel not be mined nearby. Because aggregate mining is an extractive industry, it cannot be obtained from the landscape without causing environmental impacts, which usually receive the greatest public attention. Operations associated with aggregate extraction and processing "are the principal causes of environmental concerns about sand, gravel, and crushed stone production, including the following: (a) increased dust, noise, and vibrations, (b) increased truck traffic near aggregate operations, (c) visually and physically disturbed landscapes and habitats, and (d) affected surface or groundwater" (Langer et al. 2004).

Although dust and noise are part of aggregate mining, they can be minimized and adverse effects can be avoided. Thus, a carefully prepared and implemented operational plan will keep dust and noise within the required regulatory limits. From a landscape viewpoint, minimizing unsightly changes can be achieved: (a) through proper landscape analysis, design, and operations, (b) by extracting aggregate from the most suitable deposits, and (c) through creation of *super-quarries* and the use of underground mines, depending on local conditions. In general, designing a single large operation or *superquarry* at an environmentally acceptable site is clearly preferable to many smaller operations at scattered locations. Designing to minimize visual impacts includes careful siting of the operation, limiting active extraction areas, sequential reclamation, buffering, and screening. The latter includes the construction of berms, tree plantings, fencing, or other landscaping techniques.

It is not possible to return ecosystems exactly to their original structure. Thus, instead of returning an area to its original condition, a more realistic approach is to approximate the new habitat as closely as possible to its original function and to recapture the landscape character. Reclamation is becoming a major factor in sustaining the environment and in creating habitat biodiversity. Thus, it is now recognized that "restored mineral workings can make a major contribution to both biodiversity and geodiversity; as the restoration works will remove any major variation in substrate, it is possible to increase the quality of the restored land compared to that before working" (BGS 2013). Aggregate quarries can even provide valuable nesting sites for birds on rock faces or in sand faces and a range of habitats and associated flora and fauna on silt and clean water ponds.

Reclamation can also focus on human needs including residential, business, and recreational uses. Thus, restored aggregate quarries also afford a group of recreation facilities that would otherwise be unavailable. In the present expanding suburban areas, mined-out aggregate quarries are converted into second uses, such as wildlife habitat, golf courses (◘ Fig. 2.53), recreational areas (◘ Fig. 2.54), agricultural areas, parks, botanical gardens, school grounds, high-quality lakefront housing sites, and a myriad of other land uses. Thus, a plan for reclaiming the disturbed land and its ecosystem should be an essential part of every plan to mine natural aggregate.

◘ **Fig. 2.53** Ancient quarry converted into a golf course. (Image courtesy of CEMEX)

◘ **Fig. 2.54** Ancient sand and gravel quarry converted into the recreational area of Laguna Las Madres near Madrid, Spain

2.10 Questions

Short Questions

- Define aggregate.
- Enumerate the main types of aggregates based on the production method.
- What natural resource is the most consumed?

- Define natural aggregate according to EN 12620 standard.
- Summarize the two main types of natural aggregates.
- In general, what is the maximum distance for an economic extraction of aggregate?
- What dragline is used for extraction of aggregate?
- What are the main processing techniques in sand and gravel aggregate?
- What is the heat of hydration?
- Explain the main goal of a hydrocyclone.
- Classify the main types of aggregates in terms of oven-dried particle density.
- Explain the main goal of a jaw crusher.
- What does Sonnenbrand alteration mean?
- List the main environmental concerns about sand, gravel, and crushed stone production.
- What is the main goal of an aggregate superquarry?

? Long Questions

- Explain in summary form the sand and gravel processing techniques.
- Explain the Los Angeles abrasion test.

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ASTM C128 – 15. Standard test method for density, relative density (specific gravity), and absorption of fine aggregate

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Useful Links

British Marine Aggregate Producers Association. www.bmapa.org
European Aggregate Association. www.uepg.eu
LafargeHolcim. www.lafargeholcim.com
Martin Marietta. www.martinmarietta.com
Mineral Products Association. www.mineralproducts.org
Tarmac. www.tarmac.com
The National Stone, Sand and Gravel Association. www.nssga.org
Vulcan Materials Company. www.vulcanmaterials.com