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Guideline for the Use of Steel Slag Powder in Concrete

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ABSTRACT

This document, developed by the Asian Concrete Federation, provides guidelines and recommendations for the use of steel slag powder as a mineral admixture in concrete. In this document, steel slag powder refers to a product obtained from basic oxygen furnace slag or electric arc furnace slag. The document addresses material specifications, mix design principles, production and execution procedures, as well as quality inspection and evaluation, and aims to standardize the safe and efficient use of steel slag powder in concrete across the region.

Keywords: Steel slag powder; Mineral admixture; Superfine powder; Soundness; Heavy metals; Setting time

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1. Scope

This guideline specifies requirements for the chemical and physical properties as well as quality control procedures and mix proportion design for steel slag powder for use as a mineral admixture in the production of concrete. The use of steel slag powder as a mineral admixture promotes the beneficial utilization of steelmaking by-products and reduces the consumption of Portland cement in concrete production.

Steel slag powder is defined as a product obtained from converter or electric furnace steelmaking, primarily composed of silicate and ferrite-aluminate minerals. It undergoes magnetic separation to remove iron before being ground to a specific fineness.

This guideline applies to steel slag powder concrete where steel slag powder accounts for at least 50% of the total mineral admixtures and at least 10% of the total binder materials. In this guideline, the term "binder" refers to the total amount of cement and mineral admixtures.

The use of steel slag powder in concrete shall comply with this guideline and the relevant national or regional standards currently in effect.

This guideline covers the entire process of utilizing steel slag powder in concrete, from fundamental requirements to practical implementation. It begins with the scope, definitions, followed by material specifications related to composition and mix design principles for steel slag powder concrete. Subsequent sections address production and execution practices, as well as quality inspection and evaluation procedures. The final section provides references to ensure consistency and reliability in application.

2. Definitions

Steel slag powder concrete is defined as concrete in which steel slag powder constitutes at least 50% of the mineral admixtures and at least 10% of the total binder materials.

Testing mortar is defined as mortar prepared by replacing 30% of the reference cement with steel slag powder, in accordance with ISO 679 [1] or the Chinese national standard GB/T 17671 [2], with a water-binder ratio of 0.50 and a sand-binder ratio of 3.0.

Water-binder ratio is defined as the ratio of water mass to binder material mass in concrete.

Median particle size D50 is defined as the median value where half of the particles by volume have diameters smaller than this value and half have diameters larger.

Strength activity index is defined as the ratio of compressive strength of the testing mortar (containing steel slag powder) to that of the reference mortar (without steel slag powder) under standard curing conditions at the same specified age, expressed as a percentage.

Initial setting time ratio is defined as the ratio of the initial setting time of the testing cement mixture (prepared by replacing 30% of cement with steel slag powder) to that of the reference cement mixture (without steel slag powder), expressed as a percentage. The paste shall be prepared using water in accordance with the standard consistency of the cement mixture, as specified in ISO 9597 [3] or GB/T 1346 [4].

For the purposes of this guideline, "shall" indicates a requirement; "should" indicates a recommendation; and "may" indicates a permitted option.

3. Specifications

3.1 General requirements

Steel slag powder used as a concrete mineral admixture shall meet soundness, radioactivity, heavy metals and setting requirements. Steel slag powder should not be used as the sole mineral admixture in concrete with strength grades above C45 (GB/T 50081 [5]) or equivalent C35/45 (EN 206-1 [6]).

For reinforced concrete structures subjected to severe, very severe, or extremely severe exposure conditions, as classified in GB/T 50476 [7] (see Table 1), steel slag powder shall not be used as the sole mineral admixture.

Table 1 Environmental action grades

Action grades / Environments	A Slight	B Mild	C Moderate	D Severe	E Very severe	F Extremely severe
Common environment (I)	I-A	I-B	I-C	--	--	--
Freeze-thaw environment (II)	--	--	II-C	II-D	II-E	--
Marine chloride environment (III)	--	--	III-C	III-D	III-E	
Deicing salt and other chloride environments (IV)	--	--	IV-C	IV-D	IV-E	--
Chemical corrosive environment (V)	--	--	V-C	V-D	V-E	--

Table 2 Technical specifications for steel slag powder

Technical parameters			Grade 1	Grade 2
Specific surface area (m^2/kg) [a]			⩾ 400	
Median particle size D_{50} (μm) [b]			⩽ 10	--
Density (g/cm^3) [a]			⩾ 3.0	
Moisture content (wt.%) [a]			⩽ 1.0	
Chloride content (wt.%) [a]			⩽ 0.06	
Sulfide content (wt.%) [a]			⩽ 4.0	
Free CaO content (wt.%) [a]			⩽ 4.0	
Activity index (%) [a]		7d	⩾ 75	⩾ 65
		28d	⩾ 90	⩾ 80
Fluidity ratio (%) [a]			⩾ 95	
Initial setting time ratio (%) [c]			⩾ 85 and ⩽ 140	
Soundness [a]		Boiling soundness	Qualified	
		Autoclave soundness (6h autoclave expansion rate) (%)	⩽ 0.50 [e]	
Radioactivity [d]			Qualified	
Leachable heavy metals (mg/L) [f]		Cr	⩽ 0.2	
		Mn	⩽ 1.0	

[a] The tests shall be carried out according to the methods specified in GB/T 20491 [10] (See Appendix A).
[b] D50 shall be determined by laser diffraction according to ISO 13320 [11] or equivalent GB/T 19077 [12].
[c] The initial setting time shall be determined according to ISO 9597 [3] or equivalent GB/T 1346 [4].
[d] The radioactivity inspection shall be conducted according to GB 6566 [13].
[e] If the MgO content in steel slag powder does not exceed 5%, autoclave soundness testing may be omitted.
[f] Leachable heavy metals shall be determined according to GB/T 30810 [14] and GB/T 30760 [15].

Steel slag powder concrete shall be prepared using Portland cement (P·I or P·II) or ordinary Portland cement (P·O) conforming to GB 175 [8], CEM I Portland cement or CEM II/A Portland-composite cement in accordance with EN 197-1 [9], or equivalent cement types complying with applicable national or regional standards in the place of use.

Steel slag powder concrete shall be protected from premature moisture loss and subjected to appropriate moisture curing at early ages to ensure adequate hydration and optimal performance.

3.2 Chemical and physical requirements

Steel slag powder used in concrete is classified into Grade 1 and Grade 2. The detailed technical specifications are summarized in Table 2.

3.3 Delivery and acceptance requirements

The supplier shall provide a certificate of compliance, factory inspection report, and type inspection report for each batch of steel slag powder. A batch shall consist of steel slag powder of the same grade produced under substantially identical conditions, and the batch size shall be determined in accordance with the relevant national standard. The certificate of compliance shall include the manufacturer's name, certificate number, steel slag powder grade, batch number, and production date.

The user shall inspect steel slag powder upon delivery in accordance with this guideline. The entry inspection shall include specific surface area, D50, activity index, soundness, and initial setting time. Steel slag powder that fails the soundness test shall not be used. If the D50 or activity index

does not meet the requirements for Grade 1 but satisfies the requirements for Grade 2, the material may be downgraded to Grade 2. If the material does not satisfy the requirements for Grade 2, it shall be considered non-compliant and shall not be used.

The batch classification and sampling methods shall comply with the following provisions:

(1) Steel slag powder shall be sampled in batches of 100 tons of the same type and grade supplied by the same manufacturer. If the quantity is less than 100 tons, it shall still be considered one batch.

(2) For bulk steel slag powder, samples shall be randomly taken from at least five different locations within the batch, with each sample weighing at least 2.0 kg. The samples collected shall be thoroughly mixed, and the required amount for testing shall be obtained using the quartering method (i.e., repeatedly dividing the mixed sample into four equal parts and retaining two opposite quarters until the required sample size is obtained). For bagged steel slag powder, samples shall be taken from 10 randomly selected bags, with each sample weighing at least 1.0 kg. The samples shall then be mixed and quartered in the same manner.

Steel slag powder shall be stored in a dry environment to prevent moisture absorption. If stored for more than six months, it shall be retested according to procedures in section 3.3 before use.

4. Design of Steel Slag Powder Concrete

4.1 Material requirements

The technical requirements for steel slag powder shall comply with section 3.2 of this guideline.

The cement shall be Portland cement or Ordinary Portland cement with a strength grade of 42.5 or higher, complying with the Chinese national standard GB 175 [8]. Alternatively, CEM I Portland cement or CEM II/A Portland-composite cement with a strength grade of 42.5 or higher, as specified in EN 197-1 [9], may also be used.

Fine aggregates shall conform to the Chinese national standard GB/T 14684 [16] or the European standard EN 12620+A1 [17].

Coarse aggregates shall conform to the Chinese national standard GB/T 14685 [18] or the European standard EN 12620+A1 [17].

Water shall conform to ISO 12439 [19] or the Chinese industry standard JGJ 63 [20].

Chemical admixtures shall conform to ISO 19596 [21] or the Chinese national standard GB 8076 [22].

For materials covered in section 4.1, equivalent national or regional standards may be used, provided that the corresponding technical requirements are comparable to those specified in the referenced standards.

Mineral admixtures such as slag, fly ash, and silica fume shall conform to the relevant current national or regional standards.

4.2 Mix proportion design

The compatibility of steel slag powder with chemical admixtures shall be determined through testing to verify that the required workability, setting time, and strength development of the concrete mixture can be achieved.

For mix proportion design, the testing age of steel slag powder concrete shall be determined according to the structural type and actual service loading time, typically 60 days or 90 days.

The content of steel slag powder in concrete shall be determined by testing, with the maximum recommended content specified in Table 3. The maximum content may be increased by 5% for mass concrete (e.g., foundation slabs).

However, the content shall be reduced when:

— High early strength is required;

— Construction occurs at ambient temperature below 5° C.

Table 3 Maximum content of steel slag powder (%)

Water-binder ratio	Maximum content			
	Portland cement (CEM I cement)		Ordinary Portland cement (CEM II/A cement)	
	Grade 1	Grade 2	Grade 1	Grade 2
> 0.4	25	20	20	15
⩽ 0.4	30	25	25	20

The designed concrete strength shall be calculated as follows:

$$f_{cu,0} \geqslant f_{cu,k}+1.645\sigma \quad (1)$$

where: $f_{cu,0}$——The designed concrete strength (MPa);
$f_{cu,k}$——Standard cubic compressive strength of concrete (MPa);
σ——Standard deviation of concrete strength (MPa). When sufficient test data are available, σ shall be determined from statistical analysis of the measured strength results; otherwise, the following recommended values may be adopted: 4 MPa for $f_{cu,k} \leqslant 20$ MPa, 5 MPa for 25 MPa $\leqslant f_{cu,k} \leqslant$ 45 MPa, and 6 MPa for 50 MPa $\leqslant f_{cu,k} \leqslant$ 55 MPa.

The mix proportion design of steel slag powder concrete shall be determined by either the absolute volume method, in which the sum of the constituent material volumes equals the designed concrete volume, or the density method, in which the mixture proportions are determined based on the target concrete density, and shall be verified through trial mixing. It is recommended to conduct systematic trial mixing with different mix designs to establish the empirical correlation between water-binder ratio and compressive strength.

The minimum binder material content and maximum water-binder ratio shall comply with the applicable standards at the location of use, for example GB 50010 [23] or EN 1992-1-1 [24].

5. Production and Execution of Steel Slag Powder Concrete

5.1 Production

The batching of steel slag powder shall be measured by mass, with an allowable deviation of ±2% when incorporated into concrete.

A compulsory concrete mixer shall be used, complying with ISO 18650-1 [25] or GB/T 10171 [26]. The steel slag powder concrete shall be evenly mixed, and the uniformity of the mixture in the same batch shall comply with ISO 22965-1 [27] or GB 50164 [28].

The slump loss of steel slag powder concrete over time shall be determined through testing and shall meet the construction requirements under different seasonal conditions.

5.2 Execution

Steel slag powder concrete shall be compacted by vibration during placement to ensure adequate consolidation, avoiding both over-vibration and insufficient vibration. It shall be finished at least twice, with the final finishing performed after bleeding stops and before final setting.

After placement, steel slag powder concrete shall be promptly subjected to moisture curing. Moisture curing may be achieved by water curing, wet covering, or other equivalent methods capable of preventing moisture loss and maintaining adequate moisture for hydration. The curing shall not be less than 14 days. For construction at ambient temperatures below 5° C, in addition to complying with local concrete construction regulations, the curing period shall not be less than 21 days.

When construction is carried out at ambient temperatures below 5° C, the placement temperature of freshly mixed steel slag powder concrete shall be at least 10° C.

The steam curing procedure for steel slag powder concrete in precast component production shall be established based on experimental testing. Attention should be paid to the setting time. If the setting time is significantly prolonged, the pre-curing (rest) period shall be sufficiently extended to ensure proper setting before the application of steam. When increasing the content of steel slag powder, the pre-curing period shall also be extended accordingly.

6. Quality Inspection and Evaluation of Steel Slag Powder Concrete

The compressive strength testing and assessment of steel slag powder concrete shall comply with GB/T 50107 [29], ISO 1920-4 [30], EN 12390-3 [31], or an equivalent standard applicable at the location of use.

The quality inspection and acceptance criteria for steel slag powder concrete construction shall comply with GB 50204 [32], EN 13670 [33], or an equivalent standard applicable at the location of use. Quality inspection typically covers appearance quality, dimensional tolerances, structural entity inspection, and quality control documentation.

The durability inspection and performance evaluation shall be performed according to JGJ/T 193 [34], or an equivalent standard applicable at the location of use. Durability evaluation typically covers cracking, carbonation resistance, chloride penetration resistance, freeze-thaw resistance, permeability, and other relevant durability indicators.

References

The following referenced documents are indispensable for the application of this document. The latest edition of the referenced document (including any amendments) applies.

[1] ISO 679. Cement – Test methods – Determination of strength.
[2] GB/T 17671. Method of Testing Cement Mortar Strength (ISO Method).
[3] ISO 9597. Cement – Test Methods – Determination of Setting Time and Soundness.
[4] GB/T 1346. Test methods for water requirement of standard consistency, setting time and soundness of the Portland cement.
[5] GB/T 50081. Standard for test methods of concrete physical and mechanical properties.
[6] EN 206-1. Concrete - Specification, performance, production and conformity - Part 1: Performance, requirements, factory production control and assessment criteria for individual values.
[7] GB/T 50476. Standard for Durability Design of Concrete Structures.
[8] GB 175. Common Portland Cement.
[9] EN 197-1. Cement – Part 1: Composition, Specifications, and Conformity Criteria for Common Cements.
[10] GB/T 20491. Steel Slag Powder Used for Cement and Concrete.
[11] ISO 13320. Particle size analysis — Laser diffraction methods.
[12] GB/T 19077. Particle size analysis by laser diffraction.
[13] GB 6566. Limits of Radionuclides in Building Materials.
[14] GB/T 30810. Test methods for leachable ions of heavy metals in cement mortar.
[15] GB/T 30760. Technical specification for co-processing of solid waste in cement kiln.
[16] GB/T 14684. Sand for Construction.
[17] EN 12620+A1. Aggregates for Concrete.
[18] GB/T 14685. Gravel and Crushed Stone for Construction.
[19] ISO 12439. Mixing water for concrete.
[20] JGJ 63. Standard for Water Used in Concrete.
[21] ISO 19596. Admixtures for Concrete.
[22] GB 8076. Concrete Admixtures.
[23] GB 50010. Code for Design of Concrete Structures.
[24] EN 1992-1-1. Eurocode 2: Design of Concrete Structures.
[25] ISO 18650-1. Building construction machinery and equipment — Concrete mixers Part 1: Commercial specifications.
[26] GB/T 10171. Concrete Mixing Station (Plant).
[27] ISO 22965-1. Concrete — Part 1: Methods of Specifying and Guidance for the Specifier.
[28] GB 50164. Standard for Quality Control of Concrete.
[29] GB/T 50107. Standard for Inspection and Evaluation of Concrete Strength.
[30] ISO 1920-4. Testing of Concrete — Part 4: Strength of Hardened Concrete.
[31] EN 12390-3. Testing of Hardened Concrete - Compressive strength of test specimens.
[32] GB 50204. Code for Acceptance of Construction Quality of Concrete Structures.
[33] EN 13670. Execution of Concrete Structures.
[34] JGJ/T 193. Standard for Inspection and Evaluation of

Concrete Durability.
[35] EN 196-6. Methods of Testing Cement – Part 6: Determination of Fineness (Blaine Method).
[36] ASTM C188-17. Standard Test Method for Density of Hydraulic Cement.
[37] EN 15167-1. Ground Granulated Blast Furnace Slag for Use in Concrete, Mortar and Grout - Part 1: Definitions, Specifications and Conformity Criteria.
[38] EN 196-2. Method of Testing Cement - Part 2: Chemical Analysis of Cement.
[39] EN 451-1. Method of Testing Fly Ash – Part 1: Determination of Free Calcium Oxide Content.
[40] EN 196-1. Methods of Testing cement - Part 1: Determination of Strength.
[41] EN 1015-3. Methods of Test for Mortar for Masonry - Part 3: Determination of Consistence of Fresh Mortar (by Flow Table).
[42] ASTM C151/C151M-18. Standard Test Method for Autoclave Expansion of Hydraulic Cement.

Appendix A

The general property testing of steel slag powder shall be conducted in accordance with GB/T 20491 [10]. Alternatively, the following clauses may be used as substitutes.

A.1 Specific surface area

In accordance with the European standard EN 196-6 [35].

A.2 Density

In accordance with the American standard ASTM C188-17 [36].

A.3 Moisture content

In accordance with the European standard EN 15167-1 [37].

A.4 Chloride content

In accordance with the European standard EN 196-2 [38].

A.5 Sulfide content

In accordance with the European standard EN 196-2 [38].

A.6 Free CaO content

In accordance with the European standard EN 451-1 [39].

A.7 Activity index

The activity index shall be expressed as the ratio (in percent) of the compressive strength of the combination (by mass) of 30% steel slag powder with 70% of test cement, to the compressive strength of the test cement on its own. The test cement shall conform to EN 197-1 [9] and shall be selected by the steel slag manufacturer, subjected to the following restrictions:

—It shall be a type CEM I, of strength class 42.5 or higher;

—the Blaine fineness shall be at least 300 m^2/kg;

—the tricalcium aluminate shall be between 6% and 12%;

—the alkali (Na_2O equivalent) content shall be between 0.5% and 1.2%.

The compressive strengths shall be determined in accordance with EN 196-1 [40], and the water-binder ratio shall be 0.50.

A.8 Fluidity ratio

The fluidity ratio shall be expressed as the ratio (in percent) of the fluidity of the combination (by mass) of 30% steel slag powder with 70% of test cement, to the fluidity of the test cement on its own. The fluidity shall be determined in accordance with EN 1015-3 [41], and the water-binder ratio shall be 0.50.

A.9 Autoclave soundness

The autoclave soundness shall be determined in accordance with ASTM C151/C151M-18 [42]. The test sample shall be prepared by mixing steel slag powder and test cement in a mass ratio of 3:7.

A.10 Boiling soundness

The boiling soundness shall be determined in accordance with ISO 9597 [3]. The test sample shall be prepared by mixing steel slag powder and test cement in a mass ratio of 3:7.