

Chapter 2

Industrial Waste Aggregates

2.1 Introduction

The aggregates typically account for 70–80 % of the concrete volume and play a substantial role in different concrete properties such as workability, strength, dimensional stability and durability. Conventional concrete consists of sand as fine aggregate and gravel, limestone or granite in various sizes and shapes as coarse aggregate. There is a growing interest in using waste materials as alternative aggregate materials and significant research is made on the use of many different materials as aggregate substitutes such as coal ash, blast furnace slag, fibre glass waste materials, waste plastics, rubber waste, sintered sludge pellets and others. The consumption of waste materials can be increased manifold if these are used as aggregate into cement mortar and concrete. This type of use of a waste material can solve problems of lack of aggregate in various construction sites and reduce environmental problems related to aggregate mining and waste disposal. The use of waste aggregates can also reduce the cost of the concrete production. As the aggregates can significantly control the properties of concrete, the properties of the aggregates have a great importance. Therefore a thorough evaluation is necessary before using any waste material as aggregate in concrete. Significant work has been done on the use of several types of waste materials as an aggregate in preparation of cement mortar and concrete. In this section, various properties of some waste materials used as aggregate will be presented.

2.2 Types of Industrial Waste Aggregates

The properties of waste aggregates that will be highlighted in this section are:

1. Plastics wastes;
2. Coal ash;
3. Rubber tyre;
4. Slags;
5. Waste from food and agricultural industries;
6. Pulp and paper mill waste;
7. Leather waste;
8. Industrial sludge;
9. Mining industry waste.

Depending on their generation, wastes can be separated into two types: those that directly result from industry as industrial by-products and those that can be named recycled wastes. The first type includes coal ash, various slags from metal industries, industrial sludge, waste from industries like pulp and paper mills, mine tailings, food and agriculture, and leather. The second type includes different plastic and rubber wastes.

A broad classification of industrial waste aggregate can be made depending on the chemical nature of wastes. Some waste aggregates come from production and use of organic materials. Plastics, rubber, leather and some food industries wastes are organic wastes. On the other hand, industrial slags, mining wastes, coal industry wastes and others are inorganic wastes. Glass reinforced plastics and some industrial sludge may contain both organic and inorganic materials.

Another classification of industrial waste aggregate can be done depending on the weight of waste aggregates. Some aggregates are lightweight by nature. Plastics, rubber, most food and agricultural industries wastes and coal bottom ash are of this kind. On the other hand, most of the industrial slags are heavier than conventional aggregates.

2.3 Coal Ash as an Aggregate in Concrete

Burning of coal generates two types of waste materials: fly ash and bottom ash. There are two types of bottom ashes, wet bottom boiler slag and dry bottom ash depending on both the boiler type and its design.

Coal fly ash, also known as pulverised fuel ash, is the finest fraction of these ashes, which are released from combustion chamber and transported by flue gases. Fly ash contains the non-combustible matter in coal along with a small amount of carbon that remains from incomplete coal combustion. Fly ash consists mostly of silt-sized and clay-sized glassy spheres. When pulverised coal is burned in a dry bottom boiler about 80 per cent of the unburned material or ash is entrained in the flue gas and is captured and recovered as fly ash. The remaining 20 % ash that is collected from the bottom of furnaces is called coal bottom ash (CBA), which is a coarse, incombustible by-product with a grain size similar to that of fine and coarse sized natural aggregates. Bottom ash is produced as a granular material and removed from the bottom of dry boilers.

Boiler slag, a coarse grained product, is produced from two types of wet bottom boilers, slag-tap and cyclone boilers. The slag-tap boiler burns pulverised coal while the cyclone boiler burns crushed coal. Both boiler types have a solid base with an orifice that can be opened to allow molten ash to flow into a hopper, which contains quenching water. When the molten slag comes in contact with the quenching water, the ash fractures instantly, crystallises, and forms pellets. High-pressure water jets wash the boiler slag from the hopper into a sluiceway, which then transmits the ash to collection basins for dewatering and further processing. Boiler slag is a coarse, angular, glassy, black material. When pulverised coal is

burned in a slag-tap furnace, as much as 50 % of the ash is retained in the furnace as boiler slag. In a cyclone furnace, which burns crushed coal, 70–85 % of the ash is retained as boiler slag.

Properties of coal ash depend on coal type, pulverising system, combustion conditions, temperature, type of furnace, minerals in coals and milling system. Though a significant number of references are available on the properties and use of fly ash as a mineral addition in normal Portland cement, not much literature exists on the use of fly ash, coal bottom ash (CBA) and boiler slag as a granular additive into concrete. Again compared to CBA, very little work has been done on the use of other two ashes as aggregate in concrete. The properties of these ashes will be discussed separately.

2.3.1 Bottom Ash

2.3.1.1 Dry Bottom Ash

Some of physical properties of ash generated from dry bottom boiler (henceforth called coal bottom ash, CBA) as aggregate are presented in Table 2.1. These properties depend on the burning efficiency, the method by which the CBA is obtained and the type of combustion and thus the physical properties of bottom ash greatly vary in reported works. The density parameters of CBA are considerably lower than those of natural sand ($\sim 2.6 \text{ g/cm}^3$) and therefore CBA can be used as lightweight aggregate in concrete. CBA with relatively low density or specific gravity is often indicative of the presence of porous particles. Bottom ash with relatively high specific gravity (above 3.0) may indicate the presence of high amounts of iron. The bottom ash is a porous material and generally has high water absorption capacity. However, variation in water absorption capacity in different CBA is quite large, with a range of 2–32 %. The moisture content of bottom ash used by Andrade et al. (2009) as a fine aggregate in concrete is about 55 %. On the other hand, CBA is more brittle than natural sand and has a greater resemblance to cement clinker (Rogbeck and Knutz 1999).

The porosity and void content of CBA are generally higher than in natural aggregate and thus CBA can accommodate a high amount of water in a concrete mix. Therefore there is some difficulty in determining the exact water/cement ratio of concrete mixes containing CBA. However, the ability to incorporate high amount of water by CBA can be used as a reservoir of water for future hydration of cement. This behaviour, commonly known as internal curing is particularly useful for high strength concrete, where less water is used to make concrete. In this type of concrete, the hydration process leads to shortage of water in the cement paste. At this stage, the water content in CBA can promote a supply of water internally to the concrete for continuous hydration. These hydration products fill the pores or micro-cracks and improve concrete properties.

Table 2.1 Physical properties of coal bottom ash reported as aggregate in concrete

Reference	Properties						
	Unit weight, kg/ m ³	Specific gravity/ density, kg/m ³	Water absorption (%)	Fineness modulus	Moisture content (%)	Maximum diameter (mm)	Porosity #Void content (%)
Kou and Poon (2009)		2,190 (SSD)	28.9 (1 h)	1.83			
Andrade et al. (2007)		1,674 (sp. gr.)		1.55	55		
Andrade et al. (2007)		1,67 (sp. gr.)		1.60		2.4	
Bai et al. (2005)		1,50 (SSD, sp. gr.)	30.4 (1 h)				
Bai et al. (2005)		1,58	32.2 (1 h)			5.0	
Kim and Lee (2011)		1,77 (OD) 1,87 (SSD)	5.45 (ASTM)	2.36		2.4	10.19 ^a
Kim and Lee (2011)		1,64 (OD) 1,77 (SSD)	8.14 (ASTM)			13.2	13.34 ^a
Yuksel et al.	620 (loose) 660 (dense)	1,39	6.10 (TS)			4.0	
Ghafoori and Bucholz (1996)		2,33 (OD) 2,47 (SSD)	7.0	2.80			
Lee et al. (2010)	1,268	1,84 (OD) 1,90 (SSD)		1.59		2	#33.3
	988	1,98 (OD) 2,00 (SSD)		3.81		8	#50.4
	1,040	1,78(OD) 1,90 (SSD)				11	#45.1
Park et al. (2009)	1,275	2,410	2.43			13	
Kou and Poon (2009)	1,270	2,480	2.11			20	

SSD saturated surface-dry; *sp. gr.* specific gravity; *TS* Turkish standard, *TS* EN-12620; ^a water accessible porosity

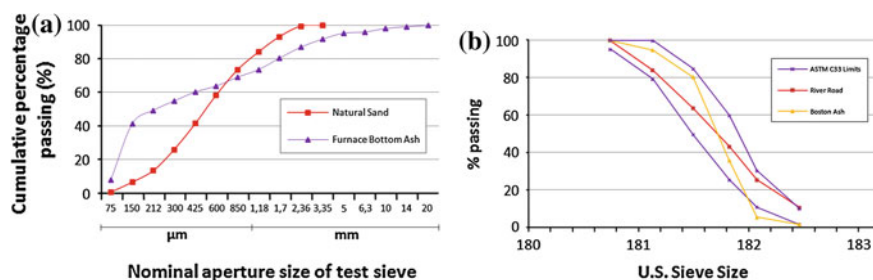


Fig. 2.1 Particle size distribution of a CBA and of natural sand **a** Bai et al. (2005); **b** Ghafoori and Bucholtz (1996)

The particle size of CBA also depends on the factors indicated earlier. In literature, the use of CBA as fine or coarse aggregate is reported (Table 2.1). The CBA used in Ghafoori and Bucholtz (1996) study was a well-graded fine aggregate with a fineness modulus (FM) of 2.80 (ASTM's recommendation of FM range for fine aggregate is 2.3–3.1). Figure 2.1 shows the particle size distribution of two typical CBA used as partial substitution of fine aggregate in concrete.

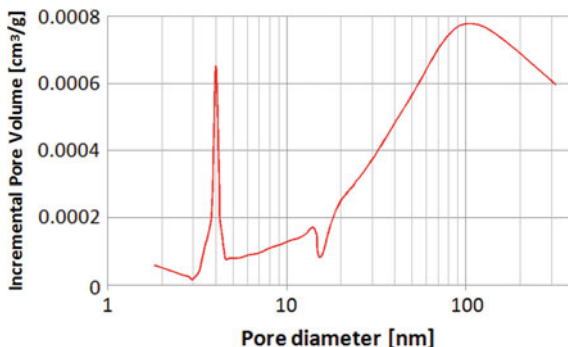
Compared to natural sand aggregate, which is dense, normally smooth in texture, and round in shape. The particles of CBA aggregate are porous and angular in shape. It has rough surface texture, large numbers of micro-pores (circular holes with a diameter in a range of 0.5–5 μm) and internal pores. Some spherical shaped fly ash particles having a few micrometer diameters can be deposited on the surfaces of CBA (Kim and Lee 2011). The shape and porous structure of CBA makes it necessary to use a high amount of water during preparation of the concrete mix. A typical pore-size distribution curve of bottom ash (presented in Fig. 2.2) indicates that the nanostructure of bottom ash is quite dense (Kim and Lee 2011).

The chemical properties of CBA are normally controlled by the properties of coal (its origin). Table 2.2 shows oxide composition of some CBA samples. CBA is composed primarily of silica (SiO_2), ferric oxide (Fe_2O_3) and alumina (Al_2O_3), with smaller quantities of calcium oxide (CaO), potassium oxide (K_2O), sodium oxide (Na_2O), magnesium oxide (MgO), titanium oxide (TiO_2), phosphorous pentoxide (P_2O_5) and sulphur trioxide (SO_3).

The minerals identified in different CBA used as aggregate in concrete are presented in Table 2.2. Figure 2.3 shows the X-ray diffraction (XRD) pattern of typical low calcium CBA. The major minerals found in CBA are quartz, mullite and a non-crystalline glassy phase. In some CBA, iron containing minerals like hematite and magnetite may also be present. The fused and glassy texture of CBA normally would make an ideal substitute for the aggregate fraction of concrete.

Unlike its companion—pulverised fuel ash (PFA) or coal fly ash, CBA usually has low pozzolanicity, which makes it unsuitable to be used as a mineral addition in cement. It may contain higher concentrations of unburned carbon. Some power plants recover coal mill rejects with bottom ash and therefore CBA may contain pyrites that come from mill rejects, which can cause expansion in concrete.

Fig. 2.2 Pore size distribution of bottom ash (Kim and Lee 2011)



2.3.1.2 Boiler Slag or Wet Bottom Ash

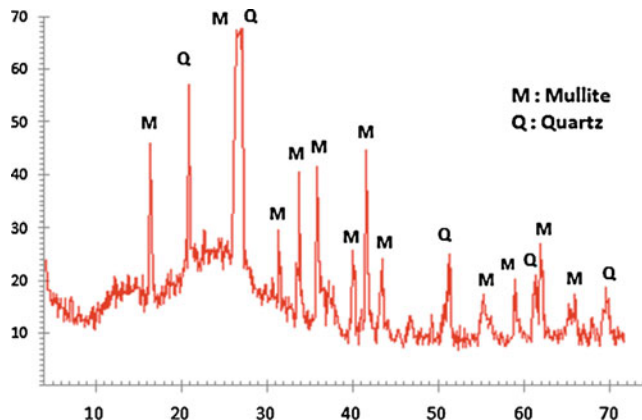
Boiler slag is a vitrified material, which is a very durable and environmentally stable form that permanently immobilises its chemical constituents into the glassy amorphous structure. Boiler slag is made of porous, glassy, angular, uniform sized smooth granular particles. The quenched slag becomes somewhat vesicular or porous if gases are trapped in the slag. Boiler slag generated from burning of lignite or sub-bituminous coal tends to be more porous than that of bituminous coals (Lovell and Te-Chih 1992).

The boiler slag primarily comprises particles, which can be regarded as single-sized coarse to fine sand with 90–100 % passing a 4.75 mm mesh sieve, 40–60 % passing a 2.0 mm mesh, 10 % or less passing a 0.42 mm mesh and 5 % or less passing a 0.075 mm mesh (Majizadeh et al. 1979). Boiler slag is black in colour, hard, and durable with a resistance to surface wear.

Boiler slag typically contains 40–60 % SiO_2 , 18–38 % Al_2O_3 , 2–7 % Fe_2O_3 , 1–4 % CaO , 0.5–3.0 % MgO and 0.5–2.0 % TiO_2 . The chemical composition of boiler slag is also governed by the coal source. Boiler slag exhibits less abrasion and soundness loss than bottom ash as a result of its glassy surface texture and lower porosity. The predominate minerals present in boiler slags are mullite, quartz, calcium silicate and quicklime. The specific gravity of boiler slag usually ranges from 2.3 to 2.9. The dry unit weight of boiler slag usually ranges from 960 to 1,440 kg/m^3 . Occasionally, the dry unit weight of boiler slag may reach 1,760 kg/m^3 .

Deleterious materials, such as soluble sulphates or coal pyrites, should be removed from the bottom ash and boiler slag before attempting to use these materials as an aggregate. Pyrites can be removed from the coal before it is burned using sink-float techniques, or from the bottom ash or boiler slag using magnetic separation. Due to salt content (soluble chlorides and sulphates) and low pH and electrical resistivity, bottom ash and boiler slag may be potentially corrosive and therefore evaluation of the corrosive nature of the bottom ash being used should be investigated. Corrosivity indicator tests normally used to evaluate bottom ash are pH, electrical resistivity, soluble chloride content and soluble sulphate content.

Fig. 2.3 The X-ray diffraction pattern of typical low calcium CBA (Cherief et al. 1999)



2.3.1.3 Fly Ash

The use of fly ash (FA) as partial replacement of normal Portland cement in concrete is very common nowadays and around 15–25 % of cement is generally replaced by FA in normal structural concrete mixes. However, the overall percentage utilisation remains very low in many countries, and most of the fly ash is dumped at landfills (Siddique 2003a, b; Ravina 1997). Much higher quantities of FA can be used in concrete if fly ash can partially replace the fine sand fraction in concrete mix. This replacement can be made by low quality fly ash too, which has low pozzolanic properties. Although many references are available on the use of fly ash as a supplementary cementing material in concrete, the number of available references on the use of fly ash as partial replacement of fine aggregates is not very large.

American Society for Testing and Materials (ASTM) C618-03 (Standard specification for coal fly ash and raw or calcinated natural pozzolan for use in concrete), classifies fly ash into two categories—Class F (low calcium) and Class C (high calcium) fly ash. Combustion of bituminous or anthracite coal normally produces Class F (low calcium) fly ash and combustion of lignite or sub-bituminous coal normally produces Class C (high calcium) fly ash.

The chemical composition of fly ash used as aggregate in concrete is presented in Table 2.3. The chemical composition of fly ash depends on the type of coal. More references are available on the use of low calcium fly ash as a replacement of fine aggregate in concrete than high calcium fly ash. High calcium fly ash contains large amounts of free lime and sulphite than that of low calcium fly ash. Due to the presence of undesirable chemical components in high calcium fly ash, the use of this material is much limited compared to low calcium fly ash.

The mineralogical composition of fly ash is very complex. Mineralogically, fly ashes are a heterogeneous mixture of mineral phases and amorphous glassy phases with small amount of unburned carbon. The glassy phase of low calcium fly ash is alumino-silicate type whereas that of high calcium fly ash is a mixture of calcium aluminate and ferrous alumino-silicate (Das and Yudhbir 2006).

Table 2.3 Chemical composition of some fly ashes used as a replacement of sand fraction in concrete

Constituents/ properties	Siddique (2003a , b)	Maslehuddin et al. (1989)	Rajamane et al. (2007)	Pofale and Deo (2010)	Papadakis (1999)	Papadakis (2000)
SiO ₂	55.3	60.5	59	55.5	53.50	39.21
Al ₂ O ₃	25.7	23.0	nr	31.3	20.40	16.22
Fe ₂ O ₃	5.3	7.5	nr	6.4	8.66	6.58
CaO	5.6	2.0	1.02	1.02	3.38 (free: 0.36)	22.78 (free: 5.18)
MgO	2.1	1.0	0.30	0.21	–	–
TiO ₂	1.3	nr		2.70	–	–
SO ₃	1.4	0.3	–	0.44	0.63	4.30
Na ₂ O	0.4	nr	0.54 (total alkalis)	–	–	
K ₂ O	0.6	nr	0.25	–	–	
LOI	1.9	1.4	1.08	0.74	2.20	2.10
Moisture content	0.3	nr	nr	Nr	–	–
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	86.3	91	–	93.2	82.16	62.01

Depending on the fly ash type, the mineral matter present in fly ash varies significantly. More than 188 minerals have been identified in fly ash, most of them trace minerals. High calcium fly ash contains large amounts of calcium-bearing minerals like lime, anhydrite, gypsum, tricalcium aluminate, alite, gehlenite, akermanite, portlandite and larnite. Some other minerals like quartz, hematite and magnetite are also present in high calcium fly ash. On the other hand, low calcium fly ash mainly contains quartz, mullite, hematite, magnetite and small amounts of calcite.

Silicon and aluminium are mainly present in a glassy phase, with small amounts of quartz and mullite included. Iron appears partly as oxides (magnetite and hematite), with the rest in a glassy phase.

The specific gravity of fly ash may vary from 1.3 to 4.8 (Joshi and Lohtia 1997). FA mainly consists of clay and silt-sized particles (particle diameter <45 micrometer), which are generally spherical in shape. There is a wide variation in the particle size distribution of fly ashes irrespective of the type of fly ash. The particle size distribution of fly ash mainly depends upon the initial grinding of the coal and the efficiency of the thermal power plant and even fluctuations in power generation (Lee et al. 2010). The shape of the FA may vary depending on the various physical and chemical factors. The glassy phase is mainly spherical in shape. However, large sized or irregular shaped particles can also be formed from the fusion of smaller fragments and incomplete melting. The colour of coal ash depends on its chemical and mineral constituents. High lime containing FA is normally tan and light in colour. Iron containing FA is brownish in colour. The dark grey to black colour of FA indicates the presence of a high amount of unburned carbon.

2.4 Industrial Slag

Slag is a partially vitreous by-product of smelting ore due to separating of the metal fraction from the worthless fraction. It can be considered a mixture of metal oxides; however, slags can contain metal sulphides and metal atoms in the elemental form.

2.4.1 Ferrous Slag

Ferrous slag is produced during the production of iron using blast furnace (blast furnace slag) as well as in the separation of the molten steel from impurities in steel-making furnaces (steel slag) (Fig. 2.4).

2.4.1.1 Steel Slag

Steel slag is produced during the separation of molten steel from impurities in steel furnaces. The slag occurs as a molten liquid and is a complex solution of silicates and oxides that solidifies upon cooling. There are several different types of steel slag produced during the steel-making process out of which basic oxygen furnace steel slag (BOF slag), electric arc furnace slag (EAF-slag) and ladle furnace slag (LDF-slag) or refining slag are important.

An electric arc furnace produces steel by melting recycled steel scrap, using heat generated by an arc, created by a large electric current. The slag is formed through the addition of lime, which is designed to remove impurities from within the steel. Slag has a lower density than steel and therefore floats on top of the molten bath of steel.

In the basic oxygen process, hot liquid blast furnace metal, scrap and fluxes, which consist of lime (CaO) and dolomitic lime (CaO.MgO), are charged into the furnace. The oxygen, injected into the furnace, combines with and removes the impurities in the charge. These impurities consist of carbon as gaseous carbon monoxide, and silicon, manganese, phosphorus and some iron as liquid oxides, which combine with lime and dolomitic lime to form the BOF steel slag.

After being tapped from the furnace, molten steel is transferred in a ladle for further refining to remove additional impurities still contained within the steel. This operation is called ladle refining because it is completed within the transfer ladle. During ladle refining, additional steel slags are generated by again adding fluxes to the ladle to melt.

Steel mill scale is produced during processing of iron in steel mills. During the processing of steel in steel mill, iron oxides, known as mill scale are formed on the surface of the metal during the continuous casting, reheating and hot rolling operations. The steel mill scale is removed by water sprays. The steel mill scale is somewhat similar to steel slag and therefore, like steel slag, it can be used in concrete production.

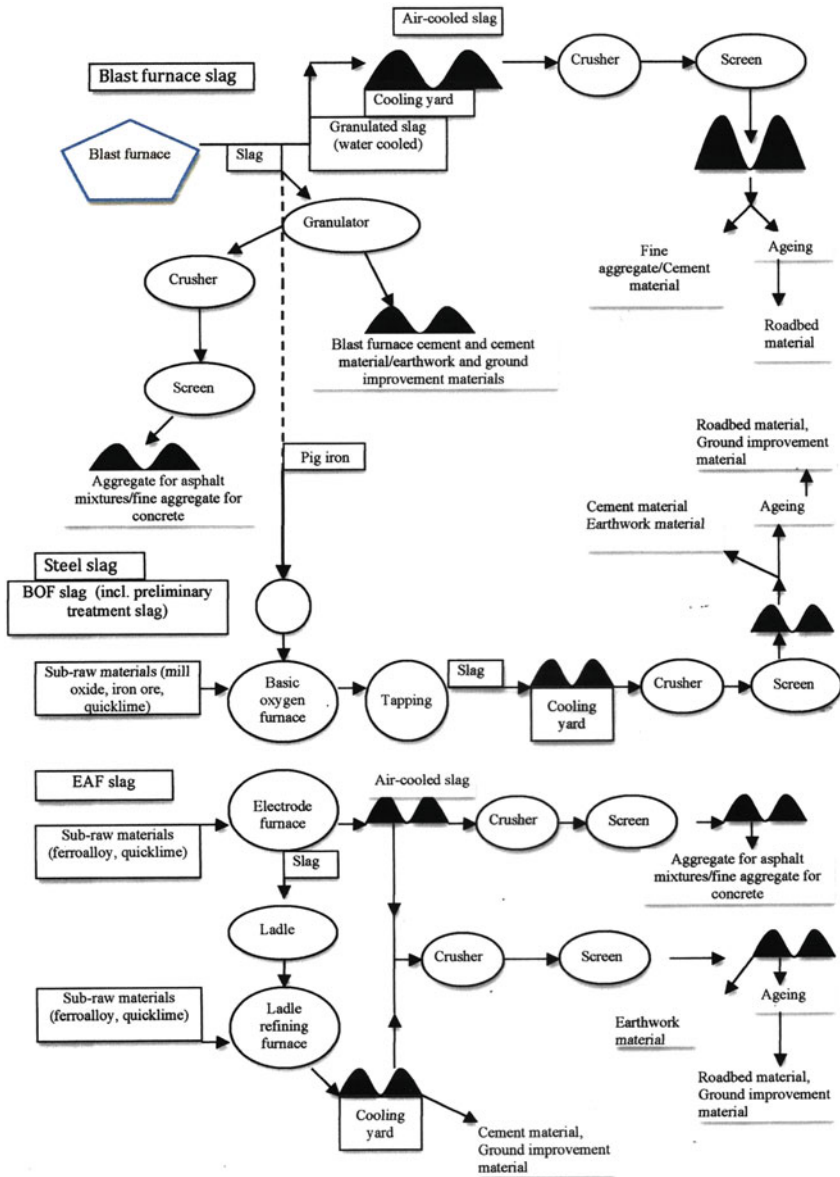


Fig. 2.4 Flowchart of production of ferrous slag (courtesy Nippon Slag Association)

The use of steel slag in the preparation of blended cement, or cement clinker, and as aggregate or hydraulic binder in road construction has been proposed by several authors for a long time (Mahieux et al. 2009; Monshi and Asgarani 1999; Shi and Qian 2000). However, not much is reported on the use of steel slag as aggregate in preparation of cement mortar and concrete. Compared to the use of

BOF-slag as aggregate in concrete, more references are available on EAF-slag. On the other hand, LDF-slag is mainly used as a mineral admixture in cement due to its particle size and possibly its mineralogy.

Steel slag is a crushed product having hard, dense, angular and roughly cubical particles (National Slag Association 2011). The EAF-slag used by Al-Negheimish et al. (1997) as a replacement of coarse aggregate in concrete was angular shaped with honeycombed surface texture. The angular shape of steel slag aggregate can help to develop very strong interlocking properties. The Flakiness Index (FI) of the steel slag aggregate is markedly lower than those for the dolerite and quartzite aggregates (Anastasiou and Papayianni 2006). The amount of clay lump and friable material content in steel slag is considerably lower than in natural aggregates (Almusallam et al. 2004).

Anastasiou and Papayianni (2006) evaluated several physical properties of crushed steel slag to be used as an aggregate in concrete. The authors concluded that the evaluated aggregate properties of steel slag are in between the limits of the standards and in the best categories. Some physical properties of the different types of steel slags used as aggregate in concrete or asphalt mix and reported by several researchers are presented in Table 2.4. Steel slag has higher abrasion resistance and lower crushing value than natural aggregates. On the other hand, the specific gravity and water absorption capacity of steel slag are higher than those of conventional aggregates. The porosity of a typical steel slag reported by Manso et al. (2004) is 10.5 %. EAF-steel slag aggregates have excellent resistance to fragmentation (Papayianni and Anastasiou 2010).

The surface texture of steel slag is rougher than that of limestone aggregate (Xue et al. 2006; Ahmedzade and Sengoz 2009). The scanning electron micrograph of EAF-slag indicates the presence of many pores on its surface. Steel slag has higher bulk density than natural aggregates (Al-Negheimish et al. 1997).

An adequate grading of steel slag is necessary to obtain better performance from concrete containing steel slag as aggregate (Manso et al. 2006). The particle size distribution curves of two typical EAF-slags used as coarse and fine aggregate in concrete are presented in Fig. 2.5. Depending on the cooling process, the particle size of steel slag may vary. Air-cooled steel slag consists of large sized granules and some powder (Wang et al. 2010).

The high content of free lime (free-CaO) and periclase (MgO) is the detrimental factor against using various steel slags as aggregate in concrete. The content of free lime (free-CaO) and periclase (MgO) in EAF-slag is considerably lower than in BOF-slag. As steel slag contains expansive materials like CaO and MgO, to be used in concrete slag is generally treated. Ageing or weathering of slag, steam and autoclave curing of slag are generally performed to reduce expansive oxide contents (Chen et al. 2007; Faraone et al. 2009; Lun et al. 2008; Pellegrino and Gaddo 2009). As the majority of the steel slag contains free CaO and MgO, experiments are generally performed to evaluate the free CaO and MgO content in the slag and soundness of steel slag aggregate.

Tables 2.5, 2.6 and 2.7 show the chemical compositions of BOF-, LDF- and EAF-slags, respectively. Steel slag is basic in nature (ratio of concentrations of

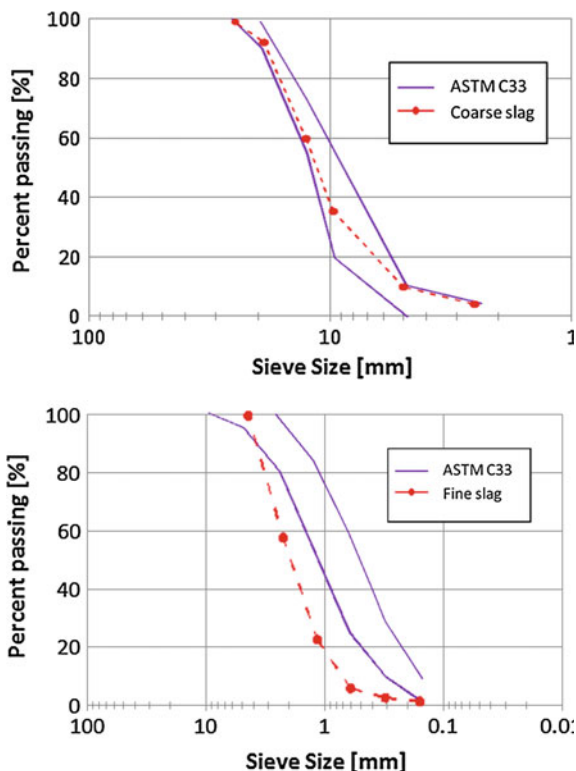
Table 2.4 Some physical properties of steel slag

Property	Steel slag	Type of steel slag	Natural aggregate	Type of natural aggregate	Reference
Specific gravity	3.51	EAF-slag	2.71	Quartzite	Almusallam et al. (2004).
Los Angeles abrasion (%)	11.6		19.2		
Water absorption (%)	0.85		1.60		
Specific gravity	3.64	EAF-slag	2.66	–	Al-Negheimish et al. (1997)
Water absorption (%)	0.54		1.67		
Specific gravity	3.35	EAF-slag			Manso et al. (2004)
Los Angeles abrasion (%)	~20				
Water absorption (%)	3.29				
Porosity (%)	10.5		–		Ahmedzade and Sengoz (2009)
Specific gravity	3.02	EAF-slag	2.63	Limestone	
Los Angeles abrasion (%)	20		29		
Shape (flat and long) (%)	<10	BOF-slag	10	Basalt	Xue et al. (2006)
LA abrasion (%)	13.1		14.9		
Crushing value (%)	12.0		12.9		Shen et al. (2009)
Water absorption (%)	1.18		0.70		
Specific gravity	3.48	BOF-slag	2.66	River crushed stone	
Water absorption (%)	2.2		1.3		
LA abrasion (%)	20.96		23.52		
Shape (flat and elongated) (%)	5.14		7.55		
Roundness index (%)	0.60		0.54		

$\text{CaO} + \text{MgO}$ to $\text{SiO}_2 + \text{Al}_2\text{O}_3$ greater than 1) (Tossavainen et al. 2007). The order of this ratio for LDF-, EAF- and BOF-slags can be arranged as $\text{EAF-slag} \leq \text{LDF-slag} \leq \text{BOF-slag}$. The reactivity and free CaO content of steel slag increases with its increasing basicity (Shi and Qian 2000). Compared to BOF- and LDF-slag, most EAF-slags contain less CaO and MgO in their chemical compositions. There are some aggregates reported as steel slags (Maslehuddin et al. 2003; Qasrawi et al. 2009), which contain more than 85 % of Fe_2O_3 and are therefore completely different from other EAF-slags (Table 2.8). This material can be considered as mill scale. The dominant minerals of EAF-slag can be classified into dicalcium silicate (C_2S), merwinite (C_3MS_2) or kirschsteinite (CFS), depending on the basicity of steel slag, of which the basicity of kirschsteinite is the lowest (Qian et al. 2002).

Although the concentrations of some toxic metals in steel slag are higher than those in normal soil, metals are strongly bound with the slag matrix and therefore are not readily leached. Therefore, steel slag cannot be considered as “characteristically hazardous” material (Proctor et al. 2000). However, in a recent report higher leachability values (above the standard limit for inert landfill) of Cr and Mo from EAF-slag were also reported (Tossavainen et al. 2007). As the chemical composition of steel slag is highly variable mineralogical composition of steel slag also varies. Table 2.9 shows the mineralogical compositions of various types of

Fig. 2.5 Particle size distribution curves of two steel slags (Manso et al. 2004)



slags as reported by various authors. Different calcium silicates, solid solution of CaO-FeO-MnO-MgO and free- CaO are the common minerals in steel slag.

2.4.1.2 Blast Furnace Slag

When the blast furnace is tapped to release the molten iron, it flows from the furnace with molten slag floating on its upper surface. These two materials are separated using a weir, the molten iron being channelled to a holding vessel and the molten slag to a point where it is to be treated further. The final form of the blast furnace slag is dependent on the method of cooling. There are four main types of blast furnace slag: granulated; air-cooled; expanded and pelletised.

Chemically, the blast furnace slag contains mainly silica (30–35 %), calcium oxide (28–35 %), magnesium oxide (1–6 %), and $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$ 1.8–2.5 %. Due to its low iron content it can be safely used in the manufacturer of cement. Two types of blast furnace slag such as air-cooled slag and granulated slag are being generated from the steel plants. The specific gravity of the slag is approximately 2.90 with its bulk density varying in the range of 1,200–1,300 kg/m^3 . The colour of granulated slag is whitish. The air-cooled slag is used as aggregate in road making

Table 2.5 Chemical compositions of BOF-slags

Author	Lun et al. (2008)	Xue et al. (2006)	Mahieux et al. (2009)	Tossavainen et al. (2007)	Altun and Yilmaz (2002)	Reddy et al. (2006)
Country Type	PR China Steel slag (from BOF)	PR China BOF-slag	France Weathered BOF-slag	Sweden BOF-slag	Turkey BOF-slag S1 S2	India BOF-slag
SiO ₂ (%)	10.10	13.71	11.8	11.1	18.01 18.87	15.3
Al ₂ O ₃ (%)	1.70	3.80	2.00	1.90	2.61 2.91	1.30
Fe and Fe _x O _y (%)	Fe ₂ O ₃ = 20.57	FeO = 21.85 Fe ₂ O ₃ = 3.24	Fe ₂ O ₃ = 22.6	FeO = 10.9 Fe ₂ O ₃ = 10.7 Fe = 2.30	14.10 11.73	Fe
(total) = 16.2						
CaO (%)	40.65	45.41	47.5	45.0	37.02 37.94	52.3
MnO (%)	0.06	3.27	1.90	3.10	7.52 7.72	0.39
MgO (%)	10.88	6.25	6.30	9.60	14.10 14.37	1.1
Free lime (%)	nr	nr	nr	nr	0.83 0.83	10
Basicity: (CaO + MgO)/(Al ₂ O ₃ + SiO ₂)	4.37	2.95	3.90	4.20	2.48 2.40	3.82

nr not reported

Table 2.6 Chemical compositions of LDF-slags

Author	Setien et al. (2009)			Tossavainen et al. (2007)		Shi and Qian (2000)	Rodriguez et al. (2009)
Country	Spain			Sweden		PR China	Spain
Type	1	2	3	LDF slag		LDF-slag fines	LDF-slag
SiO ₂ (%)	15.0	19.8	12.6	14.2		26.4–26.9	17
Al ₂ O ₃ (%)	12.5	4.3	18.6	22.9		4.3–5.2	11
Fe and Fe _x O _y (%)	Fe ₂ O ₃ = 2.1			Fe ₂ O ₃ = 1.6		Fe ₂ O ₃ = 1.0–1.6	
				Fe = 0.4			nr
CaO (%)	55.0	57.5	50.5	42.5		56.6–57.0	56
MnO (%)	0.36	0.42	0.52	0.2		0.5–1.0	
MgO (%)	7.5	11.6	11.9	12.6		3.2–4.2	10
Free lime (%)	19.0	3.5	9.5	nr		nr	nr
Free MgO (%)	3.0	10.0	8.0	nr		nr	nr
Basicity: (CaO + MgO)/(Al ₂ O ₃ + SiO ₂)	2.27	2.87	2.00	1.49		1.93	2.36

nr not reported

Table 2.7 Chemical compositions of EAF-slags

Author	Qian et al. (2002)	Luxan et al. (2000)	Manso et al. (2006)	Pellegrino and Gaddo (2009)	Tossavainen et al. (2007)
Country	Singapore	Spain	Spain	Italy	Sweden
Type	Kirschsteinite based EAF-slag S1	Black EAF-slag (fusion of scrap steel) S1	Black EAF-slag S2	EAF slag Medium	EAF slag S1
(contaminated by white slag)					
SiO ₂ (%)	19.38	6.04	15.35	10.1	32.2
Al ₂ O ₃ (%)	5.27	14.07	12.21	5.70	14.1
Fe and/or Fe _x O _y (%)	FeO = 30.54		7.4	7.20	6.70
			Fe ₂ O ₃ = 8.49		FeO = 34.36
Fe ₂ O ₃ = 1.00					
Fe = 0.10	FeO = 5.60		FeO + Fe ₂ O ₃ = 42.5	FeO = 37.2	FeO = 44.8
			Fe ₂ O ₃ = 20.3		FeO = 3.30
			Fe = 0.60		
CaO (%)	22.48	29.11	23.9	24.2	45.5
MnO (%)	1.10	15.58	4.5	5.10	2.0
MgO (%)	9.51	3.35	5.1	1.90	5.2
Free lime (%)	nd	nr	0.45	nr	nr
Free MgO (%)	nr	nr	~1.0	nr	nr
Basicity:			(CaO + MgO)/ (Al ₂ O ₃ + SiO ₂)	1.30	0.99
				1.61	1.28
1.65	1.60	1.41	2.05		

nd not detected; nr not reported

Table 2.8 Chemical composition of some steel slag described as steel slag or steel making slag and steel mill scale

Author	Faraone et al. (2009)	Al-Negheimish et al. (1997)	Chen et al. (2007)	Maslehuddinn et al. (2003)	Qasrawi et al. (2009)	Al-Otaibi (2008)
Country	Italy	Saudi Arabia	PR China	Saudi Arabia	Jordan	Kuwait
Type	Steel slag	Steel making slag (EAF-slag)	Steel slag	Steel slag	Unprocessed steel slag	Steel mill scale
SiO ₂ (%)	13.2	17.43	13.40	1.00	0.80	1.37
Al ₂ O ₃ (%)	6.80	7.85	1.04	nr	nr	0.10
Fe and/or Fe _x O _y (%)	Fe _x O _y = 9.80	Total Fe = 20.09 FeO = 18.33	FeO = 18.98 Fe _x O _y = 8.45	Fe _x O _y = 89.0	Fe _x O _y = 97.05	Fe _x O _y = 94.61
CaO (%)	37.9	30.53	51.51	CaCO ₃ = 10	0.40	0.11
MnO (%)	13.5	2.66	1.65		1.07	1.03
MgO (%)	11.9	13.19	3.45		0.40	0.03
Basicity: (CaO + MgO)/ (Al ₂ O ₃ + SiO ₂)	2.49	1.73	3.81	–	–	–

nr not reported

Table 2.9 Mineralogical compositions of various slags

Authors	Country	Type of slag	Minerals identified
Rojas and Rojas (2004)	Spain	EAF-slag	Wustite/plustite, magnesioferrite/magnetite, hematite, larnite, bredigite/merwinite, gehlenite, birnessite/groutellite (manganese oxides)
Faraone et al. (2009)	Italy	EAF-slag	Fine fraction: glaucochroite ($(\text{CaMn})_2\text{SiO}_4$), iron manganese oxide (FeMnO) Medium: calcite (CaCO_3), glaucochroite ($(\text{CaMn})_2\text{SiO}_4$), iron manganese oxide (FeMnO), magnetite (Fe_3O_4), portlandite ($\text{Ca}(\text{OH})_2$)
Tossavainen et al. (2007)	Sweden	LDF-slag	Mayenite, $(\text{Ca}_{12}\text{Al}_{14}\text{O}_{33})$, free MgO . $\beta\text{-Ca}_2\text{SiO}_4$, $\gamma\text{-Ca}_2\text{SiO}_4$, $\text{Ca}_2\text{Al}_2\text{SiO}_7$
		BOF-slag	Larnite, $\beta\text{-Ca}_2\text{SiO}_4$, solid solution of $(\text{Fe}, \text{Mg}, \text{Mn})\text{O}$, solid solution of $(\text{CaMg})\text{O}$
		EAF-slag, S1	Merwinite, $\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$, $\gamma\text{-Ca}_2\text{SiO}_4$, solid solution of spinel phase $(\text{Mg}, \text{Mn})(\text{Cr}, \text{Al})_2\text{O}_4$
		EAF-slag, S2	$\beta\text{-Ca}_2\text{SiO}_4$, wustite-type solid solution $((\text{Fe}, \text{Mg}, \text{Mn})\text{O})$, $\text{Ca}_2(\text{Al}, \text{Fe})_2\text{O}_5$, Fe_2O_3
Qian et al. (2002)	Singapore	Kirschsteinite based EAF-slag	Kirschsteinite ($\text{CaFe}^{2+}(\text{SiO}_4)$), Mg-wustite
Luxan et al. (2000)	Spain	EAF-slag, S1 and S2	Major: gehlenite $[\text{Ca}_2\text{Al}(\text{Al}, \text{Si})_2\text{O}_7]$, larnite (Ca_2SiO_4) Minor: bredigite $[\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8]$, manganese oxides (Mn_3O_4 , MnO_2), magnesioferrite (MgFe_2O_4), magnetite (Fe_3O_4)

while the granulated slag is used for cement manufacturing. Its use as aggregate in concrete is not very usual although it has no behavioural problems, and there has been little research work done on the subject.

Because of their more porous structure, blast furnace slag aggregates have lower thermal conductivities than conventional aggregates. Their insulating value is of particular advantage in applications such as frost tapers (transition treatments in pavement sub-grades between frost susceptible and non-frost susceptible soils) or pavement base courses over frost-susceptible soils.

The granulated blast furnace slag is formed due to rapid quenching of molten slag, which converts it into a glassy state. Granulated slag possesses cementitious properties if it is ground finely. The size and physical properties of granulated blast furnace slag varies, depending on the chemical composition and method of production. Numerous studies are available on the properties of cement and concrete containing ground blast furnace slag as a latent hydraulic material. Slag cement is the hydraulic cement that results when molten slag from an iron blast furnace is rapidly quenched with water, dried and ground to a fine powder. Blast furnace slag sand was recognised as meeting JIS A 5012 standards in 1981, and has also been stipulated in guidelines for the Japan Society of Civil Engineers. It is also stipulated as JIS A 5308 (ready-mixed concrete).

Air-cooled blast furnace slag (air-cooled slag) is prepared by cooling the molten blast furnace slag slowly by ambient air. A small amount of water is generally used

to spray the surface of the slag to assist in the cooling process. The air-cooled blast furnace slag is normally processed in a crushing and screening plant to manufacture products of particular maximum sizes and gradings. Crushed air-cooled slag is angular, roughly cubical, and has textures ranging from rough, vesicular surfaces to smooth glassy surfaces with conchoidal fractures. Processed air-cooled slag exhibits good abrasion resistance, good soundness characteristics and high bearing strength. The cementitious property of air-cooled slag is poorer than in other types of slag prepared by rapid quenching. Slag sand is very angular and coarse and therefore mixes containing this product require a high fine sand content or the use of a mix containing three sand types. In general, blast furnace slag processed for use as a concrete aggregate complies with the same requirements for naturally occurring dense aggregate. While complying with these requirements, air-cooled blast furnace slag aggregate differs from the range of naturally occurring dense aggregates in certain properties. The particle and bulk densities of air-cooled slag are slightly lower than those of natural aggregates. It has higher water absorption and Los Angeles value. Some typical properties of air-cooled slag are presented in Table 2.10.

If the molten slag is cooled and solidified by adding controlled quantities of water, air-, or steam, the resultant slag becomes a lightweight expanded or foamed type of product. Foamed blast furnace slag is distinguishable from air-cooled slag by its relatively high porosity and low bulk density. Crushed expanded slag is angular, roughly cubical in shape and has a texture that is rougher than that of air-cooled slag. The porosity of expanded blast furnace slag aggregates is higher than that of air-cooled slag. The bulk relative density of expanded slag is difficult to determine accurately, but it is approximately 70 % of that of air-cooled slag. Typical compacted unit weights for expanded blast furnace slag aggregates range from 800 to 1,040 kg/m³.

The molten slag can be pelletised during cooling and solidification process. The produced pellets can be made more crystalline or more vitrified (glassy). Crystalline pellet can be used as aggregate. The pelletised blast furnace slag has smooth texture and round shape. Consequently, the porosity and water absorption are much lower than those of air-cooled or expanded slag. Pellet sizes range from 13 to 0.1 mm, with the bulk of the product in the 1.0–9.5 mm range. Pelletised blast furnace slag has a unit weight of about 840 kg/m³.

Collins and Sanjayan (1999) reported the use of an air-cooled porous slag with maximum diameter of 14 mm as a coarse aggregate in preparation of alkali activated slag concrete. The specific gravity of the slag aggregate was 2.71, which was slightly lower than used basalt aggregate (2.95). The water absorption capacity of slag was 4.4 % and considerably higher than basalt aggregate (1.2 %).

Etxeberria et al. (2010) reported the use of blast furnace slag of size range of 4.75–25 mm as a complete or partial replacement of coarse aggregate in preparation of concrete. The physical properties of the aggregate were determined according to British standard, BS EN 1097-6:2000. The oven dry and saturated surface dry densities of the aggregate were 2.27 and 2.37 g/cm³ respectively, which are lower than the used natural aggregate (about 2.7 g/cm³). On the other

Table 2.10 Typical mechanical properties of air-cooled blast furnace slag (FHWA-RD-97-148)

Property	Value
Los Angeles abrasion (ASTM C131)	35–45 %
Sodium sulphate soundness loss (ASTM C88)	12 %
Angle of internal friction	40–45
Hardness (measured by Mohr's scale of mineral hardness) ^a	5–6
California bearing ratio (CBR), top size 19 mm (3/4 in) ^b	up to 250 %

^a Hardness of dolomite measured on same scale is 3–4

^b Typical CBR value for crushed limestone is 100 %

hand, the water absorption capacity of slag aggregate was 4.10 % and lower than that of natural aggregate (2.94 %).

Yuksel et al. (2011) used granulated blast furnace slag (GBFS) with maximum diameter of 4 mm as partial replacement of fine aggregate in concrete. The various properties of GBFS aggregate along with a natural fine aggregate are presented in Table 2.11.

Escalante-García et al. (2009) reported the use of a GBFS as fine aggregate in cement mortar. The GBFS employed as an aggregate was used as received and only a fraction of large sized particles was removed; 90 % was retained in the 0.420 mm sieve and 28 % was retained in the 1 mm sieve. The used GBFS has sharp edges and some particles have several surface pores.

Leshchinsky (2004) reported the use of air-cooled slag sand with maximum size of 6.3 mm as a fine aggregate in ready-mixed concrete. The moisture content of the used slag sand is within a range of 2–4 % above the saturated surface dry (SSD) content. According to the author, complete saturation is crucial for slag aggregate and for slag sand to achieve the required concrete properties.

2.4.2 Non-Ferrous Slag

Non-ferrous metallurgical slags are generated during refining of various metals such as Cu, Cr, Zn and treatment of waste such as Pb-acid batteries. Some physical properties of a few non-ferrous slags are presented in Table 2.12.

2.4.2.1 Copper Slag

Copper slag is a by-product obtained during the matte (molten copper sulphide) smelting and refining of copper (Biswas and Davenport 1976). Major constituents of a smelting charge are sulphides and oxides of iron and copper. The charge also contains oxides such as Al_2O_3 , CaO , MgO , and principally SiO_2 , which are either present in the original concentrate or added as a flux. As a result, copper-rich matte (sulphides) and copper slag (oxides) are formed as two separate liquid phases. The

Table 2.11 Physical properties of granulated blast furnace slag (Yuksel et al. 2011)

Property	Type of aggregate	
	GBFS	Natural
Loose bulk density (kg/m ³)	1,052	1,930
Dense bulk density (kg/m ³)	1,236	1,950
Specific gravity	2.08	2.60
Water absorption (%)	8.30	2.30
Amount of clay (%)	1.0	4.0
Loss on ignition (%)	1.8	5.0
Lightweight particles (%)	3.0	4.0

Table 2.12 Some physical properties of various non-ferrous slags (Publication number: FHWA-RD-97-148)

Property	Nickel slag	Copper slag	Phosphorus slag	Lead, lead–zinc, and zinc slags
Appearance	Reddish brown to brown-black	Black	Black to dark grey	Black to red
Texture	Massive, angular, amorphous texture	Glassy, more vesicular when granulated	Air-cooled is flat and elongated but granulated is uniform, angular	Glassy, sharp angular (cubical) particles
Unit weight, (kg/m ³)	3,500	2,800–3,800	Air-cooled: 1,360–1,440 Expanded: 880–100	<2,500–3,600
Absorption (%)	0.37	0.13	1.0–1.5	5.0

molten slag is discharged from the furnace at 1,000–1,300 °C. When liquid slag is cooled slowly, it forms a dense, hard crystalline product where a quick solidification by pouring molten slag into water provides amorphous granulated slag. Production of one tonne of copper generates approximately 2.2–3 tonnes of copper slag. In the United States the amount of copper slag produced is about four million tonnes (Collins and Ciesielski 1994), in Japan it is about two million tonnes per year (Ayano and Sakata 2000), and approximately 360,000, 244,000 and 60,000 tonnes of copper slag are produced every year in Iran, Brazil and Oman, respectively (Behnood 2005; Moura et al. 1999; Taeb and Faghihi 2002).

Recycling, recovering of metal, production of value added products and disposal in slag dumps or stockpiles are the options for management of copper slag. It has been widely used for abrasive tools, roofing granules, cutting tools, abrasive, tiles, glass, road-base construction, railroad ballast, asphalt pavements, cement clinker and blended cement production (Shi et al. 2008). Many researchers have investigated the use of copper slag as fine or coarse aggregate in the preparation of cement mortar and concrete.

The main concern in large-scale use of copper slags including in construction is the content of toxic elements in copper slag and the consequent leaching from slag and slag based products. However, copper slag has been excluded from the listed hazardous waste category of the United States Environmental Protection Agency

(USEPA). The United Nations (UN) Basel Convention on the Transboundary Movement of Hazardous Waste and its Disposal also ruled that copper slag is not a hazardous waste (Alter 2005).

The chemical composition of copper slag depends on the type of furnace, the metallurgical production process, and the composition of the extracted ore. The range of percentage of the main oxides of copper slag can vary as follows— Fe_2O_3 : 35–60 %, SiO_2 : 25–40 %, CaO : 2–10 %, Al_2O_3 : 3–15 %, CuO : 0.3–2.1 %, MgO : 0.7–3.5 %. The density of copper slag varies between 3.16 and 3.87 g/cm³, the average specific gravity of copper slag is about 3.5 g/cm³ and the average water absorption of copper slag is 0.15–0.55. Water-cooled copper slag has a higher water absorption and lower unit weight than air-cooled copper slag due to its more porous texture (Shi et al. 2008). Air-cooled copper slag has a black colour and glassy appearance. The specific gravity varies with iron content, from 2.8 to 3.8. The unit weight of copper slag is somewhat higher than that of conventional aggregates. The absorption capacity of the material is typically very low (0.13 %). Granulated copper slag is more porous and therefore has lower specific gravity and higher absorption capacity than air-cooled copper slag. The granulated copper slag is made up of regularly shaped, angular particles, mostly between 4.75 and 0.075 mm in size (Emery 1995; Hughes and Halliburton 1973).

Air-cooled and granulated copper slag has a number of favourable mechanical properties for aggregate use, including excellent soundness characteristics, good abrasion resistance, and good stability. It has high friction angle due to sharp angular shape. However, the slag tends to be vitreous or ‘glassy,’ which adversely affects their frictional properties (skid resistance), a potential problem if used in pavement surfaces.

Khanzadi and Behnood (2009) reported the use of copper slag as a coarse aggregate in concrete, which meet the grading requirements of ASTM C 33 for 12.5–4.75 mm size aggregates. The physical properties of the copper slag aggregates along with a coarse natural limestone aggregate are presented in Table 2.13. The used copper slag has significantly higher specific gravity than the limestone aggregate. The high specific gravity and the glass-like smooth surface properties of irregular grain shape of copper slag aggregates can increase bleeding. The water absorption capacity of copper-slag is 0.4 % and lower than limestone aggregate, which is 0.6 %. Copper slag aggregate is harder than natural limestone aggregate.

Wu et al.(2009) reported the use of copper slag as a fine aggregate in concrete. The copper slag used in this investigation had a density of 3,660 kg/m³, in contrast with the density of sand of 2,640 kg/m³. The fineness modulus of the copper slag was 1.78, which was finer than sand, with a fineness modulus of 2.91. The particle size of the copper slag was well distributed within the range of 0.1–1 mm. The shape of sand is irregular with rounded edges at 50 × magnification while that of copper slag is angular with sharp edges. The surface texture of sand is rougher than that of copper slag at 200 × magnification. Under observation at 1,000 × magnification the presence of moisture on sand surface is visible, but the surface of copper slag is glassy and dry.

Al-Jabri et al. (2011) reported the use of a copper slag as a fine aggregate in the preparation of cement mortar and concrete. Before using the slag, the material was

Table 2.13 Some physical properties of copper slag and limestone aggregate (Khanzadi and Behnood 2009)

Properties	Copper slag aggregate	Limestone aggregate
Specific gravity, g/cm ³	3.59	2.65
Aggregate crushing value, %	10–21	23
Aggregate impact value, %	8.2–16	11
Water absorption, %	0.4	0.6
Particle size, mm	4.75–12.5	4.75–12.5

grinded in the laboratory into a fine powder to the required size. The particle size distribution of the ground slag along with normal sand is presented in Fig. 2.6.

Copper slag has high concentrations of silica, alumina and iron oxides. Results from specific gravity and water absorption tests revealed that copper slag has a specific gravity of 3.4 which is higher than that of sand (2.77), whereas the water absorption values for copper slag and sand were about 0.2 and 1.4 %, respectively.

Brinda et al. (2010) used a copper slag as partial replacement of sand and cement in concrete preparation. The physical properties of copper slag are presented in Table 2.14. The slag was made of black glassy particles and granular in nature and has a particle size range similar to sand. The specific gravity of the slag is 3.91. The bulk density of granulated copper slag varied from 1.9 to 2.15 kg/m³, which is almost similar to the bulk density of conventional fine aggregate. The hardness of the slag lies between 6 and 7 in the Mohr scale. This is almost equal to the hardness of gypsum. The pH of aqueous solution of aqueous extract as per IS 11127 varies from 6.6 to 7.2. The free moisture content present in slag was found to be less than 0.5 %. The amount of silica in slag is about 26 %. The fineness of copper slag was calculated as 125 m²/kg.

Ishimaru et al. (2005) reported the use of a copper slag as a replacement of sand in the preparation of concrete. The density, water absorption and fineness modulus of used copper slag are respectively 3.46 g/cm³, 0.65 and 2.58 %.

2.4.2.2 Other Non-ferrous Slags

The use of other non-ferrous industrial slags as aggregate in concrete and cement mortar is also reported. Lead slag generated from lead smelting and from recycling of secondary lead batteries may be used as fine and coarse aggregate in the preparation of cement mortar and concrete.

Atzeni et al. (1996) reported the use of granulated slag generated during smelting of lead and zinc by two different processes (named as Imperial Smelting and Kivcet slags), as a partial and total replacement of the sand fraction in cement mortar and concrete. The slags were used as received from granulation plants. Both types of slags were essentially vitreous with small amount of gehlinit, cristobalite and iron oxides as minor crystalline components. Both slags contain FeO, SiO₂, CaO and Al₂O₃ as the major oxides with significant amounts of zinc

Fig. 2.6 Sieve analysis of a typical copper slag along with normal sand aggregate (Al-Jabori et al. 2011)

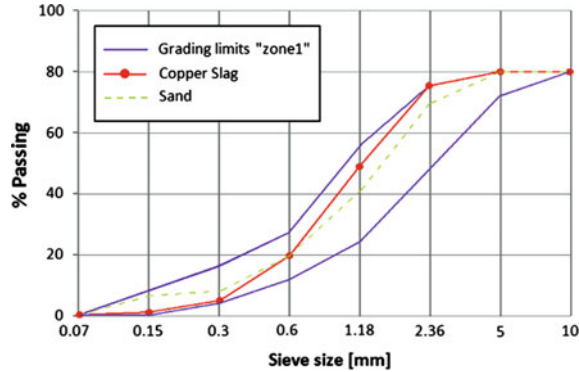


Table 2.14 Some physical properties of copper slag (Brinda et al. 2010)

Particle shape	Irregular
Appearance	Black and glassy
Specific gravity	3.91
Percentage of voids	43.20 %
Bulk density	2.08 g/cm ³
Fineness modulus	3.47
Angle of internal friction	51°20'

and lead. Most slag grains are rounded and others are polygonal as a result of conchoidal fracture caused by thermal shock induced by granulation. Imperial Smelting slag is generally less regular than Kivcet slag. The grain size distribution of both slags is similar to that of normal sand. The predominant fraction by mass is the 0.15–2 mm size range. The grains have very low porosity, on average 1 % by volume for the K slag and 3 % by volume for the IS slag.

Penpolcharoen (2005) reported the use of a secondary lead slag as an admixture and/or as an aggregate in the production of concrete blocks. The slag was produced from battery smelting using CaCO_3 as flux. The fine fraction of slag, which passed through ASTM sieve No. 200, was used as a partial substituent of ordinary Portland cement, while the coarse fraction of slag, which passed through ASTM sieve No. 4, was used to partially replace crushed limestone aggregate. The CaO content in slag is 6.2 times less than that in OPC, whereas its iron content, as FeO , is 15.1 times higher. The Fe in slag is mainly contained as FeO and therefore weight gain was observed during determination of loss on ignition test. The physical properties of fine and coarse fractions of slags are presented in Table 2.15 along with OPC and crushed stone aggregate.

Sorlini et al. (2004) reported the use of two different types of slag that contained very high amounts of Zn as aggregate in the preparation of concrete. A fresh slag obtained after water cooling and a cured slag after storage of about 6 months in landfill were used in this study. The slag is generated as a by-product of the conversion of electric arc furnace (EAF) dusts (with zinc concentration of 18–35 %) into an impure zinc oxide, called Waelz oxide (with zinc concentration

Table 2.15 Some physical properties of secondary lead slag (Penpolcharoen 2005)

Property	OPC	Fine slag	Crushed stone	Coarse slag
Specific gravity	3.15	3.62	2.71	3.62
Blain fineness	3,380	3,333	–	–
Fineness modulus	–	–	4.74	4.70

of 55–65 %), that can be reprocessed in metallurgical plants. This slag is classified as dangerous waste. Both slags contain very high concentrations of calcium (43 %). Zinc and lead concentrations are about 6 and 1 % respectively; other metals, like manganese, cadmium, copper, chromium and arsenic, are also present in considerable amounts. However, the leachability of these toxic elements in concrete blocks with this slag as aggregate is within the specified limit.

Zelic (2005) investigated the use of a high-carbon ferrochromium slag as aggregate in the preparation of concrete. Before using the slag as aggregate, the original air-cooled slag was crushed to a grain size in the range of 0–16 mm, first by a hammer crusher and then by a cone beaker. The metallic globules of ferrochromium metal were then removed from the crushed slag by the Remer jig treatment by means of difference in specific gravities of slag and metallic fraction. The specific gravity of slag and FeCr metal is 3.2 and 7.1 g/cm³, respectively. The refined slag (0–16 mm) fraction contains up to the 11 % Cr.

The part of the Cr₂O₃ component in the slag is 8.3 % in mass smaller after the jig treatment than in the original slag before the treatment, which was the actual aim of the applied process of metal concentration and its removal from the slag. No chlorides were observed in the slag and the sulphur SO₃ content of 0.50 % in mass is much lower than the allowed value of 1.00 % in mass, indicating that the slag does not contain harmful components that may be found in aggregates. The major minerals present in slag are: forsterite, (Mg, Fe)₂SiO₄, common-spinel (MgAl₂O₄), chrome-spinel ((Mg, Fe)(Cr,Al)₂O₄) as unaltered chromium ore and also of small amounts of enstatite (MgSiO₃). The slag exhibits better performance than normal limestone aggregate during the Loss Angeles and Bohme wear tests. The fineness modulus of the unfractionated slag varied from 4.0 to 5.1 suggesting a too uneven size distribution of the slag, as the upper acceptable limit is 3.6. The volume mass of ferrochromium slag particles is about 3,250–3,310 kg/m³ and that of the limestone ones about 2,700 kg/m³. The Faury coefficients, *k*, obtained for both the (4–8 mm) and the (8–16 mm) fractions of slag are 0.17 and 0.22, respectively. The results of the mortar bar expansion test indicate the slag aggregate as non-reactive in terms of alkali-silica reaction. The frost resistance of slag is comparable to natural limestone aggregate and well within the standard specifications.

Morrison et al. (2003) reported the use of ferro-silicate slag, generated during the production of zinc in Imperial Smelting Furnace (ISF-slag) was as aggregate in concrete road construction (Morrison et al. 2003, Morrison and Richardson 2004). The slag is glassy and granular in nature and has a particle size range similar to sand, indicating that it could be used as a replacement for sand present in

cementitious mixes. The density of this slag ($3,900 \text{ kg/m}^3$) is higher than that of traditional aggregates, suggesting it may have advantages over these aggregate materials in certain applications, such as in noise barriers. The X-ray diffraction (XRD) showed the presence of inclusions of metallic iron, although the principal crystalline components detected were FeO and ZnS.

Metwally et al. (2005) reported the use of a slag produced from recycling of spent lead-batteries as aggregate in concrete production. Recycled-lead slag (RLS) was used as both fine and coarse aggregate in concrete manufacture after crushing into the desired gradation by using a roller mill. The physical and mechanical properties of the used fine aggregate (sand and fine lead-slag) and coarse aggregate (gravel and coarse lead-slag) are given in Table 2.16. The coarse lead-slag were washed carefully and dried before mixing to remove any impurities and organic matters, which may weaken its bond with the cement paste. Mixing water was clean tap water free from impurities and organic matters.

Pereira et al. (2000) reported the use of a salt cake slag, produced from aluminium scrap re-melted as partial replacements of either sand or cement in the preparation of cement mortar production after washing. Non-washed slags cannot be mixed with cement due to the volumetric expansion observed during setting, high chloride content and release of high concentrations of noxious gases. As the concentrations of some toxic elements in the majority of these slags are very high, before application the environmental suitability as well as the long-term mechanical and durability performance of concrete containing slag must be evaluated for the application of these materials as aggregate in concrete.

2.5 Other Waste as Aggregate

The meat and bone mill bottom ash (MBM-BA) used by Cyr and Ludmann (2006) as a fine aggregate in cement mortar preparation has a grading size between 0 and 2 mm and a mean diameter of 0.4 mm (Fig. 2.7). The physical properties of MBM-BA are presented in Table 2.17. The bulk density of MBM-BA is around 900 kg/m^3 and much lower than that of normal sand ($1,500 \text{ kg/m}^3$). The average density of the ash is $2,900 \text{ kg/m}^3$. The external specific surface area, calculated from the density and the particle size distribution (considering cylindrical particles), is about $3 \text{ m}^2/\text{g}$. The BET method gives a specific surface area of $3,000 \text{ m}^2/\text{kg}$, which is a thousand times higher than the value calculated using the particle size distribution. This significant difference is related to a large open porosity of the grains, leading to water absorption of 11 %, a very high value compared to normalised siliceous sand (less than 1 %).

The strength of MBM-BA is evaluated using a friability coefficient, defined as the ratio between the mass of crushed particles (less than 0.1 mm) and the whole mass of material before crushing. The friability coefficient of MBM-BA, measured as 37 %, is well within the specified value, which is 40 % for 60 MPa concrete intended for building construction.

Table 2.16 Physical properties of fine and coarse lead slags along with natural aggregates (Metwally et al. 2005)

Property	Natural sand	Natural gravel	Fine lead slag	Coarse lead slag
Specific gravity	2.57	2.51	4.28	3.79
Density (kg/m ³)				
Loose	1,600	1,530	2,280	1,990
Dense	1,869	1,640	2,820	2,120
Voids (%)				
Loose	38	39	47	47
Dense	27	35	34	44
Water absorption (%)	0.42	0.35	3.95	2.35
Fineness modulus	2.49	6.90	3.35	6.95
Crushing value (%)	–	13.5	–	29.3
Impact value (%)	–	6.82	–	13.4
Loss Angeles value (%)	–	16.7	–	47.0

The major minerals present in MBM-BA are hydroxylapatite $\text{Ca}_5(\text{PO}_4)_3(\text{OH})$ and whitlockite $\text{Ca}_3(\text{PO}_4)_2$. Calcium hydroxylapatite is the major inorganic constituent of bones and teeth. Trace amounts of some minerals such as quartz, hematite and magnetite are also present in MBM-BA, which probably came from other waste used as co-combustion materials. Although MBM-BA contains small amounts of trace elements, the leachability of these meets the regulation set by French Government for using in road construction.

Öztürk and Bayraklı (2005) investigated the possibilities of the use of tobacco waste, a by-product in a cigarette factory as aggregate in lightweight concrete production. The organic and water content in this aggregate are 66.21 and 25.45 % respectively.

Yellishetty et al. (2008) evaluated the recycling potential of four different iron ore mineral wastes as aggregate in the preparation of concrete. The waste was collected randomly, from different fresh waste dumps as recommended ASTM D75; C702 sampling of aggregates. It was mixed to form a representative homogeneous mixture. The sieve analyses of typical particle overburden material from the waste dumps of the corresponding iron ore mines are presented in Fig. 2.8. A volume equivalent of approximately 50 % of the total is within the usable range as aggregates for making of concrete cubes. Of the whole volume, 20 % is in the range of sand–silt–clay material. Variability in size distribution is an indication of inherent geological properties of mine waste material and of the crushing and compaction that waste undergoes while breaking/loosening.

Various physico-mechanical properties of the mine waste were measured according to ASTM methods and presented in Table 2.18. In aggregates from different mines, the fineness modulus (FM) was within the range of IS2386 specifications prescribed for aggregate for civil constructions. Most of the physical properties of the mine aggregates, belonging to different mines, were within ± 5 % range of standard specifications and were in conformity with the concurrent Indian Standards for aggregates.

Fig. 2.7 Particle size distribution of MBM-BA, in comparison with the limits for sand used for standard mortar (Cyr and Ludmann 2006)

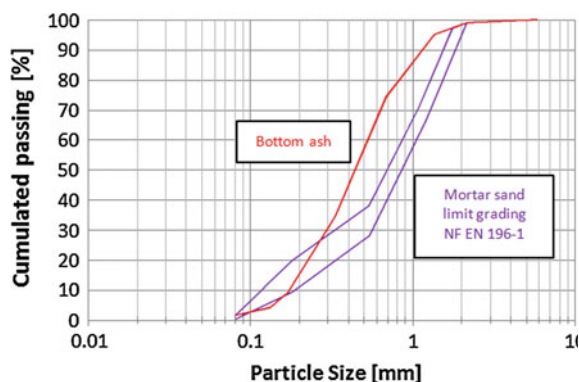


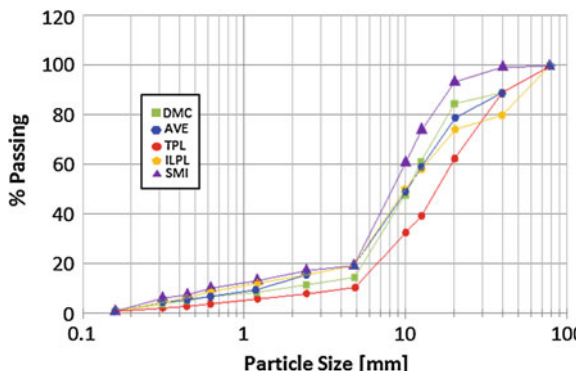
Table 2.17 Physical properties of meat and bone mill ash (Cyr and Ludmann 2006)

Density (kg/m ³)	2,900
Bulk density (kg/m ³)	900
Specific surface area, BET (m ² /kg)	3,000
Particle size range (mm)	0–2
Mean diameter (mm)	0.4
Morphology	Irregular particles
Adsorption coefficient (water) (%)	11
Friability coefficient (%)	37

Gallardo and Adajar (2006) reported the use of paper mill sludge as a partial replacement of fine aggregate in concrete preparation. The composition of paper sludge is generally a function of the raw material, manufacturing process, chemicals used, final products and wastewater treatment techniques. Sludge from pulp and paper mills are mainly cellulose fibres generated at the end of the pulping process prior to entering the paper machines. Paper sludge obtained directly from a mill wastewater treatment plant is composed generally of 50–75 % organics (cellulose fibres and tissues) and 30–50 % kaolinite clay. The paper mill sludge used in this study was air-dried for several days and facilitated by an artificial method using a blow drier. The dry sludge was then crushed and sieved using sieve No. 4 to separate the fine particles to be used as fine aggregates in the mix. The physical properties of paper sludge along with fine aggregates (sand) are presented in Table 2.19. Sludge was lighter than normal sand and it has very high water absorption capacity. The large absorption percentage of sludge is indicative of its high porosity or entrapped air content and that it absorbs water faster than sand. The high absorption rate is due to hydrogen bonding in the property of sludge. There was no silica content in paper sludge while calcium and iron is of lesser amount as compared to fine aggregates. Some other element contents in paper sludge are lower than the normal sand.

Ahmadi and Al-Khaja (2001) investigated the use of paper sludge, obtained from a tissue paper manufacturing facility as partial replacement of fine aggregate in the preparation of concrete. The sieve analysis of sludge and normal sea sand indicates

Fig. 2.8 Sieve analysis of mine wastes (Yellishetty et al. 2008)



that the used sludge is coarser than the sea sand. About 50 % of the particles of sludge are coarser than 2 mm compared with sea sand in which 100 % of the particles pass the 2.36 mm sieve. The chemical analysis of the waste shows that it has a low pH value with acceptable levels of other chemical parameters and falls within the permissible limits established in Bahrain for use of waste in construction.

Kuo et al. (2007) reported the use of petroleum reservoir sludge as fine aggregate in the preparation of cement mortar. The composition of sludge is presented in Table 2.20. The sludge contains very high amount of smectite clay (>60 %), which can cause a detrimental expansion to some extent, when it is mixed with water. Hence, reservoir sludge cannot be directly used as fine aggregates in concrete and therefore, before using it as aggregate, hydrophilic sludge is converted into hydrophobic by using a cationic surfactant.

The sieve analysis of modified sludge organically modified reservoir sludge (OMRS) along with normal sand is presented in Table 2.21. More than 80 % of the OMRS particles are smaller than 0.6 mm but larger than 0.075 mm. From the thermal analysis of reservoir sludge before and after the treatment, the authors confirmed that the OMRS particles have been organically modified and became hydrophobic before they were mixed with water, quartz sands and cement.

Kinuthia et al. (2009) reported the use of dark coloured colliery spoil, generated during mining of coal as replacement of fine and coarse aggregate in the preparation of medium strength concrete. It was obtained as two materials, a fine fraction of low plasticity, and a coarser non-plastic fraction. The two fractions were blended in equal proportions to produce a well-graded colliery spoil material, which is presented in Fig. 2.9 along with other constituents of prepared concrete. The specific gravity of both types of spoils was 1.8 and lighter than normal aggregate.

Ilangovana et al. (2008) reported the use of quarry rock dust as fine aggregate in the preparation of concrete. The authors defined the quarry rock dust as residue, tailing or other non-valuable waste material after the extraction and processing of rocks to form fine particles less than 4.75 mm. The level of utilisation of this dust in nations like Australia, France, Germany and UK has reached more than 60 % of its total production. The physical properties of the used dust are presented in Table 2.22.

Table 2.18 Physical properties of various mine waste aggregates (Yellishetty et al. 2008)

Properties	Sample 1	Sample 2	Sample 3	Sample 4
Fineness modulus: coarse	7.5	8.0	7.0	8.0
Fineness modulus: fine	3.3	3.4	3.2	3.5
Flakiness index, %	10	13	14	11
Elongation index, %	11	15	14	11
Impact value, %	19.09	29.00	15.75	21.94
Specific gravity	2.5	2.3	2.6	2.5
Water absorption, %	11.00	13.10	5.59	8.13
Bulk density: rodded, kg/l	1.39	1.25	1.40	1.30
Bulk density: loose, kg/l	1.36	1.22	1.30	1.20
Void ratio: rodded, %	44.40	46.80	46.00	48.00
Void ratio: loose, %	45.60	48.08	47.00	52.00
Crushed value, %	30.0	30.0	28.6	29.9
Abrasion value, %	29.42	30.00	30.00	29.00
Angularity number	3	3	1	7

Table 2.19 Properties of normal sand and paper sludge (Gallardo and Adajar 2006)

Properties	Sand	Sludge
Moisture content (%)	10.00	25.77
Specific gravity	2.60	1.57
Water absorption (%)	4.00	22.35
Silica (%)	18.91	0.00

The major oxide composition of the quarry rock dust and fine sand is presented in Table 2.23. Rock dust contains lesser amounts of silica and higher amounts of alumina, iron oxide, calcium oxide, magnesium oxide and titanium oxide than natural sand. On the other hand, the total alkali content in these materials is almost the same.

2.6 Ceramic Industry Waste

In the ceramic industry several types of waste are generated. According to Pacheco-Torgal and Jalali (2010), ceramic waste can be separated into two categories in accordance with the source of raw materials. In each category, the fired ceramic waste was classified according to the production process. This classification is presented in Fig. 2.10. These were produced by using red and white ceramic pastes. However, the use of white paste is more frequent and much higher in volume.

It has been estimated that about 30 % of the daily production in the ceramic industry goes to waste (Senthamarai and Devadas 2005). In Europe, the amount of waste in the different production stages of the ceramic industry reaches 3–7 % of

Table 2.20 Composition of reservoir sludge (Kuo et al. 2007)

Physical properties	
Gravel content, %	0
Sand content %	0
Silt content	31.9
Clay content	68.1
Specific gravity	2.72
Chemical composition	
Silica	53.03
Alumina	22.32
Iron oxide	8.56
Others	16.09

Table 2.21 Sieve analysis of sludge (OMRS) and quartz sands (Kuo et al. 2007)

OMRS		Quartz sand	
Sieve size	Cumulative passing (%)	Sieve size	Cumulative passing (%)
4.75	100	4.75	100
2.36	100	2.36	100
1.18	100	1.18	98.6
0.600	100	0.600	26.2
0.300	86.8	0.300	3.4
0.150	55.2	0.150	1.4
0.075	19.3	0.075	0.2

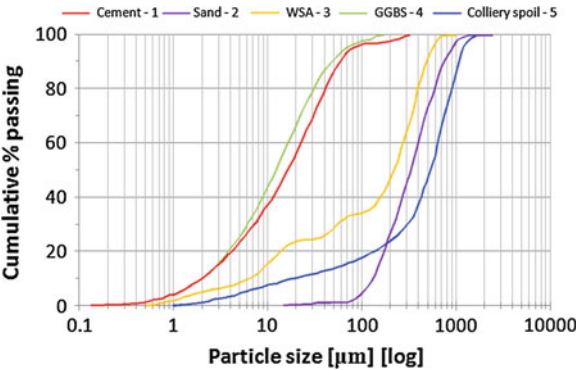


Fig. 2.9 Particle size distributions of colliery waste along with other materials (Kinuthia et al. 2009)

its global production (Fernandes et al. 2004). Although the reutilisation of ceramic waste has been practiced, the amount of waste reused in that way is still negligible (Pacheco-Torgal and Jalali 2010). Ceramic waste can be used safely in the production of concrete due to some of its favourable properties. Ceramic waste is durable, hard and highly resistant to biological, chemical and physical degradation

Table 2.22 Physical properties of quarry rock dust and natural sand (Ilangovana et al. 2008)

Properties	Quarry rock dust	Fine sand
Specific gravity	2.54–2.60	2.60
Bulk relative density (kg/m^3)	1,720–1,810	1,460
Water absorption (%)	1.2–1.5	Nil
Moisture content (%)	Nil	1.5
Particles finer than 0.075 mm (%)	12–15	6
Sieve analysis (Indian standard specification)	Zone II	Zone II

Table 2.23 Oxide composition of quarry rock dust and natural sand (Ilangovana et al. 2008)

Oxide constituents	Quarry rock dust (%)	Natural sand (%)
SiO_2	62.48	80.78
Al_2O_3	18.72	10.52
Fe_2O_3	6.54	1.75
CaO	4.83	3.21
MgO	2.56	0.77
Na_2O	Nil	1.37
K_2O	3.18	1.23
TiO_2	1.21	Nil
Loss on ignition	0.48	0.37

forces. In the following paragraphs, the aggregate properties of some ceramic waste will be discussed.

The waste used by Senthamarai and Devadas (2005) as coarse aggregate in the preparation of normal concrete was collected from a ceramic electrical insulator industry. The material was too big to be fed into a crushing machine and therefore it was broken into small pieces of about 100–150 mm with a hammer. The surface was also deglazed manually by chisel and hammer. These small pieces were then fed into a jaw crusher to reach the required 20 mm size.

The various physical properties of waste as well as those of natural aggregates are presented in Table 2.24. According to the same authors, the properties of ceramic waste aggregate were similar to those of natural crushed stone aggregate. The specific gravity and fineness modulus of aggregate were 2.45 and 6.88 respectively. The surface texture of the ceramic waste aggregate was found to be smoother than that of crushed stone aggregate. In the soundness test, after 30 cycles, the weight loss of ceramic waste aggregate was 51 % less than that of conventional crushed stone aggregate, since ceramics are more resistant to all chemicals.

Binici (2007) used ceramic industry waste as a partial replacement of fine aggregate (40–60 %) in the preparation of normal concrete. The bigger waste pieces were processed into the 4 mm or less size range by a procedure similar to that adopted by Senthamarai and Devadas (2005). The size grading of the waste ceramic fine aggregate was suitable for concrete production. The various physical properties of the waste aggregate are given in Table 2.25 along with those of conventional fine aggregate. Like the coarse aggregate properties of ceramic waste

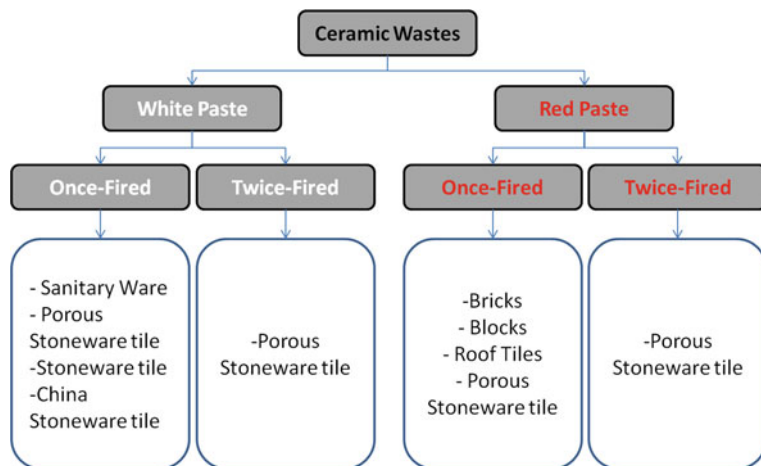


Fig. 2.10 Classification of ceramic wastes according to Pacheco-Torgal and Jalali (2010)

reported by Senthamarai and Devadas (2005), the properties of fine waste aggregates are similar to those of fine conventional aggregate. Chemically the ceramic waste fine aggregate is composed of silica (88.4 %) with 7.3 % of aluminium oxide.

Suzuki et al. (2009) used a porous waste ceramic coarse aggregate in the preparation of high-performance concrete. The aggregate was recovered from the waste of a local ceramic production plant. The aggregate was used in saturated surface-dry conditions.

Table 2.26 summarises the main characteristics of the porous ceramic waste aggregate along with natural coarse and fine aggregates and a commercial light-weight coarse aggregate that is used for internal wet-curing purposes.

The particles of the waste ceramic aggregate are coarser than those of the natural coarse aggregate (Fig. 2.11).

Topcu and Canbaz (2007) reported the use of crushed tile waste as aggregate in the preparation of concrete. Tile is produced from natural materials sintered at high temperatures and it does not contain any harmful chemicals. The tile waste was crushed into 4–16 mm and 16–31.5 mm sizes before using. The unit weight, specific weight and water absorption of crushed tiles were 925, 1,904 kg/m³ and 11.56 % respectively. Abrasion losses were 21 and 82 % for the Los Angeles abrasion tests at 100 and 500 cycles, respectively. The abrasion of crushed tile was quite high. The maximum amount of abrasion was 50 % at 500 cycles.

Guerra et al. (2009) investigated the use of a crushed recycled sanitary porcelain ceramic ranging from 5 to 20 mm as a partial substitution of natural coarse aggregate. The composition of the clay from which sanitary porcelain was made was: quartz 30 %, feldspar 26 %, kaolin 26 %, clay 18 % and lastly, glazes and metal oxides. The waste was used without cleaning due to the purity of the materials. However, the porcelain was crushed and sieved in the laboratory to get the required size range. The density and moisture content in the porcelain aggregate were 2.36 g/cm³ and

Table 2.24 Physical properties of coarse ceramic aggregate (Senthamarai and Devadas 2005)

Properties	Ceramic waste aggregate	Crushed stone aggregate
Specific gravity	2.45	2.68
Maximum size (mm)	20	20
Fineness modulus	6.88	6.95
Water absorption, 24 h (%)	0.72	1.20
Bulk density (kg/m ³)		
Loose	1,200	1,350
Compacted	1,325	1,566
Voids (%)		
Loose	50	48
Compacted	45	44
Crushing value (%)	27	24
Impact value (%)	21	17
Abrasion value (%)	28	20
Soundness test: weight loss after 30 cycles (%)	3.3	6.8

Table 2.25 Physical properties of coarse ceramic aggregate (Binici 2007)

Properties	Ceramic waste aggregate	Fine aggregate
Specific gravity	2.44	2.65
Maximum size (mm)	4	4
Fineness modulus	2.68	2.68
Water absorption, 24 h (%)	0.71	0.75
Bulk density (kg/m ³)	1,395	1,695
Voids (%)	44.20	46.20
Abrasion value (%)	28	–
Soundness test: weight loss after 30 cycles (%)	4.2	–

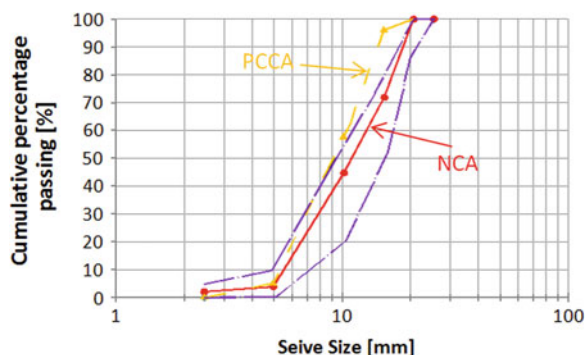
0.11 % respectively. The sieve analyses of this type of aggregate and of normal coarse aggregate (gravel) are presented in Table 2.27.

Torkittikul and Chaipanich (2010) reported the use of earthenware ceramic waste collected from ceramic industry as fine aggregate in the preparation of normal concrete. The larger ceramic waste pieces were broken with a hammer into smaller pieces (≤ 10 mm) and then they were crushed using a jaw crusher until the percentage passing sieve mesh No. 4 (opening 4.75 mm) was 100 %. The particle size distribution of ceramic waste used in this investigation was kept the same as that of sand by using sieves of mesh Nos. 4, 8, 16, 30, 50 and 100. The maximum particle size, water absorption and specific gravity of ceramic waste were 4 mm, 1.25 % by mass and 2.31, respectively. The particle shape of the crushed and sieved ceramic aggregate as observed by optical microscope (OM) was more angular than that of natural sand. The surface texture of ceramic waste as observed by scanning electron microscope (SEM) was found to be rougher than that of sand.

Pacheco-Torgal and Jalali (2010) reported the use of four different types of ceramic waste as coarse and aggregate as well as replacement of cement in the

Table 2.26 Physical properties of porous ceramic waste aggregate, natural coarse aggregate and a commercial lightweight aggregate (Suzuki et al. 2009)

Properties	Ceramic waste aggregate	Natural coarse aggregate	Natural fine aggregate	Commercial lightweight aggregate
Specific gravity	2.27	2.92	2.62	1.27
Water absorption capacity (%)	9.31	0.88	2.41	12.2–22.3
Fineness modulus	6.66	6.51	3.21	6.47
Crushing rate	21.4	7.86	–	37.0

Fig. 2.11 Grading curve of porous coarse ceramic aggregate (PCCA) and of natural coarse aggregate (Suzuki et al. 2009)

production of concrete. These are: ceramic bricks; white stoneware once fired; sanitary ware; white stoneware twice-fired. The major oxide constituents present in these waste types are silica and alumina. The major mineral phases present in all the waste types are quartz and feldspars. All the waste types were crushed with a jaw crusher to make the ceramic aggregate. The coarse and fine sized aggregates and ceramic powder were obtained after sieving. The densities of sand and coarse sized ceramic waste were 2,210 and 2,263 kg/m³ respectively. The water absorption capacities of sand and coarse sized ceramic aggregates were 6.1 and 6.0 % respectively.

De Brito et al. (2005) reported the use of ceramic hollow bricks fragments from the making of partition walls as a coarse aggregate for the production of non-structural concrete for pavement slabs. To characterise ceramic waste aggregate along with natural aggregate, the volume index of the different size fractions, the compacted oven dry bulk density of both types of aggregates, the compacted air-dried and water saturated bulk densities of waste ceramic aggregate, the specific densities of both types of aggregates at dry and saturated surface dry conditions, and the water absorption capacity were measured. The results are presented in Table 2.28.

The volume index indicates the shape of the particles: aggregates nearly spherical have an index near 1, compared to elongated ones with a smaller index. From the results of volume indices of various size fractions, the authors conclude that the grinding process of the recycled aggregates is a critical parameter since it strongly affects the volume index and therefore deserves further study. From the

Table 2.27 Sieve analysis of waste porcelain aggregate and natural gravel (Guerra et al. 2009)

Sieve mesh size (mm)	Amount retained after sieving (%)	
	Waste porcelain	Gravel
20	95.08	100
10	23.32	25.02
5	1.32	4.10
2.5	0.06	2.18
1.25	0.04	2.04
0.63	0.03	1.95
0.32	0.03	1.82
0.16	0.03	1.59

Table 2.28 Some physical properties of waste ceramic aggregate and of natural limestone aggregate (de Brito et al. 2005)

Properties	Waste ceramic aggregate	Limestone aggregate
Volume index of size fractions (mm)		
6.35–9.52	0.202	0.162
4.76–6.35	0.144	0.149
2.38–4.76	0.153	0.239
Bulk density (kg/m ³):		
Oven dry	1,159	1542
Air-dry	1,167	–
Saturated surface dry	1,265	–
Specific density (kg/m ³)		
Dry	2,029	2,626
Saturated surface dry	2,273	2,657
Water absorption (%)	12	1

water absorption value, the authors conclude that pre-saturation of ceramic aggregate is necessary and the weight of water absorbed by the ceramic aggregates should be measured by deducting the total weight of the aggregates just before they are mixed from their weight before saturation.

Guney et al. (2010) investigated the use of waste foundry sand as aggregate in the preparation of high-performance concrete. Foundry sand is high-quality silica sand and is a by-product from the production of both ferrous and non-ferrous metal casting. The raw sand used to cast metal is normally of higher quality than a typical bank run or the natural sand used in construction. However a small amount of clay (bentonite or kaolinite) is used as a binding material, binding the sand, and this mix is referred as green sand. Thus, foundry sand or green sand consists of high-quality 85–95 % silica sand, 7–10 % bentonite or kaolinite clay, 2–5 % water and about 5 % sea coal. Chemical binders, such as phenolic urethane, are also used to create sand cores (American Foundrymen's Society 2004). In the casting process, moulding sand is recycled and reused several times and therefore the recycled sand degrades to a point that it cannot be reused in the casting process. At this

Table 2.29 Physical properties of waste foundry sand (Guney et al. 2010)

Properties	Waste foundry sand
Specific gravity	2.45
Co-efficient of uniformity	5.50
Fines content (<74 μm), %	24
Active clay content (<2 μm), %	5
Moisture content (%)	3.25
pH	9.1
Organic content (%)	4.3

point, the old sand is removed from the cycle as a by-product, new base sand is introduced, and the cycle begins again.

The waste foundry green sand used by Guney et al. (2010) was used as foundry sand in steel and metal moulding facilities for the production of metal-steel parts at high temperatures (1,500 °C) for about 8–10 times until losing its moulding properties. The grain size distribution of waste foundry sand was uniform, with 100 % of the material under 1 mm, 10 % of foundry sand greater than 0.5 mm and 5 % smaller than 0.125 mm; it is black in colour due to the sea-coal organic binder used in the foundry sand. The used waste foundry sand is composed mainly of silica (98 %) with very small amounts of other oxides. The physical properties of waste foundry sand are presented in Table 2.29. The waste foundry sand was generally sub-angular to round in shape and have rough surface texture.

2.7 Use of Plastic Waste as Aggregate

Many references are available on the use of waste plastic as aggregate, filler or fibre in the preparation of cement mortar and concrete (Siddique et al. 2008). In this section, only the cases where plastic is used as aggregate replacement are presented. The various aggregate properties of the different types of plastic waste are presented. Finally, the possible future studies on plastic waste as aggregate in cement mortar and concrete are evaluated.

2.7.1 Types of Plastic Waste Used in the Preparation of Cement Mortar and Concrete

Different types of plastic waste such as polyethylene terephthalate (PET) bottle (Akcaozoglu et al. 2010; Albano et al. 2009; Choi et al. 2005, 2009; Kim et al. 2010; Marzouk et al. 2007; Yesilata et al. 2009), polyvinyl chloride (PVC) pipe (Kou et al. 2009), high density polyethylene (HDPE) (Naik et al. 1996), thermo-setting plastics (Panyakapo and Panyakapo 2008), shredded plastic waste (Al-Manaseer and Dalal 1997; Ismail and Al-Hashmi 2008), expanded polystyrene

foam (EPS) (Kan and Demirboga 2009), glass reinforced plastic (GRP) (Asokan et al. 2010) have been used as aggregate and filler in the preparation of cement mortar and concrete. Here, only the properties of those waste plastics which are used as aggregate will be discussed.

2.7.2 Sources and Preparations of Plastic Aggregate

The majority of plastic aggregate used in different studies came from plastic bottles or containers waste. In general plastic bottles are grinded at the laboratory by using a grinding machine and then sieved to get the suitable size fraction. However, in some studies, plastic waste with suitable sizes is collected from a plastic waste treatment plant. In this case, sieving into suitable size range was done at the laboratory. In some of the studies, treatment of plastic waste was done by heating, melting followed by mixing with other materials or other techniques.

Akcaozoglu et al. (2010) used granules from shredded PET bottle waste as aggregate, which were supplied from a commercial company. The bottles were obtained by picking up waste PET and then washing and mechanically crushing them into granules.

The waste PET (WPET) aggregate used in the Frigione (2010) study was manufactured from PET-bottle waste, unwashed and not separated on the basis of colour. To prepare WPET aggregate, PET-bottle waste, with a thickness of 1–1.5 mm, was grinded in a blade mill to the size of 0.1–5 mm. Then, the resulting particles were separated, through sieves, into a similar size grading to that of natural sand.

In the Batayneh et al. (2007) study the plastic waste aggregate was prepared by grinding original waste plastics into small sized particles. The size distribution of the prepared plastic aggregate was within the fine aggregate specified gradation limit as recommended in BS882:1992.

Ismail and AL-Hashmi (2008) studied the behaviour of concrete containing fibre-shaped plastic waste, which represents the discarded waste from plastic containers collected from plastic manufacturing plants. It consists of approximately 80 % polyethylene and 20 % polystyrene. After collection of plastic waste it was crushed into suitable size range.

In the Marzouk et al. (2007) investigation the polyethylene terephthalate (PET) waste was obtained from drinking water bottles that were first separated, washed and shredded. The shredded plastics were shredded once again, using a propeller crusher with grids of differently-sized meshes, at room temperature and moisture, in order to yield differently-sized aggregate. Plastic aggregate with three different size ranges, i.e. 50, 20 and 10 mm, were used in this study.

In the Remadania et al. (2009) study PET aggregate was prepared from drinking water bottles. For this purpose, PET-bottles were first separated, washed and shredded. The particles thus derived were then shredded once again, using a propeller crusher in order to control granular limit with crushing and to facilitate matrix-aggregate adhesion due to their irregular shape and rough surface texture.

Kou et al. (2009) produced PVC plastics granules by grinding scraped PVC pipes into small granules with about 95 % passing the 5 mm sieve.

Panyakapo and Panyakapo (2008) prepared an aggregate by grinding melamine waste. In this study, the ground melamine waste, retained by ASTM sieve numbers 10–40, was used.

In the Hannawi et al. (2010) investigation polyethylene terephthalate (PET) and polycarbonate (PC) waste was obtained from an industry.

Fraj et al. (2010) used the coarse rigid polyurethane foam waste with size range of 8–20 mm as coarse aggregate, which came from the destruction of insulation panels used in building industry. In order to maintain a comparable aggregate size distribution in the various concrete compositions this waste was sieved into five different size ranges. Mounanga et al. (2008) reported the behaviour of lightweight cement mortar containing rigid polyurethane foam waste with 0–10 mm size range as aggregate, which also came from the destruction of insulation panels used in building industry.

Laukaitis et al. (2005) used crumbled recycled foam polystyrene waste as well as spherical large and fine blown polystyrene waste in his investigation. Polystyrene granules of three types: blown (large + fine) and crumbled were used in this study. The crumbled granules were produced by mechanically disintegrating unusable or poor quality polystyrene slabs and from recycled polystyrene foam plastic. The foam was beaten for 5 min in a horizontal beater, which expanded the foam volume by 40 times. The hydrophilised polystyrene granules were prepared by soaking in water and under water saturated condition in vacuum desiccators.

Choi et al. (2009) prepared an aggregate by mixing granulated waste PET-bottle with powdered river sand at 250 °C. After air-cooling the mixture, the prepared aggregate and remaining powdered sand fraction was screened by using a 0.15 mm sieve. Choi et al. (2005) also prepared another type of plastic-based aggregate by mixing powdered blast furnace slag with granulated waste PET-bottle at 250 °C. The schematic diagram to produce PET aggregate according to Choi et al. (2009) is presented in Fig. 2.12.

Kan and Demirboga (2009) prepared an aggregate from waste-expanded polystyrene (EPS) foams. This modified waste-expanded polystyrene (MEPS) aggregate was prepared by melting EPS foam waste in a hot air oven at 130 °C for 15 min. The aggregate was separated into two size fractions similar to those of natural aggregate: 0–4 mm (fine aggregate) and 4–16 mm (coarse aggregate).

2.7.3 Evaluation of Properties of Plastic Aggregate

The major property, evaluated in almost all waste plastic aggregate related studies, was their size grading that was generally done by standard sieving methods (Batayneh et al. 2007; Frigione 2010; Ismail and Al-Hashmi 2008; Kou et al. 2009; Panyakapo and Panyakapo 2008; Marzouk et al. 2007). However Albano et al. (2009) adopted a different approach to estimate the size distribution of plastic aggregate. In his approach, sizes of the plastic aggregate were measured by means

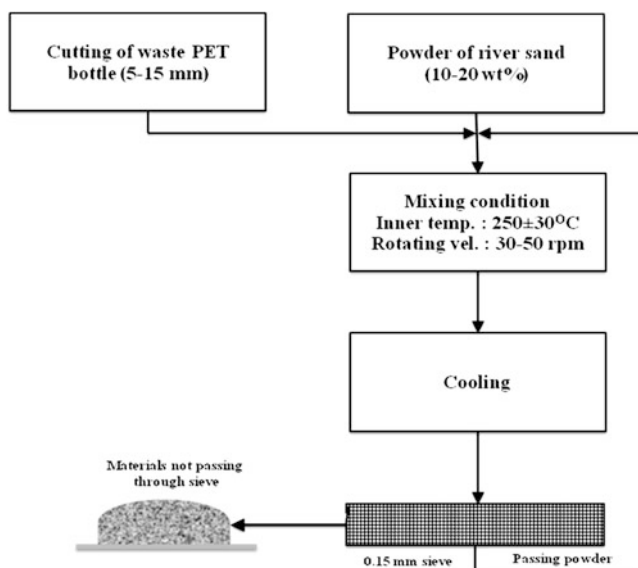


Fig. 2.12 Manufacturing process of sand coated PET aggregate (Choi et al. 2009)

of an electronic magnifying glass and the average particle size was determined using a software application. In the Mounanga et al. investigation (2008) the fine and coarse fractions of rigid polyurethane foam were analysed by laser size grading and sieve analysis method, respectively.

Other aggregate properties, such as bulk density, specific gravity, and water absorption, were also evaluated. Although the adopted procedure to evaluate these parameters was not described, standard procedures used for natural aggregate can be used. On the other hand, some other properties of plastic aggregate, such as tensile and compressive strengths, elasticity modulus, and decomposition temperature, were also reported. However, details of the experimental methods adopted to evaluate these properties were not provided. In some studies, parameters such as melting and initial degradation temperatures and melt flow index (MFI), which may be interesting for the evaluation of the fire behaviour of concrete containing plastic waste, heat capacity and thermal conductivity, were also determined.

2.7.4 Types and Ratio of Substitution of Natural Aggregate by Plastic Aggregate in Cement Mortar/Concrete Mixes

Plastic aggregate is generally produced from big sized waste plastic samples like drinking water bottles, other plastic containers and pipes. Therefore, both coarse and fine sized natural aggregate can be replaced by plastic aggregate. Both partial

and full substitutions of natural aggregate by plastic aggregate were reported in various references (Table 2.30).

2.7.5 Properties of Plastic Aggregate

In different studies, several types of plastic waste were used as aggregate. As the origins of this aggregate were completely different from that of natural aggregate i.e. one is organic and the other is inorganic, a big difference in properties was generally observed. The properties of the types of plastic used as aggregate in concrete are presented in Table 2.31.

The use of polyethylene terephthalate (PET) as aggregate was studied extensively compared to other types of plastic aggregate, namely the replacement of fine (≤ 4 mm) and coarse (≥ 4 mm) natural aggregate with similar size fractions of PET. However, in several studies fine natural aggregate of cement mortar and concrete was replaced with coarse sized PET aggregate too (Albano et al. 2009; Ismail and Al-Hashmi 2008).

Polyethylene terephthalate (PET) is used in various purposes such as in the preparation of beverage, food and other containers, thermoforming applications and synthetic fibre. PET may exist both as an amorphous and a semi-crystalline polymer (with particle sizes in nanometre to micrometre ranges) depending on its processing and thermal history. PET consists of polymerised units of the monomer ethylene terephthalate, with repeating $C_{10}H_8O_4$ units. The molecular formula of PET can be represented as $(C_{10}H_8O_4)_n$ and the molecular structure is presented in Fig. 2.13.

The degradation of PET is possible in highly alkaline solution like concrete pore fluid (Silva et al. 2005). The ions present in pore fluid, Ca^{2+} , Na^+ , K^+ , and OH^- , can attack the C–O bonds of PET and split the polymer into two groups: the group of the aromatic ring and that of aliphatic ester. The alkali ions can interact with aromatic rings and form Ca, Na, and K-terephthalates. On the other hand, hydroxyl ion can form ethylene glycol by reacting with aliphatic ester group.

Polyethylene terephthalate is thermoplastic polyester with Young's modulus in the range of 1,700–2,500 MPa and tensile strength up to 75 MPa. It has excellent chemical resistance properties. It is a semi-crystalline polymer, with a melting point of about 260 °C and initial degradation temperature of about 412 °C. In several references, the specific gravity and bulk density of the plastic aggregate were reported in the ranges of 1.24–1.36 g/cm³ and 326–547 kg/m³ respectively. The PET has very low thermal conductivity (0.13–0.24 W m⁻¹ K⁻¹) compared to limestone (1.26–1.33 W m⁻¹ K⁻¹) and sandstone (1.7 W m⁻¹ K⁻¹). Again the specific heat capacity of PET (1.0–1.1 kJ kg⁻¹K⁻¹) is higher than that of limestone (0.84 kJ kg⁻¹K⁻¹) and sandstone (0.92 kJ kg⁻¹K⁻¹).

Table 2.30 Types of substitution of natural aggregate by plastic aggregate in cement mortar/concrete

Reference	Types of composite	Types and amounts of substitution	Origin of plastic waste
Albano et al. (2009)	Concrete	Fine aggregate 10 and 20 vol. %	PET-bottle
Batayneh et al. (2007)	Concrete	Fine aggregate 5, 10, 15, 20 vol. %	–
Ismail and Al-Hashmi (2008)	Concrete	Fine aggregate	Plastic containers (80 % polyethylene and 20 % polystyrene)
Kou et al. (2009)	Lightweight aggregate concrete	10, 15, 20 wt % Fine aggregate	PVC pipe
Marzouk et al. (2007)	Mortar	5, 15, 30, 45 vol. % Fine aggregate 2, 5, 10, 15, 20, 30, 50, 70, 100 vol. %	PET-bottle
Panyakapo and Panyakapo (2008)	Non-load-bearing lightweight concrete	With sand fraction in aerated concrete	Melamine waste
Fraj et al. (2010)	Concrete	Coarse aggregate 34, 35, 45 vol. % of concrete	Waste polyurethane foam collected after destruction of insulation panels used in the building industry
Frigione (2010)	Concrete	Fine aggregate 5 wt %	PET-bottle
Remadnia et al. (2009)	Mortar	Fine aggregate 30, 50, 70 vol. %	PET-bottle
Hannawi et al. (2010)	Mortar	Fine aggregate 3, 10, 20 50 vol. %	A mixture of polyethylene terephthalate (PET) and polycarbonate industrial waste

(continued)

Table 2.30 (continued)

Reference	Types of composite	Types and amounts of substitution	Origin of plastic waste
Kan and Demirboğa (2009)	Concrete	Fine and coarse aggregate	Waste packaging materials composed of expanded polystyrene foams
Mounanga et al. (2008)	Mortar	25, 50, 75, 100 vol. % Fine aggregate	Waste polyurethane foam collected after destruction of insulation panels used in the building industry
Akcaozoglu et al. (2010)	Mortar	13.1–33.7 vol. % of concrete Fine aggregate	PET-bottle
Choi et al. (2005, 2009)	Mortar and concrete	50 and 100 wt % Fine aggregate 25, 50, 75, 100 vol. %	PET-bottle

Table 2.31 Properties of the types of plastic used as aggregate in concrete

Reference	Type of plastic	Particle size/shape	Density/specific gravity*/ apparent bulk density#	Water absorption	Other properties
Albano et al. (2009)	PET	0.26 and 1.14 cm (average size of two fractions)	–	–	MP: 248 °C Initial degradation temperature: 412 °C MFI: 70 g/ 10 min
Batayneh et al. (2007)	Waste plastic (PET?)	0.15–4.75 mm	–	–	–
Ismael and Al- Hashmi (2008)	80 % polyethylene + 20 % polystyrene	Length: 0.15–12 mm; Width: 0.15–4 mm; Fibre-shaped	#386.7 kg/m ³	0.02 %	CS: poor; TS: 5,000 psi
Marzouk et al. (2007)	PET	Type A: ≤0.5 cm; Type C: ≤0.2 cm; Type D: ≤0.1 cm	Type A: #326 kg/m ³ ; Type C: #345 kg/m ³ ; Type D: #408 kg/m ³	–	–
Remadnia et al. (2009)	PET	≤4 mm/Thin	#327 kg/m ³	0	TS: 75 MPa MP: 249–271 °C TC: 0.13 W/m K MHC: 1.1–1.3 kJ/ kg K
Akcaozoglu et al. (2010)	PET	0.25–4 mm	*1.27 g/cm ³		
Hannawi et al. (2010)	PET	1.6–10 mm	#547 kg/m ³ /*1.36		Colour: white; MP: 255; YM: 1,700– 2,510 MPa
Hannawi et al. (2010)	PC	≤5 mm	#646 kg/m ³ /*1.24	–	Colour: transparent; MP: 230–250; YM: 2,700 MPa
Choi et al. (2005)	PET (coated with slag)	Round and smooth	1.39/#844 kg/m ³	0	FM: 4.11
Choi et al. (2009)	PET (coated with sand)	0.15–4.75 mm/round and smooth	1.39/#844 kg/m ³	–	FM: 4.11

(continued)

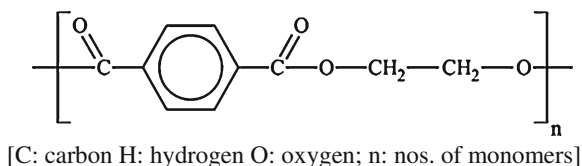
Table 2.31 (continued)

Reference	Type of plastic	Particle size/shape	Density/specific gravity*/ apparent bulk density#	Water absorption	Other properties
Frigione (2010)	PET	Thickness: 1–1.5 mm	–	–	–
Kou et al. (2009)	PVC	Size: 0.1–5 mm ≤5 mm/granular	1,400/#546 kg/m ³	–	CS: 65 MPa
Panyakapo and Panyakapo (2008)	Melamine waste	<10 mm	*1.48	5.6 %	TS: 60 MPa temperature resistance: 300 °C
Fraj et al. (2010)	Rigid polyurethane foam	8–20 mm	*45/#21 kg/m ³	13.9 %	Porosity: 98 %; CS: 174 kPa; YM: 5.6 MPa
Mounanga et al. (2008)	Rigid polyurethane foam	<10 mm	45 ± 2 kg/m ³ (apparent density)/2,191 kg/m ³ (density without porosity)	–	Porosity: 98 %
Kan and Demirboğa (2009)	Treated polystyrene foam	Coarse: 4–8 mm; Fine: 0–4 mm	#Coarse: 220 kg/m ³ ; #Fine: 162 kg/m ³	4.1 % (w/ w)	CS: 1.76–8.22 MPa; TC: 0.037– 0.052 W/m K; SGF: 0.22–0.24 (coarse) 0.31–0.34 (fine)

MP melting point; *MFI* melt flow index; *CS* compressive strength; *TS* tensile strength; *TC* thermal conductivity; *MHC* mass heat capacity; *YM* Young modulus; *FM* fineness modulus; *SGF* specific gravity factor

*: specific gravity; #: apparent bulk density

Fig. 2.13 Molecular formula of polyethylene terephthalate (C carbon; H hydrogen; O oxygen; n nos. of monomers)



2.8 Waste Tyre Rubber

The tremendous growth of automobile industry and the increasing use of car as the main means of transportation have increased its production, thus generating huge amounts of tyre rubber wastes. Extensive research works have been carried out to find the way to utilise the rubber tyre waste in various applications. Like plastic wastes, rubber tyre is non-degradable in nature at ambient conditions. This has generated massive stockpiles of used tyre and is creating huge environmental problems including fire hazards. Recently many countries have forbidden land filling of scrap tyres and therefore recycling of this material in the production of other products has immense importance. Out of several management options, the use of waste scrape tyre in the production of cement mortar and concrete is a promising path.

About 300 million tyres were generated in the USA in 2005 and the total number of scrap tyres consumed in end-use markets reached approximately 260 million (Rubber Manufacturer Association 2006). About 190 million scrap tyres remained in stockpile at the end of 2005 in the USA (Rubber Manufacturer Association 2006). This is a simple example and if this scenario is considered for the whole world, the amount of rubber tyres remaining as waste will be increased manifold.

Ganjian et al. (2009) classified tyre rubber into two classes according to the type of vehicles that use the tyre. The natural and synthetic rubber contents in car tyres are different from those in truck tyres (Table 2.32).

According to the use of tyre rubber in concrete preparation, it can be separated into three types (Ganjian et al. 2009):

1. Shredded or chipped rubber is used to replace gravel. By shredding the rubber pieces, particles about 13–76 mm big are produced.
2. Crumb rubber is used to replace sand with size range 0.425–4.75 mm and is manufactured by using special mills. The size of rubber particles depends on the type of mill used and the generated temperature.
3. Ground rubber can be used as a filler material to replace cement. The tyres are subjected to two stages of magnetic separation and screening to produce this size of rubber particles. In micro-milling process, the rubber particles made are in the range of 0.075–0.475 mm.

Several studies were made to evaluate the properties of concrete incorporating recycled tyre rubber as aggregate or filler material. The size, proportion in concrete mix, and surface texture of rubber particles affect the strength of concrete

Table 2.32 Compositions of car and truck tyres (Ganjian et al. 2009)

Constituents	Content in	
	Car	Truck
Natural rubber	14	27
Synthetic rubber	27	14
Black carbon	28	28
Fabric, filler accelerators, anti-ozonants	16–17	16–17
Steel	14–15	14–15

containing used tyre rubber. In the following sections, a literature survey on the aggregate properties of tyre rubber will be presented.

Ganjian et al. (2009) used two types of tyre waste as replacement of coarse aggregate and of cement in the preparation of concrete. The chipped rubber to replace coarse aggregates in normal concrete was prepared from big pieces of tyre rubber in the laboratory using scissors. The grading size of the rubber aggregate was similar to that of coarse natural aggregates (Fig. 2.14).

The relative density of chipped rubber as reported by these authors was 1.3. They found very low values of various strength properties of concrete containing rubber aggregate compared to concrete containing natural aggregate due to lack of proper bonding between rubber aggregates and the cement paste as compared to cement paste and natural aggregates. This is due to the organic nature of the rubber aggregate, which does have any interaction with cement paste.

Khaloo et al. (2008) reported the use of two types of scrap tyre rubber particles as aggregate in concrete preparation. The used crumb rubber was a fine material with grading close to that of sand and the coarse tyre chips used as coarse aggregate were produced by mechanical shredding. According to Neville (1995) tyre particles finer than 0.15 mm can disturb the cement paste reaction and therefore in this study, these particles were removed from the tyre aggregate source.

The various physical properties of tyre rubber aggregate along with those of fine and coarse aggregates were determined according to ASTM standard test methods and presented in Table 2.33. The low specific gravity and unit weight of rubber aggregate reduces the unit weight of concrete, which is prepared by replacing heavy natural aggregates with rubber aggregate. Due to the non-polar nature of rubber particles and their tendency to entrap air on their rough surfaces, concrete containing rubber aggregate has a higher air content than normal concrete. The modulus of elasticity of rubber aggregate with respect to mineral aggregates is very low and therefore rubber aggregates act as large pores, and do not significantly contribute to the resistance to externally applied loads.

The grading of tyre rubber materials was determined based on the ASTM C136 method and presented in Fig. 2.15. The grading curve of rubber materials was determined by using crushed stones in each sieve in order to provide adequate pressure on tyre rubber particles to pass the sieves.

Benazzouk et al. (2003) investigated the use of two types of rubber aggregates, compact rubber aggregates (CRA) and expanded rubber aggregates (ERA) as a

Fig. 2.14 Grading size of chipped rubber and natural coarse aggregate (Ganjian et al. 2009)

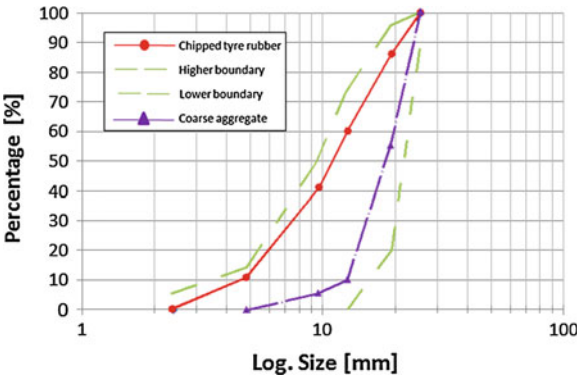


Table 2.33 Physical properties of different aggregates (Khaloo et al. 2008)

Aggregate type	Specific gravity	Water absorption (%)	Fineness modulus	Unit weight (kg/m ³)
Natural coarse aggregate	2.65	2.66	NA	1,701.3
Natural fine aggregate	2.67	5.01	5.34	1,716.8
Tyre rubber aggregate	1.16	–	NA	1,150

partial replacement of natural aggregate in the preparation of concrete. CRA has smooth surfaces with a water-accessible porosity of 0.3 %. The magnitude of the strain before fracture (strain is defined as the ratio of the length at failure and the initial length) is 85 %. ERA is a soft aggregate with alveolar surfaces. The magnitude of the strain before fracture and the water absorption of ERA are 200 and 3 % respectively.

The tyre rubber waste particles were reduced into three groups of 1–4, 4–8 and 8–12 mm size grading by means of mechanical grinding followed by sieving. According to author, the rubber aggregate differed from mineral aggregates in terms of both the strain magnitude and the non-brittle characteristic under loading.

The physical and mechanical properties of rubber aggregates are shown in Table 2.34. The hardness of the rubber aggregates was determined according to ASTM D 2240-75, where hardness is defined as the resistance offered by a specimen to the penetration of a hardened steel truncated cone.

Snelson et al. (2009) reported the preparation of concrete by using tyre rubber waste and ash. Rubber chips ranging from 15 to 20 mm were used to replace equal proportions of two different sized coarse limestone aggregate. The steel wires present in rubber chips were removed by an electromagnet during the shredding process.

Pierce and Blackwell (2003) reported the use of crumb tyre rubber as light-weight aggregate in the preparation of controlled low-strength material. The crumb rubber was produced from recapping truck tyres by using a sharp rotating disc. The tread was shaved off into 15 cm and smaller strips. The strips were then grinded down into crumb rubber. According to the authors, the production of crumb rubber

Fig. 2.15 Grading curves of natural and tyre aggregates (Khaloo et al. 2008)

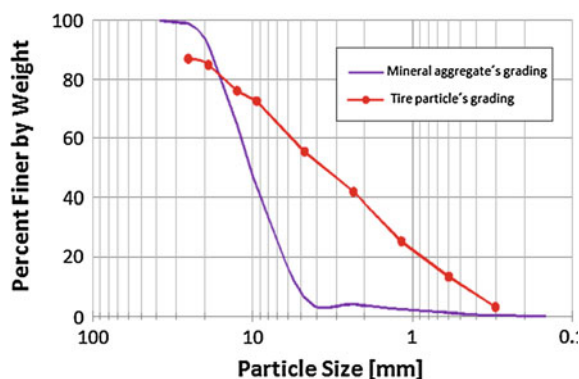


Table 2.34 Properties of rubber aggregates (Benazzouk et al. 2003)

Properties	CRA	ERA
Unit weight (kg/m^3)	1,286	1,040
Hardness (shore)	85	35
Modulus of elasticity (Mpa)	68	12

from truck tyre recaps was less expensive than that from the whole tyre because the tread is free from any fibrous material. The used crumb rubber aggregate was coarser than the ASTM C 33-02A specified limit for concrete sand. The crumb rubber used in this study was in dry state. However used crumb rubber aggregate can absorb a small amount of water equal to 2.4 % of its dry weight in the saturated surface dry condition that was higher than that of concrete sand, which is normally about 0.5 % or less. The bulk specific gravity of the crumb rubber aggregate varied between 0.53 and 0.60, which is nearly five times less than sand. Crumb rubber can thus be considered a lightweight aggregate source due to its low specific gravity.

The authors compared some properties measured during the investigation including cost of crumb rubber aggregate with some lightweight aggregates available in the markets and they are presented in Table 2.35.

The authors concluded that the cost of crumb rubber aggregate compared favourably with that of other lightweight aggregates and were lower than the costs of microlite and perlite.

Sukontasukkul and Chaikaew (2006) reported the use of crumb tyre rubber as a partial replacement of aggregate to produce concrete paving blocks. The crumb rubber particles passing ASTM sieve No. 6 and ASTM sieve No. 20 were used separately as aggregate in concrete. The specific gravity and fineness modulus of both crumb rubber aggregates are presented in Table 2.36 and their particle size distributions were presented in Fig. 2.16. According to the authors, the higher water requirement of concrete mix containing rubber aggregate than that of a conventional concrete mix was due to the low specific gravity and high specific surface area of rubber crumb.

Table 2.35 Comparison of properties of crumb rubber aggregate with some commercially available lightweight aggregates (Pierce and Blackwell 2003)

Types of lightweight aggregates	Bulk specific gravity	Bulk dry density (kg/m ³)	Cost per ton (US \$)
Crumb rubber	0.53–0.63	0.4	200+
Speccrete microlite®	0.40–0.45	0.1	500
Vermiculite	2.5 (unexpanded)	0.06–0.16 (unexpanded)	100–150
Perlite	2.2–2.4 (unexpanded)	0.03–0.40 (unexpanded)	320–400

Table 2.36 Some physical properties of crumb rubber aggregates (Sukontasukkul and Chaikaew 2006)

Properties	Crumb rubber No. 6	Crumb rubber No. 20
Average bulk specific gravity	0.97	0.88
Average bulk specific gravity (SSD)	0.98	0.89
Average apparent specific gravity	0.98	0.89
Average absorption (%)	1.01	1.70
Fineness modulus	4.98	2.62

2.9 Concluding Remarks

The aggregates typically account for 70–80 % of the concrete volume and play a substantial role in different concrete properties such as workability, strength, dimensional stability and durability. There is a growing interest in using waste materials as alternative aggregate materials and significant research is made on the use of many different materials as aggregate substitutes. The waste aggregates whose properties are highlighted in this section are: 1. Coal ash; 2. Ferrous and non-ferrous Slag; 3. Waste from food and agricultural industries; 4. Pulp and paper mill waste; 5. Leather waste; 6. Industrial sludge; 7. Mining industry waste; 8. Ceramic wastes; 9. Plastics wastes and 10. Rubber tyre.

Depending on the physic-chemical properties of aggregates, these can be classified in various ways. Out of several industrial waste aggregates, some waste types like coal ash aggregates, some types of slag and ceramic waste can be beneficially used as an aggregate in the preparation of concrete and cement mortars. On the other hand, some waste aggregates like coal bottom ash, plastic wastes and rubber tyre can be used as lightweight aggregates. Some types of waste like rubber waste and plastic waste are organic in nature and therefore they do not interact with cement pastes, ultimately reducing various mechanical properties of the resulting concrete composites.

The majority of the industrial waste aggregates have some special properties, which can be applied to develop some special purpose cement-based materials. For example, plastic and rubber aggregates have high toughness value, can absorb

- Akcaozoglu S, Atis CD, Akcaozoglu K (2010) An investigation on the use of shredded waste PET bottles as aggregate in lightweight concrete. *Waste Manage* 32(2):285–290
- Albano C, Camacho N, Hernandez M, Matheus A, Gutierrez A (2009) Influence of content and particle size of waste pet bottles on concrete behaviour at different w/c ratios. *Waste Manage (Oxf)* 29(10):2707–2716
- Al-Jabri KS, Al-Saidy AH, Taha R (2011) Effect of copper slag as a fine aggregate on the properties of cement mortars and concrete. *Constr Build Mater* 25(2):933–938
- Al-Manaseer AA, Dalal TR (1997) Concrete containing plastic aggregates. *Concr Int* 19(8):47–52
- Almusallam AA, Beshr H, Maslehuddin M, Al-Amoudi OSB (2004) Effect of silica fume on the mechanical properties of low quality coarse aggregate concrete. *Cem Concr Compos* 26(7):891–900
- Al-Negheimish AI, Al-Sugair FH, Al-Zaid RZ (1997) Utilization of local steel making slag in concrete. *J King Saud Univ Eng Sci* 9(1):39–55
- Al-Otaibi S (2008) Recycling steel mill scale as fine aggregate in cement mortars. *Eur J Sci Res* 24(3):332–338
- Alter H (2005) The composition and environmental hazard of copper slags in the context of the Basel convention. *Resour Conserv Recycl* 43(4):353–360
- Altun IA, Yilmaz I (2002) Study on steel furnace slags with high MgO as additive in Portland cement. *Cem Concr Res* 32(8):1247–1249
- American Foundrymen's Society (2004) Foundry sand facts for civil engineers. Report No.: FHWA-IF-04-004 prepared by American Foundrymen's Society Inc. for Federal Highway Administration Environmental Protection Agency Washington, DC, USA, 80 p
- Anastasiou F, Papayianni I (2006) Criteria for the use of steel slag aggregates in concrete. In: Konsta-Gdoutos MS (ed) *Measuring, monitoring and modeling concrete properties*. Springer, The Netherlands, pp 419–426
- Andrade LB, Rocha JC, Cheriaf M (2007) Evaluation of concrete incorporating bottom ash as a natural aggregates replacement. *Waste Manage (Oxf)* 27(9):1190–1199
- Andrade LB, Rocha JC, Cheriaf M (2009) Influence of coal bottom ash as fine aggregate on fresh properties of concrete. *Constr Build Mater* 23(2):609–614
- Asokan P, Osmani M, Price ADF (2010) Improvement of the mechanical properties of glass fibre reinforced plastic waste powder filled concrete. *Constr Build Mater* 24(4):448–460
- Atzeni C, Massidda L, Sanna U (1996) Use of granulated slag from lead and zinc processing in concrete technology. *Cem Concr Res* 26(9):1381–1388
- Ayano T, Sakata K (2000) Durability of concrete with copper slag fine aggregate, Fifth CANMET/ACI international conference on durability of concrete, SP-192. American Concrete Institute, Farmington Hills, pp 141–158
- Bai Y, Darcy F, Basheer PAM (2005) Strength and drying shrinkage properties of concrete containing furnace bottom ash as fine aggregate. *Constr Build Mater* 19(9):691–697
- Batayneh M, Marie I, Ibrahim A (2007) Use of selected waste materials in concrete mixes. *Waste Manage (Oxf)* 27(12):1870–1876
- Behnood A (2005) Effects of high temperatures on high-strength concrete incorporating copper slag aggregates. In: *Seventh international symposium on high-performance concrete*, SP-228-66, Washington, USA, pp 1063–1075
- Benazzouk A, Mezreb K, Doyen G, Goullieux A, Queneudec M (2003) Effect of rubber aggregates on the physico-mechanical behaviour of cement–rubber composites-influence of the alveolar texture of rubber aggregates. *Cem Concr Compos* 25(7):711–720
- Binici H (2007) Effect of crushed ceramic and basaltic pumice as fine aggregates on concrete mortars properties. *Constr Build Mater* 21(6):1191–1197
- Biswas AK, Davenport WG (1976) *Extractive metallurgy of copper*, 1st edn. Pergamon Press, Oxford
- Brinda D, Baskaran T, Nagan S (2010) Assessment of corrosion and durability characteristics of copper slag admixed concrete. *Int J Civil Struct Eng* 1(2):192–211
- Chen M, Zhou M, Wu S (2007) Optimization of blended mortars using steel slag sand. *J Wuhan Univ Technol* 22(4):741–744

- Cherif M, Rocha JC, Pera J (1999) Pozzolanic properties of pulverized coal combustion bottom ash. *Cem Concr Res* 29(9):1387–1391
- Choi YW, Moon DJ, Chung JS, Cho SK (2005) Effects of waste PET bottles aggregate on the properties of concrete. *Cem Concr Res* 35(4):776–781
- Choi YW, Moon DJ, Kim YJ, Lachemi M (2009) Characteristics of mortar and concrete containing fine aggregate manufactured from recycled waste polyethylene terephthalate bottles. *Constr Build Mater* 23(8):2829–2835
- Collins RJ, Ciesielski SK (1994) Recycling and use of waste materials and by-products in highway construction, NCHRP (National Cooperative Highway Research Program, Synthesis of Highway Practice), Issue No. 199, Transportation Research Board, Washington, USA
- Collins F, Sanjayan JG (1999) Strength and shrinkage properties of alkali-activated slag concrete containing porous coarse aggregate. *Cem Concr Res* 29(4):607–610
- Cyr M, Ludmann C (2006) Low risk meat and bone meal (MBM) bottom ash in mortars as sand replacement. *Cem Concr Res* 36(3):469–480
- Das SK, Yudhbir (2006) Geotechnical properties of low calcium and high calcium fly ash. *Geotech Geol Eng* 24(2):249–263
- de Brito J, Pereira AS, Correia JR (2005) Mechanical behaviour of non-structural concrete made with recycled ceramic aggregates. *Cem Concr Compos* 27(4):429–433
- Emery JJ (1995) Dominican Republic mega project uses hi-tech hot mix, Ontario Hot Mix Producers Association, OHMPA. *Asphalttopics* 8(2):23–56
- Escalante-Garcia JJ, Magallanes-Rivera RX, Gorokhovskiy A (2009) Waste gypsum-blast furnace slag cement in mortars with granulated slag and silica sand as aggregates. *Constr Build Mater* 23(8):2851–2855
- Etcheberria M, Pacheco C, Meneses JM, Berridi I (2010) Properties of concrete using metallurgical industrial by-products as aggregates. *Constr Build Mater* 24(9):1594–1600
- Faraone N, Tonello G, Furlani E, Maschio S (2009) Steelmaking slag as aggregate for mortars: effects of particle dimension on compression strength. *Chemosphere* 77(8):1152–1156
- Fernandes M, Sousa A, Dias A (2004) Environmental impact and emissions trade. Ceramic industry. A case study, Portuguese Association of Ceramic Industry APICER, Coimbra, Portugal
- Fraj AB, Kismi M, Mounanga P (2010) Valorization of coarse rigid polyurethane foam waste in lightweight aggregate concrete. *Constr Build Mater* 24(6):1069–1077
- Frigione M (2010) Recycling of PET bottles as fine aggregate in concrete. *Waste Manage (Oxf)* 30(6):1101–1106
- Gallardo RS, Adajar MAQ (2006) Structural performance of concrete with paper sludge as fine aggregates partial replacement enhanced with admixtures. In: Symposium on infrastructure development and the environment 2006, 7–8 Dec 2006, SEAMEO-INNOTECH, University of the Philippines, Diliman, Quezon City, Philippines
- Ganjian E, Khorami M, Maghsoudi AA (2009) Scrap-tyre-rubber replacement for aggregate and filler in concrete. *Constr Build Mater* 29(5):1828–1836
- Ghafoori N, Bucholtz J (1996) Investigation of lignite-based bottom ash for structural concrete. *J Mater Civ Eng* 8(3):128–137
- Guerra I, Vivar I, Llamas B, Juan A, Moran J (2009) Eco-efficient concretes: the effects of using recycled ceramic material from sanitary installations on the mechanical properties of concrete. *Waste Manage (Oxf)* 29(2):643–646
- Güney Y, Sari YD, Yalcin M, Tuncan A, Donmez S (2010) Reuses of waste foundry sand in high-strength concrete. *Waste Manage (Oxf)* 30(8–9):1705–1713
- Hannawi K, Kamali-Bernard S, Prince W (2010) Physical and mechanical properties of mortars containing PET and PC waste aggregates. *Waste Manage* 30(11):2312–2320
- Hughes ML, Halliburton TA (1973) Use of zinc smelter waste as highway construction material. *Highw Res Rec* 430:16–25
- Ilangovana R, Mahendran N, Nagamani N (2008) Strength and durability properties of concrete containing quarry rock dust as fine aggregate. *ARPN J Eng Appl Sci* 3(5):20–26

- Ishimaru K, Mizuguchi H, Hashimoto C, Ueda T, Fujita K, Ohmi M (2005) Properties of concrete using copper slag and second class fly ash as a part of fine aggregate. *J Soc Mater Sci* 54(8):828–833 (in Japanese)
- Ismail ZZ, Al-Hashmi EA (2008) Use of waste plastic in concrete mixture as aggregate replacement. *Waste Manage (Oxf)* 28(11):2041–2047
- Joshi RC, Lohia RP (1997) Fly ash in concrete production, properties and uses. Gordon and Breach Science Publishers, India
- Kan A, Demirboga R (2009) A novel material for lightweight concrete production. *Cem Concr Compos* 31(7):489–495
- Khaloo AR, Dehestani M, Rahmatabadi P (2008) Mechanical properties of concrete containing a high volume of tire-rubber particles. *Waste Manage (Oxf)* 28(12):2472–2482
- Khanzadi M, Behnood A (2009) Mechanical properties of high-strength concrete in-corporating copper slag as coarse aggregate. *Constr Build Mater* 23(6):2183–2188
- Kim HK, Lee HK (2011) Use of power plant bottom ash as fine and coarse aggregates in high-strength concrete. *Constr Build Mater* 25(2):1115–1122
- Kim SB, Yi NH, Kim HY, Kim JHJ, Song YC (2010) Material and structural performance evaluation of recycled PET fibre reinforced concrete. *Cem Concr Comp* 32(3):232–240
- Kinuthia J, Snelson D, Gailius A (2009) Sustainable medium-strength concrete (CS-concrete) from colliery spoil in South Wales UK. *J Civil Eng Manage* 15(2):149–157
- Kou SC, Poon CS (2009) Properties of concrete prepared with crushed fine stone, furnace bottom ash and fine recycled aggregate as fine aggregates. *Constr Build Mater* 23(8):2877–2886
- Kou SC, Lee G, Poon CS, Lai WL (2009) Properties of lightweight aggregate concrete prepared with PVC granules derived from scraped PVC pipes. *Waste Manage (Oxf)* 29(2):621–628
- Kuo WY, Huang JS, Tan TE (2007) Organo-modified reservoir sludge as fine aggregates in cement mortars. *Constr Build Mater* 21(3):609–615
- Kurama H, Topcu IB, Karakurt C (2009) Properties of the autoclaved aerated concrete produced from coal bottom ash. *J Mater Process Technol* 209(2):767–773
- Laukaitis A, Zurasukas R, Keriene J (2005) The effect of foam polystyrene granules on cement composite properties. *Cem Concr Compos* 27(1):41–47
- Lee HK, Kim HK, Hwang EA (2010) Utilization of power plant bottom ash as aggregates in fibre-reinforced cellular concrete. *Waste Manage (Oxf)* 30(2):274–284
- Leshchinsky A (2004) Slag sand in ready-mixed concrete. *Concrete* 38(3):38–39
- Lovell CW, Te-Chih K (1992) Corrosivity of Indian bottom ash, Transportation Research Record No. 1345, Transportation Research Board, Washington, DC, USA, 52 p
- Lun Y, Zhou M, Cai X, Xu F (2008) Methods for improving volume stability of steel slag as fine aggregate. *J Wuhan Univ Technol* 23(5):737–742
- Luxan MP, Sotolongo R, Dorrego F, Herrero E (2000) Characteristics of the slags produced in the fusion of scrap steel by electric arc furnace. *Cem Concr Res* 34(4):517–519
- Mahieux PY, Aubert JE, Escadeillas G (2009) Utilization of weathered basic oxygen furnace slag in the production of hydraulic road binders. *Constr Build Mater* 23(2):742–747
- Majzadeh K, Bokowski G, El-Mitiny R (1979) Material characteristics of power plant bottom ashes and their performance in bituminous mixtures: a laboratory investigation, In: 5th international ash utilization symposium. Report No. METC/SP-79/10, Part 2, US Department of Energy, Morgantown, West Virginia
- Manso JM, Gonzalez JJ, Polanco JA (2004) Electric arc furnace slag in concrete. *J Mater Civ Eng* 16(6):639–645
- Manso JM, Polanco JA, Losanez M, Gonzalez JJ (2006) Durability of concrete made with EAF slag as aggregate. *Cem Concr Compos* 28(6):528–534
- Marzouk OY, Dheilly RM, Queneudec M (2007) Valorisation of post-consumer waste plastic in cementitious concrete composites. *Waste Manage (Oxf)* 27(2):310–318
- Maslehuddin M, Al Mana AI, Samim M, Saricimen H (1989) Effect of sand replacement on the early-age strength gain and corrosion-resisting characteristics of fly ash concrete. *ACI Mater J* 86(1):58–62

- Maslehuddin M, Sharif AM, Shameem M, Ibrahim M, Barry MS (2003) Comparison of properties of steel slag and crushed limestone aggregate concretes. *Constr Build Mater* 17(2):105–112
- Metwally MEA, Seleem MH, Balaha MM, Abd El-Rahman H (2005) Utilizing of slag produced from recycling of spent lead-batteries as concrete aggregate. *Alex Eng J* 44(6):883–892
- Monshi A, Asgarani MK (1999) Producing Portland cement from iron and steel slags and limestone. *Cem Concr Res* 29(9):1373–1377
- Morrison C, Richardson D (2004) Re-use of zinc smelting furnace slag in concrete. *Eng Sustain* 157(4):213–218
- Morrison C, Hooper R, Lardner K (2003) The use of ferro-silicate slag from ISF zinc production as a sand replacement in concrete. *Cem Concr Res* 33(12):2085–2089
- Mounanga P, Gbongbon W, Poullain P, Turcry P (2008) Proportioning and characterization of lightweight concrete mixtures made with rigid polyurethane foam wastes. *Cem Concr Compos* 30(9):806–814
- Moura W, Masuero A, Dal Molin D, Vilela A (1999) Concrete performance with admixtures of electrical steel slag and copper concerning mechanical properties. In: 2nd CANMET/ACI international conference on high-performance concrete, SP-186 American Concrete Institute, Farmington Hills, MI, pp 81–100
- Naik TR, Singh SS, Huber CO, Brodersen BS (1996) Use of post-consumer waste plastics in cement-based composites. *Cem Concr Res* 26(10):1489–1492
- National Slag Association (2011) NSA product information: steel slag base and subbase aggregates, PI 207. National Slag Association, 25 Stevens Avenue, Building A, West Lawn, PA 19609. (http://www.nationalslag.org/archive/sf_prod_info_sheet.pdf. Accessed January 2011)
- Neville AM (1995) Properties of concrete, 4th edn. Longman, London
- Ozkan O, Yuksel I, Muratoglu O (2007) Strength properties of concrete incorporating coal bottom ash and granulated blast furnace slag. *Waste Manage* 27(2):161–167
- Öztürk T, Bayraklı M (2005) The possibilities of using tobacco wastes in producing lightweight concrete. *Agricultural Engineering International: the CIGR E-Journal*, Vol. VII, Manuscript BC 05 006
- Pacheco-Torgal F, Jalali S (2010) Reusing ceramic wastes in concrete. *Constr Build Mater* 24(5):832–838
- Panyakapo P, Panyakapo M (2008) Reuse of thermosetting plastic waste for lightweight concrete. *Waste Manage (Oxf)* 28(9):1581–1588
- Papadakis VG (1999) Effect of fly ash on Portland cement systems Part I. Low-calcium fly ash. *Cem Concr Res* 29(11):1727–1736
- Papadakis VG (2000) Effect of fly ash on Portland cement systems Part II. High-calcium fly ash. *Cem Concr Res* 30(10):1647–1654
- Papayianni I, Anastasiou E (2010) Production of high-strength concrete using high volume of industrial by-products. *Constr Build Mater* 24(8):1412–1417
- Park SB, Jang YI, Lee J, Lee BJ (2009) An experimental study on the hazard assessment and mechanical properties of porous concrete utilizing coal bottom ash coarse aggregate in Korea. *J Hazard Mater* 166(1):348–355
- Pellegrino C, Gaddo V (2009) Mechanical and durability characteristics of concrete containing EAF slag as aggregate. *Cem Concr Compos* 31(9):663–671
- Penpolcharoen M (2005) Utilization of secondary lead slag as construction material. *Cem Concr Res* 35(6):1050–1055
- Pereira DA, de Aguiar D, Castro F, Almeida MF, Labrincha JA (2000) Mechanical behaviour of Portland cement mortars with incorporation of Al-containing salt slags. *Cem Concr Res* 30(7):1131–1138
- Piercea CE, Blackwell MC (2003) Potential of scrap tire rubber as lightweight aggregate in flowable fill. *Waste Manage (Oxf)* 23(3):197–208
- Pofale AD, Deo SV (2010) Comparative long term study of concrete mix design procedure for fine aggregate replacement with fly ash by minimum voids method and maximum density method. *KSCE J Civil Eng* 14(5):759–764

- Proctor DM, Fehling KA, Shay EC, Wittenborn JL, Green JJ, Avent C, Bigham RD, Connolly M, Lee B, Shepker TO, Zak MA (2000) Physical and chemical characteristics of blast furnace, basic oxygen furnace, and electric arc furnace steel industry slags. *Environ Sci Technol* 34(8):1576–1582
- Qasrawi H, Shalabi F, Asi I (2009) Use of low CaO unprocessed steel slag in concrete as fine aggregate. *Constr Build Mater* 23(2):1118–1125
- Qian G, Sun DD, Tay JH, Lai Z, Xu G (2002) Autoclave properties of kirschsteinite-based steel slag. *Cem Concr Res* 32(9):1377–1382
- Rajamane NP, Annie Peter J, Ambily PS (2007) Prediction of compressive strength of concrete with fly ash as sand replacement material. *Cem Concr Compos* 29(3):218–223
- Ravina D (1997) Properties of fresh concrete incorporating a high volume of fly ash as partial fine sand replacement. *Mater Struct* 30(8):473–479
- Reddy AS, Pradhan RK, Chandra S (2006) Utilization of basic oxygen furnace (BOF) slag in the production of a hydraulic cement binder. *Int J Miner Process* 79(2):98–105
- Remadnia A, Dheilly RM, Laidoudi B, Quéneudec M (2009) Use of animal proteins as foaming agent in cementitious concrete composites manufactured with recycled PET aggregates. *Constr Build Mater* 23(10):3118–3123
- Rodriguez A, Manso JM, Aragon A, Gonzalez JJ (2009) Strength and workability of masonry mortars manufactured with ladle furnace slag. *Resour Conserv Recycl* 53(11):645–651
- Rogbeck J, Knutz A (1999) Coal bottom ash as light fill material in construction. *Waste Manage (Oxf)* 16(1):125–128
- Rojas MF, Sanchez de Rojas MI (2004) Chemical assessment of the electric arc furnace slag as construction material: expansive compounds. *Cem Concr Res* 34(10):1881–1888
- Rubber Manufacturer's Association (2006) Scrap tire markets in the United States, 2005 edn. Nov 2006, Rubber Manufacturer's Association, 1400 K Street, NW, Washington DC 20005 (http://www.rma.org/scrap_tires. Accessed May 2011
- Senthamarai RM, Devadas MP (2005) Concrete with ceramic waste aggregate. *Cem Concr Compos* 27(9–10):910–913
- Setien J, Hernandez D, Gonzalez JJ (2009) Characterization of ladle furnace basic slag for use as a construction material. *Constr Build Mater* 23(5):1788–1794
- Shen D-H, Wu C-M, Du J-C (2009) Laboratory investigation of basic oxygen furnace slag for substitution of aggregate in porous asphalt mixture. *Constr Build Mater* 23(1):453–461
- Shi C, Qian J (2000) High performance cementing materials from industrial slag—a review. *Resour Conserv Recycl* 29(2):195–207
- Shi C, Meyer C, Behnood A (2008) Utilization of copper slag in cement and concrete. *Resour Conserv Recycl* 52(11):1115–1120
- Siddique R (2003a) Effect of fine aggregate replacement with Class F fly ash on the mechanical properties of concrete. *Cem Concr Res* 33(4):539–547
- Siddique R (2003b) Effect of fine aggregate replacement with Class F fly ash on the abrasion resistance of concrete. *Cem Concr Res* 33(11):1877–1881
- Siddique R, Khatib J, Kaur I (2008) Use of recycled plastic in concrete: a review. *Waste Manage* 28(10):1835–1852
- Silva DA, Betioli AM, Gleize PJP, Roman HR, Gomez LA, Ribeiro JLD (2005) Degradation of recycled PET fibres in Portland cement-based materials. *Cem Concr Res* 35(9):1741–1746
- Snelson DG, Kinuthia JM, Davies PA, Chang S-R (2009) Sustainable construction: composite use of tyres and ash in concrete. *Waste Manage (Oxf)* 29(1):360–367
- Sorlini S, Collivignarelli C, Plizzari G, Foglie MD (2004) Reuse of Waelz slag as recycled aggregate for structural concrete. In: International RILEM conference on the use of recycled materials in building and structures, Barcelona, pp 1086–1094
- Sukontasukkul P, Chaikaew C (2006) Properties of concrete pedestrian block mixed with crumb rubber. *Constr Build Mater* 20(7):450–457
- Suzuki M, Meddah MS, Sato R (2009) Use of porous ceramic waste aggregates for internal curing of high-performance concrete. *Cem Concr Res* 39(5):373–381
- Taeb A, Faghihi S (2002) Utilization of copper slag in the cement industry. *ZKG Int* 55(4):98–100

- Topcu IB, Canbaz M (2007) Utilization of crushed tile as aggregate in concrete. *Iran J Sci Technol Trans B Eng* 31(5):561–565
- Torkittikul P, Chaipanich A (2010) Utilization of ceramic waste as fine aggregate within Portland cement and fly ash concretes. *Cem Concr Compos* 32(6):440–449
- Tossavainen M, Engstrom F, Yang Q, Menad N, Larsson ML, Bjorkman B (2007) Characteristics of steel slag under different cooling conditions. *Waste Manage (Oxf)* 27(7):1335–1344
- Wang G, Wang Y, Gao Z (2010) Use of steel slag as a granular material: volume expansion prediction and usability criteria. *J Hazard Mater* 184(1–3):555–560
- Wu W, Zhang W, Ma G (2009) Optimum content of copper slag as a fine aggregate in high strength concrete. *Mater Des* 31(6):2878–2883
- Xue Y, Wu S, Hou H, Zha J (2006) Experimental investigation of basic oxygen furnace slag used as aggregate in asphalt mixture. *J Hazard Mater B* 138(2):261–268
- Yellishetty M, Karpe V, Reddy EH, Subhash KN, Ranjith PG (2008) Reuse of iron ore mineral waste in civil engineering constructions: A case study. *Resour Conserv Recycl* 52(11):1283–1289
- Yesilata B, Isiker Y, Turgut P (2009) Thermal insulation enhancement in concretes by adding waste PET and rubber pieces. *Constr Build Mater* 23(5):1878–1882
- Yüksel I, Bilir T (2007) Usage of industrial by-products to produce plain concrete elements. *Constr Build Mater* 21(3):686–694
- Yüksel I, Siddique R, Özkan O (2011) Influence of high temperature on the properties of concretes made with industrial by-products as fine aggregate replacement. *Constr Build Mater* 25(2):967–972
- Zelic J (2005) Properties of concrete pavements prepared with ferrochromium slag as concrete aggregate. *Cem Concr Res* 35(12):2340–2349

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