Committee Report : JCI-TC054A

Technical Committee on Aggregate Qualities and Effective Use of Poor Quality Aggregates

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Abstract

Amid the demand for various performances of concrete, deterioration in the quality of aggregate has been posing problems, while the effective use of natural resources has been a significant issue facing society. With this as a background, the Committee clarified the actual state of the deterioration of aggregate qualities, particularly regarding fines in crushed rock, grading, and absorption, by a questionnaire survey to aggregate manufacturers and users, with the aim of making efficient use of limited resources for concrete while ensuring its qualities. The relationship between the aggregate qualities and concrete performances was then organized, based on which the Committee summarized the problems of the current standards and proposed a concept of future quality specifications for aggregate.

Keywords: aggregate, aggregate quality, performance of concrete, standards

1. Introduction

It goes without saying that the quality of aggregate is one of the crucial factors affecting the performance of resulting concrete. However, a stringent code for aggregate qualities can cause aggregate manufacturers to label more resources unusable and dispose of them, thereby adversely affecting the natural environment. It is therefore necessary from the standpoint of the efficient use of resources that the specifications for aggregate be closely reexamined according to the performance requirements. The Technical Committee on Aggregate Qualities and Effective Use of Poor Quality Aggregates began with a questionnaire survey of the problems and state of quality control both on the manufacturer and user sides to elucidate current problems to be solved. Based on literature searching, the Committee then clarified the relationship between the aggregate qualities and concrete performances. It sorted out item by item the effects of aggregate qualities on various properties of fresh concrete, as well as the strength/elasticity, thermal properties, and durability of hardened concrete, while organizing the requirements of aggregate for concrete, such as its physical properties and interaction between aggregates. The problems of the current standards related to aggregate were also sorted out to investigate the concept of quality specifications, thereby presenting a new idea of aggregate standards. The results of research into the history of Japan's aggregate standards and various overseas standards were also summarized.

Table 1 Committee members

Chairperson: *Katsuro KOKUBU(Tokyo Metropolitan Univ.)*
Chief organizer: *Shigeyuki SOGO(Obayashi Corp.)*
Managers: *Hirotaka KAWANO(Kyoto Univ.), Takafumi NOGUCHI(Univ. of Tokyo)*
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Shunichi YONEDA(Limestone association of Japan)
Cooperators: *Toyoharu NAWA(Hokkaido Univ.), Toshiro KAMADA(Osaka Univ.),*
Masanao ARAI(General Building Research Corporation of Japan), Katsunori AYANO(Okayama Univ.),
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Table 2 Specifications for aggregates

Items	JIS A 5005		JIS A 5308		JSCE		AIJ (JASS5)	
	Crushed stone	Crushed sand	Gravel	Sand	Coarse agg.	Fine agg.	Coarse agg.	Fine agg.
oven dry density (g/cm^3)	2.5≦	2.5≦	2.5≦	2.5≦	2.5≦	2.5≦	2.5≦	2.5≦
absorption (%)	3.0≧	3.0≧	3.0≧	3.5≧	3.0≧	3.5≧	3.0≧	3.5≧
solid content in a given grading (%)	55≦	53≦	−	−	−	−	−	−
soundness (%)	12≧	10≧	12≧	10≧	12≧	10≧	12≧	10≧
finer materials content (%)	1.0≧	7.0≧	1.0≧	3.0≧	1.0≧	3.0≧	1.0≧	3.0≧
wear percentage (%)	40≧	−	35≧	−	35≧	−	−	−
clay lumps (%)	−	−	0.25≧	1.0≧	0.25≧	1.0≧	0.2≧	1.0≧
NaCl content (%)	−	−	−	0.04≧	−	0.04≧	−	0.04≧

2. Overview and trend of aggregate resources

2.1 Overview of aggregate for concrete

Aggregate for concrete includes the varieties shown in **Fig. 1**. The recent annual aggregate demand is 639 million tons, in which river sand/river gravel, pit sand/pit gravel, terrace sand/terrace gravel, sea sand/sea gravel, crushed sand/crushed rock, and imported aggregates/slag aggregates account for 3%, 12%, 13%, 6%, 62%, and 4%, respectively[1), 3)]. The percentage of river sand and river gravel tends to decrease, while crushed sand and crushed rock have now become predominant aggregates for concrete. On the other hand, recycled aggregate reclaimed from demolished concrete, blast-furnace slag and other slag aggregates from metal refineries, and melt-solidified slag aggregates made from municipal solid waste have been standardized as JIS-specified aggregates for concrete. These were added to the standard to promote the use of by-products and industrial wastes, reflecting the importance of mitigating the environmental impact and effective use of resources.

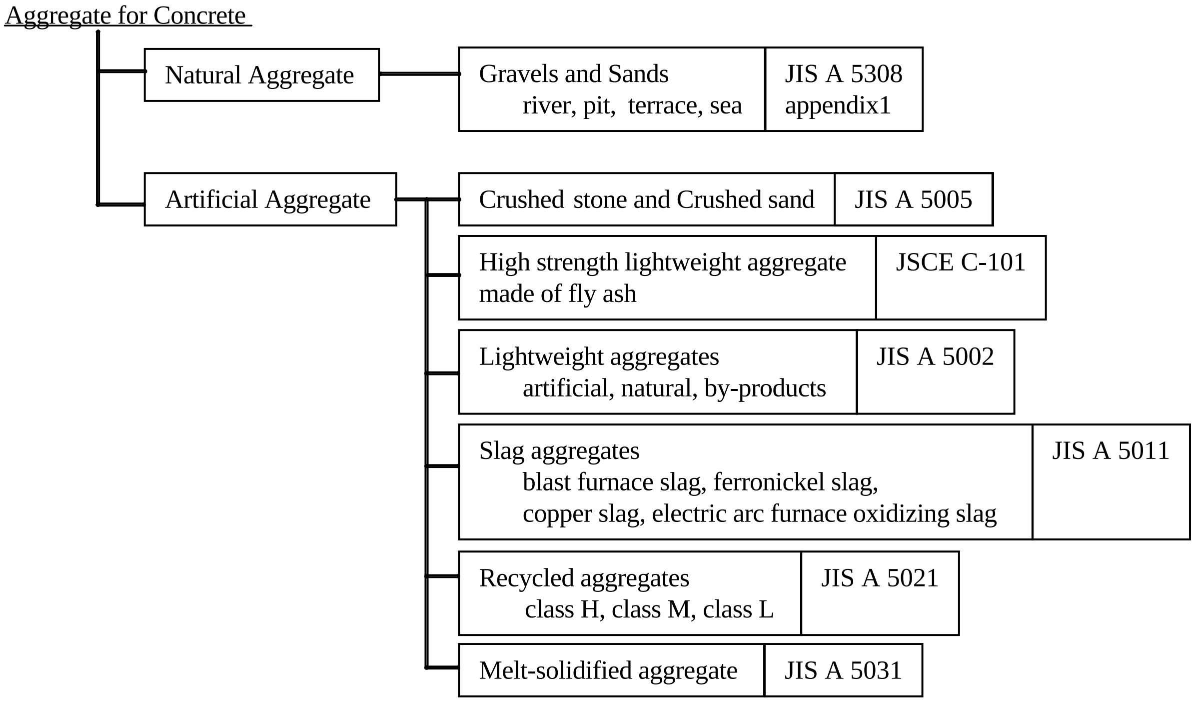


Fig.1 Aggregates for concrete

The current specifications are as given in **Table 2**. The specifications by the Japan Society of Civil Engineers and the Architectural Institute of Japan are similar to those of JIS A 5308 (Ready-mixed concrete).

2.2 Overview of other aggregate resources

(1) Weathered granite, *masa*

In the Chugoku District, the use of *masa* has been promoted in place of sea sand[2)]. Granite used as aggregate can cause an increase in the unit water content and reduction in the strength of concrete, due to its weathered porous portions forming weaknesses and residual clay minerals, such as mica, contained in its fines. However, *masa* can be used as aggregate for concrete by being properly crushed, with the grading adjusted, and thoroughly washed.

(2) Weathered volcanic sand, *shirasu*

Shirasu mostly consists of particles of crushed glass chips with angular shapes and smooth surfaces. The density of *shirasu*, which also contains pumice, is generally about 2.4 g/cm^3. Particles deposited near the outer surfaces are prone to weathering and aeration. Studies have been proceeding in Southern Kyushu to use *shirasu* as fine aggregate for concrete.

(3) Sediment in dams

Sediment behind Japan's dams, which is estimated to total over 3 billion tons, has scarcely been used as aggregate for concrete because of the low profitability due to the generally high transportation cost incurred to convey it to distant points of demand.

(4) Imported aggregate

With domestic aggregate resources being depleted, imported aggregate has been increasing in recent years. The import of fine aggregate dates back to the time of the asset-inflated "bubble" economy in the 1990s, when around 1 million tons were brought from Taiwan, China, and other neighboring countries. Though the amount has now increased to over 4 million tons, such importing is vulnerable to various hazards, such as supply stability dependent on the domestic situation of the exporters, price stability dependent on the exchange rate fluctuations, and questions of marine transportation and cargo handling. It should be noted that aggregate export from China has been banned since March 2007.

3. Actual state of aggregate for concrete

A questionnaire survey was conducted on aggregate producers and users throughout Japan in regard to the current status of its production and quality and actual practice of using aggregate with the aim of clarifying the problems and points requiring improvement as described below.

The subjects included manufacturers of gravel/sand, crushed rock/crushed sand, and limestone aggregate, as well as ready-mixed concrete producers as the users of aggregate. The questionnaire was sent to 742 manufacturers, in which 304 (41.0%) responded, and 372 users, in which 230 (61.8%) responded, with the total numbers of distribution and collection and collection rate being 1,114, 534, and 47.9%, respectively.

3.1 Reponses of manufacturers

(1) Types of aggregates produced

The types of aggregates produced are classified by region as shown in **Fig. 2**. Relatively high percentages of plants produce gravel in Hokkaido, Koshinetsu, Tokai, and Hokuriku Districts, whereas plants producing crushed rock predominate in other districts.

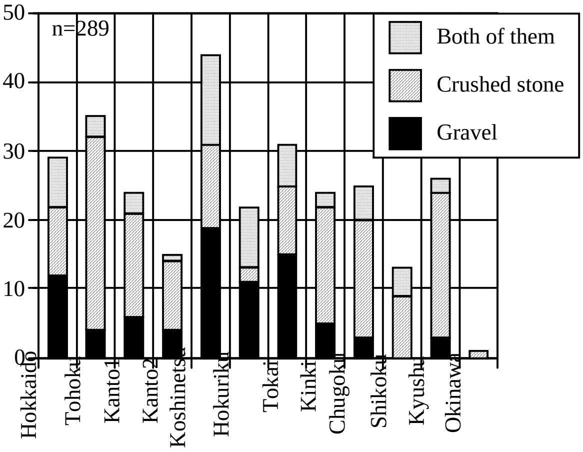
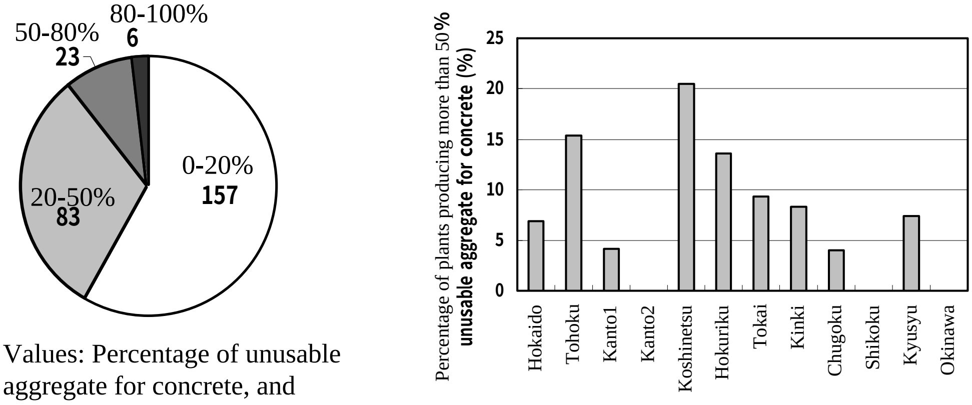


Fig.2 Types of aggregates produced

(2) Percentage of aggregate unusable as aggregate for concrete

About 60% of the responding plants answered that the percentage of aggregate unusable due to specification-related problems was not more than 20%, while about 10% of the responding plants answered that such unusable aggregate exceeded 50%. The percentage of aggregate not meeting the specifications for aggregate for concrete tended to be high in Tohoku, Koshinetsu, and Hokuriku Districts (see **Fig. 3**).



Values: Percentage of unusable aggregate for concrete, and number of plants in each category

Fig.3 Percentage of unusable for concrete

(3) Technical concerns about aggregate production

Forty-six percent of the responding plants answered that they have technical concerns about aggregate production. Specific concerns are as shown in **Fig. 4**. Quality-related concerns, such as “large fluctuations in the quality of rock veins and sedimentary layers,” “low production efficiency,” and “presence of rocks that are out of the specifications for aggregate” were ranked as the top three, followed by issues related to the environment and mineral composition. Other concerns ranked high included those about sludge, the amount and disposal of fines, and substance, such as alkali-silica reactivity, and rocks prone to breaking into flat pieces.

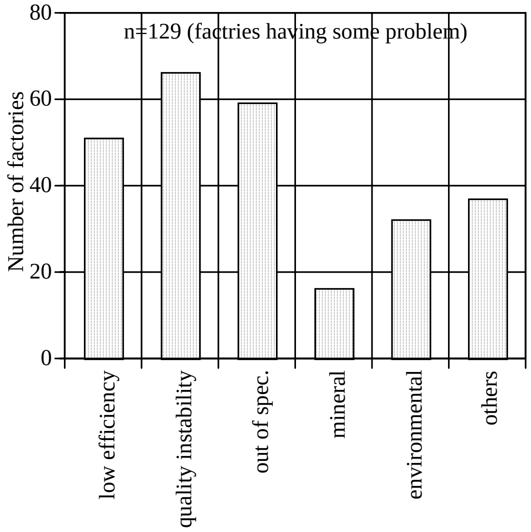


Fig.4 Technical concerns about aggregate production

(4) Blending of multiple aggregates during production

Figure 5 shows the answers to a question asking if the manufacturer blends multiple aggregates. The numbers of plants answering “yes” and “yes, on demand” accounted for about 30% of the total, while about 70% of the total answered “no”.

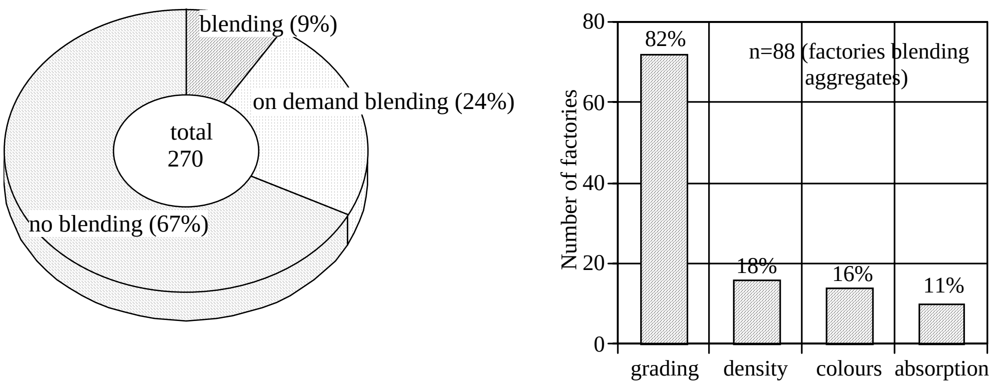


Fig.5 Blending of aggregates

As for the reasons for such blending, about 80% of the blending plants answered “to adjust grading,” followed by “to meet the requirements for density”, “color”, and “absorption”.

(5) Means to improve production efficiency

Figure 6 shows the survey results regarding means to improve the production efficiency.

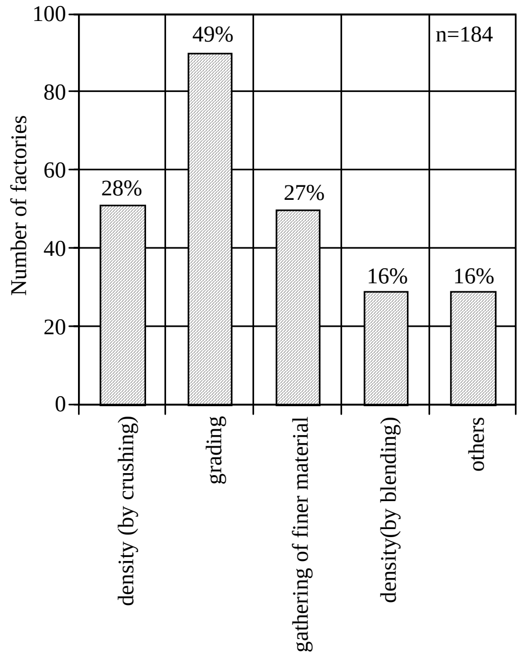


Fig.6 Means to improve the efficiency

Sixty percent of the total respondents answered this question. Plants that blend aggregates having different size profiles account for the largest percentage, being 49% of the total plants answering this question. This is followed by plants that adjust the density by alternating crushing of aggregates having different qualities (28%), those that remove fines generated during crushing (27%), and those that blend aggregates having different densities (16%).

(6) Means to improve quality

Figure 7 shows the survey results regarding means to improve the product qualities. Among the plants that answered this question, which account for 80% of the total respondents, 69% answered that they take measures related to washing. This is followed by the improvement of particle shapes by the improvement of crushers (54%), adjustment of the number of times of crushing (19%), and introduction of a special crusher (14%), and control of fines generation by improvement in the process flow (5%).

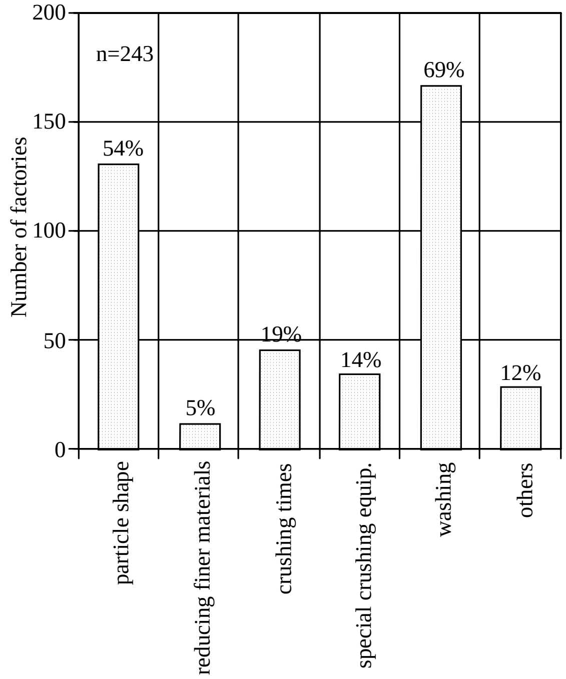


Fig.7 Means to improve qualities

3.2 Results of questionnaire survey on users

(1) Concerns about aggregate purchasing

Fifty-three percent of the responding users answered that they had concerns about aggregate purchasing. These included matters related to aggregate quality (78%), supply (33%), and price (17%). Their concerns about aggregate quality mostly related to its physical properties, such as grading, density, fines content, and absorption (see **Fig. 8**).

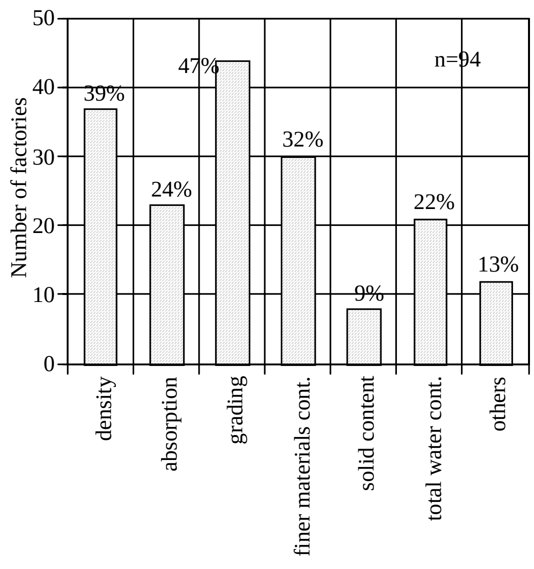


Fig.8 Concerns about aggregate purchasing

(2) Means to minimize grading fluctuations

Figure 9 shows the survey results regarding measures taken to reduce the fluctuation of aggregate grading. Users are found to exercise care to minimize segregation during operation by storing aggregates separately according to the particle size, discharging the stored aggregate alternately though different gates, and keeping silos full. In regard to the grading control of fine aggregate, about 75% of the users are found to adjust its grading by blending multiple fine aggregates at their plants.

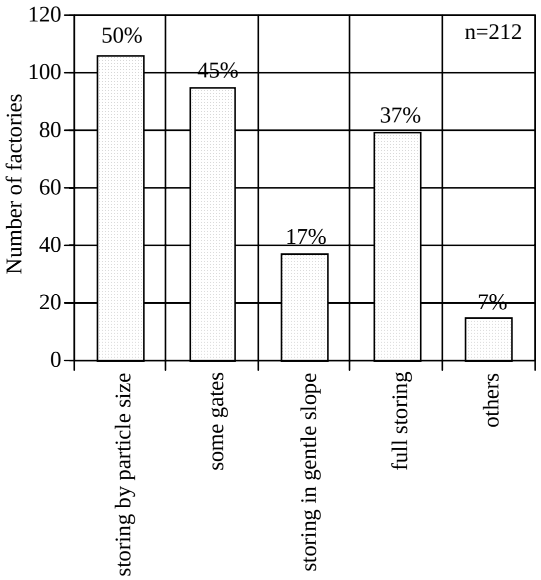


Fig.9 Means to minimize grading fluctuations

(3) Means to minimize surface moisture fluctuations

Figure 10 shows the survey results regarding measures taken to minimize the fluctuation in the surface moisture percentage of aggregate. The answers included the following: extending the storage period until the surface moisture percentage becomes sufficiently low; taking measures to prevent the surface moisture dripping from the gates of storage bins from staying on the belt conveyers; and installing drainage pipes at the bottom of storage bins to reduce the moisture content of aggregate.

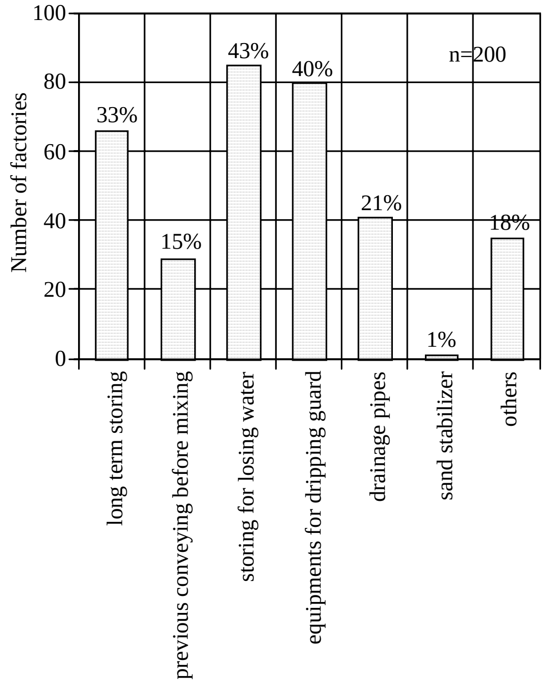


Fig.10 Means to minimize surface moisture fluctuations

4. Aggregate quality and concrete performance

4.1 Interrelatedness among aggregate quality items

Table 3 gives the results of investigation into interrelatedness among 21 quality items. In this table, these items are classified into five groups: aggregate particles, strength/hardness, shape/grading, impurities, and other. The effects of quality items marked with alphabetic characters on the items marked with numbers are expressed in four levels: significant effect, marginal effect, marginal effect at the production stage, and effect depending on the test method.

4.2 Effects of aggregate qualities on concrete performances

Table 4 gives the effects of aggregate qualities on the concrete performances.

Among the qualities of aggregate, solid content, grading, and particle shapes produce strong effects on the fluidity of concrete.

Also, the soundness of coarse aggregate is strongly related to the compressive strength of concrete (see **Fig. 11**[4]).

Table 3 Interactions between qualities of aggregate

		categories	agg. particles			strength/hardness				shape/grading							impurities					other	
		column #	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
categories	line #	quality items	density	absorption	secific surface area	strength of agg.	abrasion loss	BS crushing value	soundness	max. size	finer materials cont.	shape	grading	solid cont. in a given grading	solid cont.	unit weight	lower than 1.95g/cm3	clay lumps	soft particles	organic impurities	NaCl cont.	ASR	silicate cont.
agg. particles	1	density		●													●	○	○				
	2	absorption									＊												
	3	secific surface area																					
strength/hardness	4	strength of agg.		○													●		●				
	5	abrasion loss		○		●						○					●	●	●				
	6	BS crushing value		○		●						○					●	●	●				
	7	soundness		○		○											●	●	●				
shape/grading	8	max. size																					
	9	finer materials cont.					□											●					
	10	shape				□	□																
	11	grading				□	□			●	●												
	12	solid cont. in a given grading										●											
	13	solid cont.								●	○	●	●	●									
	14	unit weight	●							●	○	●	●	●	●		○						
impurities	15	lower than 1.95g/cm3																					
	16	clay lumps																					
	17	soft particles																					
	18	organic impurities																					
	19	NaCl cont.																					
other	20	ASR																					●
	21	silicate cont.																					

●: significantly affects, ○: slightly affects, ＊: depend on test method, □: sligthly affects in manufacutring

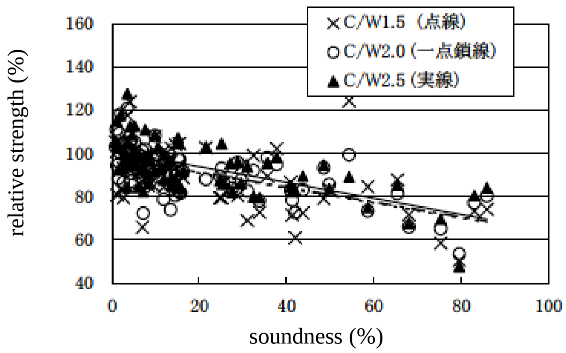


Fig.11 Soundness of coarse aggregate and strength of concrete

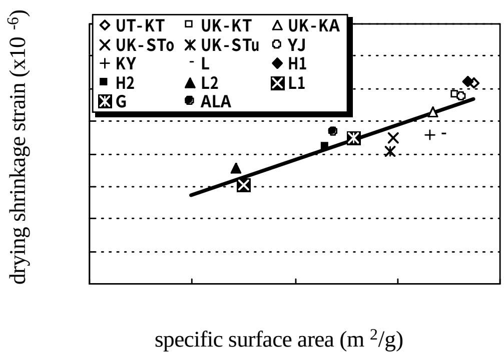


Fig.12 Specific surface area of aggregate and drying shrinkage of concrete

The specific surface of aggregate including air voids in aggregate particles has a dominating effect on the drying shrinkage properties of concrete[5), 6)]. For instance, **Fig. 12** shows the relationship between the specific surface of aggregate calculated by the BET specific surface three point method (BET method) and the drying shrinkage strain.

The thermal properties of concrete are primarily affected by the amount and lithological characteristics of aggregate, which accounts for 70 to 80% of the volume of concrete. **Table 5** gives the thermal conductivity of concrete and aggregate[8]. **Figure 13** shows the results of organizing the durability factor of concrete with respect to the oven-dry density and the abrasion loss. This figure reveals that the durability factor is 60% or less when neither of the oven-dry density and abrasion loss meets the specifications.

Table 4 Influence of aggregate qualities on performance of concrete

concrete performance		aggregate qualities	agg. particles			strength/hardness				shape/grading							impurities					other			
			density	absorption	secific surface area	strength of agg.	abrasion loss	BS crushing value	soundness	max. size	finer materials cont.	shape	grading	solid cont. in a given grading	solid cont.	unit weight	lower than 1.95g/cm3	clay lumps	soft particles	organic impurities	NaCl cont.	ASR	silicate cont.	detrimental minerals	colours
	principal index	yield value/viscosity								●	●	●	●	○	●										
		setting									●									●	●			●	
	performance	slump (slump flow)								●	●	●	●	○	●										
		segregating resistance	●							●	●		●												
		pumpability		●						●	●	○		○											
		throughability								●	●	●		●	○										
		bleeding	●							○	●	○	●	○	○					○					
	principal index	comp. strength		○		○			○																
		tensile strength		○		○			○																
		bending strength		○		○			○																
	performance	wearing resistance	●			●	●			●	○				○	○									
	principal index	elastic modulus	●	●					●																
		creep modulus	●	●		●	●	●																	
	performance	hydrating shrinkage resistance	●	●		○																			
		drying shrinkage resistance			●	○																			
	principal index	thermal conductivity																					●		
	performance	thermal cracking resistance																					●		
		fire resistance																							
	performance	watertightness		●																					
		carbonation resistance		●																					
		ionic movement resistance		●																					
		durability for freezing & thawing action		●					●																
		acidic solutions resistance																							
		ASR resistance																				●	●		
		wetting & drying durability							●																
	principal index	unit weight	●																						
		colours									○		○												●
	performance	sound shield																							
		radiation shield	●	○												○									
		other problems by agg.																						●	

●: significantly affects, ○: slightly affects

Table 5 Thermal conductivity of concrete and aggregate

concrete			aggregate	
types	density (kg/m^3)	thermal conductivity (kJ/mh℃)	types	thermal conductivity (kJ/mh℃)
heavyweight concrete	4020	8.8～10.9	magnetite	9.6～10.5
	3640	4.2～5.0	barite	4.5～4.6
normal weight concrete	2430	12.6～13.0	silica	12.5～13.0
	2450	11.0～11.7	limestone	11.3～11.7
	2420	9.2	granite	8.8～9.6
	2510	7.5	basalt	7.1～8.0
	2300	5.4	river gravel	5.4～7.1
lightweight concrete	1600～1900	2.3～2.8	pumice	—

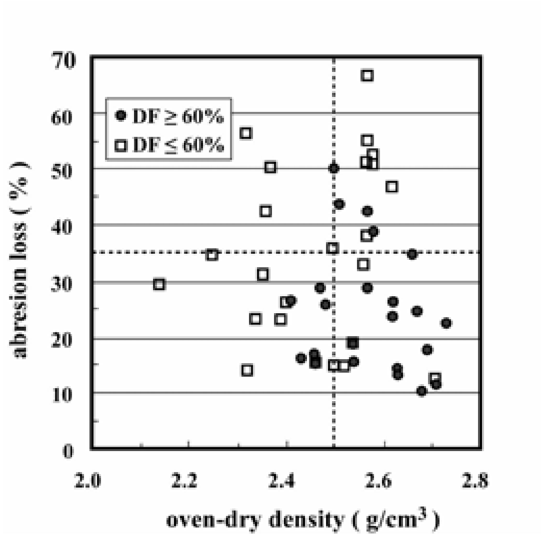


Fig.13 Oven-dry density and abrasion loss for 60% DF of concrete

5. Subjects and proposal for aggregate specifications

5.1 Concept of aggregate specifications

Aggregate originally available in the region should as a rule be effectively used for concrete. Recycled industrial byproducts should also be used locally in a suitable manner. The quality requirements of aggregate should also allow selection according to the performance requirements of the concrete structure for which the aggregate is to be used. Nevertheless, it is difficult in practice to deal with individual cases separately, excepting large-scale and long-term jobs, such as dam construction. It is more practical to prepare a standard that is specification-based to a certain extent and make full use of it, particularly in consideration of the delivery system of ready-mixed concrete plants supplying concrete to any job sites.

Though Japanese Industrial Standards (JIS) for qualities of aggregates and related test methods have already been established, the social, technical, and economic circumstances have changed over the last few decades, including the changes of aggregate sources and uses of concrete. The time has come to review the current specifications. The looming depletion of good quality aggregate naturally leads to an idea of classifying aggregates.

5.2 Aggregate standards abroad and changes of domestic standards

Aggregate standards in Europe, the United States, Australia, and China were examined. All of these standards classify aggregates, presumably due to the vast areas of aggregate sources and wide ranges of environmental conditions.

In Japan, three grades of aggregate that had been specified in the 1975 issue of the Japanese Architectural Standard Specification (JASS 5) were abandoned 10 years later presumably due to practical difficulty.

5.3 Single and blended uses of aggregate

When blending two or more aggregates for use in concrete, the averages of certain quality items of all aggregates may affect the qualities of the resulting concrete, while the effect of certain qualities of one of the aggregates can also predominate over the others. The former quality items include density, grading, and chloride ion content, whereas the latter quality items are represented by those related to durability, such as alkali-aggregate reactivity and resistance to frost damage.

Accordingly, the Committee began with organizing the effects of the blends of aggregates in regard to representative quality items, and went on to determine who should be responsible for quality assurance at what time and place, assuming actual supply systems, such as blending at a ready-mixed concrete plant and blending at an aggregate manufacturer’s plant.

5.4 Future of quality standard for aggregate

The Committee investigated the way the future standard should be, referring to the survey results described in Chapters **3** and **4**. While the concept of standard can widely vary depending on the standpoint and perspective, a concept discussed in the Committee is presented below.

Aggregate should be classified into five types according to the performance requirements of the resulting concrete: high-strength type, water-saving type, high-durability type, standard type, and environmentally available type. This concept is shown in **Fig. 14**, with specific values being given in **Table 6**. Note that the values in the table are tentative and subject to revisions based on future study data.

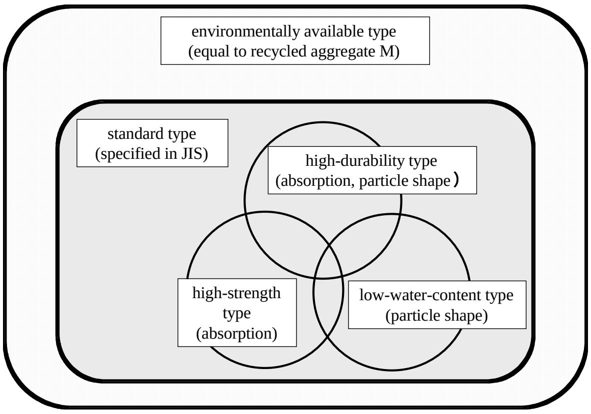


Fig.14 Schema of aggregate quality standards in future

Table 6 Image of specified values for aggregate in every type

	types	density (g/cm^3)	absorption(%) severe	absorption(%) moderate	absorption(%) toropical	solid cont. in same grading (%)	soundness(%) severe	soundness(%) moderate	soundness(%) tropical
	high-strength		1.5≧	1.5≧	1.5≧	55≦			
	low-water-cont.		2.5≧	3.0≧	4.0≧	60≦			
	high-durability		2.0≧	2.0≧	3.0≧	60≦			
	standard	2.5≦	2.5≧	3.0≧	4.0≧	55≦	7≧	12≧	not specifeid
	low-impact	2.3≦	3.0≧	4.0≧	5.0≧	53≦			
	low-water-cont.		2.5≧	3.5≧(sand) 3.0≧(crushed sand)	4.5≧	58≦			
	high-durability		2.5≧(sand) 2.0≧(crushed sand)	3.0≧(sand) 2.5≧(crused sand)	3.5≧(sand) 3.0≧(crused sand)	58≦			
	standard	2.5≦	2.5≧	3.5≧(sand) 3.0≧(crused sand)	4.5≧	53≦	5≧	10≧	not specified
	low-impact	2.3≦	3.0≧	4.5≧(sand) 4.0≧(crused sand)	7.0≧	50≦			

5.5 Proposed revision of current aggregate standards

Being established quite some time ago, JIS specifications and test methods for aggregate include items that have become insignificant and requirements that are no longer relevant to current needs. Accordingly, the Committee proposed the following, giving consideration to fulfillment of performance requirements for concrete, simplification (elimination of redundancy), and elimination of test methods involving hazardous chemicals and those with low reliability:

(1) Unification of requirements for oven-dry density and water absorption

Since oven-dry density and water absorption are both indices to the denseness and void percentage of aggregate particles, the Committee proposed their unification into requirements for water absorption, which is slightly more relevant to the physical properties of concrete.

(2) Abolition of requirements for soft stone content

Unclearness of the test procedure and judgment criteria for soft stone has been pointed out. The ASTM standard for this item, based on which the JIS standard was established, has already been abolished.

(3) Unification of amount of materials passing a 75 μm sieve and clay lump content

Though test methods for these items are specified in JIS A 1103 and JIS A 1137, it was judged that both can be evaluated as the total fines content including clay lumps in aggregate by modifying the test method for the amount of materials passing a 75 μm sieve.

(4) Abolition of requirements for particles that float on a liquid with a density of 1.95 g/cm^3

These requirements were specified primarily to detect coal and lignite included in aggregate during extraction and transportation by freight train, but the needs for these have now become less significant. Moreover, the test liquid is hazardous, posing health- and environment-related problems. The abolition of this item was therefore proposed.

6. Afterword

Problems of current specifications were sorted out, and a new orientation of aggregate standards has been proposed. The Committee hopes that aggregate resources will be used more efficiently in the future.

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