RECOMMENDATIONS FOR DESIGN AND CONSTRUCTION OF CONCRETE STRUCTURES USING HIGH STRENGTH LIGHTWEIGHT AGGREGATE MADE OF FLY ASH
- DRAFT -

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JSCE Research Subcommittee on High Strength Lightweight Aggregate Concrete

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ABSTRACT:
Now in Japan, approximately 8 million tons of coal ash is produced each year and this amount is expected to increase gradually in the years ahead. In order to effectively use this coal ash, a lightweight aggregate has been developed using fly ash as raw material. This aggregate has a bulk density of approximately 1.8 g/cm^3 and is lighter than ordinary aggregate, yet has almost the same water absorption and strength as ordinary aggregate. This new aggregate is expected to come into widespread use as a new concrete material from the standpoint of effective utilization of resources.
For this reason, the Japan Society of Civil Engineers (JSCE), in response to a request from the Research Organization for High Strength Artificial Aggregate Concrete, established a new Research Subcommittee on High Strength Lightweight Aggregate Concrete under the auspices of its Concrete Committee. Based on the knowledge obtained through the laboratory tests on

basic properties tests, site feasibility tests, structural tests and application in actual works, the JSCE published its "Recommendations for Design and Construction of Concrete Structures Using High Strength Lightweight Aggregate Made of Fly Ash (Concrete Library 106)" in July 2001. This paper summarizes the content mainly of the text of the draft recommendations.

Keywords : concrete structures, fly ash, high strength lightweight aggregate, specification, standard test method

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PREFACE

In November 1999, the JSCE Concrete Committee, acting on a request from the Research Organization for High Strength Lightweight Aggregate Concrete (chaired by the Electric Power Development Co., Ltd.), established a Research Subcommittee on High Strength Lightweight Aggregate Concrete and began what was expected to be a year and a half of research aimed at preparing "(Draft) Recommendations for Design and Construction of Concrete Structures Using High Strength Lightweight Aggregate Made of Fly Ash."

In order to prepare the draft recommendations, the following four working groups were established within this subcommittee:

- Aggregate Manufacture & Quality
- Concrete Properties
- Structure & Design
- Construction Procedures

These working groups held numerous discussions and performed numerous experiments in the process of investigating the properties of this material.

The aggregate is characterized by having a bulk density of approximately 1.8 g/cm^3 and is lighter than ordinary aggregate, yet having a water absorption and strength that are almost the same as ordinary aggregate. Accordingly, in order to determine the applicability of this new concrete material from the standpoint of the effective utilization of resources, the pumpability and freeze-thaw resistance of the material and the shear strength, which pose problems for conventional lightweight aggregate, were considered to be critical properties, and therefore tests were performed for these properties; more detailed tests were conducted as well. Furthermore, salt penetration, strength performance in dry environments and scaling were also tested. The results of these tests were reflected in the draft recommendations. In addition, the aggregate was ranked as a material that could be used in place of ordinary aggregate, and a quality standard separated from JIS A 5002 "Lightweight Aggregates for Structural Concrete" was prepared for this aggregate.

In the JSCE Concrete Library, the results of study by the subcommittee are published in the form of the (Draft) Recommendations for Design and Construction as well as JSCE standards and supplementary materials. It is our hope that this Library will help encourage the widespread use of concrete using high strength lightweight aggregate made of fly ash.

Finally, we would like to express our deep appreciation to Chief Secretary Toshiharu Kishi and all of the members of the committee for their efforts in various aspects of the preparation of these recommendations, from summing up the activities of the committee through publication.

July 2001

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RECOMMENDATIONS FOR DESIGN AND CONSTRUCTION OF CONCRETE STRUCTURES USING HIGH STRENGTH LIGHTWEIGHT AGGREGATE MADE OF FLY ASH

CHAPTER 1 GENERAL

1.1 Scope

(1)These recommendations consist of general standards for the design and construction of concrete structures using high strength lightweight aggregate made of fly ash. For points not specifically covered by these standards, refer to the JSCE's Standard Specifications for Design and Construction of Concrete Structures.

(2)These recommendations apply to concrete containing high strength lightweight aggregates compliant with JSCE-C 101 "Specification for high strength lightweight aggregate made of fly ash for concrete (Draft)."

(3)These recommendations cover concrete in which the coarse aggregates consist entirely of high strength lightweight aggregates.

[Commentary]

Japan's 1999 coal ash production was 7.6 million tons, about 75% of which was from the coal-fired electric power plants of utilities companies. About 80% of this ash was recycled as a raw material for use in cement and earthworks, while the remainder was disposed of in landfills. With landfill sites coming under pressure from environment-related regulations, there will be a shortage of disposal capacity in the near future, even as output of ash continues to increase. This makes it necessary to develop new ways of effectively using waste ash.

One issue facing the construction industry is a dwindling supply of natural aggregates for use in concrete and the negative impact of quarrying on the environment. The industry has been looking for a useful alternative to such natural aggregates. This has prompted efforts to develop techniques for manufacturing high strength lightweight aggregates from fly ash.

Such aggregates are dense, non-foaming materials manufactured by adding a conditioner (such as calcium carbonate powder) and a binder (such as bentonite) to the principal raw material, fly ash. The fly ash itself which is collected in electric precipitators and accounts for 90% of the coal ash. The resulting material is granulated and calcined into coarse aggregate of two grades of maximum size 15 mm and 20 mm, respectively. Chemically, these aggregates consist of stable minerals such as anorthite and mullite, and are dense, hard, and sufficiently durable for use as concrete aggregates.

(1)These recommendations consist of general standards for the design and construction of plain, steel-reinforced, and prestressed concrete structures using concrete containing aggregates meeting the standard. In cases where the recommendations are to be applied to special types of concrete structure, detailed studies including reviews and testing should be carried out with reference to these recommendations.

There is no separate chapter in these recommendations concerning the checking of durability of structures. The reason for this is that checking is based on characteristic values of the concrete, and the Construction Volume of the JSCE's Standard Specifications for Design and Construction of Concrete Structures (the "Construction Volume") is applicable to concretes containing these aggregates. It should also be noted that the framework given in the Construction Volume is applicable, as is, to the design of mix proportions when using these aggregates, as long as performance values for the concrete are calculated using empirical equations or determined from tests. However, if instead the checks are based on a review of specifications, such as the water-to-cement ratio, a different set of considerations becomes necessary. For example, it has been reported that the freeze-thaw resistance of concrete using these aggregates is slightly lower than that of concrete made with ordinary aggregates, so a table of maximum water-to-cement ratios that satisfy certain values of relative dynamic modulus of elasticity is provided in Chapter 5, "Design of mix proportions." Further, Chapter

10, "General design considerations" gives a description of how to apply these aggregates to high strength concrete.

A striking feature of concrete containing these fly ash aggregates is that strength is comparable to that of concrete mixed with ordinary aggregates, while its weight is approximately 10% less. This is because the coarse aggregate is as strong as ordinary aggregates, yet its density in the absolute dry state is approximately 1.8 g/cm^3, which is considerably less than that of ordinary aggregates. In terms of manufacture and construction, concrete containing these aggregates is more flowable when fresh because of the particles of aggregate are spherical, reguires less water per unit volume for a given flowability, and exhibits minimal drying shrinkage. Further, the concrete is more resistant to frost damage than concrete containing conventional artificial lightweight aggregates because the aggregates absorb no more than 3.0% water; this is as low as ordinary aggregates. With regard to deformability, the concrete has a slightly smaller Young's modulus than concrete containing ordinary aggregates, though it is larger than when conventional artificial lightweight aggregates are used.

Given these various advantages, concrete containing fly ash aggregate is expected to rationalize the design of bridges, piers, and other structures where dead loads can be reduced, and increase transportation efficiency where prefabricated items are shipped. Additionally, quality and supply can be better managed because the aggregates are manufactured at a plant. Already, this type of concrete has been used for the pre-tensioned, simply-supported main girders of slab bridges and reinforced concrete retaining walls.

(2)In comparison with conventional artificial lightweight aggregates, these aggregates are much closer to ordinary aggregates in terms of strength and percentage of water absorption. Accordingly, the recommendations not only categorize these aggregates as suitable for conventional artificial lightweight aggregates, but also as replacements for ordinary aggregates to achieve weight-saving. Given this categorization, the JSCE has prepared specifications for the quality of high strength lightweight aggregates made of fly ash separately from JIS A 5002 "Lightweight aggregates for structural concrete." These specifications accord with related items in JIS A 5002 as well as in JIS A 5005 "Crushed stone and manufactured sand for concrete." More specifically, as with ordinary aggregates, quality standards are established as follows to reflect the physical properties of the aggregates: not more than 3.0% in water absorption, 5.0% in soundness, 30% in resistance to abrasion, and 1.0% in fine particle content, respectively. Further, the following three levels of crushing load are established: 0.70, 1.50, and 2.10 kN or more. Taking into account the fact that the aggregates are artificial, standards are also established for chemical stability, which is related to chemical composition and chemical properties, and grading.

(3)The recommendations focus on concrete in which the coarse aggregate comprises high strength lightweight aggregates only, with river, terrestrial, or crushed sand or others as the fine aggregate. The recommendations do not cover cases where gravel or crushed stone aggregates are also used, but they do not preclude the use of such mixtures. Mixed coarse aggregates may be used by reference to the recommendations if verification is obtained that concrete with the desired performance be manufactured.

Standard usage conditions for aggregates call for surface dryness, meaning that the surface water has been removed after free absorption of water for 24 hours under normal pressure. The use of aggregates under the air-dried state or a state close to absolute dryness, i.e. where the aggregates are held after manufacture in a storage facility without water-absorption treatment, is not specifically prohibited. However, this also requires detailed studies, including review and testing, in advance.

1.2 Definition of terms

The terms used in these recommendations are defined as follows.

(1)"High strength lightweight aggregates made of fly ash" are artificial aggregates derived from fly ash as the principal raw material. Their manufacture is by granulation and calcination, in compliance with JSCE-C 101. For convenience, such aggregates are referred to as HFA aggregates in this text.

(2)"Concrete containing high strength lightweight aggregates made of fly ash" refers to concrete in which the coarse aggregate is high strength lightweight aggregate made of fly ash. For convenience, such concrete is referred to as HFA aggregate concrete in this text.

CHAPTER 2 QUALITY OF HFA AGGREGATE CONCRETE

2.1 General

HFA aggregate concrete shall exhibit minimal variations in quality, good workability, suitable for concreting, desirable strength, durability, watertightness, resistance to cracking and steel-protecting capability once hardened.

[Commentary]

HFA aggregate concrete for use in structures is required to possess the following characteristics to ensure that suitable performance is attained: good workability suitable for concreting work, strength, durability, watertightness, resistance to cracking, steel-protecting capability, and minimal variations in quality. That is, highly consistent quality is necessary. These requirements are no different from those for ordinary concrete. To ensure that HFA aggregate concrete satisfies these requirements, it is important to choose materials and to design mix proportions in full consideration of any effects the HFA aggregate has on concrete quality, while also taking into account the other materials used and factors such as design, construction, environmental conditions, and the use and significance of the structure.

HFA aggregate concrete is lighter than concrete made with ordinary aggregates and exhibits compressive strengths up to approximately 100 N/mm^2. Thus one feature of this concrete is that it can deliver greater strength than conventional artificial lightweight aggregate concrete. The properties of HFA aggregate concretes with a water-to-cement ratio of 25-60% (a compressive strength of 20-100 N/mm^2) and a slump of 8-21 cm are described below.

Fresh concrete

In general, HFA aggregates are used as coarse aggregate and ordinary aggregates as fine aggregates in HFA aggregate concrete. The density of the fresh concrete then ranges from 1,900 to 2,100 kg/m^3; that is, HFA aggregate concrete reduces weight by 10-15% as compared with ordinary concrete. Water content per unit volume is also lower by approximately 10% as compared with ordinary concrete of the same slump value. It has been proved that the HFA aggregates are suitable for use in self-compacting concrete that must exhibit self-filling properties, resistance to aggregate-mortar segregation, and good flowability. The high flowability and resistance to segregation of HFA aggregate concrete arises from the small difference in density between HFA aggregates and mortar, as well as the spherical shape of HFA aggregates and their high bulk density.

At relatively high water-to-cement ratios and slump values, HFA aggregate concrete indicates a stronger tendency to bleed than ordinary aggregate concrete. This seems to be due to the fact that, although the water content per unit volume is low, the aggregate particles are spherical and smooth-surfaced.

It has been confirmed that the water content of HFA aggregate concrete remains unchanged during transportation if an agitator is used. However, care needs to be taken in cases where the concrete may absorb water during pumping operations, leading to loss in slump values.

Hardened concrete

Strength

The compressive strength of HFA aggregate concrete cured under standard conditions varies linearly with water-to-cement ratio up to high strength values (approximately 85 N/mm^2); that is, up to a water-to-cement ratio of approximately 35%. Hardened HFA aggregate concrete gains compressive, flexural, and tensile strength values as high as those of ordinary aggregate concrete. In the case of HFA aggregate concrete with a compressive strength of 50 N/mm^2 or more and which has been cured under dry conditions (at a relative humidity of 60% and 20°C), no increase is seen in tensile or flexural strength from the moment the forms are removed (at the age of 2 days). HFA aggregate concrete is lower in bonding strength by 20-30% as compared with ordinary aggregate concrete, and almost same as ordinary artificial lightweight aggregate concrete. It is also as high in bearing strength as ordinary aggregate concrete (at a bearing area ratio A/A_a of 10.)

Deformability

The Young's modulus of HFA aggregate concrete is 10-20% less than that of ordinary aggregate concrete while exceeding that of artificial lightweight aggregate concrete by approximately 30%. This characteristic remains unchanged under dry conditions. The creep coefficient of HFA aggregate concrete is comparable to that of ordinary aggregate concrete, whereas drying shrinkage strain is approximately 30% smaller than that of ordinary aggregate concrete because the water content per unit volume can be reduced for the same water-to-cement ratio and slump value. The autogenous-shrinkage strain of HFA aggregate concrete is approximately the same as that of ordinary aggregate concrete.

Thermal properties

HFA aggregate concrete has a coefficient of thermal expansion slightly smaller than that of ordinary aggregate concrete, and it is almost equal to that of concrete made with crushed limestone. The other thermal properties of HFA aggregate concrete, such as thermal conductivity and diffusivity, are comparable to those of ordinary aggregate concrete.

Durability

HFA aggregate concrete shows less frost resistance than the ordinary aggregate concrete. However, this can be improved to comparable level by decreasing the water-to-cement ratio by approximately 10% and increasing the air content by 1-2% as compared with ordinary aggregate concrete. No alkali aggregate reaction takes place nor are heavy metals eluted in HFA aggregate concrete. The carbonation rate and salt permeability of HFA aggregate concrete can be regarded as practically equal to those of ordinary aggregate concrete.

CHAPTER 3 EXECUTION SCHEME

3.1 Execution scheme

(1)When planning to carry out construction with HFA aggregate concrete, an appropriate scheme of execution shall be developed in full consideration of the quality of aggregates to be used.

(2)The execution scheme shall be developed in accordance with the Construction Volume of JSCE's Standard Specification for Design and Construction of Structures.

[Commentary]

(1)HFA aggregates absorb little water and can be handled in the same manner as ordinary aggregates; that is, by keeping them under surface-dried or wet state. However, even when stored under these conditions, they may absorb additional water when under pressure, such as when being pumped long distances. This may result in excessive slump loss, and makes it necessary to check the slump in advance. When handling the concrete in a state close to absolute dryness, allowance should be made for slump; that is, the slump should be set a little larger than required. The scheme of execution shall be developed with due consideration of the aggregate quality, and slump must be checked prior to placing of the concrete.

(2)HFA aggregate concrete can be placed using the same techniques as for ordinary concrete, so the execution scheme shall be developed in compliance with the Construction Volume of JSCE's Standard Specification for Design and Construction of Structures.

Because HFA aggregates are composed chiefly of fly ash, coal ash can be put to other uses and natural aggregates preserved if HFA aggregates are used, thereby offering the advantage of reduced environmental impact. The concrete should also be placed in a manner that reduces the environmental impact of the work.

There is little difference in density between HFA aggregates and mortar, so as a consequence HFA aggregate concrete is more resistant to segregation. However, it is still necessary to select a an appropriate and cost-effective method of transporting the concrete such that segregation is minimized. This is of particular importance when a concrete pump is to be used, since it is not only the quality/performance of the hardened concrete that is affected by transportation, but also pumpability. This means that it is important to plan the sequence of operations in a well-balanced manner. It should also be noted that, when HFA aggregates are handled under air-dried state or conditions close to oven-dry state, there is a necessity for advance study of the concrete mix proportion, the type, number, and location of concrete pumps, the layout plan of pipes, and the pumping conditions.

3.2 Establishment of execution method

In developing an execution scheme for HFA aggregate concrete, methods of transporting, placing, compacting, finishing, curing, and jointing the concrete at the job site shall be established such that concrete performance comparable to or better than that assumed at the design phase is achieved, as specified in the Construction Volume of JSCE's Standard Specification for Design and Construction of Structures.

[Commentary]

HFA aggregate concrete can be handled in the same way as ordinary aggregate concrete. Consequently, the execution method should be established in accordance with the Construction Volume of JSCE's Standard Specification for Design and Construction of Structures.

3.3 Changes to the scheme

If changes to the execution method for HFA aggregate concrete become necessary during the course of the work, all changes shall be made in compliance with the construction and performance requirements, and the execution scheme must be revised if the method is changed.

[Commentary]

Just as in the case of concrete made with ordinary aggregates, any change to the method of execution when using HFA aggregate concrete shall be carried out such that the construction and performance requirements are realized. If changes are made to the execution method, the execution scheme must also be revised. It should be noted that changes to the method should be designed to ensure minimal influence elsewhere. In general, changes should be made such that original execution performance and design mix proportions remain unchanged, while they should also remain within the original scope of execution. If this is impossible, it is necessary to carry out a redesign, and the performance of the structure must be checked again.

CHAPTER 4 CONSTRUCTABILITY PERFORMANCE OF CONCRETE

4.1 Workability

(1)HFA aggregate concrete must have suitable workability for operations such as transportation, placing, compacting, and finishing.

(2)Workability can, as a rule, be established in terms of slump value and in terms of slump flow value in the case of self-compacting concrete.

(3)The slump of HFA aggregate concrete can be established from the list shown as Table 4.1.1.

Table 4.1.1 Standard slump values

Type	Slump value (cm)	
	Ordinary concrete	Concrete using AE superplasticizer
Reinforced concrete	5-12	12-18
Plain concrete	5-12	-

(4)The slump flow of self-compacting concrete containing HFA aggregates shall be established with reference to flowability, filling property, ability to pass through spaces, and resistance to segregation.

[Commentary]

(1)The term "suitable workability" means that normal concreting operations, such as transportation, placing and compacting, should be easy to carry out whatever the placing location, cross-sectional configuration and dimensions of the structural members, and the steel arrangement. At the same time, segregation should not occur during these operations. These requirements are not specific to HFA aggregate concrete.

(2) and (4) Workability is generally considered to depend on concrete's consistency and its resistance to segregation. Workability can be established from the slump value of the concrete. For self-compacting concrete, the slump flow is a suitable value on which to base a decision about workability. For self-compacting concrete with self-filling properties, it is recommended to refer to "Recommendations for construction of self-compacting concrete" for further information.

When the HFA aggregates are used in self-compacting concrete, the spherical shape of the aggregates lead to expectations of high flowability and improved ability to pass through spaces. Further, the content of HFA aggregates is higher in such concretes, so the cement content per unit volume is lower. In establishing a slump flow for self-compacting concrete containing HFA aggregates, it is necessary to take into account the difference in density between HFA and ordinary aggregates. In the case of ordinary aggregates, insufficient resistance to segregation leads to settlement of the aggregate, leaving the mortar alone to flow. With HFA aggregates, on the other hand, the aggregate particles remain suspended and difficulties emerge in keeping the concrete homogeneous if there is inadequate resistance to segregation.

(3)According to work records to date, HFA aggregate concrete is mainly used with the addition of an AE superplasticizer to produce self-compacting concrete, because of the need to ensure good pumpability. For use in precast concrete products, however, it is often the case that ordinary HFA aggregate concrete with sufficient workability can be obtained with no use of AE superplasticizer and is more cost-effective than HFA aggregate concrete with AE superplasticizer. For this reason, standard slump values for concretes with and without the AE superplasticizer are listed in the table.

4.2 Pumpability

(1)HFA aggregate concrete shall have characteristics suitable for pumping operations.

(2)Pumpability can be established by measuring the pressure loss per meter of horizontal pipe.

[Commentary]

HFA aggregates absorb less water than conventional artificial lightweight aggregates. Under excessive pumping pressure, however, they may absorb additional water, leading to significant changes in concrete properties during or after pumping operations. To avoid this, it is recommended for safety reasons that the pressure loss per meter of horizontal pipe multiplied by the equivalent horizontal distance to be pumped should not exceed 70% of the maximum theoretical pump discharge pressure, unless pumpability has already been verified through preliminary testing and other means.

CHAPTER 5 DESIGN OF MIX PROPORTIONS

5.1 General

The materials used in HFA aggregate concrete and the mix proportions adopted shall be determined such that the required performance is met while taking properly into consideration the limitations of concrete plants, material availability, and cost effectiveness (including transportation costs).

[Commentary]

The design of a mix is a multi-step process of determining the materials and their mix proportions such that established measures of concrete performance are attained. In the design of mix proportions for HFA aggregate concrete, all materials except the coarse aggregate and their mix proportions are first assumed, and checking is repeated until concrete performance requirements are satisfied. In this case, durability verification of the concrete structure shall be done in accordance with the Construction Volume.

Characteristics relating to the strength and durability of HFA aggregate concrete are comparable to those of ordinary aggregate concrete, except in the case of freeze-thaw resistance as noted earlier in Chapter 2. If testing is not carried out in accordance with JIS A 1148 "Freeze-thaw test method for concrete," the relative dynamic modulus of elasticity of the concrete shall be carried out in accordance with Section 5.4.2 of these recommendations. The checking of other concrete performances shall be carried out in accordance with the Construction Volume. It is recommended that the design of mix proportions for self-compacting concrete using HFA aggregates should follow "I. Recommendations for construction of self-compacting concrete" and "II. Manual for the design of mix proportions" of the "Recommendations for construction of self-compacting concrete."

5.2 HFA aggregates

(1)HFA aggregates shall comply with JSCE-C 101.

(2)HFA aggregates shall, as a rule, be used under the surface-dried state.

[Commentary]

(1)The HFA aggregates covered by these recommendations are manufactured in a process involving granulation and calcination of a mixture consisting of the principal raw material, fly ash, and subsidiary raw materials such as calcium carbonate powder and bentonite. Aggregates manufactured using other processes may also be used, as long as the required quality standards are met. The quality standards are as set in JSCE-C 101.

(2)Because HFA aggregates are densely packed, or in the non-foaming range, during the calcination process to increase strength, they are very sound, durable, resistant to abrasion, and low in water absorption. In fact, their tendency to absorb water is much lower than that of conventional artificial lightweight aggregates, and is close to that of ordinary aggregates. As a result, the water content of HFA aggregates can be controlled with relative ease during storage. Standard usage of the aggregates is under the surface-dried state; that is, in a state such that surface water is removed after submersion in water for 24 hours at normal pressure. If the aggregates are used under wet state, a correction must be made. For this reason, it is a general rule that the aggregates be surface-dried when used.

Research to date indicates that HFA aggregates used in a state of air-dried, or close to absolute dryness, bond more tightly to the mortar. As a result, the hardened properties of the concrete are superior to when the aggregate is used under the surface-dried state. However, although there is no prohibition on using air-dried aggregates, the amount of data amassed so far is still insufficient to prove the case. Accordingly, if aggregates are to be used in this way, it is important to carry out a prior verification the effects of water absorption during the course of concrete production on various properties of the concrete.

5.3 Fine aggregates

The fine aggregates used in HFA aggregate concrete shall be appropriately graded ordinary aggregates that are clean, hard, and durable. The content of deleterious materials, such as dust, dirt, organic matter, and chlorides, must be below permissible levels.

[Commentary]

The advantage of HFA aggregate concrete is its low weight. To gain further weight advantage, the use of a lightweight fine aggregate might be considered. However, there is a lack of experimental data available to clarify whether suitable performance can be obtained in this case. Accordingly, ordinary aggregates having a density of 2.5 g/cm^3 or greater under the absolute dry state, as specified in the Construction Volume, must be used as the fine aggregates in HFA aggregate concrete.

5.4 Concrete performance verification

5.4.1 General

Verification shall be made that concrete made of the selected materials using the chosen mix proportion does in fact satisfy the performance requirements.

[Commentary]

Concrete performance is generally verified by carrying out tests or by making performance estimations on the basis of past records. Although the track record of HFA aggregate concrete in actual use is short, laboratory tests indicate it delivers performance comparable to that of ordinary aggregate concrete, aside from freeze-thaw resistance. Accordingly, the performance of HFA aggregate concrete, except its relative dynamic modulus of elasticity, shall basically be verified in accordance with the Construction Volume. Even if the compressive strength is high (in the range 60-80 N/mm^2), strength verifcation should be based on the Construction Volume, because the water-to-cement ratio and the compressive strength are directly proportional to each other.

Of the check items for durability specified in the Construction Volume, the rate of carbonation and the chloride ion diffusion coefficient require the establishment of certain coefficients based on past records and research results. The results of tests using standard materials prove that the carbonation rate and chloride ion permeability of HFA aggregate concrete are comparable to those of ordinary concrete. Further, the density of the mortar matrix surrounding coarse aggregate particles has a significant effect on mass transfer, e.g. the transfer of gases and ions. The determinants of carbonation rate and chloride ion diffusion coefficient seem to be the water-to-cement ratio and the type and amount of binder rather than coarse aggregate properties. Accordingly, when carrying out verifications for HFA aggregate concrete, the same coefficients as specified for ordinary concrete in the Construction Volume can be used in equations for estimating carbonation rate and chloride diffusion. However, given the short track record of HFA aggregate concrete in the real world, it is recommended that an appropriate safety factor be set.

5.4.2 Checking of relative dynamic modulus of elasticity

When standard materials are used and no testing is carried out according to JIS A 1148, the relative dynamic modulus of elasticity shall be verified as below.

When freeze-thaw conditions are within the range established under JIS A 1148 and standard materials are selected as specified in Sections 5.2 and 5.3 of these recommendations and in the Construction Volume, it should be verified that the water-to-cement (binder) ratio of the concrete does not exceed the values listed in Table 5.4.1 and that the lower limit of air content is not below 5.5%.

Table 5.4.1 Maximum water-to-cement ratio of AE concrete permissible for HFA aggregate concrete under various freeze-thaw conditions (%)

Climatic conditions / Cross section / Surface condition of structures exposed to air	Harsh climate or regular freezing and thawing		Mild climate or temperature often falls below zero	
	Small[2)]	Ordinary	Small[2)]	Ordinary
(1) Constantly or frequently saturated with water[1)]	45 (85)	50 (70)	45 (85)	55 (60)
(2) Normal exposure aside from (1) above	50 (70)	55 (60)	50 (70)	55 (60)

Parenthesized values are the required relative dynamic modulus of elasticity of the concrete (%).
1)Including water channels, water tanks, abutments, retaining walls, tunnel linings, structural components in proximity to water or saturated with water, and girders and floor slabs distant from water but saturated with snowmelt, runoff, or water spray.
2)Parts of structures less than approximately 20 cm in cross-sectional thickness, etc.

[Commentary]

Laboratory tests have revealed that the resistance of HFA aggregate concrete to freezing and thawing is lower than that of ordinary concrete. When verifying the relative dynamic modulus of elasticity without carrying out actual tests according to JIS A 1148, the maximum water-to-cement ratios that satisfy the performance requirements are those listed in the table. If tests are carried out, the relative dynamic modulus of elasticity obtained through testing is compared directly with the characteristic values.

The modulus of elasticity of HFA aggregate concrete is greatly affected by curing conditions, variations in surface water content on the aggregate surface, and errors in material measurement. Accordingly, the target water-to-cement ratio used in the design of a mix proportion should be made 2-3% smaller than the value given in Table 5.4.1. The lower limit of air content, 5.5%, is based on the actual air content of fresh concrete obtained in a series of freeze-thaw tests on HFA aggregate concrete. For significant structures, it is suggested that freeze-thaw tests should be carried out to verify that the required relative dynamic modulus of elasticity satisfies the requirements. The air content can be determined in accordance with JIS A 1116, JIS A 1118, or JIS A 1128. However, when applying JIS A 1128 "Method of test for air content of fresh concrete by volumetric method" to HFA aggregate concrete, it is necessary to determine in advance an appropriate correction factor.

When concrete is exposed to salt, such as in antifreezing material and seawater, scaling of concrete tends to be deposited on the surface. To prevent this, the water-to-cement ratio should be reduced below 45% and the air content raised above 6%.

CHAPTER 6 STORAGE FACILITIES

6.1 General

Storage facilities for HFA aggregates shall allow for the separate storage of different types and grain sizes. The facilities shall be designed to prevent segregation of larger and smaller particles, to drain water from the bottom, and to maintain a stable water content on the aggregate surface.

[Commentary]

Storage facilities used for HFA aggregates must allow for separate storage of aggregates of different types and grain sizes. Moreover, since the aggregate particles are spherical, greater attention is needed to the storage facilities than in the case of ordinary aggregates. For instance, sloping sections should be minimized to prevent rolling of the aggregates during receipt and transportation.

When aggregates are used under conditions close to absolute dry, they must be stored in moisture-proof facilities.

CHAPTER 7 READY-MIXED CONCRETE

7.1 General

When HFA aggregates are used in ready-mixed concrete, they shall as a rule conform to JIS A 5308.

[Commentary]

Ready-mixed concrete containing HFA aggregates is equated with lightweight concrete in JIS A 5308 "Ready-mixed concrete." In purchasing ready-mixed concrete, it is important to specify quality requirements in compliance with the specifications given here and in the Construction Volume.

The nominal strength of lightweight concrete under JIS goes up to 33. Ready-mixed concrete over this nominal strength of 33 may be purchased as an off-specification product, thus taking advantage of HFA aggregates.

A suitable ready-mixed concrete plant should be selected in accordance with the specifications given in the Construction Volume.

CHAPTER 8 CONSTRUCTION

8.1 General

In carrying out construction with HFA aggregate concrete, adequate consideration shall be given to the particular properties of this type of concrete.

[Commentary]

Although the HFA aggregates are much lower in water absorption than conventional artificial lightweight aggregates, attention does need to be paid to the effects on pumpability of water absorption when under pressure. For buildings to reliably meet performance targets, it is essential to station experienced field engineers on site to monitor the construction procedure. Such engineers should at least be qualified to the level of registered professional engineer (with special expertise in concrete), registered chief concrete engineer, or concrete engineer.

8.2 Transport, placement, and compaction on site

8.2.1 Concrete pumping

(1)To ensure problem-free pumping of HFA aggregate concrete, suitable consideration shall be given to the following points:

(i)Choice of appropriate mix proportion considering the execution scheme, including plans for the transport and placement of the concrete

(ii)Development of the piping plan and choice of appropriate pipe size

(2)Determination of suitable number of concrete pumps for the execution scheme based on pump discharge rate and the capacity of pumps to be used.

[Commentary]

(1)Problem-free delivery of HFA aggregate concrete with pumps is achieved by reducing the pump discharge pressure through minimizing the pressure loss in the piping system.

In general, the higher the slump value, the smaller the pressure loss in the piping system and, therefore, the more stable the delivery process. If the slump value is too high, however, segregation may occur, resulting in detrimental effects on concrete performance. Accordingly, an appropriate slump value should be determined by balancing pumpability against required performance.

As with conventional artificial lightweight aggregates, water should ideally be well absorbed into HFA aggregates before they are used. However, because HFA aggregates absorb much less water than conventional artificial lightweight aggregates, they may be used under close to oven-dry state or under air-dried state. There are in fact reports of concrete containing HFA aggregates in close to oven-dry state being successfully pumped. If HFA aggregates are air-dried or close to absolute dryness when used, it is important to thoroughly examine the effects on concrete properties of water absorption during the mixing, delivery, and pumping processes.

Generally speaking, the larger the pipe size, the smaller the pump load. However, larger pipes are harder to handle during placing and require more time for relocation. For this reason, a close examination of pumping conditions is needed to determine an appropriate pipe size.

Pipe diameters should be 5 in. or larger, and joints must be strong enough to suit the pumping conditions. Pipework must be free from deformation, pitting, projections, damage, and deposits of hardened concrete. Bends should have a radius of 0.5 m or greater.

If conditions not specifically detailed in these recommendations are considered when designing plans for the delivery of HFA aggregate concrete using pumps or for its use as self-compacting concrete, the intent of the recommendations must be followed in squaring reality with the guidelines. In such cases, reference to the Construction Volume of JSCE's Standard Specification for Design and Construction of Structures, "Recommendations for the construction of concrete with pumps," and "Recommendations for the construction of self-compacting concrete" is recommended.

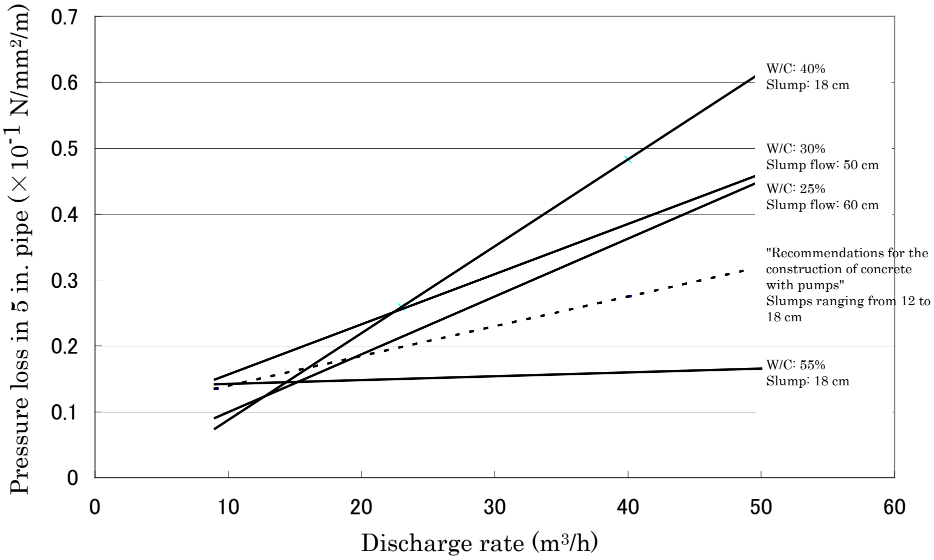
(2)Concrete pumping operations should be carried out by a member of the All Japan Concrete Pump Operators Association, and operators should be properly certified by the Ministry of Health, Labor and Welfare.

In selecting the concrete pumps themselves, it is important to comprehensively consider the following points: the type of fine aggregates to be used, the slump value, the cement content per unit volume, the type of concrete to be pumped, the mix proportion, the concrete quality, the piping plan, and the pump operating conditions. The planned discharge rate should be used as the basis for selecting an appropriate pump capacity and number of pumps to be employed. In doing so, adequate consideration should be given to work holdups, the time taken to relocate piping, wait times for mixer trucks on standby, and the time taken to switch mixer trucks.

When selecting a concrete pump, the maximum load that will act on the pump (P_{max}) can be calculated from the commonly used equation given below. It will be possible to pump the concrete if the calculated P_{max} is not more than 70% of the maximum theoretical discharge pressure of the pump. In any case, however, pumps with a discharge pressure of at least 4.0 N/mm^2 should be selected.

$$P_{max} = (\text{pressure loss per meter of horizontal pipe}) \times (\text{equivalent horizontal length})$$

For reference, the pressure loss of HFA aggregate concrete in a pipe is given in Commentary Figure 8.2.1. In the case of a self-compacting concrete with a low water-to-cement ratio or concrete with a low slump value, the pressure loss is relatively large. There is a lack of measured data on the pressure loss of HFA aggregated concrete in pipes in such situations, so actual measurements may well deviate from the values given in the figure. For this reason, it is suggested that pumping operations should be tested in advance. In particular, difficulty may be experienced in pumping HFA aggregate concrete under certain circumstances: if the concrete is a high strength, rich-cement concrete or a lean-cement concrete with a low slump, if the concrete temperature is especially high (as in hot weather), or if the concrete is delivered over a long distance or to a high elevation. If such situations are envisaged, concrete pumping should certainly be tested in advance of actual construction work, using a piping system that emulates the actual piping conditions. In such tests, the operating conditions of the concrete pump, the loads acting on the pump, and the properties of concrete samples taken at the pipe end should be monitored. To calculate the equivalent horizontal length for HFA aggregate concrete, the equivalent horizontal length for artificial lightweight aggregate concrete as in "Recommendations for the construction of concrete with pumps" can be used, as listed in Commentary Table 8.2.1.



Commentary Figure 8.2.1 Pressure loss of HFA aggregate concrete in a 5 in. pipe

Commentary Table 8.2.1 Equivalent horizontal length

Item	Unit	Nominal pipe size	Equivalent horizontal length (m)
Upward pipe	per meter	5 in. 6 in.	3
Tapered pipe*1	per section	7 in. to 6 in. 6 in. to 5 in.	3
Bend	per bend	90°, r = 0.5 m r = 1.0 m	6
Flexible hose	per section 5-8 m in length		20

*1 Tapered pipe has a standard length of one meter. The equivalent horizontal length is based on the smaller pipe size.

8.2.2 Placement and compaction

(1)HFA aggregate concrete shall be placed using a method that minimizes segregation.

(2)When using a vibrator, the depth of the concrete layer to be compacted, the vibration period, and the interval between periods of vibration shall be determined in advance.

[Commentary]

(1)The segregation of materials in HFA aggregate concrete results from settlement of the mortar and floating of the HFA aggregate, just as with conventional artificial aggregate concretes. However, it should be remembered that the behavior of ordinary concrete is the opposite.

HFA aggregates are often used in high-flowability or self-compacting concrete, as well as in concrete with ordinary properties. When HFA aggregates are used to produce ordinary concrete, it can be placed in the same manner as conventional artificial lightweight aggregate concrete. When HFA aggregates are used for self-compacting concrete, the concrete should be placed in accordance with "Recommendations for construction of self-compacting concrete."

(2)A vibrator should be used, as a rule, for the compaction of HFA aggregate concrete. Excessive vibration of the concrete may cause the HFA aggregate to float upward, so the compaction regime must be properly designed such that segregation does not take place. It is recommended that the depth of concrete to be compacted should be reduced, the period of vibration shortened, and the number of uses of the vibrator increased.

8.3 Forms and falsework

8.3.1 Vertical loading

In calculations used for the design of forms and falsework, the standard density of HFA aggregate concrete shall be taken to be 2,100 kg/m^3. For reinforced concrete, an additional 150 kg/m^3 shall be considered as the density of the steel reinforcement.

[Commentary]

Because HFA aggregate concrete combines the use of HFA coarse aggregates with ordinary fine aggregates, its density ranges from 1,900 to 2,100 kg/m^3. For this reason, the standard density used in calculations for the design of forms and falsework is taken to be 2,100 kg/m^3.

8.3.2 Lateral pressure

(1)In the design of forms, the lateral pressure exerted by the fresh concrete shall be taken into account.

(2)The lateral pressure exerted by HFA aggregate concrete using ordinary Portland cement and with a density of 2,100 kg/m^3 and a slump value of 10 cm or less can be calculated using Equations 8.3.1 to 8.3.3.

(a)For columns

$$p = 7.8\times10^{-3} + 0.78R/(T+20) \le 0.15 \text{ (N/mm}^2\text{) or } 2.1\times10^{-2}\, H \text{ (N/mm}^2\text{)} \qquad (8.3.1)$$

(b)For walls and R ≤ 2 m/hr.

$$p = 7.8\times10^{-3} + 0.78R/(T+20) \le 0.1 \text{ (N/mm}^2\text{) or } 2.1\times10^{-2}\, H \text{ (N/mm}^2\text{)} \qquad (8.3.2)$$

(c)For walls and R > 2 m/hr.

$$p = 7.8\times10^{-3} + (1.18+0.245R)/(T+20) \le 0.1 \text{ (N/mm}^2\text{) or } 2.1\times10^{-2}\, H \text{ (N/mm}^2\text{)} \qquad (8.3.3)$$

where:

p = lateral pressure (N/mm^2)
R = casting rate (m/hr.)
T = temperature of concrete in the form (°C)
H = height of concrete above point in question (m)

[Commentary]

The lateral pressure that concrete exerts on a form is an important factor in the design of the form. As with concrete containing ordinary aggregates, the placing of HFA aggregate concrete results in a distribution of lateral pressures similar to that of a liquid. Particularly careful attention should be paid in the case of concrete with a slump of 10 cm or more, superplasticized concrete, concrete using an AE superplasticizer, or self-compacting concrete; such concretes exert greater lateral pressure than ordinary HFA aggregate concrete.

8.4 Surface finish

The surface of placed concrete shall be finished as required.

[Commentary]

The density of HFA aggregates is approximately 1.8 g/cm^3 less than that of ordinary aggregates. Depending on the mix proportion, particles of HFA aggregate may float to the top, particularly if the concrete is excessively compacted. If the aggregate does float, the concrete should be first rough-finished with a wooden trowel to press the HFA aggregates down into the concrete, then with a steel trowel as required. Premature finishing with a wooden trowel may allow the HFA aggregate to float again. Thus the recommendation is to finish the concrete after bleeding has ended or surface water removed.

CHAPTER 9 INSPECTIONS

9.1 Acceptance inspection for HFA aggregates

All HFA aggregates shall be inspected at the time of acceptance to ensure that they meet the quality requirements. This acceptance inspection shall be carried out in accordance with Table 9.1.1.

Table 9.1.1 Acceptance inspection for HFA aggregates

Type of aggregate	Inspection item	Test and inspection methods	Timing and frequency	Criteria for acceptance
HFA aggregate	Quality control items specified in JSCE-C 101	Inspection of the test certificate issued by the manufacturer or by the method specified in JSCE-C 101	At least once a month before commencement of construction and during construction, or when beginning to use a new lot	Conformity with JSCE-C 101

[Commentary]

When HFA aggregates are delivered, they should be identified against delivery notices and labels as being the correct materials. Instead of actual testing on arrival, a test certificate awarded by a public laboratory or by the manufacturer, with respect to the items specified in JSCE-C 101, may be accepted as proof of quality. Where necessary, a test is to be carried out.

9.2 Acceptance inspection for HFA aggregate concrete

Acceptance inspections for HFA aggregate concrete shall be conducted in accordance with the Construction Volume.

[Commentary]

The pumpability of HFA aggregate concrete shall be checked by monitoring the maximum load acting on the concrete pump. The criteria for acceptance is that the maximum load does not exceed 70% of the maximum theoretical discharge pressure of the pump.

9.3 Inspection of work execution

Concreting work shall be inspected in accordance with the Construction Volume.

[Commentary]

Inspections of concreting work should be carried out in the same manner as for ordinary aggregate concrete. With certain mix proportions, however, HFA aggregates have a tendency to float if excessive compaction takes place. So visual inspection for floating is recommended during the pouring process.

CHAPTER 10 GENERAL DESIGN CONSIDERATIONS

10.1 General

(1)This chapter describes general design considerations pertaining to structures built with HFA aggregate concrete.

(2)The recommendations given in this chapter shall apply to HFA aggregate concrete with a specified design strength up to 80 N/mm^2 and a density not less than 1,900 kg/m^3.

(3)Standards for items other than those specified in this document shall be as specified in the Design Volume of the JSCE's Standard Specifications for Design and Construction of Concrete Structures (the "Design Volume"). The earthquake-resistant design of the concrete shall conform to the Earthquake-resistant Design Volume of the JSCE's Standard Specifications for Design and Construction of Concrete Structures (the "Earthquake-resistant Design Volume").

[Commentary]

(1)The design of structures to be built with HFA aggregate concrete is basically the same as that of structures using ordinary aggregate concrete. However, particular care is needed as regards the following characteristic features of HFA aggregate concrete:

(i)The density of HFA aggregate concrete is 1,900-2,100 kg/m^3, or 10%-15% lower than that of ordinary aggregate concrete.

(ii)The Young's modulus of HFA aggregate concrete is 10%-20% smaller than that of ordinary aggregate concrete.

(iii)The tensile strength of HFA aggregate concrete increases with compressive strength when the aggregate is used wet, as with ordinary aggregate concrete. However, tensile strength reaches a peak when the aggregate is in the air-dried state at compressive strength of 50 N/mm^2 or above.

(iv)The bonding strength of massive HFA aggregate concrete containing steel reinforcement is comparable to that of ordinary aggregate concrete. However, the results of tests conducted in accordance with the JSCE-G 503 "Method of testing the bonding strength of concrete with steel reinforcement by the pull-out method" indicate that the bonding strength of HFA aggregate concrete may be 20%-30% lower than that of ordinary aggregate concrete.

(v)The fatigue strength of HFA aggregate concrete is as high as that of ordinary aggregate concrete.

(vi)The shear strength of flexural members without shear reinforcement and the punching shear strength of plane members using HFA aggregate concrete are approximately 20% lower than the values for ordinary aggregate concrete.

(2)HFA aggregate concrete can achieve high strengths, exceeding 80 N/mm^2, without difficulty. However, there is little data available with regard to these high strengths, so an upper limit of strength is specified. The lower limit of density, on the other hand, is set on the basis of test conditions from which design equations for shear strength were obtained. These recommendations are applicable to concrete beyond these artificial limits if it can be verified through appropriate tests that the required performance can be met.

(3)Standards for items other than those specified in this document shall conform to the Design Volume. For instance, safety factors are not specified in these recommendations, because the standards given in the Design Volume are directly applicable. Because the basic standards for earthquake-resistant design are basically the same as for ordinary aggregate concrete, the earthquake-resistant design of structures built with HFA aggregate concrete should conform to the Earthquake-resistant Design Volume. However, it is recommended that the deformation characteristics of HFA aggregate concrete members subjected to large cyclic loads should be verified by testing, because there remain many points that need to be cleared.

10.2 Design values of materials

10.2.1 Strength

(1)The characteristic strength values of HFA aggregate concrete shall, as a rule, be determined from the test values obtained at an age of 28 days. However, strength values may be determined from test values obtained at other appropriate ages according to the intended use of the structure in question, the time at which the primary load is applied to the structure, and the execution scheme. Compressive, tensile, and flexural strength tests shall be conducted in accordance with JIS A 1108, JIS A 1113, and JIS A 1106, respectively.

(2)When using ready-mixed concrete in conformance with JIS A 5308, the nominal strength designated by the purchaser of the concrete can be used as the characteristic value of compressive strength, f'_{ck}.

(3)Characteristic values of bonding, tensile, and fatigue strength for HFA aggregate concrete shall be determined from values obtained in appropriate tests.

(4)Characteristic values of flexural, tensile, bonding, and bearing strength for HFA aggregate concrete can be calculated from the (specified) compressive strength, f'_{ck}, using Equations 10.2.1 to 10.2.4. Strength is given in units of N/mm^2.

Flexural strength:

$$f_{bk} = 0.42\, f'_{ck}{}^{2/3} \qquad (10.2.1)$$

Tensile strength:

$$f_{tk} = 0.23\, f'_{ck}{}^{2/3} \qquad (10.2.2)$$

where:

$f_{tk} \leq 3.1$ N/mm^2 for structures with surfaces not normally wetted

Bonding strength:

For deformed bars that satisfy the requirements in JIS G 3112,

$$f_{bok} = 0.20\, f'_{ck}{}^{2/3} \qquad (10.2.3)$$

where:

$f_{bok} \leq 2.9$ N/mm^2

For ordinary round bars, the bonding strength shall be calculated as 40% of that when deformed bars are used. Semi-circular hooks shall be provided at the ends of steel reinforcement.

For deformed bars in massive concrete,

$f_{bok} = 0.28\, f'_{ck}{}^{2/3}$

where:

$f_{bok} \leq 4.2$ N/mm^2

Bearing strength:

$$f'_{ak} = \eta f'_{ck} \tag{10.2.4}$$

where:

$\eta = \sqrt{A / A_a} \leq 2$

A = area of concrete surface over which load is borne

A_a = area subjected to bearing load

(5)The design fatigue strength of HFA aggregate concrete under compression, flexural compression, tension, and flexural tension, f_{rd}, can be determined as a function of the number of cycles to failure, N, and the stress imposed by permanent loading, σ_p, from Equation 10.2.5.

$$f_{rd} = k_1 f_d (1 - \sigma_p / f_d)\left(1 - \frac{logN}{K}\right) \tag{10.2.5}$$

where:

$N \leq 2 \times 10^6$

f_d = design strength of HFA aggregate concrete, which can be determined using a material factor, γ_c of 1.3

(i)K = 10 in the case where the HFA aggregate concrete is constantly or frequently saturated with water.

K = 17 in other cases

(ii)In general, k_1 can be determined as follows:

k_1 = 0.85 under compression or flexural compression

k_1 = 1.0 under tension or flexural tension

(iii)The stress in concrete under permanent loading, σ_p, shall be set to zero when the structure is subject to cyclic loading.

[Commentary]

(4)Equations 10.2.1 and 10.2.2 are derived from tests on specimens with f'_c ranging from 30 to 80 N/mm^2 under standard curing conditions. These equations are the same as those derived for specimens made with ordinary aggregate concrete. In the case of Equation 10.2.2, note that an upper limit is specified because the results of tensile tests using specimens cured in air indicate little increase in tensile strength at compressive strengths exceeding approximately 50 N/mm^2.

The results of bonding strength tests conducted in accordance with JSCE-G 503 have demonstrated that bond strength of HFA aggregate concrete is less than ordinary aggregate concrete, though as well as conventional artificial lightweight aggregate concrete. Accordingly, the bonding strength indicated in Equation 10.2.3 is 70% that of ordinary aggregate concrete; the same factor as applied to conventional lightweight concrete containing artificial lightweight aggregates. HFA aggregate concrete is prone to splitting failure when cover over the steel reinforcement is small, as is the case with conventional artificial lightweight aggregate concrete. The reason for this is that the bonding strength of HFA aggregate concrete is lower than that of ordinary aggregate concrete. However, it has been shown in bonding strength tests using large specimens that HFA aggregate concrete achieves a bonding strength comparable to that of ordinary aggregate concrete when the steel reinforcement is constrained by the surrounding concrete. An example of this would be when the axial steel reinforcement of columns is anchored in the footings.

(5)The results of fatigue tests using HFA aggregate concrete under compression indicate that its fatigue strength is as high as that of ordinary aggregate concrete.

10.2.2 Stress-strain curve

(1)When carrying out studies of HFA aggregate concrete, a suitable stress-strain curve shall be chosen to suit the particular purpose of the investigation.

(2)When studying failures in the cross section of a member under bending moment or a combination of bending moment and axial load, the modeled stress-strain curve given in the Design Volume may be used.

[Commentary]

Tests on HFA aggregate concrete aimed at obtaining a stress-strain curve indicated that its behavior is the same as ordinary concrete. As a consequence, the modeled stress-strain curve given in the Design Volume is applicable to the study of failures in the cross section of a member under bending moment or a combination of bending moment and axial load.

10.2.3 Young's modulus

(1)The determination of the Young's modulus of HFA aggregate concrete shall, as a rule, be determined by the following method. First, a test is carried out in accordance with JIS A 1149 to obtain a stress-strain curve. Then, Young's modulus is determined from the average test value of the secant modulus of elasticity connecting the one-third compressive strength point with the point marking a strain of 50×10^{-6}.

(2)Where it is necessary to determine Young's modulus without testing, the values in Table 10.2.1 can be used for the Young's modulus of HFA aggregate concrete, E_C.

Table 10.2.1 Young's modulus of HFA aggregate concrete

f'_{ck} (N/mm^2)	18	24	30	40	50	60	70	80
E_C (kN/mm^2)	19	21	23	25	27	29	30	32

[Commentary]

Test results have revealed that Young's modulus is 10%-20% smaller for HFA aggregate concrete than for ordinary aggregate concrete, while it is about 30% larger than for conventional artificial lightweight aggregate concrete. Consequently, the standard values given in the table are established by reducing the values for ordinary concrete given in the Design Volume by a factor of 15%.

10.2.4 Poisson's ratio

Poisson's ratio for HFA aggregate concrete may be set at 0.2 within the elastic limit. However, it shall be made zero if the concrete is subject to tension and cracking is permitted.

[Commentary]

Test results indicate that Poisson's ratio for HFA aggregate concrete ranges from 0.18 to 0.22, which is almost the same as that of ordinary aggregate concrete. Consequently, the same value is adopted.

10.2.5 Thermal properties

(1)The thermal properties of HFA aggregate concrete shall, as a rule, be determined based on empirical or performance data.

(2)The coefficient of thermal expansion of HFA aggregate concrete can be set at 10×10^{-6}/°C.

[Commentary]

(2)The coefficient of thermal expansion of HFA aggregate concrete is slightly smaller than that of ordinary aggregate concrete, while it is almost the same as that of concrete made with crushed limestone. Given the small difference, the same value is used as for ordinary aggregate concrete. In a situation where temperatures are such that thermal properties are likely to have a significant effect, the coefficient may be determined empirically through tests.

10.2.6 Shrinkage

The shrinkage strain of HFA aggregate concrete can be taken to be that of ordinary aggregate concrete as specified in the Design Volume.

[Commentary]

Tests of autogenous shrinkage strain and drying shrinkage strain indicate that autogenous shrinkage strain develops more slowly in HFA aggregate concrete than in ordinary aggregate concrete, while the ultimate autogenous shrinkage strain is almost the same. Further, the drying shrinkage strain of HFA aggregate concrete is very slightly less than that of both ordinary aggregate concrete and conventional artificial lightweight aggregate concrete. For this reason, the strain values given for ordinary aggregate concrete in the Design Volume can be used.

10.2.7 Creep

The creep coefficient of HFA aggregate concrete can be taken to be that of ordinary aggregate concrete as given in the Design Volume.

[Commentary]

Test results have proven that the creep of HFA aggregate concrete is broadly similar to that of ordinary aggregate concrete. Therefore, the coefficient of creep for ordinary aggregate concrete given in the Design Volume can be used.

In a situation where creep is likely to have a significant effect on a structure, the coefficient may be empirically determined through tests.

10.2.8 Density

The density of HFA aggregate concrete, as required in the calculation of design dead load, shall be set in the range 1,900 to 2,100 kg/m^3. The actual density shall be used if known.

[Commentary]

If the density value for HFA aggregate concrete is taken from the range given in these recommendations, it is recommended that a value on the safe side be chosen.

10.3 Ultimate limit state

10.3.1 General

The study of ultimate limit states for structures using HFA aggregate concrete shall be carried out in conformity with this section. Where studies other than those specified in this section are carried out, they shall conform to the Design Volume.

[Commentary]

The cross-sectional strength of structural members made with HFA aggregate concrete and subjected to a bending moment and axial force is equivalent to that of structures in which ordinary aggregate concrete is used. However, it has been verified that HFA aggregate concrete exhibits lower shear strength of flexural members and punching shear strength in the case of plane members without shear reinforcement. For this reason, this section specifies only the design requirements for shear strength. Other requirements shall conform to the Design Volume.

10.3.2 Safety under shear forces

10.3.2.1 General

In the studying the shear safety of structural members using HFA aggregate concrete, the design shear strength of bars and the design punching shear strength of plane members shall be determined by the methods in 10.3.2.2 and 10.3.2.3, respectively. Other studies shall be made in accordance with the Design Volume.

10.3.2.2 Design shear strength of bar members

The design shear strength of bar members, V_{yd}, can be calculated from Equation 10.3.2.1. When both bent bars and stirrups are used as shear reinforcement, at least half of the shear force carried by the shear reinforcement shall be borne by the stirrups.

$$V_{yd} = V_{cd} + V_{sd} + V_{ped} \qquad (10.3.2.1)$$

where:

V_{cd} = design shear strength of bar members without shear reinforcement, given by Equation 10.3.2.2

$$V_{cd} = \beta_d \cdot \beta_p \cdot \beta_n \cdot f_{vcd} \cdot b_w \cdot d/\gamma_b \qquad (10.3.2.2)$$

$$f_{vcd} = 0.16\sqrt[3]{f'_{cd}} \ (\mathrm{N/mm^2}), \text{ where } f_{vcd} \leq 0.58 \ (\mathrm{N/mm^2}) \qquad (10.3.2.3)$$

$\beta_d = \sqrt[4]{1/d}$, (d in m), where $\beta_d = 1.5$ if $\beta_d > 1.5$

$\beta_p = \sqrt[3]{100 p_w}$, where $\beta_p = 1.5$ if $\beta_p > 1.5$

$\beta_n =$ $1 + M_0/M_d$ (for $N'_d \geq 0$), where $\beta_n = 2$ if $\beta_n > 2$
$1 + 2M_0/M_d$ (for $N'_d < 0$), where $\beta_n = 0$ if $\beta_n < 0$

N'_d = design axial compressive force
M_d = design bending moment
M_0 = bending moment required to counteract the axial stresses induced at the

extremity of the bars on the tension side under the design bending moment M_d

b_w = width of web

d = effective height

p_w = $A_s/(b_w \times d)$

A_s = cross-sectional area of steel member on the tension side

f'_{cd} = design compressive strength of concrete in N/mm^2

γ_b = 1.3 in most cases

V_{sd} = design shear strength supported by shear reinforcement, given by Equation 10.3.2.4

$$V_{sd} = [A_w f_{wyd} (\sin\alpha_s+\cos\alpha_s)/s_s+A_{pw}\sigma_{pw} (\sin\alpha_p+\cos\alpha_p)/s_p] z/\gamma_b \qquad (10.3.2.4)$$

A_w = total cross-sectional area of shear reinforcing bars at s_s

A_{pw} = total cross-sectional area of tendons at s_p

σ_{pw} = tensile stress of shear reinforcement tendons when the shear reinforcing bars yield

$\sigma_{pw} = \sigma_{wpe} + f_{wyd} \leq f_{pyd}$

σ_{wpe} = effective tensile stress of shear reinforcement tendons

f_{wyd} = design yield strength of shear reinforcing bars, which should not be higher than 400 N/mm^2

f_{pyd} = design yield strength of shear reinforcement tendons

α_s = angle of shear reinforcing bars to the axis of the member

α_p = angle of shear reinforcement tendons to the axis of the member

s_s = spacing between shear reinforcing bars

s_p = spacing between shear reinforcement tendons

z = distance between point at which the resultant of compressive stresses act and the centroid of a tensile steel member

γ_b = 1.15 in most cases

V_{ped} = component of effective tensile force acting on axial tendons in parallel to the shear force, given by Equation 10.3.2.5

$$V_{ped} = P_{ed} \cdot \sin\alpha_p/\gamma_b \qquad (10.3.2.5)$$

P_{ed} = effective tensile force acting on axial tendons

α_p = angle of axial tendons to the axis of the member

γ_b = 1.15 in most cases

[Commentary]

It has been proven in tests that the shear strength of bar members when used with HFA aggregate concrete is approximately 20% lower than when ordinary aggregate concrete is used or when no shear reinforcement steel is used. In consideration of recent results that indicate correlation between shear strength and density, the f_{vcd} value of HFA aggregate concrete is made 80% that of ordinary aggregate concrete.

When shear reinforcement steel is used with prestressed concrete, test results indicate that the shear strength of bars in the case of HFA aggregate concrete is as high as when ordinary aggregate concrete is used. If shear strength has great significance to the design of a structural member, it should be verified through tests.

10.3.2.3 Design strength of punching shear of plane members

The design punching shear strength, V_{pcd} , can be determined from Equation 10.3.2.6 if the plane on which the load acts is distant from the free end of the structural member and any openings, and if the force eccentricity is small.

$$V_{pcd} = \beta_d \cdot \beta_p \cdot \beta_r \cdot f_{pcd} \cdot u_p \cdot d/\gamma_b \qquad (10.3.2.6)$$

where:

$$f_{pcd} = 0.16\sqrt{f'_{cd}} \text{ (N/mm}^2) \qquad (10.3.2.7)$$

$\beta_d = \sqrt[4]{1/d}$, (d in m), where β_d = 1.5 if β_d > 1.5

$\beta_p = \sqrt[3]{100p}$, where β_p = 1.5 if β_p > 1.5
$\beta_r = 1 + 1/(1 + 0.25u/d)$
f'_{cd} = design compressive strength of concrete, N/mm^2
u = perimeter length of plane on which load acts
u_p = perimeter length of design cross section, which should be calculated at the point $d/2$ distant from the plane on which the load acts
d and p = effective height and steel reinforcement ratio, respectively. These should be the average values in the case of two-way steel reinforcement
γ_b = 1.3 in most cases

[Commentary]

Test results indicate that the punching shear strength of plane structural members consisting of HFA aggregate concrete is slightly lower than that of those using ordinary aggregate concrete. In consideration of recent study results that indicate a correlation between shear strength and density, the f_{pcd} value of HFA aggregate concrete is reduced to 80% that of ordinary aggregate concrete.

10.4 Serviceability limit state

10.4.1 General

Studies of HFA aggregate concrete structural members at the serviceability limit state can be carried out in accordance with the Design Volume.

[Commentary]

Test results indicate that the spacing between flexural cracks in a beam consisting of HFA aggregate concrete is almost the same as in the case of ordinary aggregate concrete. The results also reveal that the maximum crack width is approximately equal to the value obtained using the equation for flexural crack width given in the Design Volume, and that deviations are on the safe side. Further, tests have also shown that there is no difference in shear crack width between HFA and ordinary aggregate concrete. For this reason, studies of the serviceability limit state can be implemented in accordance with the Design Volume.

10.5 Anchoring and lap splicing of steel reinforcement

Methods of anchoring and lap splicing of the steel reinforcement shall conform to the bonding strength requirements given in Section 10.2.1 and the Design Volume.

[Commentary]

When HFA aggregate concrete is placed with little cover over steel reinforcement, the structure is prone to splitting failures, as is the case with conventional artificial lightweight aggregate concrete. It is for this reason that the bonding strength of HFA aggregate concrete is lower than that of ordinary aggregate concrete. However, it has been shown in bonding strength tests using large specimens that HFA aggregate concrete achieves a bonding strength comparable to that of ordinary aggregate concrete when the steel reinforcement is constrained by the surrounding concrete. One example of this is when the axial steel reinforcement of columns is anchored in footings. In this case, the basic anchorage length is to be designed such that the bonding strength meets the conditions specified in Section 10.2.1.

CHAPTER 11 CONCRETE REQUIRING SPECIAL CONSIDERATIONS

11.1 Prestressed concrete

When HFA aggregate concrete is used in prestressed concrete structures, the concrete shall conform to the Design and Construction Volumes. Appropriate studies must be carried out to verify that such structures can deliver sufficient performance.

[Commentary]

HFA aggregate concrete can be designed to give high strength with relatively ease. Accordingly, when it is used in prestressed structures, there is a possibility of taking advantage of this strength to reduce the cross-sectional dimensions of members under compression and supporting a dead load. In the design of such prestressed concrete structures using HFA aggregate concrete, it is desirable to take into account this ability to achieve high strength.

11.2 Precast concrete products

Where HFA aggregate concrete is used to fabricate concrete products in a factory, the concrete shall conform to the Design and Construction Volumes. Appropriate studies must be carried out to verify that such products can deliver sufficient performance.

[Commentary]

HFA aggregates are almost spherical in shape, so concrete made with them has good flowability. This makes it possible to reduce the water content of the concrete for a given workability. Depending on the mix proportion, however, HFA aggregate particles may float upwards, particularly if excessive vibration is applied during compaction. In this way, the concrete's characteristics are similar to those of conventional artificial lightweight aggregate concrete. Therefore, when fabricating products using HFA aggregate concrete in a factory, these characteristics need to be taken into consideration when selecting appropriate mix proportions and manufacturing processes.

Precast concrete products are generally fabricated using a stiff-consistency concrete with low water-to-cement ratio, so forced mixing is most suitable for HFA aggregate concrete. It is recommended that the sequence of material charging, mixing time, and delivery method should be verified by testing.

In the case of items manufactured in a yard close to the site and where the manufacturing process is under consistent control, similar considerations should apply.

11.3 Concrete for marine structures

When HFA aggregate concrete is used for marine structures, it shall conform to the Design and Construction Volumes. Appropriate studies must be carried out to verify that such structures can deliver sufficient performance.

[Commentary]

One characteristic of HFA aggregate concrete is its density. Further, high strength is easy to obtain, so reduced thickness and weight of members may be achieved if the concrete is prestressed. These properties make the such concrete suitable for offshore floating structures and structures built on soft ground.

Concrete to be used for marine structures must meet certain additional quality control standards, including fatigue strength when exposed to seawater, freeze-thaw resistance,

resistance to abrasion, chemical resistance to various salts contained in seawater, resistance to permeation of chloride ions, and resistance to water permeation.

It has been verified in tests that HFA aggregate concrete offers performance in these areas comparable to that of ordinary aggregate concrete, except with respect to freeze-thaw resistance. Accordingly, it can be used for marine structures as long as care comparable to that applied in the case of ordinary aggregate concrete is exercised.

It has been reported that the freeze-thaw resistance of HFA aggregate concrete is slightly lower than that of ordinary aggregate concrete if the air content is low. Further, the resistance of HFA aggregate concrete to water penetration may fall when the air content is high. Accordingly, structures which have particular requirements with respect to these characteristics shall meet the specifications given in the Construction Volume, and due consideration should be given to the mix proportion of the concrete.

11.4 Steel-concrete composite structures

HFA aggregate concrete to be used in steel-concrete composite structures shall conform to the Design and Construction Volumes. Appropriate studies must be carried out to verify that such structures can deliver sufficient performance.

[Commentary]

Steel-concrete composite structures take full advantage of the strength properties of both steel and concrete. Such structures can be further rationalized by making the most of the high strength characteristics of HFA aggregate concrete. Also, with flowability easy to achieve, constructability can be improved through the use of HFA aggregate concrete in concrete-filled columns and other members.

On the other hand, bond strength of HFA aggregate concrete is less than ordinary aggregate concrete, so care must be taken to ensure integrity. Where antislip devices are used to ensure integrity of the concrete and steel, specifications should be established with consideration given to the steel plate thickness (which has a bearing on weldability of the antislip components) as well as to the fact that HFA aggregate concrete offers lower tensile and shear strength than ordinary aggregate concrete.

Specification for high-strength lightweight aggregates made of fly ash for concrete (Draft) (JSCE-C 101-2001)

1.Scope

This standard defines quality requirements for high strength lightweight aggregates made of fly ash for use in concrete (HFA aggregates.)

2.Reference standards

The following reference standards constitute part of this standards document. The latest editions of all referenced standards shall be referred to.

JSCE-C 505	Test method for crushing load of high-strength lightweight aggregate made of fly ash
JIS A 0203	Concrete terminology
JIS A 1102	Method of test for sieve analysis of aggregates
JIS A 1103	Method of test for amount of material passing standard sieve 75 μm in aggregates
JIS A 1104	Methods of test for bulk density of aggregates and solid content in aggregates
JIS A 1121	Method of test for resistance to abrasion of coarse aggregates by use of the Los Angeles machine
JIS A 1122	Method of test for soundness of aggregates by use of sodium sulfate
JIS A 1135	Methods of test for particle density and water absorption of light weight coarse aggregates for structural concrete
JIS A 1145	Method of test for alkali-silica reactivity of aggregates (by the chemical method)
JIS A 1146	Method of test for alkali-silica reactivity of aggregates by mortar-bar method
JIS A 5002	Lightweight aggregates for structural concrete
JIS R 5202	Methods for chemical analysis of cements
JIS Z 8801-1	Test sieves - Test sieves of metal wire cloth

3.Definition of terms

The terms used in this standard are based on JIS A 0203 with the following additions:

a)HFA aggregates : The term HFA aggregates refers to artificial aggregates for use in concrete that contain fly ash as the principal raw material. They are manufactured by granulation and burning.
b)Crushing load : Crushing load is the maximum compressive load required to crush one HFA aggregate particle, represented by an average of many measurements.

4.Classification of HFA aggregates

The HFA aggregates are classified and designated according to grain size range, as shown in Table 1.

Table 1 Classification of HFA aggregates according to the grain size

Classification	Range of grain sizes (mm)	Designation
2005	20-5	HFA20
1505	15-5	HFA15

5.Quality

5.1 General

HFA aggregates shall not contain any substances that may have an ill effect on the quality of the concrete.

5.2 Chemical composition and properties

HFA aggregates shall be tested for chemical composition and properties in accordance with Sections 6.2 to 6.5 to prove that quality reaches the standards listed in Table 2.

Table 2 Chemical composition and properties

Quality requirement	Standard
Ignition loss, %	Not more than 1.0
Calcium oxide content (as CaO), %	Not more than 30
Sulfur trioxide content (as SO_3), %	Not more than 0.5
Chloride content (as NaCl), %	Not more than 0.01

5.3 Physical properties

The HFA aggregates shall be tested for physical properties in accordance with Sections 6.6 to 6.10 to prove that quality reaches the standards listed in Table 3.

Table 3 Physical properties

Quality requirement	Standard
Crushing load, ø5-10 mm grain size range, kN	Not less than 0.70
Ditto, ø10-15 mm grain size range, kN	Not less than 1.50
Ditto, ø15-20 mm grain size range, kN	Not less than 2.10
Density under oven-dry state, g/cm^3	Not more than 2.0
Percentage water absorption (after 24 hours), %	Not more than 3.0
Soundness, %	Not more than 5
Resistance to abrasion (percentage abrasion loss by weight), %	Not more than 30
Fine particle content, %	Not more than 1.0

5.4 Alkali-silica reactivity

HFA aggregates shall be tested for alkali-silica reactivity in accordance with Section 6.11 to prove that reactions between silica in the HFA aggregates and alkalis in the concrete are harmless.

5.5 Grain size distribution

HFA aggregates shall be tested for grain size distribution in accordance with Section 6.12 to prove that grain sizes are within the range listed in Table 4.

5.6 Solid content in aggregates

HFA aggregates shall be tested for solid content in accordance with Section 6.13 to prove that the solid content is not less than 55%.

Table 4 Grain size distribution

Classification of HFA aggregates according to grain size range	Percentage of grains finer than sieve by weight, %														
	Nominal sieve size(1), mm														
	100	80	60	50	40	25	20	15	10	5	2.5	1.2	0.6	0.3	0.15
2005	-	-	-	-	-	100	90-100	-	20-55	0-10	-	-	-	-	-
1505	-	-	-	-	-	-	100	90-100	40-70	0-15	-	-	-	-	-

Note (1) Nominal sieve sizes are nominal test sieves of metal wire cloth according to JIS Z 8801-1: 106 mm, 75 mm, 63 mm, 53 mm, 37.5 mm, 26.5 mm, 19 mm, 16 mm, 9.5 mm, 4.75 mm, 2.36 mm, 1.18 mm, 600 μm, 300 μm and 150 μm.

6.Test methods

6.1 Sampling

Representative samples shall be taken and reduced by a rational method for use as test specimens.

6.2 Ignition loss

A sample of approximately 500 g dried at 100-110°C until it has become a constant mass is crushed for use as a test specimen in ignition loss testing. The test shall be conducted in accordance with JIS R 5202.

6.3 Calcium oxide content

A sample of approximately 500 g dried at 100-110°C until it has become a constant mass is crushed for use as a test specimen in calcium oxide content testing. The test shall be conducted in accordance with JIS R 5202.

6.4 Sulfur trioxide content

A sample of approximately 500 g dried at 100-110°C until it has become a constant mass is crushed for use as a test specimen in sulfur trioxide content testing. The test shall be conducted in accordance with JIS R 5202.

6.5 Chloride content

The chloride content test shall be conducted in accordance with JIS A 5002.

6.6 Crushing load

The crushing load test shall be conducted in accordance with JSCE-C 505.

6.7 Density under oven-dry state and water absorption

Density under absolute dry-state and water absorption shall be tested in accordance with JIS A 1135.

6.8 Soundness

The soundness test shall be conducted in accordance with JIS A 1122. But, the number of repetitions shall be five.

6.9 Resistance to abrasion

Resistance to abrasion shall be tested in accordance with JIS A 1121.

6.10 Fine particle content

The fine particle content shall be tested in accordance with JIS A 1103.

6.11 Alkali-silica reactivity

The alkali-silica reactivity test shall be conducted in accordance with JIS A 1145 or JIS A 1146.

6.12 Grain size distribution

The grain size distribution shall be tested in accordance with JIS A 1102.

6.13 Solid content in aggregate

The solid content shall be tested in accordance with JIS A 5002.

7.Indications

The product invoice shall display the following information:

a)Classification (in accordance with the designations in Section 4)
b)Date of manufacture or its abbreviation
c)Manufacturer or its abbreviation
d)Manufacturing plant or its abbreviation
e)Date of shipment
f)Weight or volume
g)Name and address of company or factory to which the product is to be delivered
h)Usage precautions

8.Reporting

The manufacturer shall submit test certificates to the purchaser as requested.

Test method for crushing load of high strength lightweight aggregate made of fly ash (Draft) (JSCE-C 505-2001)

1.Scope

This standard defines the method to be used for testing the crushing load of high-strength lightweight aggregates made of fly ash for concrete (HFA aggregates).

2.Reference standards

The following reference standards constitute part of this standards document. The latest editions of all referenced standards shall be referred to.

JIS A 0203 Concrete terminology

3.Definition of terms

The terms used in this standard are based on JIS A 0203 with the following additions:

a)Crushing load : Crushing load is the maximum compressive load required to crush one HFA aggregate particle, represented by an average of many measurements.

4.Principle

The maximum compressive load is measured at the moment when one HFA aggregate particle is crushed during compressive loading at a specified rate.

5.Test apparatus

The load application and indicating parts of the test equipment shall meet the following requirements:

5.1 Load application part

a)The load applicator shall have a capacity two to three times larger than the expected crushing load.
b)The loading plates shall be flat and parallel, and the surfaces that come into contact with the test specimen shall be of steel.
c)The rate of loading shall be set at 0.02-0.05 kN/s.

5.2 Load indicating part

5.2.1 Load measuring system

a)The applied load shall be monitored with a load cell or mechanical lever.
b)The system shall have a capacity two to three times larger than the expected crushing load.

5.2.2 Load indicator or recorder

a)If the load measuring system consists of a load cell, an electrical load indicating system (a chart plotter, a meter with a peak pointer, or other appropriate device) shall be used. In the case of a lever-type measuring system, a mechanical indicator (gauge with a peak pointer or other appropriate device) shall be used.

b)In the case of a chart plotter, the maximum pen speed shall not exceed 1.0 second for full-scale travel.
c)The minimum gradation (reading) possible with the indicator or recorder shall be 1/100 of the full-scale reading or better.
d)The compression system shall be regularly calibrated.

A typical crushing load test machine is shown in Figure 1.

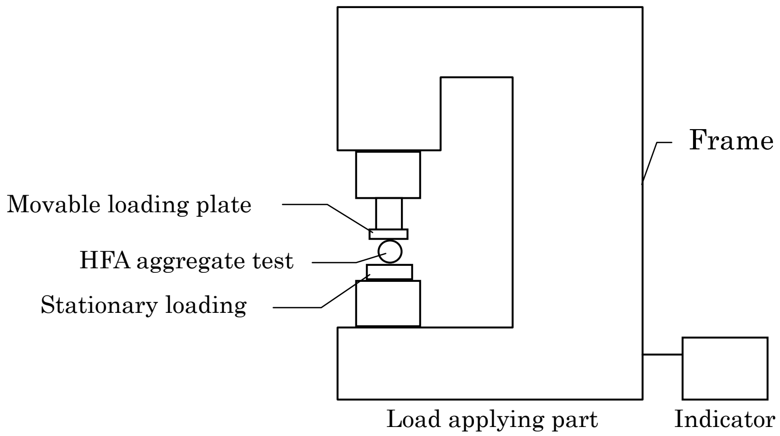


Figure 1 Typical crushing load test machine

6.Preparation of test specimens

6.1 Sampling

Grains of size 5 to 20 mm shall be used for testing. Test specimens shall consist of aggregate particles categorized into three grain size ranges: 5-10 mm, 10-15 mm, and 15-20 mm. Prior to testing, a test specimen shall be dried at 100-110°C until it has constant mass, and then cooled to room temperature. Specimens in each grain size range shall be chosen in such a manner that the sampling is homogeneous, and shall be reduced by a rational method.

6.2 Number of test specimens

At least 100 specimens shall be tested, with the number agreed between the parties.

7.Test method

7.1 Placement on loading plate

One specimen shall be placed at rest in the center of the loading plate.

7.2 Compressive load application

The compressive load shall be applied to the specimen at a loading rate of 0.02-0.05kN/s.

7.3 Result recording

The maximum compressive load at the moment of specimen crushing shall be recorded in units of kN to an accuracy of two decimal places.

7.4 Cleaning of loading plates

The loading plates shall be cleaned before beginning a test on a subsequent specimen.

8.Indication of test results

The crushing load shall be calculated using the following equation and rounded to two decimals:

$$P = \Sigma p_i / n$$

where:

P = crushing load
P_i = maximum compressive load of the i-th HFA aggregate
n = number of test specimens

9.Recording

The following test data shall be recorded.

a)Date of the test
b)Date of test specimen preparation
c)Number of test specimens
d)Maximum compressive load for each test specimen
e)Grain size range and crushing load of test specimens

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