STUDIES ON COMPACTIBILITY AND ITS TEST METHOD OF EXTREMELY DRY CONCRETE USED FOR ROLLER COMPACTED CONCRETE PAVEMENTS

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ABSTRACT

As extremely dry concrete for roller compacted concrete (RCC) pavements, maximum stiffness is preferred for the operation of vibratory rollers. On the other hand, a less stiff mix is appropriate for attaining full consolidation. Accordingly, it is very difficult to select consistencies suitable for RCC.

This paper reports a fundamental study on the compactibility of RCC. Samples of RCC were consolidated with a magnetic table vibrator. The settlement of fresh concrete during vibration was measured at very short intervals of time and was input into a personal computer. Then the data was converted to consolidation curves, which show the process of the increase in the filled volume ratio due to the vibrating energy.

The consolidation curves vary depending on the materials used and the mix proportions, and are expressed as a function. The consolidation behavior can be explained by four indices derived from the consolidation function.

INTRODUCTION

The first ever RCC pavement in Japan is the Sapporo-Chitose road constructed in 1953, but the RCC method had not been used since then until 1987 when a new RCC pavement was adopted for a yard in a cement factory in Osaka. The good performance of this project set off the trend of RCC pavement as a new construction method for road and yard pavements. The total area of RCC pavements in Japan reached over 10,000 m² in 1991.

Basic research on the consistency of RCC is scarcely found, although its practical applications have been rather extensively studied. Maximum stiffness is preferred for the operation of vibratory rollers, but a less stiff mix is appropriate for attaining full consolidation. In Japan, consistency of RCC is tested by the filled volume ratio of the Marshal compaction method(1) for asphalt concrete testing or VC time(1) developed in the field of dam construction, i.e. the rolled concrete dam (RCD) method. These test results are applicable to practical use, but provide little data for improving RCC construction. Accordingly, the consistency suitable for RCC pavement is very difficult to specify and to test. Since the au-

thors consider that the consistency of RCC is very important in preventing voids in hardened RCC pavement, they describe in this report their investigation on the newly developed test method for compactibility.

In this experiment, the tests were performed not only on the compactibility testing method but also on the effects of mix proportions and chemical admixtures.

EXPERIMENT

Materials

Cement

The cement used in this experiment is ordinary portland cement available on the market.

Aggregates

Pit sand or crushed sand was used as the fine aggregate, and crushed stone with a maximum size of 20 mm was used as the coarse aggregate. Two different combinations of fine and coarse aggregates as summarized in table 1 were used for the water content series and for the sand percent and chemical admixture series.

Chemical admixtures

Three types of chemical admixtures, RP, SRR, and WR, were used to examine the effect of improving the compactibility of extremely dry concrete. The main components of these admixtures are a composite of polyalkylene glycol derivative and lignin (RP), hydroxylated carboxylate (SRR), and lignosulfonates (WR). WR is used generally in conventional concrete as a water reducing and air entraining agent, and the others have recently been developed in Japan for extremely dry concrete. The purpose of these newly developed admixtures is to make the concrete wetter, to reduce the water content, and to minimize the change in consistency over time.

Mix proportion

In the series of water content, the water-cement ratio was fixed at a constant 35 percent, and the mortar volume ratio (Km) against the void volume of coarse aggregate, at 1.60, whereas the unit water content varied from 90 to 120 kg/m³. This series was tested as the plain concrete and the test method for compactibility was discussed concerning these mixtures. In the series of sand percentage, the water-cement ratio was fixed at a constant 35 percent, and the unit water content, at 115 kg/m³, whereas Km varied from 1.40 to 1.80 corresponding to the sand percentage of 34 to 42 percent. The water content of each mixture containing a chemical admixture was adjusted by trial batches, so as to lead to the same filled volume ratio of 97 percent by the Marshal compaction method, which is widely

Table 1 Physical Properties of Aggregates

Kind of agg.	Specific gravity Oven dry	SSD	Absorption (%)	Unit weight (kg/l)	Fineness modulus
Water content series					
Pit sand	2.57	2.61	1.60	1.851	3.11
Crushed agg.	2.63	2.65	0.66	1.580	6.66
Sand percent series and chemical admixtures series					
Crushed sand	2.57	2.61	1.41	1.764	2.75
Crushed agg.	2.60	2.62	0.95	1.552	6.65

Table 2 Mix proportions of concrete

Water content series:		1	2	3	4	
Water/Cement ratio	(%)	35	35	35	35	
Km		1.60	1.60	1.60	1.60	
sand percentage	(%)	37.2	38.7	40.2	41.6	
Water content	(kg/m³)	120	110	100	90	
Cement content	(kg/m³)	343	314	286	257	
Fine aggregate	(kg/m³)	749	799	849	899	
Coarse aggregate	(kg/m³)	1283	1283	1283	1283	
Sand percentage series:		1	2	3	4	5
Water/Cement ratio	(%)	35	35	35	35	35
Km		1.40	1.50	1.60	1.70	1.80
Sand percentage	(%)	34.0	36.2	38.3	40.2	42.1
Water content	(kg/m³)	115	115	115	115	115
Cement content	(kg/m³)	329	329	329	329	329
Fine aggregate	(kg/m³)	694	739	781	820	858
Coarse aggregate	(kg/m³)	1350	1305	1262	1223	1185
Chemical admixture series:		PL	WR	RP	SRR	
Water/Cement ratio	(%)	35	35	35	35	
Km		1.57	1.56	1.54	1.56	
Sand percentage	(%)	38.5	38.5	38.5	38.5	
Water content	(kg/m³)	110	108	105	108	
Cement content	(kg/m³)	314	309	300	309	
Fine aggregate	(kg/m³)	794	798	804	798	
Coarse aggregate	(kg/m³)	1274	1280	1289	1280	
Dosage	(C x %)	0.00	0.25	1.50	0.50	

adopted for practical projects in Japan(1).

Method of Compactibility Test

Apparatus

The apparatus for the compactibility test is composed of an electromagnetic table vibrator, a control unit, and a measuring unit as shown in Fig.1. The change in the filled volume ratio during vibration is calculated from the settlement of the concrete sample in the cylinder of 10 cm in diameter and 20 cm in height. The consolidation curve is plotted on the screen of a cathode-ray tube, which shows the relationship between the filled volume ratio and the vibrating energy. The electromagnetic vibrator has the maximum centrifugal force of 400 kgf, and the frequency range of 5 to 3500 Hz. Experiments were performed under vibrations by sinusoidal waves of the combinations of accelerations of two, five and eight times the gravity acceleration and frequencies of 75, 100 and 150 Hz. The settlement of concrete was measured on the top surface by a laser displacement apparatus at every 0.3 sec, and the data is input into a personal computer. The displacement data is converted to the filled volume ratios, with which a consolidation curve is displayed on the cathode-ray tube. The measured data is approximated to a function, from which four indices to indicate the compactibility of the extremely dry concrete are

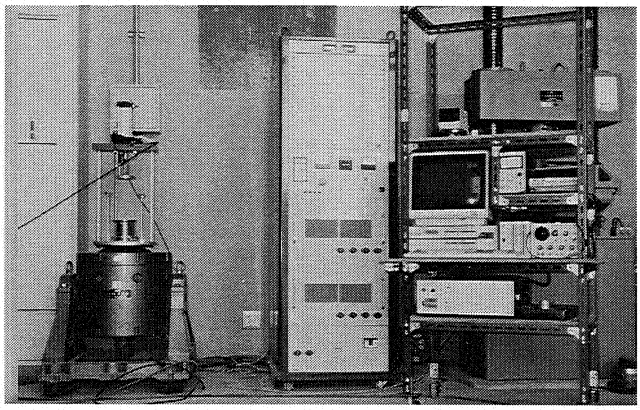


Fig.1 Apparatus for Compactibility Test

derived. The vibrating time is three min per sample.

Preparation of Samples

Concrete samples were prepared by precisely weighing the amount equivalent to 100 percent filled volume ratio based on the unit weight of the specified mix proportions without any void. Concrete was cast into the cylinder in three layers, each layer being rodded in fifteen strokes.

RESULTS AND DISCUSSION

Vibrating Energy

Figs.2 and 3 show typical examples of the relationship between the vibrating time and the filled volume ratio of a mix of a unit water content of 100 kg/m³. These consolidation tests were conducted with various combinations of accelerations and frequencies. It is found that when the acceleration is constant, the consolidation is more efficient with lower frequencies as in Fig.2, whereas when the frequency is constant, the consolidation is more efficient with greater accelerations as in Fig.3.

Thus great acceleration or great amplitude is a prominent factor of consolidation, but the effects of vibrating conditions on the consolidation cannot be expressed simply by the acceleration, amplitude, frequency and vibrating time. Consequently, vibrating energy should be considered as the factor for evaluating the consolidation quantitatively. An ACI Committee reports on the behavior of fresh concrete during vibrations(2), but the vibrating energy is not specifically discussed in the report.

Kinetic energy of the vibrating table changes two times a cycle, and the decrease in the energy is equal to the work of consolidation. As the kinetic energy of the vibrating table decreases, the compacting force acting on the concrete sample increases. The consolidation is considered to be a process in which individual particles in the concrete mixtures move to fill the voids or to minimize the distance between themselves, when the compacting force overcomes the friction between the particles. The force acting on the particles decreases after a maximum acceleration, and the force in the decreasing phase does not contribute to the increase in the degree of consolidation. In

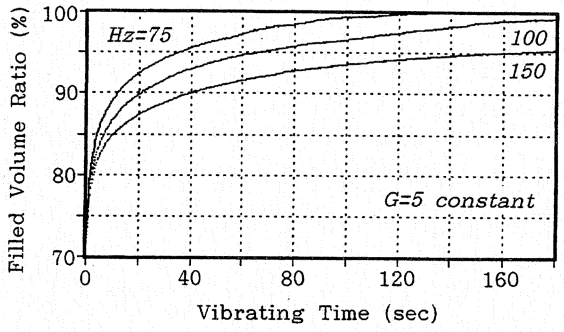


Fig.2 Consolidation Curves under Constant Acceleration

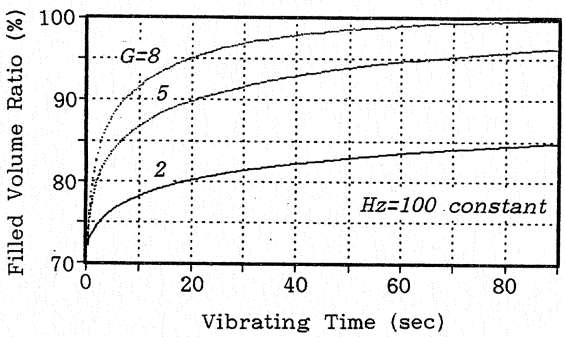


Fig.3 Consolidation Curves under Constant Frequency

the next phase, the direction of the force acting on the particles reverses in the manner of the sinusoidal wave, and the acting force contributes to the increase in the degree of consolidation. As the concrete under sinusoidal acceleration receives vibrating energy two times a cycle, the total vibrating energy on a unit mass of concrete during the vibrating time of t sec is expressed as follows:

$$E = m \alpha_{max}^2 t / (4\pi^2 f) \qquad \text{(Eq. 1)}$$

where E : vibrating energy (erg/cm³)

α_{max} : maximum acceleration (cm/sec²)

f : frequency (Hz)

m : unit mass of concrete (g/cm³)

t : vibrating time (sec)

Consolidation curves are expressed by the filled volume ratio on the ordinate and the vibrating energy defined as Eq.1 on the abscissa. Fig.4 contains six combinations of the accelerations and the frequencies excluding the acceleration of two times the gravity acceleration. It is found that the consolidation curves of the same mix proportions with a water content of 90 kg/m³ coincides independently of the vibrating conditions. The effect of the magnitude of acceleration will be discussed later in this paper.

Consolidation Function And Evaluation of Compactibility

Since the consolidation curve is constant provided that the consolidating acceleration is greater than a certain value, the curves should be expressed as a function. A form of the consolidation function was selected as follows:

$$\gamma = C_i + (C_u - C_i)[1 - exp(-b E^d)] \qquad \text{(Eq. 2)}$$

Where γ : filled volume ratio at vibrating energy E (%)

E : vibrating energy per unit mass of concrete (erg/cm³)

C_i : initial filled volume ratio (%)

C_u : ultimate filled volume ratio (%)

b, d : experimental coefficients

C_i was determined from the initially measured value and the others were determined by the Simplex method based on all measured points. Consolidation curves of the mixtures of different water contents are shown in Fig.5. It is observed as a general tendency that the consolidation curve becomes more upright as the water content increases. The initial filled volume ratio (C_i) denotes the filled

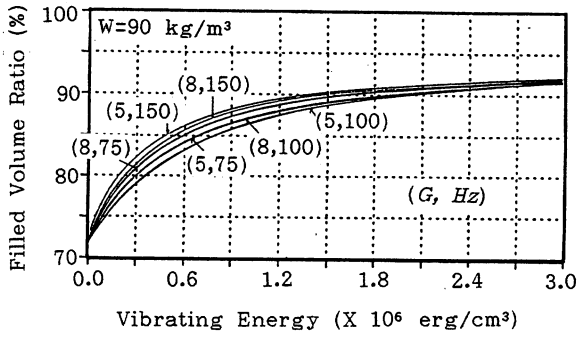


Fig.4 Relation between Vibrating Energy and Filled Volume Ratio

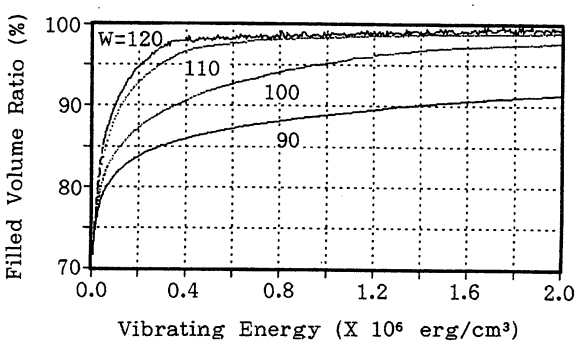


Fig.5 Consolidation Curves Influenced by Water Content

volume ratio after the rodding. The ultimate filled volume ratio (C_u) denotes the estimated filled volume ratio with infinite vibrating energy. The C_u values were greater than 98 percent for the mixtures with a water content of 100 kg/m³ or more, whereas the value for the mixtures with a water content of 90 kg/m³ was 94.3 percent, which shows that the water content of 90 kg/m³ is insufficient for full consolidation however long the vibration time may be extended. Thus, such a concrete mixture is not suitable for RCC.

The higher the water content, the greater the gradient of the consolidation curve, as shown in Fig.5. It is observed that the mixtures with a higher water content have greater efficiency of consolidation. Fig.6 shows the changes in the gradients with the increase in the vibrating energy. At the beginning of vibration the gradients of the curves are maximum, and they decrease to the levels where the differences between the gradients due to the differences in water content become clear at a vibrating energy of approximately 1 x 10^4 erg/cm³. The gradient at this vibrating energy is defined as the consolidation efficiency (C_e) and is calculated as follows:

$$C_e = d\gamma / dE \qquad \text{(Eq. 3)}$$

where C_e : consolidation efficiency, i.e. the gradient of consolidation curve at 10,000 erg/cm³

Fig.7 shows the change in the consolidating efficiency affected by the unit water content. It is found that the gradient changes proportionally to the water content until 110 kg/m³ and the water content is a main factor that affects the degree of consolidation.

It is convenient to know the time in which a concrete mixture attains a certain degree of consolidation under a given vibration as VeBe time or VC time for RCC. By substituting the filled volume ratio of 98 percent into the consolidation function, the vibrating energy required for the practi-

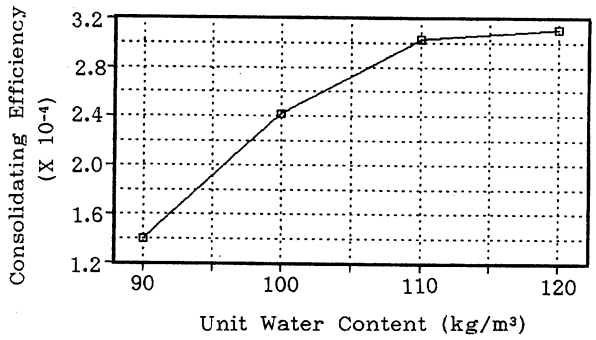


Fig.7 Consolidating Efficiency Influenced by Water Content

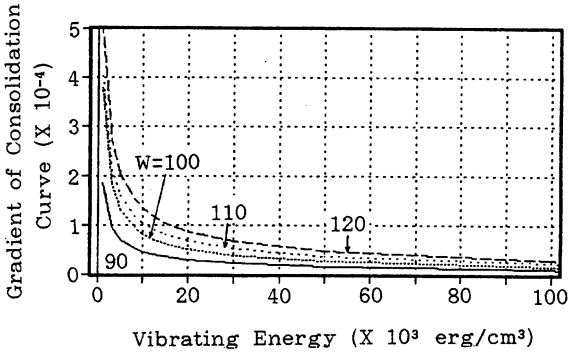


Fig.6 Gradient of Consolidation Curves Varied by Given Energy

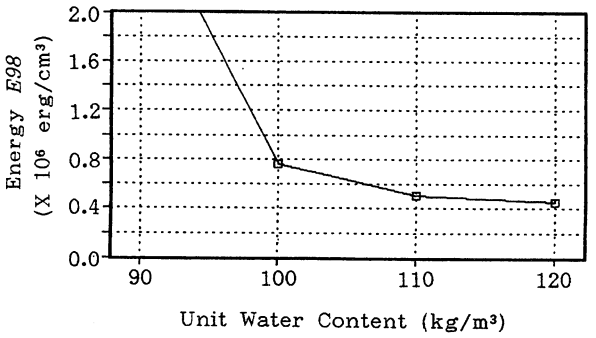


Fig.8 Energy E98 Influenced by Water Content

cally full consolidation can be calculated. The resulting energy is expressed as *E98* in this paper and the value shows the rate of full consolidation of the tested concrete. The change in the energy, *E98*, influenced by the water content is shown in Fig.8. As shown in this figure, a mixture with a water content as low as 90 kg/m³ was not able to attain the 98 percent level, and *E98* decreased as the water content increased.

To summarize the above, the relationship between the settlement and the vibrating energy, i.e. the consolidation function, is considered to be effective in expressing the behavior of extremely dry concrete under vibration. The consolidation behavior affected by the mix proportions is expressed quantitatively by the initial filled volume ratio, ultimate filled volume ratio, consolidating efficiency, and the energy required to attain full consolidation, *E98*.

Critical Acceleration for Consolidation

As mentioned above, the acceleration equivalent to two times the gravity acceleration (2*g*) was insufficient for consolidating. It is considered to be important to examine the reasons why 2*g* is not sufficient for consolidating. Mixtures of two different water contents, 90 and 100 kg/m³, were tested with the accelerations ranging from one to eight times the gravity acceleration and a constant frequency of 75 Hz. The initial filled volume ratios of both mixtures were approximately 80 percent, while the ultimate filled volume ratios were as shown in Fig.9. The ultimate filled volume ratios with the acceleration equivalent to *g* were nearly equal to the initial filled volume ratios,

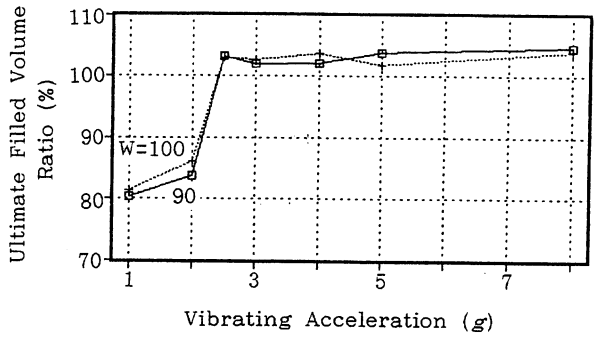


Fig.9 Ultimate Filled Volume Ratio Influenced by Acceleration

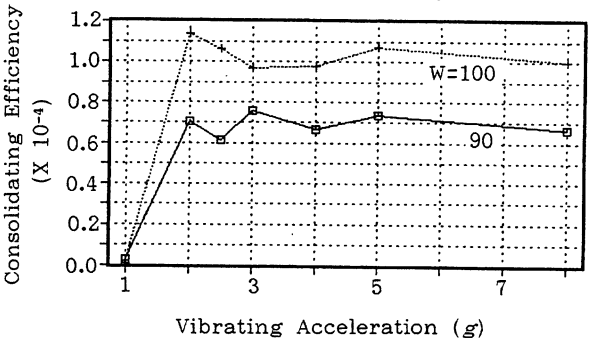


Fig.10 Consolidating Efficiency Influenced by Acceleration

which means no consolidation resulted from the vibration. The acceleration of 2*g* contributed to the increase in the ratios by only three to six percent over the initial filled volume ratios, while those over 2.5*g* attained full consolidation. The reason why the ultimate filled volume ratios exceed 100 percent is that the excess paste or mortar moves up by the vibration to the opening between the disk and the wall of the container. The changes in consolidating efficiency are shown in Fig.10. The efficiency values by the different accelerations were nearly equal for both mixtures of the water content of 90 and 100 kg/m³ except for the acceleration equivalent to *g*. These results show that an acceleration of over 2.5*g* is necessary to consolidate the extremely dry concrete. This critical acceleration for consolidation is consid-

ered to be required for overcoming the internal friction between the aggregate particles of the mixtures. Kolek(3) and Yamada(4) reported that an acceleration of at least 1.5*g* is required for stiff concrete.

Effects of Sand Percentage on Consolidation

The effects of sand percentage on compactibility are shown in Figs.11-13. The initial filled volume ratio remarkably increased with the increase in the sand percentage as shown in Fig.11. The reason for this tendency is considered to be that the increase in the sand percentage causes to increase the distances between coarse aggregate particles and to reduce the friction between them. As a result, large voids among the particles are expelled only by rodding. However, a large amount of sand is apt to form small voids, which are hardly vanished by vibrations. Therefore, the consolidating efficiency decreases with the increase in the sand percentage. This is shown in Fig.12. The interaction of the increase in the initial filled volume ratio and the decrease in the consolidating efficiency with the sand percentage, produced a minimum in *E98* as shown in Fig.13. The sand percentage corresponding to the minimum energy is considered optimum for extremely dry concrete.

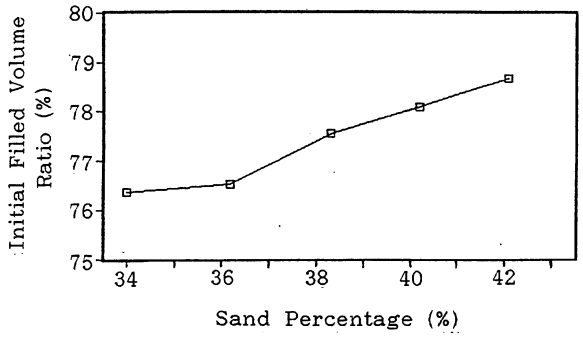


Fig.11 Change of Initial Filled Volume Ratio with Sand Percentage

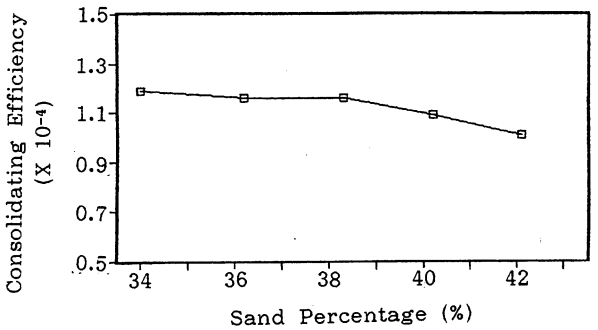


Fig.12 Change of Consolidating Efficiency with Sand Percentage

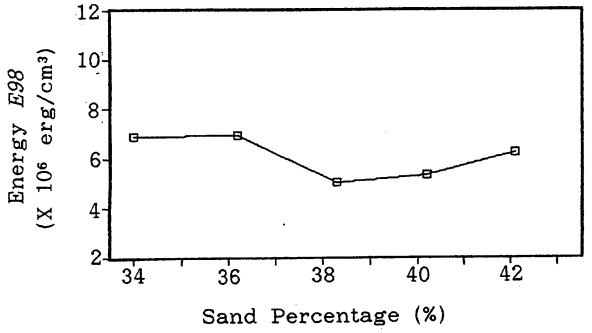


Fig.13 Change of Energy *E98* with Sand Percentage

Effects of Admixtures

Chemical admixtures are required to minimize the change in consistency during delivery from mixing plants to sites or to ensure fresh joints. Extremely dry concrete containing chemical admixtures was tested in terms of the effects on compactibility immediately after mixing and after certain periods.

The concrete containing a chemical admixture became wetter than plain concrete, and the unit water content of the mixture was reduced by 2 or 5 kg/m³ from that of the plain concrete with the same density by the Marshal compaction at a temperature of 20 °C, as shown in Table 2. In the case of the concrete temperature of 30 °C, the water content of

each mixture was increased by approximately 7 kg/m³. In the case of the concrete temperature of 10 °C, the water content was reduced by 7 kg/m³ in each mixture.

The change in the consolidating efficiency over time at temperatures of 20 and 30 °C is shown in Figs.14 and 15, respectively. The efficiencies of the plain and WR concretes show straight decreases until 60 or 90 min, whereas those of RP and SRR concretes show moderate decreases. At a temperature of 10 °C the consolidating efficiencies exhibit marginal changes as shown in Fig.16. The consolidating efficiencies at 10 °C are low due to excessive reduction in the water content, but the efficiencies are almost constant because of the delayed hydration and the admixture addition.

Fig.17 shows the change in *E98* over time at 30 °C. *E98* of the plain concrete increased with time, but that of the concretes containing an admixture remained constant. It was proved that the newly developed admixtures for extremely dry concrete are effective in reducing water content and keeping compactibility for 90 min.

SUMMARY

As the compactibility of the extremely dry concrete for RCC pavements is considered to be an important factor to prevent void formation in the hardened concrete, the authors developed a test method for compactibility of concrete in the laboratory.

Concrete samples were consolidated with an electromagnetic vibrator. The settlement data of fresh concrete during vibration was measured and input into a personal computer, and then processed into consolidation curves, which show the processes

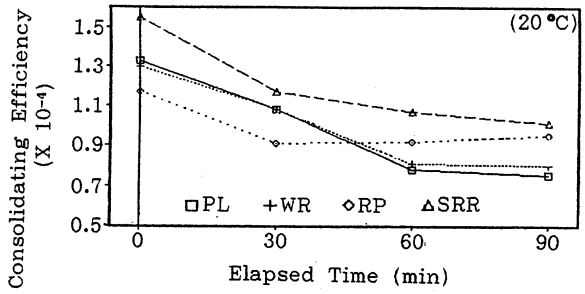


Fig.14 Change of Consolidating Efficiency with Elapsed Time at 20 °C

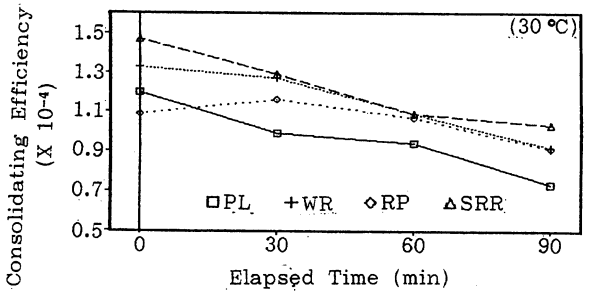


Fig.15 Change of Consolidating Efficiency with Elapsed Time at 30 °C

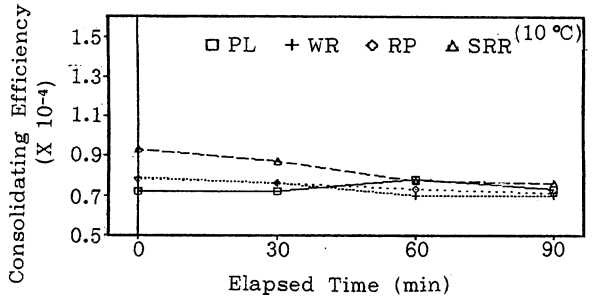


Fig.16 Change of Consolidating Efficiency with Elapsed Time at 10 °C

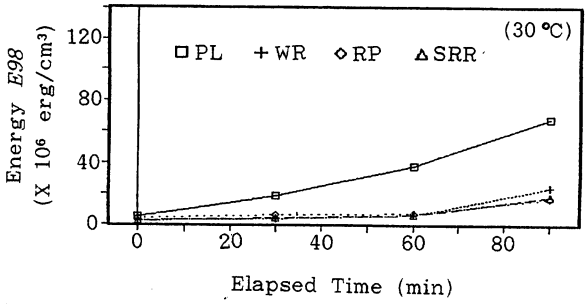


Fig.17 Change of Energy *E98* with Elapsed Time at 30 °C

of increase in the filled volume ratio by the vibrating energy. The consolidation curves were approximated to a consolidation function.

The evaluation of the compactibility is expressed by four indices derived from the consolidation curve. These indices represented well the consolidation behavior affected by the materials used and the mix proportions.

It was elucidated that the consolidation curves expressed by the filled volume ratio and the vibrating energy are constant independently of the frequency and acceleration, provided that it is over 2.5 times the gravity acceleration. It was also revealed that the acceleration required for consolidating the extremely dry concrete should be over 2.5*g*.

The indices for evaluating the compactibility of concrete are initial filled volume ratio, ultimate filled volume ratio, consolidating efficiency and energy, *E98*. Easiness of consolidation is expressed by the consolidating efficiency, which is affected by not only water content but also sand percentage. Quickness to attain full consolidation is expressed by energy *E98*, and the minimum *E98* indicates the optimum sand percentage. If the ultimate filled volume ratio of a mixture is under 100 percent, the mixture is not appropriate for RCC pavements.

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