



Standard Descriptive Nomenclature of Constituents of Aggregates for Radiation-Shielding Concrete¹

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1. Scope

1.1 This nomenclature is intended to give accurate descriptions of some common or important naturally occurring and synthetic constituents of aggregates for radiation-shielding concrete, that, at the same time, are not common or important constituents of concrete aggregates in general use. While most of the minerals and rocks discussed below may occur in small quantities in aggregates in general use, they are not major constituents of such aggregates. Common constituents of aggregates in general use are described in Descriptive Nomenclature C 294. Radiation-shielding concrete often contains such aggregates, but other special aggregates are used in some circumstances.

1.2 The synthetic aggregates included are ferrophosphorus and boron frit.

1.3 The descriptions are not adequate to permit the identification of materials, since accurate identification of natural and synthetic aggregate constituents in many cases can only be made by a qualified geologist, mineralogist, or petrographer, using the apparatus and procedures of those sciences.

2. Referenced Documents

2.1 ASTM Standards:

C 294 Descriptive Nomenclature for Constituents of Concrete Aggregates²

3. Types of Materials

3.1 Two classes of materials are described below. The first class consists of minerals and rocks formed from them, and synthetic materials, that have high specific gravity and in addition contain substantial proportions of atoms of high or moderately high atomic weight. They are referred to as heavy or high-density aggregates. The second class consists of minerals and synthetic glasses of substantial boron content that are particularly effective in absorbing thermal neutrons without producing highly penetrating gamma rays. The boron-frit glasses are included because of their frequent use.

¹ This nomenclature is under the jurisdiction of ASTM Committee C09 on Concrete and Concrete Aggregates and is the direct responsibility of Subcommittee C09.41 on Concrete for Radiation Shielding.

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² *Annual Book of ASTM Standards*, Vol 04.02.

HEAVY AGGREGATES

4. Descriptions of Naturally Occurring Constituents

4.1 Members of this group have higher specific gravities than aggregates in general use. Six are iron minerals, of which five are important iron ore minerals and the sixth is an ore of titanium. Two are barium minerals worked as the principal sources of barium salts. The other is ferrophosphorus, a mixture of synthetic iron phosphides.

4.2 The constituents are described below first as minerals, and then as major constituents of ores when their aspect as major constituents of ores affects the behavior of ores as concrete aggregates.

5. Iron Minerals and Ores

5.1 *Hematite* (Fe_2O_3)—Hematite has a hardness of 5 to 6 on Mohs' scale (will be scratched by hard steel), and a specific gravity of 5.26 when pure. The color varies from bright red to dull red to steel gray; luster varies from metallic to submetallic to dull; the streak is cherry red or reddish brown; it is nonmagnetic.

5.1.1 *Hematite Ores*—Rocks of which hematite is the major constituent vary from one deposit to another, and within the deposit, in specific gravity, toughness, compactness, amount of impurities, degree of weathering, and suitability for use as concrete aggregate. Hematite appears to be the iron ore mineral most exploited as a source of iron. The ores of the Lake Superior region are banded sedimentary ores consisting of layers rich in hematite, and sometimes goethite, iron silicates, such as stilpnomelane, minnesotaite, greenalite, grunerite, and iron carbonate, alternating with silica-rich layers of chert or fine-grained quartz or a mixture. The Birmingham, AL ores are oolitic with hematite replacements of oölites and fossils in a matrix that ranges from fine-grained earthy hematite, with or without calcite, to crystalline calcite. Hematite ores dust in handling, with the dust ranging in color from moderate red to dusky red to moderate reddish brown (5R 4/6 to 5R 3/4 to 10R 4/6).³

5.2 *Ilmenite* (FeTiO_3 with minor Mg and Mn)—Ilmenite has a hardness of 5 to 6 and specific gravity of 4.72 ± 0.04 when

³ National Research Council, Washington, DC, *Rock Color Chart* (1948) reissued 1964 by Geological Soc. Am., New York, NY.

pure. The color is iron black with metallic to submetallic luster; the streak is black; it is feebly magnetic.

5.2.1 *Ilmenite Ores*—These ores consist of crystalline ilmenite with either magnetite or hematite and constituents of the associated gabbroic or orthonostitic rocks. Massive ilmenite ores can form coarsely crystalline massive tough rocks but vary, from deposit to deposit, and within a deposit, in specific gravity, composition, hardness, and suitability for use as concrete aggregate. Many ilmenite ores consist of ilmenite disseminated in rock rather than concentrated as a major rock-forming mineral. Ilmenite concentrated from beach sands is usually altered to a variable degree, and its mechanical properties probably differ from those of unaltered ilmenite. One of the most widely used types of heavy aggregates is ilmenite ore.

5.3 *Lepidocrocite* ($\text{FeO}(\text{OH})$)—Lepidocrocite has a hardness of 5 and specific gravity of 4.09 when pure. The color varies from ruby red to reddish brown and the streak is dull orange. Lepidocrocite and goethite occur together, and lepidocrocite may be a constituent of goethite and limonite ores.

5.4 *Goethite* (HFeO_2)—Goethite has the same chemical composition as lepidocrocite but crystallizes differently. The hardness is 5 to $5\frac{1}{2}$ and the specific gravity is 4.28 ± 0.01 when pure and 3.3 to 4.3 in massive goethite. The color varies with the form, from crystals that are blackish brown with imperfect adamantine-metallic luster, to dull or silky luster in fibrous varieties; massive goethite is yellowish brown to reddish brown; clayey material is brownish yellow to ochre yellow. The streak is brownish yellow to ochre yellow.

5.4.1 *Goethite Ores*—These ores range from hard tough massive rocks to soft crumbling earths; these alterations frequently occur within fractions of an inch.

5.5 *Limonite*—A general name for hydrous iron oxides of unknown composition frequently cryptocrystalline goethite with adsorbed and capillary water, and probably mixtures of such goethite with similar lepidocrocite or hematite, or both, with adsorbed and capillary water⁴. The specific gravity ranges from 2.7 to 4.3 and the color from brownish black through browns to yellows. Limonite deposits range from recognizable crystalline goethite to dull massive material of indefinite composition, and therefore, properly limonite. Limonites of high iron content are also called brown iron ores. Frequently they contain sand, colloidal silica, clays, and other impurities.

5.6 *Magnetite* (FeFe_2O_4)—Magnetite has a hardness of $5\frac{1}{2}$ to $6\frac{1}{2}$ and specific gravity of 5.17 when pure. It is strongly magnetic; the color is black with metallic to semimetallic luster; the streak is black.

5.6.1 *Magnetite Ores*—These ores can form dense, tough, usually coarse-grained rocks with few impurities. Magnetite ores are associated with metamorphic or igneous or sedimentary rocks, and therefore, the impurities associated with magnetite ores may include a wide variety of rock-forming and accessory minerals. Magnetite occurs in association with hematite and ilmenite; magnetic ores are widely distributed,

but many are not suitable for use as heavy aggregate because the magnetite occurs disseminated through rock rather than as a major rock-forming mineral. One of the most widely used types of heavy aggregates is magnetite ore.

6. Barium Minerals

6.1 *Witherite* (BaCO_3)—Witherite has a hardness of 3 to $3\frac{1}{2}$ and a specific gravity of 4.29 when pure. The color ranges from colorless to white to grayish or many pale colors. Like calcite and aragonite, witherite is decomposed with effervescence by dilute hydrochloric acid (HCl). Witherite, the second most common barium mineral, occurs with barite and galena. England is the chief producer of witherite, and barium-containing heavy aggregates in Great Britain might be expected to contain witherite as a major constituent.

6.2 *Barite* (BaSO_4) (also, but improperly, called barytes)—Barite has a hardness of 3 to $3\frac{1}{2}$ and a specific gravity of 4.50 when pure. The color ranges from colorless to white to many usually pale colors.

6.2.1 Barite is the most common barium mineral and the major barium ore. It occurs in veins transecting many kinds of rocks, concentrated in sedimentary rocks, and as residual nodules in clays formed by the solution of sedimentary rocks. In many of its occurrences it is accompanied by clay or a calcium sulfate mineral (gypsum or anhydrite) or both. Although barite from residual deposits is often weathered, it is possible to obtain clean, well-graded barite aggregate.

7. Ferrophosphorus

7.1 Ferrophosphorus, a material produced in the production of phosphorus, consists of a mixture of iron phosphides, and has been used as coarse and fine aggregate in radiation-shielding concrete. Published specific gravities range from 5.72 to 6.50 for coarse aggregate. The coarse aggregate is reported to degrade easily and has been associated with extreme retardation of set in concrete. Ferrophosphorus in concrete releases flammable, and possibly toxic, gases which can develop high pressures if confined⁵.

7.2 Several iron phosphides are known, including silver gray to blue gray Fe_2P , with specific gravity of 6.50, FeP_2 with specific gravity of 5.07, and Fe_3P and FeP . Ferrophosphorus aggregates are silver gray but develop some rusty staining on exposure.

BORON-CONTAINING MATERIALS

8. Boron Minerals

8.1 The gamma rays that result from neutron capture by the lighter isotope of boron, boron-10, are much less penetrating than those which result from neutron capture by hydrogen; and for this reason boron and boron compounds are often used in

⁵ Clendenning, T. G., Kellam, B., and MacInnis, C., "Hydrogen Evolution from Ferrophosphorous Aggregate in Portland Cement Concrete," *Journal of the American Concrete Institute*, No 12, December 1968, *Proceedings*, Vol 65, pp. 1021–1028.

Mather, Bryant, discussion of Davis, Harold S., "Concrete for Radiation Shielding—In Perspective," and closure by author in "Concrete for Nuclear Reactors," ACI SP-34, Vol 1, 1972, pp 11–13.

⁴ Palache, Charles, et al., *The System of Mineralogy of J. D. Dana and E. S. Dana, Vol 1, Elements, Sulfides, Sulfosalts, Oxides*, Ed. 7, New York, NY, 1944, p 685.

TABLE 1 Commercially Important Boron Minerals

Name	Chemical Composition	Solubility in Cold Water	Produced
Borax	$\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$	1.6g/100 mL at 10°C: 3.86 g/ 100 mL at 30°C	United States, Argentina, Chile
Kernite	$\text{Na}_2\text{B}_4\text{O}_7 \cdot 4\text{H}_2\text{O}$	slowly soluble	United States, Argentina
Colemanite	$\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 5\text{H}_2\text{O}$	0.09 g/100 mL	United States, Turkey, USSR
Ulexite	$\text{NaCaB}_5\text{O}_9 \cdot 8\text{H}_2\text{O}$	slightly decomposed with loss of Na_2O	United States, Turkey, USSR, Argentina, Chile
Sassolite (boric acid)	H_3BO_3	5.15 g/100mL	Italy
Tncalconite	$\text{Na}_2\text{B}_4\text{O}_7 \cdot 5\text{H}_2\text{O}$	like borax	common dehydration product of borax
Priceite	$\text{Ca}_4\text{B}_{10}\text{O}_{19} \cdot 7\text{H}_2\text{O}$	insoluble	Turkey, USSR, United States
Inyoite	$\text{Ca}_2\text{B}_6\text{O}_{11} \cdot 13\text{H}_2\text{O}$	relatively insoluble	USSR, United States
Hydroboracite	$\text{CaMgB}_6\text{O}_{11} \cdot 6\text{H}_2\text{O}$	relatively insoluble	USSR
Szaibelyite	$(\text{Mg, Mn})(\text{BO}_2)(\text{OH})$	insoluble	USSR

neutron shields. The unusually high capture capability of boron-10 permits its use in relatively small quantities. Boron is most frequently incorporated in the concrete as borate minerals or synthetic boron frits. Both methods of incorporating boron cause some retardation of time of setting of the concrete, which can be counteracted by the use of a suitable accelerator. The experience recorded in the United States suggests that the cost of synthetic frits, which is higher than the cost of borate, may be counterbalanced by uniform composition of the frits, which permits effective control of the properties of the concrete.

8.2 Minerals that are commercially important sources of boron are principally sodium, calcium, and magnesium borate precipitates from waters in arid volcanic regions, or alteration products of such precipitates (Table 1)⁶. These hydrated minerals include some that are easily altered by changes in relative humidity and temperature. Some of them are soluble in or partly decomposed by cold water. Clay, gypsum, and salt are found in borate deposits. The presence of one or more of these in varying unknown amounts in a borate ore used in shielding concrete may cause problems in making concrete with controlled strength, setting time, volume stability, and workability, aside from the problem of varying degrees of retardation as the time composition, and thus the solubility, of the borate ore may range from lot to lot or within a lot.

8.3 Borate production in the United States is virtually limited to borax and borax derivatives obtained from natural brines at Searles Lake, CA, and brines produced by treating borates from the Kramer deposit at Boron, CA. California colemanite deposits, which also contain ulexite, are apparently not regularly worked but colemanite ores have been obtained from them for use in shielding concrete. Turkish borate ores, which have been referred to as “borocalcite,” but probably are

ulexite or colemanite or mixtures of the two, have been used in shielding concrete in Germany and Japan⁷.

8.4 Boron minerals that are stable and insoluble are usually not available in large quantities for use as aggregates. The recorded exceptions are described below.

8.4.1 *Paigeite*— $(\text{Fe}^{++}\text{Mg})\text{Fe}^{+++}\text{BO}_5$ —Paigeite has a hardness of 5 and specific gravity ranging from 4.7 at the paigeite end to 3.6 at the ludwigite end of the paigeite-ludwigite series. It is coal black or greenish black and insoluble in water, and tough. It is a high-temperature mineral occurring with magnetite in contact metamorphic deposits. Paigeite has been used as a heavy boron-containing aggregate in Japan.

8.4.2 *Tourmaline* $(\text{Na}(\text{Mg, Fe, Mn, Li, Al})_3\text{Al}_6[\text{Si}_6\text{O}_{18}](\text{BO}_3)_3(\text{OH}, \text{F})_4)$ —Tourmaline has a hardness of 7 and specific gravity ranging from 3.03 to 3.25; it ranges widely in color, but common varieties are brown or black. It is characteristically a mineral of granites, pegmatites, and pneumatolytic veins, but persists as a detrital mineral in sediments. Concrete having effective neutron-shielding characteristics has been described in which the coarse aggregate was serpentine and the fine aggregate a tourmaline sand concentrate.

9. Boron-Frit Glasses


9.1 Boron-frit glasses are clear, colorless, synthetic glasses produced by fusion and quenching used in making ceramic glazes. They may be obtained in many compositions, but those most useful in shielding concrete contain calcium, relatively high amounts of silica and alumina, and low amounts of alkalis. Increased silica and alumina decrease the solubility of the frits and thus diminish their retarding effect in shielding concrete. When there is a hazard from secondary radiation, limits on allowable proportions of sodium and potassium may be imposed.

10. Keywords

10.1 aggregates; boron; concrete; iron; minerals

⁶ Compiled from: Smith, W. C., “Borax and Borates,” Gillson, J. L., ed., *Industrial Rocks and Minerals*, 3rd Ed., American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, NY, 1960, pp 103–118, and Palache, C., Berman, H., and Frondel, C., *Dana’s System of Mineralogy*, 7th ed., Vol II, John Wiley and Sons, New York, NY 1951.

⁷ Henrie, J. O., “Properties of Nuclear Shielding Concrete,” *Journal of the American Concrete Institute*, Vol 31, July 1959, *Proceedings*, Vol 56, pp 37–46.

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