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MIX DESIGN OF EXTREMELY DRY CONCRETE EVALUATED BY CONSOLIDATION EFFORT

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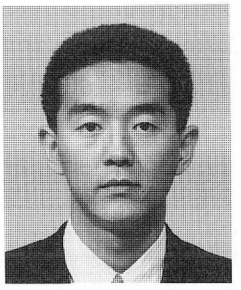

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SYNOPSIS

This paper reports on the compactibility and mix design of extremely dry concrete. The compaction curves of extremely dry concrete are tested, and the compaction function, which is the relationship between filled-volume ratio and consolidation effort, is discussed. The compaction curve of a certain concrete is dependent on the consolidation effort if the vibrating acceleration is greater than a critical value of about 2.5G. The compactive characteristics are evaluated in terms of this function and four indices derived from it. The effects of mix proportion and fine aggregate characteristics are discussed, and a design method for concrete with high compactibility is proposed.

Keywords: *extremely dry concrete, mix design, consolidation effort, filled-volume ratio, compactibility, shape factor of aggregate*

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1. INTRODUCTION

Extremely dry concrete is used in the construction of dams, pavements, and factory-cast concrete blocks. These concretes have to be compacted to high density using powerful vibrators, but a porosity of several percent sometimes remains in the hardened concrete because of an inappropriate mixture and/or insufficient compaction. Low-density concrete is not able to attain high strength and long-term durability[1-4]. Accordingly, the selection of appropriate mix proportion and optimum consistency are very important to obtaining concrete of good performance.

Generally, the filled-volume ratio of compacted concrete increases with water content under certain conditions of vibration. However, the operation of vibratory rollers becomes difficult when the water content rises. Accordingly, certain standard values of appropriate consistency for roller compaction have been published. The VC time in the Vibrating Table Method with a surcharge of 20 kg is specified in Recommendations for Roller-Compacted Concrete Dams[5] by the Japan Institute of Construction Engineering, while the VC time by the Vibrating Table Method as well as the moisture-density by the Marshall Hammer Test and the 2.5 kg Rammer Impact Test are specified in Recommendations for Roller-Compacted Concrete Pavements[6] by the Japan Road Association. However, these tested values represent the consistency of a given concrete only and give no information for full compaction.

The authors have proposed a new test method for the compactibility of extremely dry concrete[7], giving a relationship between filled-volume ratio and consolidation effort. The values yielded by this method indicate the compactibility rather than the consistency of the concrete. J. Kolek[8] reported a consolidation curve similar to this method in 1959, but the consolidation factors were relative acceleration of the internal vibrator, concrete consistency, and vibration time. J. Murata[9] proposed a similar consolidation curve by expressing the consolidation energy as a product of kinetic energy multiplied by vibration time. There are many reports on consolidation or compaction which discuss the effects of acceleration, frequency, and amplitude of vibration. But the comparative effects of vibrating parameters on consolidation are discussed only, and the fundamental mechanism of compaction is not studied. The most popular explanation of the mechanism is liquefaction of concrete under vibration.

In this paper, the energy contributing to the compaction of extremely dry concrete is discussed, and the relationship between filled-volume ratio and consolidation or compaction effort expressed as compacting energy per unit volume of concrete is clarified. Further, the effects of mix proportion and aggregate characteristics on compaction properties are discussed using the compactibility test method.

2. EXPERIMENT

(1)Materials

a) Cement

Ordinary portland cement conforming to JIS R 5210 was used in this experiment.

b) Aggregates

The physical properties of the fine and coarse aggregates used in this test are shown in **Table 2.1**. The coarse aggregate is crushed stone of 20 - 5 mm grading. Since crushed stone is generally used as a coarse aggregate at most sites today, we look at how differences in fine aggregate affect compaction. The kinds of fine aggregate used in the series III tests are nine normal sands and six different sources of copper slag: three types of crushed sand, four of pit sand from river plains and terraces, two of blended sand, and the copper slags. The reason for using copper slag is that its angular shape is advantageous in discussing how to design an easily compactible mix proportion. The physical properties of these aggregates are shown in **Table 2.1** and details of each aggregate are given in the discussion.

(2) Mix Proportions

So as to understand the internal friction between aggregates in a given mixture, the mix designs were calculated using eqs.(1), (2), and (3) [10].

$$km = m \,/\, (G \cdot e_g) \tag{1}$$

$$kp = p \,/\, (S \cdot e_s) \tag{2}$$

$$s/a = km \cdot e_g \cdot \rho_g \,/\, (km \cdot e_g \cdot \rho_g + kp \cdot e_s \cdot \rho_s + 1) \tag{3}$$

$$e_g = 1/T_g - 1/\rho_g, \quad e_s = 1/T_s - 1/\rho_s$$

where, km : mortar volume to inter-particle void ratio in coarse aggregate; kp : paste volume to inter-particle void ratio in fine aggregate; m : volume of mortar per unit volume of concrete (l/m^3); p : volume of cement paste per unit volume of concrete (l/m^3); G and S : unit contents of coarse and fine aggregate, respectively (kg/m^3); s/a : sand / aggregate ratio; ρ_g and ρ_s : specific gravity (SSD) of coarse and fine aggregate respectively; T_g and T_s : bulk density (SSD) of coarse and fine aggregate (kg/l)

The mix proportions of concrete used in this experiment are shown in Table 2.2. The aim of test series I was to examine the effects of vibration parameters on compaction. The mix proportion in the series I tests was 35% of water/cement ratio and km=1.60, and the unit water contents were 100 and 90 kg/m^3.
The aim of test series II was to examine the effects of the mix proportion on compactibility, so three sand/aggregate ratios (s/a), unit water contents (W), and water/cement ratios (W/C) were used. The s/a tests were carried out with different km under a constant 35% water/cement ratio and 115 kg/m^3 of unit water content. A variation in km is equivalent to a variation in sand/aggregate ratio through eq.(3). The optimum sand/aggregate ratio was selected as the mixture with minimum consolidation effort. The W tests were carried out between 100 to 120 kg/m^3 at the optimum sand/aggregate ratio. The W/C tests were at 30% to 40 % with the optimum sand/aggregate ratio of 38.5 % and a constant water content of 110 kg/m^3; this seems to be popular choice for RCC pavements. The aim of test series III was to examine the effects of the different fine aggregates. The mix proportions of the concrete used normal fine aggregates are designed so as to be constant in each volume of materials, and those of the concrete used copper slag fine aggregates are designed so as to be constant in kp.

(3) Mixing

The concretes in series I and II were mixed with a 50-liter pan-type mixer, and for series III a 20-liter mixer was used.

Table 2.1 Physical Properties of Aggregates

	Sort of Aggregates		Specific Gravity S.S.D	Specific Gravity O.D.	Absorption %	Bulk Dens. kg/l	Solid Vol.R. %	F.M.
I	Pit Sand		2.62	2.59	1.07	1.79	69.1	2.90
	Crushed Stone		2.64	2.61	0.92	1.57	59.9	6.67
II	Blended Sand		2.61	2.57	1.41	1.76	68.5	2.75
	Crushed Stone		2.62	2.60	0.95	1.55	59.8	6.63
III	Normal Sand	Min.	2.58	2.54	0.88	1.51	59.2	1.66
		Max.	2.65	2.63	3.77	1.84	70.1	2.99
	Crushed Stone		2.62	2.60	0.95	1.55	59.8	6.63
	Copper Slag	Min.	3.38	3.36	0.45	2.20	64.4	2.21
		Max.	3.65	3.63	0.55	2.43	67.3	2.59
	Crushed Stone		2.64	2.61	0.92	1.57	59.9	6.67

Table 2.2 Mix Proportion of Concretes

Test	Series	Km	Kp	W/C	s/a	Unit Content (kg/m^3) W	C	S	G
I	W 100	1.60	1.30	0.35	0.404	100	286	857	1274
	W 90	1.60	1.11	0.35	0.418	90	257	907	1274
II	s/a series	1.40	1.79	0.35	0.340	115	329	694	1350
		1.50	1.69	0.35	0.362	115	329	739	1305
		1.60	1.59	0.35	0.383	115	329	781	1262
		1.70	1.52	0.35	0.402	115	329	820	1223
		1.80	1.45	0.35	0.421	115	329	858	1185
	W series	1.50	1.33	0.35	0.385	100	286	814	1304
		1.54	1.41	0.35	0.385	105	300	804	1289
		1.57	1.50	0.35	0.385	110	314	794	1274
		1.68	1.59	0.35	0.385	115	329	784	1258
		1.76	1.68	0.35	0.385	120	343	775	1243
	W/C series	1.64	1.65	0.30	0.385	110	367	778	1247
		1.57	1.50	0.35	0.385	110	314	794	1274
		1.52	1.39	0.40	0.385	110	275	807	1294
III	Normal	1.60	var.	0.35	0.405	100	286	var.	1262
	Copper	var.	1.40	0.35	var.	110	314	var.	var.

(note) var. : variable by samples

(4) Test Methods

a) Compactibility Test
The compactibility test[7] is a method of determining the relationship between filled volume ratio and consolidation effort. The consolidation effort is defined as the energy acting on a unit volume of the sample and is calculated from vibration parameters, vibration time, and density of concrete using eq.(6). The filled volume ratio is the compacted volume of the sample as a percentage of the nominal volume calculated from the specific proportion of concrete with no voids.

The sample is weighed up precisely the mass equivalent to the volume of test container (100 mm in diameter and 200 mm in height). The sample is placed into the container and rodded fifteen times in each of three layers and a covering steel plate with a shaft is placed on the sample. The settling of the concrete in the container during vibration is automatically measured every 0.3 second using a laser displacement apparatus, with readings input into a computer and converted into values of filled volume ratio. The vibration parameters are 5G of acceleration and a frequency of 75 Hz. The measured curves representing the process of compaction can be approximated by a statistical equation as follows.

$$\gamma = Ci + (Cf - Ci)[1 - \exp(-bE^{d})] \quad (4)$$

where, γ : filled-volume ratio at compaction effort E (%); E : compaction effort (J/l); Ci : initial filled-volume ratio (%); Cf : final filled-volume ratio (%); b, d : experimental constants

A typical compaction curve and function are shown in Fig.2.1. As can be seen, the value of Cf is the potential filled-volume ratio estimated at infinite compaction effort. Ce is defined as the gradient of the relationship at a compactive effort of 1 J/l and is used to quantify the efficiency of the compaction process. A compaction effort that achieves a 98% filled-volume ratio is considered the effort (E98) required to achieve the maximum practical density.

b) VC Test
The VC test[5] is a modified VeBe test in which the table vibrates at 50 Hz and with an amplitude of 0.5 mm, and the container is 240 mm in diameter and 200 mm in depth. The surcharge mass on the sample is 20 kg. This method is designed for mearsuring the VC time until mortar is observed on the top surface of the sample, but in this experiment the table vibrator was stopped at 3, 10, and 60 seconds and the wet density was determined by measuring the depth of the sample. The compaction effort in this test was calculated from eq.(6) disregarding inertial vibrations and the surcharge.

c) Marshall Hammer Test
The Marshall hammer test[6] gives the wet density of a sample in a cylinder that is 100 mm in diameter and 200 mm in height after impact compaction. A Marshall hammer is 4.5 kg in mass and is dropped 50 times from a height of 457 mm. The testing device used in this experiment was remodelled so as to measure automatically the depth of the sample just after every impact. The compaction effort was calculated from the potential energy of the hammer mass and the number of impacts.

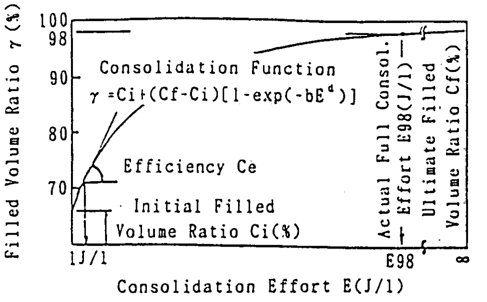

Fig.2.1 Consolidation Curve

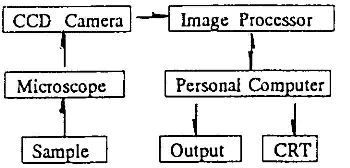

Fig.2.2 Outline of Image Processing Technique

d) Shape Factor of Fine Aggregate

The shape of the fine aggregate particles was determined using an image processing system. An image magnified by sixty times was input to the image processor using a microscope and a CCD camera. The image of a particle is treated with the edge- preserving smoothing and converted into a set of binary image. The shape factor is shown as follows.

$$s = L^2 / (4\pi \cdot F) = 1/\text{roundness factor} \qquad (5)$$

where, s : shape factor of a grain; L : perimeter of projection (mm); F : area of projection (mm^2)

The sample tested indicated a sieve size of 0.6 to 1.2 mm, and the shape factor was taken as the average of measured value from 30 particles. Six particles were measured at a time on the screen. The perimeter and the area of the image were derived from the number of scanning spots [11]. This shape factor taken from many particles would seem to be correct, but the measured value represent only the two-dimensional characteristics of three-dimensional objects.

3.RESULTS AND DISCUSSIONS

(1) Testing Methods and Consolidation Effort

a) Consolidation effort

Figure 3.1 (top) shows the relationship between filled-volume ratio and vibration time under constant vibration acceleration of 2, 5, and 8G, respectively, for frequencies of 75, 100, and 150 Hz. These figures show that a greater acceleration and lower frequency contribute to a higher filled-volume ratio for a given vibration time. The force acting on the sample increases if the vibration acceleration is larger. If the frequency under constant acceleration is low, the resulting amplitude becomes larger. These phenomena seem to suggest that the consolidation effort generated by the table vibrator plays an important role in consolidation.

Since the sample being tested was confined by an upper steel plate with a rod or mass as surcharge, the vibrations of the sample should coincide with the motion of the table vibrator. Accordingly, the vibrating behaviour of a sample being consolidated can be simplified as shown Fig. 3.2. The maximum kinetic energy applied to a unit volume of concrete is $(1/2)m[\alpha^2_{max}/(2\pi \cdot f)]^2$ according to our knowledge of physics. The concrete constituents are forced into the voids by this force, which amounts to the product of constituent

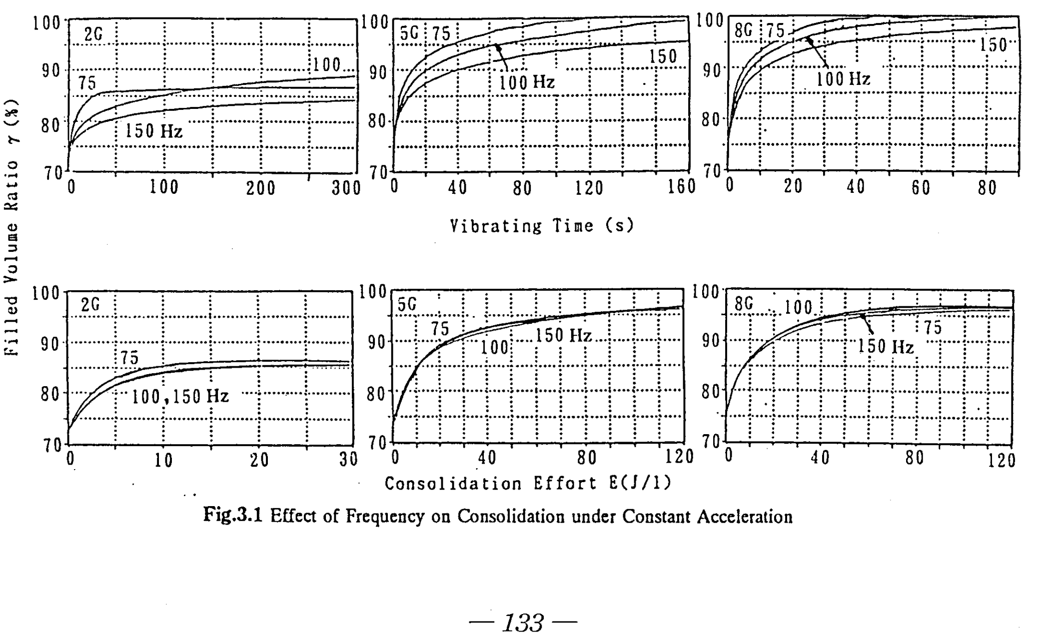

Fig.3.1 Effect of Frequency on Consolidation under Constant Acceleration

density and acceleration as the kinetic energy decreases. Since consolidating energy is applied to a unit volume of concrete twice per cycle, the consolidation effort during vibration time t seconds can be expressed as eq.(6). As the density of concrete increases with compaction progress, the value of density(m) in eq.(6) is taken to be that 0.3 s earlier.

$$E = m \cdot \alpha^2_{max} \cdot t / [(2\pi)^2 \cdot f] \qquad (6)$$

where, E : consolidation effort during vibration time t s (J/l); t : vibration time (s); m : density of sample (kg/l); α_{max} : maximum acceleration (m/s^2); f : frequency (s^{-1})

When the consolidation effort is expressed as eq.(6), the consolidation curves for different frequencies but with constant acceleration overlap each other, as shown at the bottom of Fig. 3.1. Figure 3.3 shows consolidation curves for different vibration parameters laid down upon the same curve; there is negligible error except for the case of a 2G acceleration. The authors have reported [7] that the relationship between filled-volume ratio and consolidation effort seems to be same under different vibration conditions above a critical acceleration of 2.5G. This critical acceleration in the consolidation of concrete implies that the driving force acting on the granular materials must overcome internal friction to fill the voids.

b) Relationship between Consolidation Effort and Filled-Volume Ratio

Figure 3.4 shows the relationship as determined by three different methods: compactibility test, VC test, and Marshall hammer test. The filled-volume ratios by the VC test with vibration times of 3, 10, and 60 s approximate closely to that given by the compactibility test. While the opinion has been expressed that a greater surcharge shortens the VC time[12], the filled-volume ratio seems to be affected little by the surcharge mass.

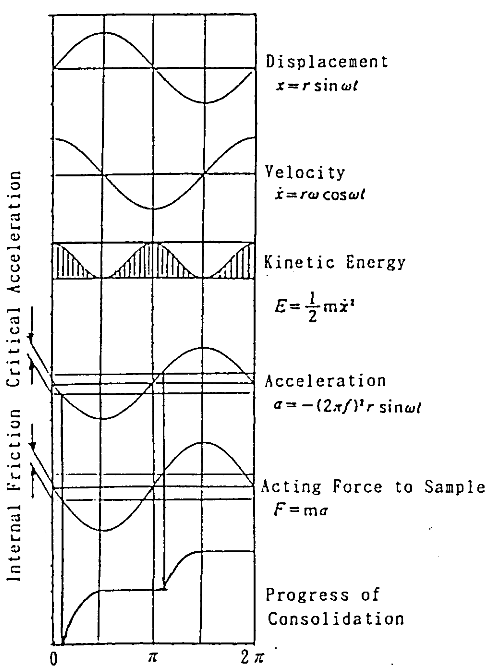

Fig.3.2 Schematic Process of Vibration and Consolidation

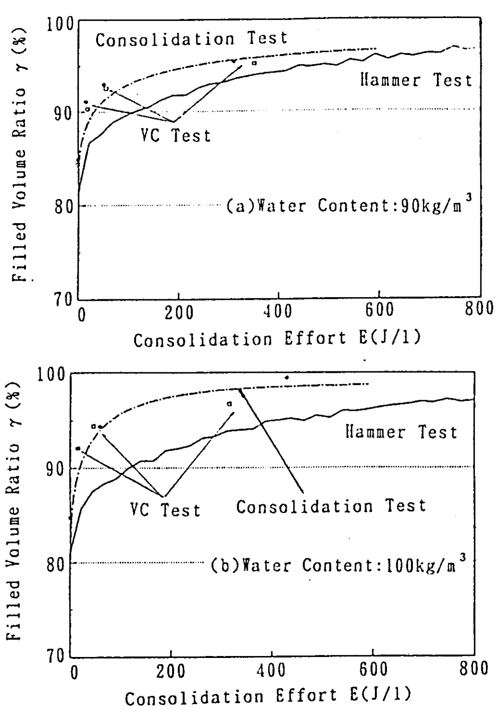

Fig.3.4 Relationship between Consolidating Effort and Filled Volume Ratio in Different Test Methods

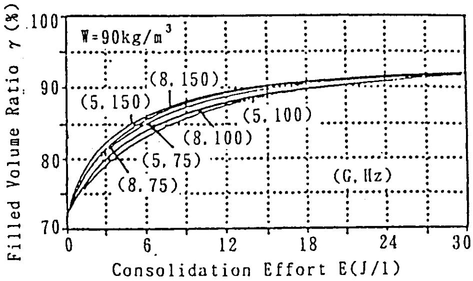

Fig.3.3 Consolidation Curves under Different Vibrating Conditions

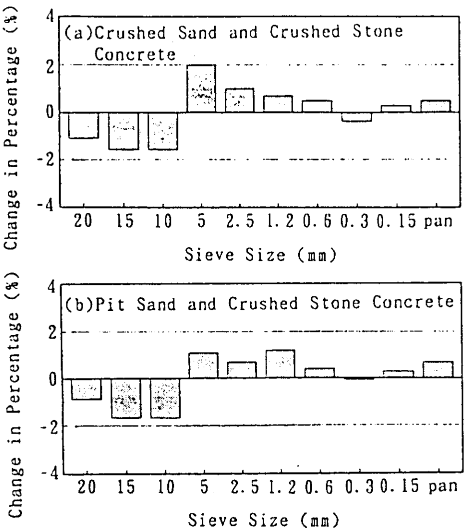

Fig.3.5 Change of Aggregates Grading after Hammer Test

The relationship determined by the Marshall hammer test shows a filled-volume ratio for a certain consolidation effort that is smaller than the value given by vibrating methods. Under hammer testing, the granular materials seem to collapse or be forced downward with significant friction. Some of the compaction energy may be consumed in the sound of the impact, breaking the particles[12], and frictional resistance.

To confirm this, the change in aggregate grading was determined. Samples before and after the hammer test were washed on a set of standard test sieves. The particle size distributions were compared with the nominal one estimated from that of fine and coarse respective aggregates and the specific proportion of the tested concrete. The difference in fineness modulus of the washed sample just after mixing was less than 0.05, so the particles to be crushed little by mixing. The grain size distribution of the mixture containing crushed sand and crushed stone was unchanged after the compactibility test, as was the case for the crushed sand and river gravel sample after the hammer test. But in the crushed sand and crushed stone sample and the river plain sand and crushed stone sample, the percentage remaining on the 10 mm sieve became smaller, while that passing the 5 mm sieve became larger than the nominal value. The decrement in fineness modulus of the total aggregate was about 0.2. This proves clearly that the hammer impact consumes some of the compaction energy in breaking the particles. It is possible that the crushed sand is broken too, but this could not be clarified in this experiment. River gravel seems not to be crushed because of its hardness and roundness, whereas crushed stone is apt to lose its angles and edges.

As will be mentioned later in 3.(2) a), the compactive behaviour of extremely dry concrete is affected greatly by the size distribution of the mixture. Thus the impact method is not suitable for determining consistency because of the changing the particle size distribution.

(2)Effect of Mix Proportion on Compaction Characteristics

a) Sand/Aggregate Ratio

When the sand/aggregate ratio was increased by every 2 % (km=0.1) from 34.0% to 42.1% with a constant water content of 115 kg/m³, the increased sand content resulted in increased values of Ci but reduced values of compaction efficiency Ce. This is clearly shown in Fig.3.6. The reason for this tendency is thought to be that a larger amount of sand reduces the volume of large inter-gravel voids when placing the concrete into the container, but increases the small inter-sand voids which are expelled little by vibration. The overall effect of changes in sand content is that there is an optimum percentage of sand at 38.5% for a minimum application of energy E98 to achieve maximum compaction. As shown Fig.3.7, the optimum sand/aggregate ratio is the same when determined by the VC test and hammer test.

Because of the good appearance of the rolled surface and/or minimal dry segregation, mixtures with high sand/aggregate ratio are sometimes used in RCC pavement projects. It must be noted that such high sand content mixtures tend to result in porous concrete as described above.

b) Water Content

Figure 3.8 shows the effects of water content on compaction characteristics at the optimum sand/aggregate ratio of 38.5%. Even if the water content is changed between 100 to 120 kg/m^3, the measured values of Ci varies little, but the value of efficiency Ce increases linearly with the water content. Where the water content is insufficient to give lubrication under vibration, the values of Cf are smaller than 100%. If there is sufficient water, the values of Cf are between 100 and 102%. This increase to 102% is due to the loss of part of the mortar into the opening between the top plate and the wall of the container, and therefore should be taken as 100 % if corrections are made.

The Cf value represents the potential filled-volume ratio with infinite consolidation effort, and a mixture that fails to attain a Cf of 98% or more should not be used. A mixture with Cf over 100% should be compacted with more than a consolidation energy of E98 for maximum compaction. The value of E98 decreases hyperbolically with increasing water content, as shown **Fig.3.8**, and the appropriate level of E98 for actual vibratory roller operations needs to be determined in another study.

c) Water / Cement Ratio

The test to assess the effect of water / cement ratio on compactibility were carried out using the mixes with optimum sand/aggregate ratio and water content of 110 kg/m^3. As shown in **Table 3.1**, the value of E98 were decreased with the increased water/cement ratio. This reason seems to be that the higher water/cement ratio lowers the viscosity of cement paste between aggregates and/or decreasing the cement content under constant water content makes easy to compact. But this tendency is negligible to compare the reduction of E98 by water content.

(3) Effects of Fine Aggregate on Compaction Characteristics

a) Properties of Aggregate

1) Solid-Volume Ratio and Fineness Modulus

The results of compactibility tests on nine mixes using different fine aggregates are shown in **Table 3.2** with their physical properties, and consolidation curves are shown in Fig. 3.9. The mixtures, which contained the same unit volume of materials, exhibited scattered consolidation curves. Generally, mixtures containing crushed sand showed low compactibility, but mixture with river plain sand P-C had good compactibility. The solid-volume ratio and fineness modulus of this sample was the largest among those tested. Among the crushed sands, only C-C exhibited high compactibility; its properties are similar to those of the sand P-Cmixture. The mixture using terrace sand M was the worst in compactibility, and its solid-volume ratio and fineness modulus are the lowest among the tested samples. It appears that roundness and proper grading of the sand are important for full compaction.

2) Shape Factor of Particles

Since the properties of the fine aggregate have certain important effects on compaction, as described above, further experiments were carried out in respect of the shape of the fine aggregate particles. Particles that

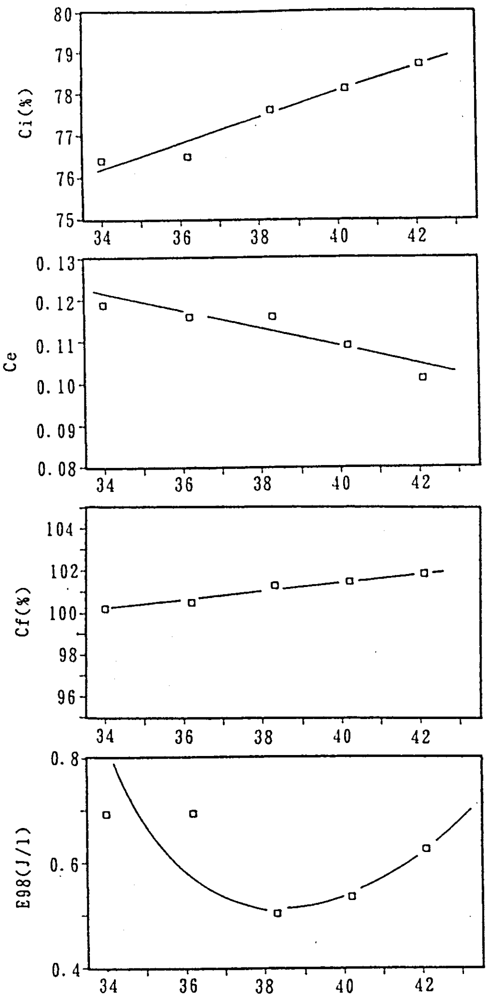

Fig.3.6 Effect of Sand/Aggregate Ratio on Consolidation

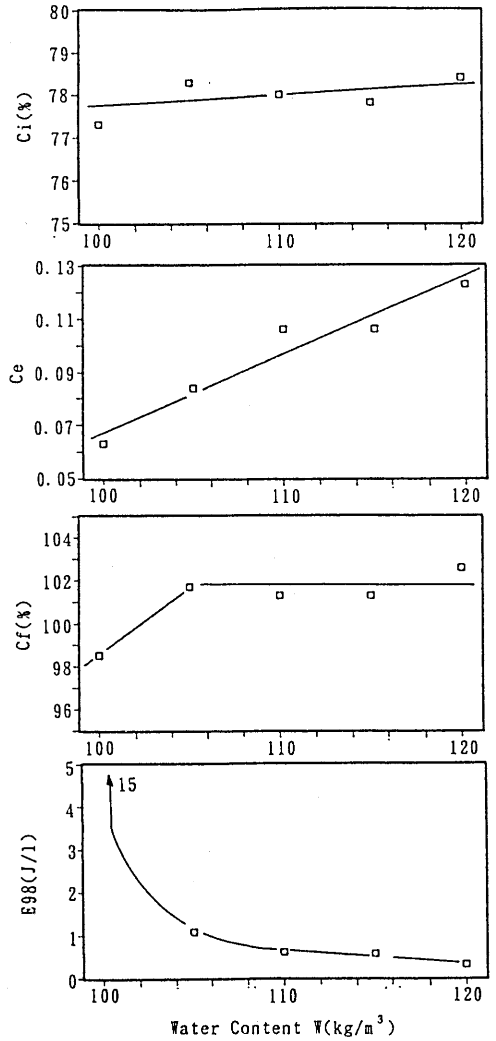

Fig.3.8 Effect of Water Content on Consolidation

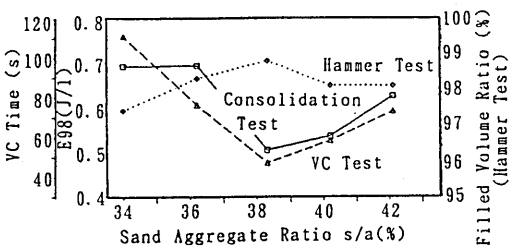

Fig.3.7 Optimum Sand/Aggregate Ratio in Different Tests

Table 3.1 Effects of Water Cement Ratio on Consolidation

Condition of Mix Proportion		W=100, s/a=0.385		
Water Cement Ratio	W/C	0.30	0.35	0.40
Initial Filled Volume	Ci (%)	77.2	77.3	78.8
Efficiency	Ce (%/J/l)	0.10	0.10	0.09
Ultimate Filled Volume	Cf (%)	100.5	101.0	102.3
Consolidation Effort	E98 (J/l)	1.13	0.81	0.80

Table 3.2 Properties of Normal Sands and Results of Consolidation Test

Kind of Fine Aggregate	Pit Sand			Crushed Sand			Blended S.		Mount
	P-A	P-B	P-C	C-A	C-B	C-C	B-A	B-B	M
Character of Fine Aggregates									
Fineness Mod.	2.21	2.27	2.99	2.85	2.51	2.99	2.53	2.76	1.66
Under 0.15mm S.%	15	7	3	10	14	6	10	5	5
Shape Factor	1.11	1.20	1.15	1.33	1.33	1.19	1.24	1.19	1.17
Solid Vol. R.	70.1	69.4	68.7	64.8	67.5	68.3	68.6	68.5	59.2
Mix Proportion									
Condition	W/C=35%, s/a=40.5%(Km=1.60), W=100kg/m³								
Kp	1.36	1.31	1.28	1.07	1.20	1.25	1.27	1.27	0.84
Results of Consolidation Test									
Initial F.V.Ci	80.8	79.2	81.0	77.2	76.9	78.6	78.0	78.3	78.9
Efficiancy Ce	0.84	0.87	1.05	0.78	0.77	0.98	0.77	0.89	0.67
UltimateF.V.Cf	95.0	98.0	99.4	89.4	91.2	98.4	90.8	95.4	86.9
Effort E98	-	1389	319	-	-	1379	-	-	-

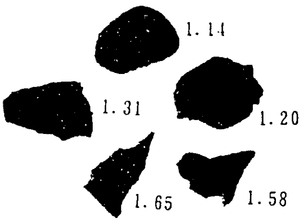

Fig.3.10 Example of Shape and Shape Factor

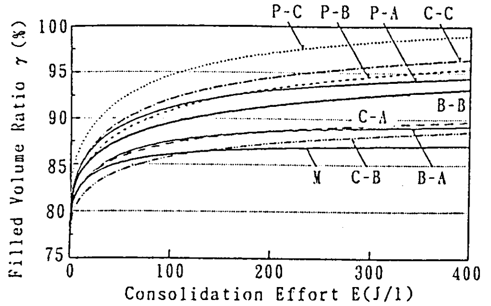

Fig.3.9 Consolidation Curves of Various Concretes with Different Normal Sands

Table 3.3 Correlation Factor between Consolidation Index and Sand Charactor

Consolidation Test \ Character of Sand	Fineness Modulus	Shape Factor	Solid Vol. R.
Initial Filled Volume Ci(%)	-0.135	-0.917	0.695
Efficiency Ce(%/J/l)	0.581	-0.633	0.333
Ultimate Filled Volume Cf(%)	0.370	-0.753	0.616

pass a 0.15 mm sieve are thought to have some effect on compaction too, but these are neglected because the content is small exccept in the case of sand M as shown Table 3.2. The effects of grading are considered by measuring the fineness modulus, and the effects of shape by a shape factor. This shape factor is nearly 1.0 if the particle resemble spheres. Some examples of the value of the shape factor for certain particle projections are shown in Fig. 3.10.

The solid-volume ratio is clearly controlled mainly by the particle shape, but there is also a tendency for the solid-volume ratio to become extremely small if the particles are tiny as in the case of terrace sand M. The value for river plain sand P-A, which is close to spherical, is very small too.

The correlation between the physical properties of fineness modulus, shape factor, and solid-volume ratio and the results of compactibility tests on a constant mix shown in Table 3.3. The data for terrace sand M are excluded because of its small value of solid-volume ratio. The irregular shape of fine aggregate decreases the compactibility. In particular the values of Ci and Ce are affected strongly by the particle configuration and this tendency does not conflict with the solid-volume ratio. As the finer particles are apt to entrap air voids, they reduce the efficiency of compaction. These trends are recognised in the discussion in 3.(2) a).

b) Effects of Inter-Particle Space

Since compactibility is affected by the properties of the fine aggregate, it is important that the mix proportion should be designed to give easy compaction. There are some reports[13,14] that the consistency of the concrete can reasonably be considered in terms of the thickness of excessive paste around the aggregate. This method requires the total surface area of all aggregate, but determining this surface area seems to be a problem. The parameters kp and km in mix design are considered to be alternative indices of the thickness of excessive paste around the fine aggregate and of excessive mortar around the coarse aggregate, respectively. The aggregate particles are in contact with each other and the thickness is zero if the value of kp or km is equal to 1.

The mix proportions shown in Table 3.2 are constant as regards the value of km and the volumetric content of each material, but the values of kp change according to the sand used. As the paste content is constant, the value of kp is large when a sand has a large solid-volume ratio. Then the distance between sand particles is greater and the mixture is easy to compact. The value of kp in the mixture using terrace sand M is less than 1. The content of paste is insufficient to fill the inter-particle space and such a mixture cannot be compacted completely. The determined value of Cf for the mixture using sand M is 86.9%. In case of crushed sand C-A, the value of kp is scarcely over 1 so the value of Cf results is 89.4% because of the significant friction between particles. Mixtures using other sands have kp values of 1.20 to 1.35, and the effects of particle shape are diminished and their compactibility seems to be better. Considering previous experience[1], the value of kp should be at least 1.4 .

c) Compactibility of Mixtures with Proper Inter-Particle Distance

The shape of copper slag fine aggregate is irregular, and this proves advantageous in discussing how to design an easily compactible mix proportion.

The results of compactibility tests with copper slag mixtures are shown in Table 3.4 with the properties of the particles and the mix proportions. The consolidation curves are shown in Fig. 3.11. The mix proportions were calculated for a water/cement ratio of 35%, a water content of 110 kg/m^3, and a fixed kp value of 1.4 considering the results of the previous work. The consolidation curves of these mixtures are almost identical in spite of the difference in particle characteristics, and compactibility was good.

In case of the mixtures using a fine aggregate with a high solid-volume ratio, the value of km is large and the mortar content or sand content is higher given fixed water/cement ratio, water content, and kp value. Only the mixture using slag C had a Cf of less than 98%. For this reason, it is important that the optimum sand/aggregate ratio should be located by changing s/a or km at the assumed water content, as mentioned in 3.(2) a). If a mixture fails to give good compactibility characteristics, the water and/or cement content should be adjust so as to be enable proper compaction.

Table 3.4 Charactor of Copper Slag and Results of Consolidation

Copper Slag	A	B	C	D	E	F
Character of Fine Aggregates						
Fineness Modulus	2.44	2.33	2.41	2.21	2.59	2.57
Under 0.15mm Sieve (%)	7	9	10	10	9	8
Shape Factor	1.28	1.26	1.23	1.18	1.24	1.29
Solid Volume Ratio(%)	64.4	65.6	67.3	66.1	66.8	65.4
Mix Proportion						
Condition	W/C=35%, Kp=1.40, W=110kg/m^3					
Km	1.38	1.46	1.60	1.50	1.56	1.45
s/a	34.2	36.2	38.9	36.9	38.1	35.8
Results of Consolidation Test						
Initial Fill.Vol.Ci(%)	83.1	82.5	82.4	84.2	83.0	82.7
Efficiancy Ce (%/J/l)	1.14	1.11	1.10	1.15	1.12	1.11
Ultimate Fill.Vol.Cf(%)	98.3	98.1	97.8	98.2	98.4	98.6
Consolidation EffortE98	338	473	-	212	170	211

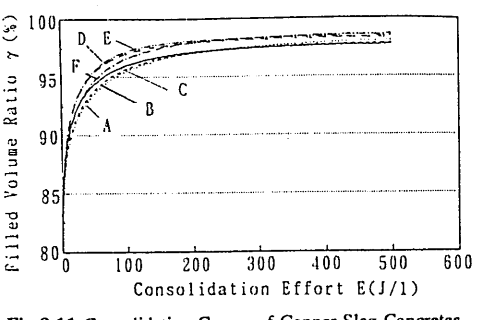

Fig.3.11 Consolidation Curves of Copper Slag Concretes

(4) Optimal Mix Proportioning

The results obtained indicate that the optimal mix should be obtained by optimising the s/a ratio, since there is an optimum sand/aggregate ratio for minimum full-compaction energy. And the appropriate amount of water should be selected so as to attain practically complete compaction.

4. CONCLUSIONS

Based on the experimental work presented in this study, the following conclusions are offered.

(1) The consolidation effort applied by vibration can be calculated as equivalent to the maximum kinetic energy acting twice per cycle. The consolidation curve of certain mix proportions is the same above the critical acceleration of 2.5G in spite of different vibration parameters.

(2) When the compaction energy applied in the hammer test is obtained by assuming that the initial potential energy of the hammer is applied as compactive effort, the filled-volume ratio in the consolidation curve is less than in the case of vibration methods. This is because the hammer impact loses some of its energy in breaking the particles.

(3) Increasing the sand/aggregate ratio results in a higher initial filled-volume ratio, but reduces consolidation efficiency. As a result, there is an optimum sand/aggregate ratio at which the consolidation effort is a minimum for maximum compaction.

(4) When the water content is changed between 100 and 120 kg/m^3, the initial filled-volume ratio is affected little but the consolidation efficiency rises linearly with water content. The consolidation effort required for practical full compaction decreases hyperbolically with water content. A mixture which is below 98% in final filled-volume ratio should not be put to practical use.

(5) The effects of water/cement ratio on compactibility are negligible compared to those of water content.

(6) With a constant content of water and coarse aggregate, a mixture using sand with a higher solid-volume ratio and larger fineness modulus exhibits superior compaction performance. The use of finer sand reduces consolidation efficiency.

(7) Where the paste/inter-sand void ratio kp is equal to 1.35 or below, the configuration of sand affects the compactibility strongly. This effect tends to fall off at about 1.40 or over.

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