The Fundamental Study on the Rheological Properties of Fresh Concrete

——The Propagation Characteristics under the Ultrasonic Transmitted——

by

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Such characteristics of fresh concrete as workability, consistency, finishability, etc., belong to complex qualities which can not be measured directly. In order to evaluate quantitatively the characteristics of fresh concrete, it is necessary to seek the help of the knowledge of rheology which is a field of science dealing with the flow and deformation of material.

From the point of view, the authors previously obtained the successful results in the static range in which were included the examinations by means of the rotation viscometer and the tri-axial compression test device.

The present paper describes an experimental investigation on the propagation properties of ultrasonic wave. The main results obtained are as follows,

(1) The velocity of propagation wave of mortar decreases with increase of flow or slump, but that of cement paste indicated the convex curve having a peak.

(2) The water contents have a great affect upon the velocity of propagation, whereas the influence of cement and sand contents is not so remarkable.

(3) Maximum velocity of propagation is 800m/sec for both cement paste and mortar, however, viscosity and yield value of mortar at the maximum velocity is larger than those of cement paste.

1. Introduction

A concrete satisfying some conditions is said to be workable, but to say merely that workability determines the ease of placement and the resistance to segregation is too loose a description of this vital property of concrete.

According to the definition, the fundamental characteristics by which the workability is judged are the mobility and the resistance to segregation. The estimation of a quality of fresh concrete is made in general by the use of the consistency test, such as slump test, penetration test, compacting factor test, flow test, Vee-Bee test, etc., and some of these tests can estimate the certain properties in relation to the

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mobility of fresh concrete. However, the concept of the mobility experienced in those conventional tests is not clear in distinction between flow and deformation which are the basic properties producing the mobility.

Therefore, to evaluate exactly the properties of fresh concrete, it is necessary that the mobility of concrete in the fresh state subjected to some external force is separated into the behaviors of flow and deformation, and that these behaviors are interpreted physically by the rheological terms.

The rheology is a science concerned with the flow represented by the viscous flow and the deformation represented by the elastic deformation. The rheological behavior of materials can be expressed by means of the rheological equation which consists of the terms of stress, displacement, time elapsed or velocity and time.

When material deforms due to applied external forces, the Hooke's elasticity shows the linear relationship between stress and strain, and the proportional constant E is called the modulus of elasticity. If the relationship is not conforming to Hooke's law, it is called non-Hookean elasticity, and the modulus of elasticity changes together with stress or strain.

On the other hand, when a certain relationship between stress and rate of strain is recognized, its relation is called the flowability. If the rate of strain does not change during the elapsed time, the flow is called uniform flow or stationary flow, and the other flows are classified as accelerating flow and decelerating flow. The linear relationship between stress and rate of strain for the stationary flow is called Newtonian flow, and the propotional constant η is called the coefficient of viscosity whose reciprocal ϕ is called the fluidity. The other stationary flow in which the coefficient of viscosity changes with stress or rate of strain is called non-Newtonian flow.

The characteristic which presents elastic behavior at low stress and begins to flow just exceeding some critical stress, named as yield stress or yield value θ_f , is called plasticity. If the fluidity at further yield value is constant, this flow are called the plastic flow. Especially, the linear relationship between stress and rate of strain for the plastic flow is called the Bingham flow, and the proportional constant η' is called the coefficient of pseudo-viscosity or plastic viscosity.

In such flows and deformations as mentioned above, the relationships between stress and strain or rate of strain in materials, can be expressed with the fundamental rheological equations.

Cement paste and mortar in the fresh state will not flow as well as the solid body if no external force is applied, but they can be easily molded due to a slight force. The rheological equation for this flow behavior may be more likely expressed in the following formula corresponding with the Bingham flow,

$$\eta'\dot{\gamma} = \tau - \theta_o$$

where

η' : plastic viscosity,

θ_0 : Bingham yield stress,

τ : shearing stress,

$\dot{\gamma}$: rate of shearing strain.

But, fresh concrete does not show the ideal Bingham flow, and presents a curve as shown in Fig.1. This curve can be approximated to the linear in the range of high stress, and plastic viscosity η' and yield value θ_f can be obtained from the gradient and the intercept on the τ axis, respectively.

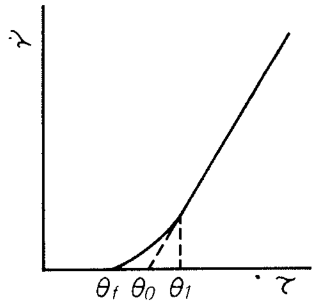

Fig.1 Bingham flow on rotation viscometer

Thus the following three methods are considered as a rheological investigation of fresh concrete.[1]

(i) When some external force is applied to fresh concrete, the mobility is assumed as the Bingham flow having viscosity and yield stress, and coefficient of plastic viscosity and yield value are adopted as the rheological characteristics.

(ii) Cohesion and internal resistance (angle of internal friction) which are obtained from the direct shear test or the tri-axial compression test, are considered as the rheological characteristics.

(iii) When an elastic wave or ultrasonic wave is transmitted through fresh concrete, the measured propagation properties such as velocity of propergation, attenuation of wave, dynamic viscosity etc. are adopted as the rheological characteristics.

2. Previous researches

A rotation viscometer for fresh concrete was designed and built up by our laboratory and some results have been obtained by using this apparatus.

In the first report,[2] it appeared that the coefficient of viscosity η' and the water cement ratio (w/c) could be expressed as an exponential relationship and the yield value θ_f increased suddenly beyond some of the cement aggregate ratio(c/s).

In the second report,[3] η' of mortar was larger than that of cement paste and the degree was remarkable with lightweight aggregate than with normal weight sand. Regardless of kinds of aggregate, $\eta' \sim w/c$ curves were completely similar and could also be expressed as exponential relationship. The consistency of mortar decreased and both η' and θ_f increased according to the decrease of particle size, therefore fluidity became undesirable. η' of mortar using gap grading gapped 0.3 $\sim$ 0.6 mm was smaller than that of normal continuous grading and the quality of mortar became harsh or stiff.

In the third report,[4] the behavior of mortar with added chemical admixture was considerably improved over plain mortar, and this tendency was remarkable in mortar with added WR-2 (polycycle sulphonate acid).

There are direct shear test[5] and tri-axial compression test[6),7] as the method mentioned above (ii).

L'Hermite et al[5] used direct shearing apparatus of the type used for testing the strength of soil and they studied the resistance of fresh mixed concrete to shearing stress. They obtained typical date from experiments on non-plastic material as shown in Fig. 2, and explained as follows; Each curve repressents a test made with a different normal stress. Since in a non-plastic system, the particles are initially in contact with each other, shear strain gives rise to stress immediately, as indicated by the rising portion of each curve reachs a maximum stress, at which point the sample becomes divided into two part by shearing and the sample begins to slide; this is failure in shear. The decrease of shearing stress and its leaving off indicate the resistance to failure; the maximum stress corresponds to static friction, and the lower stress to sliding friction.

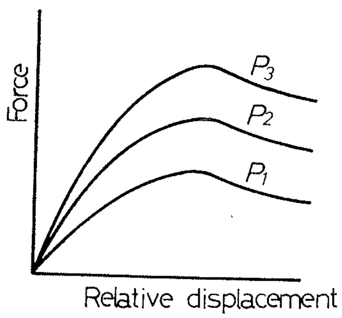

Fig. 2 Relationships between force and relative displacement by the direct shear test. ***P*** **stands for normal stress.**

Ritchie[6] obtained internal friction and cohesion by means of tri-axial compression tests. The specimen which was a cylinder 4 in. diameter by 8 in. high (ϕ 10 × 20cm) was encircled by a rubber sleeve and subjected to lateral hydraulic pressure giving a radial compressive stress, σ_3 . Then, an increasing axial load was applied, reaching stress σ_1 at which point the deviator stress, $\sigma_1 - \sigma_3$, exceeded the shearing strength of the specimen. He obtained the following results; The angle of friction was found to be smaller, the lower the cement content of the mixture, which is to say the richer mixtures gave lower coefficients of internal friction. Also, cohesive strength was highest for the richest mixture.

Those methods have been applied in the range of statics, but have not been applied in the dynamic range yet. Therefore, elastic wave or ultrasonic wave being applied to the fresh concrete, as described in (iii), is useful to investigate the rheological characteristics dynamically. Some research in this area is taking place now.

3. Theory of propagation of an elastic wave through a visco-elastic body

In order to determine the rheological quantity of fresh concrete from the propagation properties of an elastic wave, it must be made clear initially how assumptions and boundary conditions are theoretically prepared, what measurements are taken, and how characteristics of deformation and flow are obtained.

It is common knowledge that many solid bodies such as concrete, have plastic and viscous characteristics in addition to elasticity.

The equations of motion of specimen having viscous resistance can be expressed with viscosity-elasticity analogy by the following formulas ;

$$\rho \frac{\partial^2 u}{\partial t^2} = G \nabla^2 u + \left(K + \frac{G}{3}\right) \frac{\partial \varepsilon_v}{\partial x} + \eta \nabla^2 \dot{u} + \left(\eta_v + \frac{\eta}{3}\right) \frac{\partial \dot{\varepsilon}_v}{\partial x} \qquad (2)$$

$$\rho \frac{\partial^2 v}{\partial t^2} = G \nabla^2 v + \left(K + \frac{G}{3}\right) \frac{\partial \varepsilon_v}{\partial y} + \eta \nabla^2 \dot{v} + \left(\eta_v + \frac{\eta}{3}\right) \frac{\partial \dot{\varepsilon}_v}{\partial y} \qquad (3)$$

$$\rho \frac{\partial^2 w}{\partial t} = G \nabla^2 w + \left(K + \frac{G}{3}\right) \frac{\partial \varepsilon_v}{\partial z} + \eta \nabla^2 \dot{w} + \left(\eta_v + \frac{\eta}{3}\right) \frac{\partial \dot{\varepsilon}_v}{\partial z} \qquad (4)$$

where, η is the coefficient of shear viscosity which indicates the resistance for the rate of shear and corresponds to the modulus of rigidity G which indicates the resistance to the shear strain in elasticity. η_v is the coefficient of volumetric viscosity which indicates the resistance for the rate of volumetric strain and corresponds to the bulk modulus K which indicates the resistance to the volumetric strain in elasticity. Corresponding to Lame's constant λ and μ in elasticity, η_1 and η_2 are taken as the first and second coefficients of viscosity, respectively, then, the viscosity-elasticity analogy can be obtained as follows,

$$\eta_1 = \eta \quad \text{for} \quad \mu = G$$

$$\eta_1 + \eta_2 = \eta_v + \eta/3 \quad \text{for} \quad \lambda + \mu = K + G/3$$

(i) In Eqs. (2), (3) and (4), if we differentiate with respect to x, y, z in order from top and add, we can obtain the following formula,

$$\left(K + \frac{4}{3} G\right) \nabla^2 \varepsilon_v + \left(\eta_v + \frac{4}{3} \eta\right) \nabla^2 \dot{\varepsilon}_v = \rho \frac{\partial^2 \varepsilon_v}{\partial t^2} \qquad (5)$$

This formula indicates the wave equation of volumetric strain.

Next, if we differentiate Eqs. (3) and (4) with respect to z and y, respectively, and take the substraction, we can obtain the wave equation of the propagation of rotational component ω_x with respect to x axis,

that is

$$G \nabla^2 \omega_x + \eta \nabla^2 \dot{\omega}_x = \rho \frac{\partial \omega_x}{\partial t^2}$$

The other rotational components ω_y and ω_z are also determined similarly.

These are the equations of the propagation of the transverse wave through the infinite visco-elastic medium. If the medium is elastic, $\eta = \eta_v = 0$.

(ii) If we consider the plane wave in any directions, for example, in the x direction, each component of displacement is a function of x and t only,

$$u = u\,(x,\,t) \quad , \quad \dot{u} = \partial u/\partial t = \dot{u}\,(x,\,t)$$
$$v = v\,(x,\,t) \quad , \quad \dot{v} = \partial v/\partial t = \dot{v}\,(x,\,t)$$
$$w = w\,(x,\,t) \quad , \quad \dot{w} = \partial w/\partial t = \dot{w}\,(x,\,t)$$

Thus, Eqs. (2), (3) and (4) can be expressed as follows,

$$\left(K + \frac{4}{3}G\right)\frac{\partial^2 u}{\partial x^2} + \left(\eta_v + \frac{4}{3}\eta\right)\frac{\partial^2 u}{\partial x^2} = \rho\frac{\partial^2 u}{\partial t^2} \tag{7}$$

$$G\frac{\partial^2 v}{\partial x^2} + \eta\frac{\partial^2 v}{\partial x^2} = \rho\frac{\partial^2 v}{\partial t^2} \tag{8}$$

$$G\frac{\partial^2 w}{\partial x^2} + \eta\frac{\partial^2 w}{\partial x^2} = \rho\frac{\partial^2 w}{\partial t^2} \tag{9}$$

We consider initially the propagation of the longitudinal wave. If the attenuation of the wave due to the various resistances is assumed to have exponential attenuation with distance as well as Newtonian flow, the solution of Eq. (7) is satisfied with the following formula,

$$u = u_0 e^{-\alpha x} e^{-ik(x-ct)} \tag{10}$$

where u_0 : the amplitude which is givin by initial conditions,

$e^{-\alpha x}$: the attenuation of amplitude due to distance,

α : the attenuation constant,

c : the velocity of propagation,

kc : angular frequency.

Substituting Eq. (10) into Eq. (7), the relation between α, k, c and η_v, η is obtained, that is,

$$\eta_v + \frac{4}{3}\eta = \frac{2\alpha\rho k^2 c}{(\alpha^2 + k^2)^2} \tag{11}$$

This value is called the dynamic viscosity. The dynamic modulus of elasticity can be obtained similarly by the following reationship,

$$K + \frac{4}{3}G = \frac{\rho k^2 c^2 (k^2 - \alpha^2)}{(\alpha^2 + k^2)^2}$$

For the transverse wave, a similar analysis is possible using Eqs. (8) and (9).

The results mentioned above are summarized as follows;

The velocity of propagation of longitudinal wave, V_l, and the attenuation constant

α_l through the visco-elastic body are,

$$V_l = \sqrt{\frac{K + \frac{4}{3} G}{\rho}} \tag{12}$$

$$\alpha_l = \frac{2\pi^2 n^2}{\rho V_l^3} \left(\eta_v + \frac{4}{3} \eta \right) \tag{13}$$

and also, the velocity of propagation of a transverse wave, V_t, and the attenuation constant α_t through the visco-elastic body are,

$$V_t = \sqrt{\frac{G}{\rho}} \tag{14}$$

$$\alpha_t = \frac{2\pi^2 n^2}{\rho V_t^3} \eta \tag{15}$$

The analysis mentioned above is valid for free vibration (oscillation), and the general solution for the forced vibration is given by the superposition of the solution for the free vibration and the particular solution corresponding to the external force.

4. Purpose of this study

Attempts to investigate the rheological properties of fresh concrete have been performed by means of rotation viscometer, direct shearing tests and triaxial compression tests, and many excellent results have been obtained.[1)]

But, the rheological investigations based on the propagation characteristics when the elastic wave or ultrasonic wave is applied to fresh concrete are under way at present, and future development is expected in this field.

The methods of the determination of the various rheological values based on the propagation characteristics of the elastic wave are classified as follows;

(1) If the materials are assumed to be perfectly elastic, it is not necessary to consider the attenuation of wave due to the viscosity, and two methods are applied practically to the hardened concrete, that is,

(i) The method of determining the elastic constants from the propagation velocities of longitudinal or transverse wave.

(ii) The method of determining the elastic constants from the the resonant frequency from longitudinal, transverse (bending) or torsional vibration.

(2) If the materials are assumed to be visco-elastic, it is necessary to add the term of attenuation to the results obtained above.

(i) In order to determine the elastic constants, the velocity of propagation of longitudinal or transverse wave or resonant frequency must be measured.

(ii) In order to determine the coefficient of viscosity from the attenuation of the wave, the attenuation in free vibration due to time elapsed, the attenuation in free and forced vibration due to propagation distance of longitudinal or transeverse wave, the resonant frequency or resonant amplitude of longitudinal or transverse wave, etc. are measured.

Therefore, the various combinations of the methods for determining the elastic constant and the viscous constant are considered.

Then, as the fundamental experiment to investigate rheologically, the dynamic modulus of elasticity and the coefficient of dynamic viscosity of fresh concrete, the measurements of the velocity of propagation of the ultrasonic transmitted through the fresh paste and mortar were tried.

5. Materials used and test procedures

(1) Materials

The physical properties of material used in this test are shown in Table I and II.

(2) Mix proportion

The mix proportions of cement paste and mortar were shown in Table III with the test results. In the table, P, MS and MN show cement paste, mortar using standard sand and normal river sand, and the middle and last numbers show water cement

Table I Physical properties of cement

Specific gravity	Fineness, Blains specific surface (cm^2/g)	Soundness (Pat test)	Settnig time (hr.-min.)		Flow	Flexural strength (kg/cm^2)			Compressive strength (kg/cm^2)		
			Initial	Final	(mm)	3 (days)	7 (〃)	28 (〃)	3 (〃)	7 (〃)	28 (〃)
3.15	3220	O.K.	2-34	3-50	252	32.7	49.2	70.4	126	232	415

Table II Physical properties and grading of aggregate used

Kinds of aggregate	Specific gravity	Water absorption (%)	Grading							Bulk density (kg/m^3)
			Retaining % (by weight)						Fineness modulus F. M.	
			5.0mm	2.5	1.2	0.6	0.3	0.15		
S*	2.65	0.65	0	0	0	0	1	96	0.97	1530
N**	2.63	1.54	0	10	30	60	80	100	2.80	1600

* Standard sand specified by JIS

** Natural river sand

Table III Test Results (included Mix proportion)

Kinds of mortar	w/c	$c/s(a)$	SL (mm)	FL_{15} (mm)	η' (poise)	θ_f (dyne/cm²)	V_{l-30} (m/sec)	V_{l-60} (m/sec)	V' (V_{l-60}/V_{l-30})
P	25		5	121	1057	391	531	584	1.10
	30		9	168	542	215	497	599	1.21
	35		30	208	348	138	724	804	1.11
	40		40	260	138	105	705	845	1.20
	45		48	280	41	58	628	688	1.10
	50		55	300	31	25	388	456	1.18
M S	30	1/1	4	125	671	801	694	764	1.10
	35		9	147	249	466	699	758	1.08
	40		14	172	168	255	608	652	1.07
	45		35	251	124	113	540	579	1.07
	50		41	280	80	100	434	497	1.15
M S	30	1/2	0	110	288	1060	550	577	1.05
	45		5	127	214	628	543	572	1.05
	50		7	134	162	337	461	480	1.04
	55		13	168	142	160	430	447	1.04
	60		20	210	141	46	310	343	1.11
M S	30	30	8	142	670	551	562	603	1.07
		40	0	110	484	1015	705	729	1.03
		50	—	—	—	—	575	592	1.03
M S	40	30	24	242	180	166	484	543	1.12
		40	13	173	249	298	536	638	1.19
		50	0	109	208	1029	511	541	1.06
M S	50	40	27	242	96	143	410	481	1.17
		50	3	123	106	530	431	453	1.05
		60	0	101	—	—	456	470	1.03
M N	30	1/1	10	144	707	346	688	759	1.10
	35		22	188	377	136	554	602	1.09
	40		33	235	240	103	356	406	1.14
	45		43	274	87	83	333	354	1.06
	50		46	300	68	67	269	284	1.06
M N	40	1/2	8	142	308	401	352	391	1.11
	45		20	182	207	249	439	459	1.05
	50		33	233	151	158	361	375	1.04
	55		40	261	133	107	362	368	1.02
	60		45	288	94	90	338	345	1.02
M N	30	20	17	175	783	59	359	391	1.09
		30	14	172	791	104	510	566	1.11
		40	8	148	482	164	610	687	1.13
M N	40	30	36	245	205	75	315	345	1.10
		40	32	231	247	139	462	517	1.12
		50	11	168	216	248	357	455	1.27
M N	50	40	43	269	84	96	359	372	1.04
		50	27	223	145	173	562	601	1.07
		60	2	112	85	596	495	529	1.07

Remarks P : Paste, MS : Mortar used standard sand, MN : Mortar used natural river sand, w/c : %, c/s or a(%) : Ratio or amounts of sand, SL : Slump, FL_{15} : Flow after 15 times jiging, η' : Coefficient of viscosity, θ_f : Yield value, V_{l-30} : Rate of propa gation at 30 min., V_{l-60} : Rate of propagation at 1 hour.

ratio (w/c) and cement aggregate ratio (c/s) or amount of sand per unit volume (%), respectively.

(3) Measuring method

The mechanism of the ultrasonic propagation apparatus used (named ultra soni scope) is shown by the block diagram as Fig. 3.

The sample was a cylinder 5 cm in diameter by 25~50 mm high and the procedures of measurement were as follows; At first, the oscillator and the receptor were connected directly and the start mark showing the start of time measurement was concentrated to the pointed head of wave pattern received, and traced on the Braun tube.

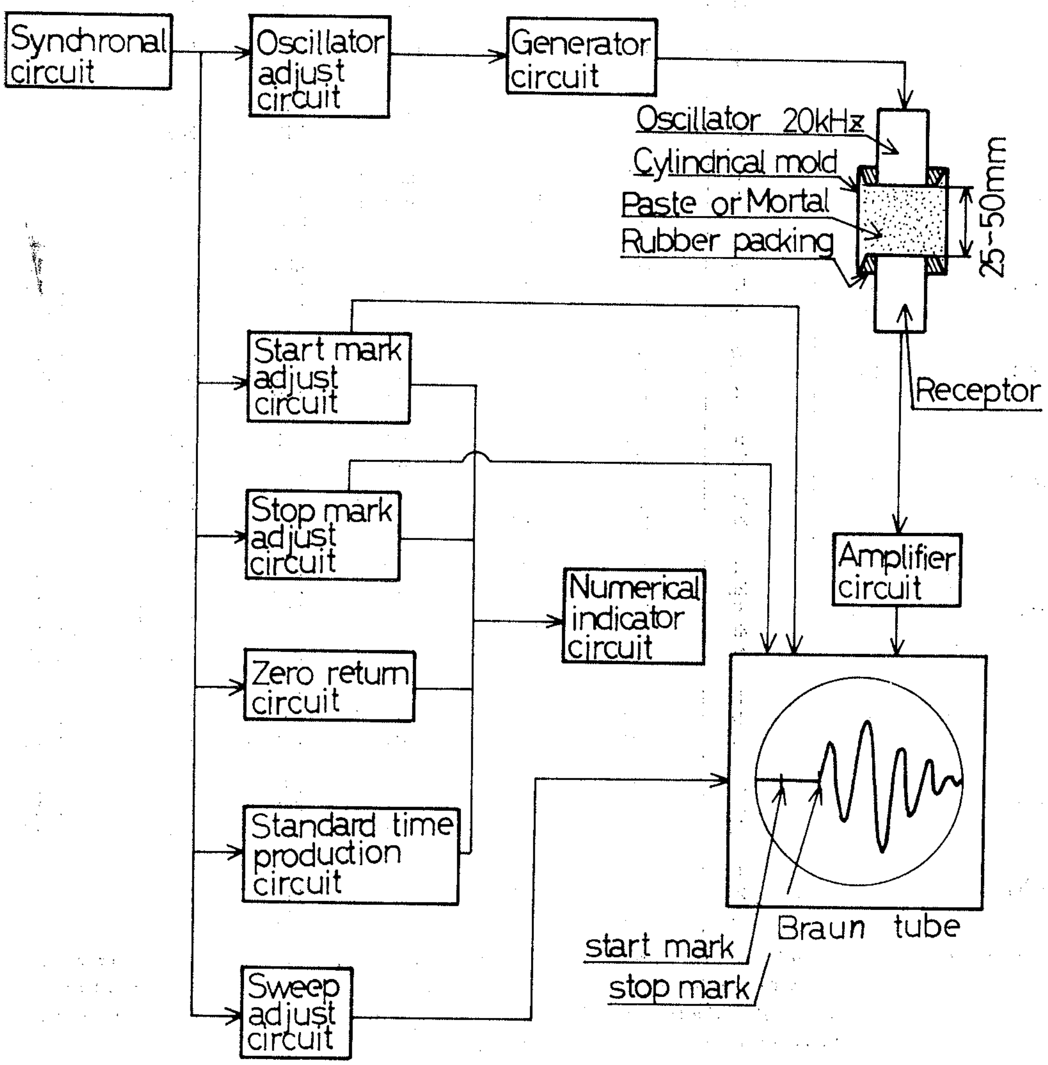

Fig.3 Apparatus for measuring the propagation of ultrasonic wave in fresh paste and mortar

In this case, it indicated that the propagation distance between the oscillator and the receptor was zero, that is, it was the moment of the ultrasonic incidenting from the oscillator to measured sample.

Then, the oscillator and the receptor were contacted with upper and lower surfaces of sample, respectively. In this case, because the recieved wave pattern traced on the Braun tube rose with time lag corresponding to the distance between the oscillator and receptor and to the velocity of propagation, the stop mark showing the stop of measurement was concentrated to the pointed head of the risen part of the wave pattern. It showed the moment that ultrasonic transmitted from the measured sample to the receptor.

Therefore, the required propagation time was given with the distance between start and stop mark on the time axis on the Braun tube, and the propagation time was automatically expressed on the numerical indicator tube, by the accuracy of 0.1 μ sec.

The velocity of propagation can be calculated by following formula;

$$V_l = \frac{l}{t} \times 10^4 \tag{16}$$

where V_l : the velocity of propagation (m/sec),

l : distance between oscillator and receptor (cm),

t : time of propagation (μ sec).

6. Results and discussion

The test results are summarized in Table III.

(1) The fundamental test for the properties of the velocity of propagation

(i) The velocity of propagation for water, cement, standard sand and natural sand

Relationships between the distance of propagation(depth of sample) and the velocity of propagation (V_l) are shown in Fig. 4. From this figure, even if the distance of propagation was changed in the range of 25~50 mm, the difference in measurement of V_l was only 10 % even in natural sand which gave the maximum difference, and this scattering could be practically neglected.

By the way, the propagation velocity of water was 1474 m/sec on the average(temperature was 13.2 °C), and this value gave fairly good agreement with the theoretical value, so it was deduced that the apparatus used had sufficient accuracy.

(ii) The velocity of propagation and the elapsed time

The change of the velocity of propagation for MS during 15 hours (900 minutes) is plotted in Fig. 5. The curve represents S type which sudden changes at about half

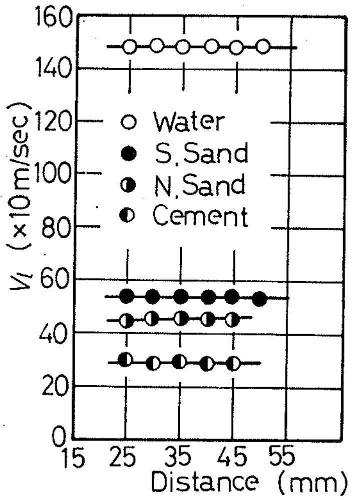

Fig.4 Relationships between V_l and distance from oscillator to receptor

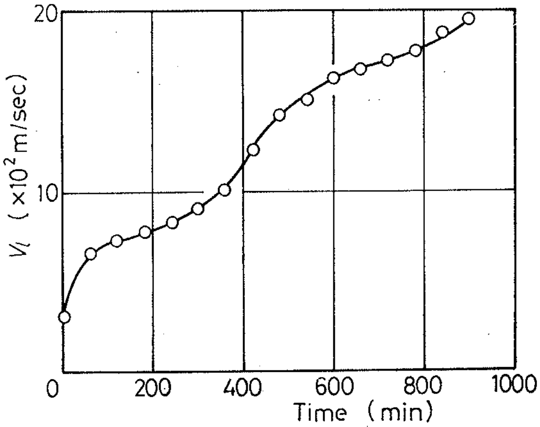

Fig.5 V_l and time after mixing finished for the case of MS 40 1/1

hour and six hours after measurement started, but the slope during the 1~6 hour period and the 8~15 hour period is nearly the same and increases slightly.

As shown in Fig. 6, the velocity of propagation for P, in w/c =25% and 30%, presented the convex curve against time axis, but in w/c = 35~50% presented the concave curve which increased slightly or was uniform during several minutes after the measurement was started and decreased greatly during the following 20~25 minutes and then increased again. This decrease of the velocity of propagation is expected to be caused by the fact that the surface of the sample tends to separate from the oscillator and receptor since the sample experiences shrinkage.

As shown in Fig. 7, in MS and MN, the velocity of propagation increased suddenly during the initial period of measurement. This sudden increase will occur because cement particle and fine particle of sand sink and are rearranged somewhat regularly in the bottom of the cylindrical mold by the high frequency oscillation such as ultrasonic. And the velocity of propagation in general increased slightly by nearly the same proportion after the sudden change.

But in mortar having extremely large water content, the velocity of propagation decreased temporarily during the 10~40 minute period as did P. This early de-

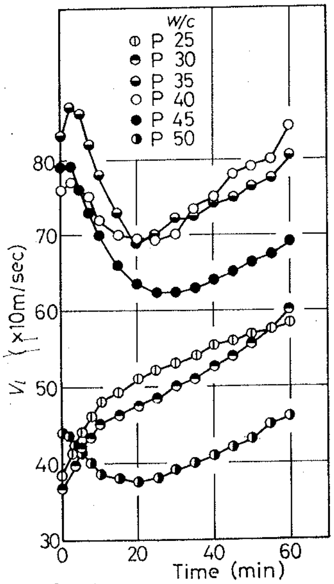

Fig. 6 V_l and time after mixing finished for the pastes

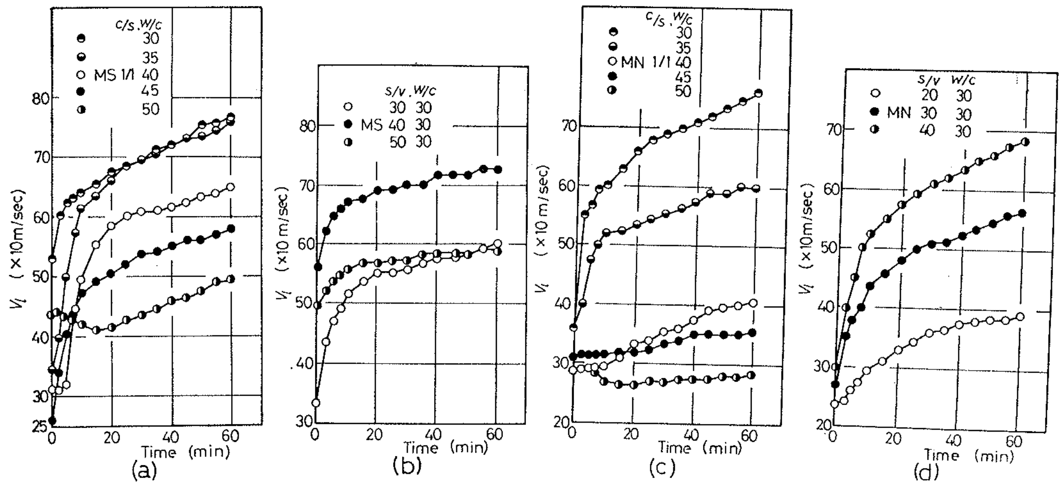

Fig.7 V_l **and time after mixing finished for the mortars**

crease of the velocity of propagation is analogous to the early shrinkage of mortar.

(iii) The velocities of propagations for 30 minutes (V_{l-30}) and 60 minutes (V_{l-60}) after measurement was started

To describe quantitatively the change with time of the velocity of propagation, the ratio of V_{l-60} to V_{l-30} (V') which could be considered as the stable values was adopted for the investigation.

From the relationships between V' and w/c or amount of sand (a) as shown in Figs. 8 and 9, the velocity of propagation decreased with increase of w/c and a. The linear formulas obtained by the least square methods are,

for cement paste P,

$$V' = 1.190 - 0.0008\,x,$$

for MS and MN,

$$V' = 1.149 - 0.0017\,x,$$

$$V' = 1.159 - 0.0020\,a.$$

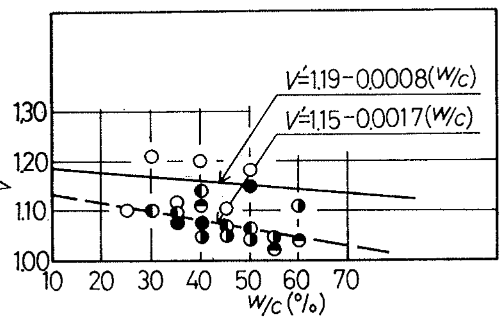

Fig. 8 V' ($= V_{l-60}/V_{l-30}$) **and** w/c

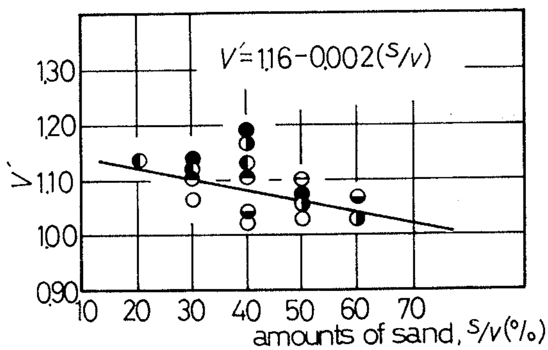

Fig. 9 V' ($= V_{l-60}/V_{l-30}$) **and** a

where V' : V_{l-60}/V_{l-30}, x : water cement ratio (%),
a : amount of fine aggregate (in Fig. 9, shown s/v (%)).

The change of V' is almost similar even if the factor is selected as either x or a, therefore, we can expect that both factors contribute to the change of the velocity of propagation with nearly the same degree.

(2) Relationships between the velocity of propagation and flow or slump

(i) Relationships between the velocity of propagation (V_{l-60}) and flow (FL_{15})

As the relationships were shown in Figs. 10-(a) and (b), in MS and MN having a constant amount of sand and various w/c, the velocity of propagation generally de-

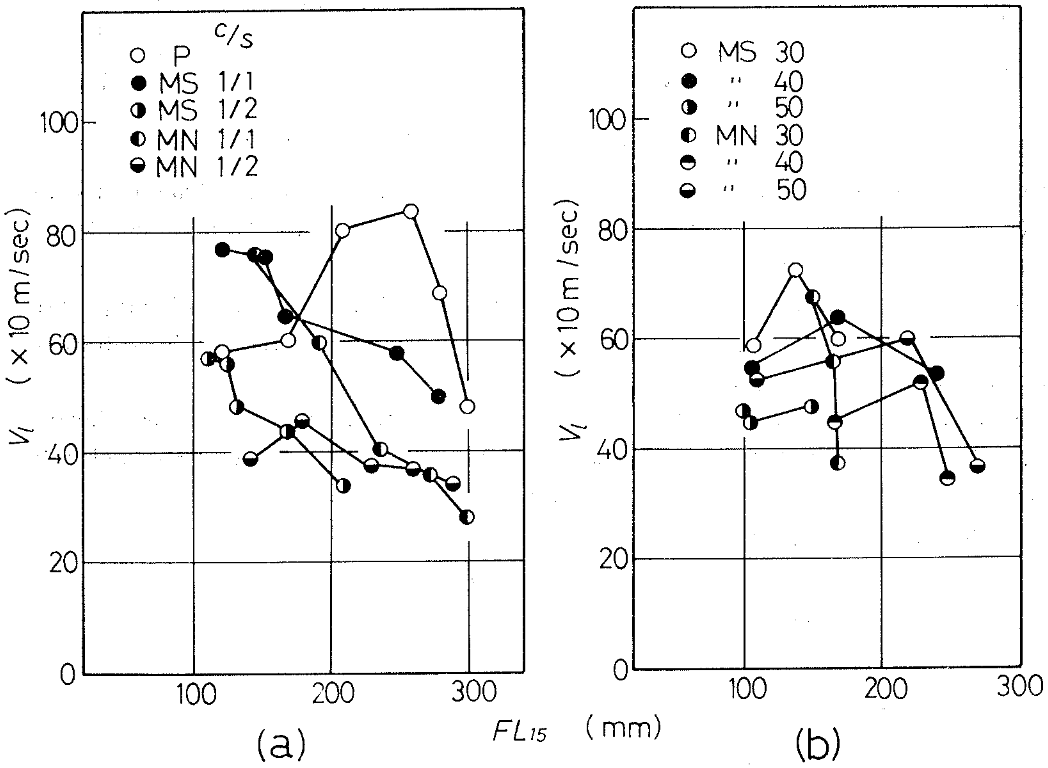

Fig. 10 V_l **and** FL_{15} **(flow value)**

creased with the increase of flow value. But in mortar having a constant w/c and various amounts of sand, the curve of $V_{l-60} \sim FL_{15}$ had a peak at some amount of sand, regardless of flow value corresponding to the givin w/c. Therefore, although the velocity of propagation of mortar was considerably influenced by the amount of sand, as a whole the velocity of propagation decreased with increase of FL_{15}, that is, as mortar became more soft.

On the other hand, the relationship between V_{l-60} and FL_{15} for cement paste showed the convex curve, having the apparent peak at about $FL_{15} = 260$.

(ii) Relationships between the velocity of propagation and slump (Fig. 11)

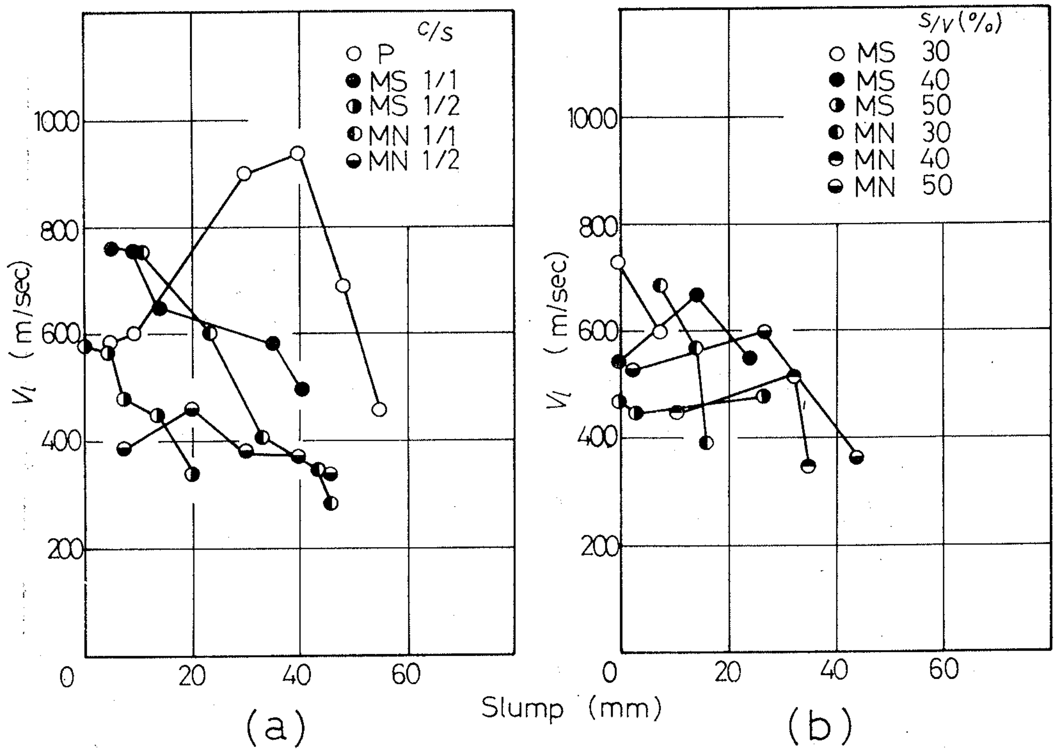

Fig. 11 V_l **and slump value**

It has been recognized from previous research that the relationships between slump and flow were indicated by a linear function. Therefore, the relationships between V_{l-60} and SL were completely similar to that of V_{l-60} and FL_{15}, that is, in general, the velocity of propagation decreased with increase of slump.

(3) Relationships between the velocity of propagation and w/c or amount of fine aggregate

The relationship between the velocity of propagation and w/c, in mortars, decreased uniformly with the increase of w/c, and in cement paste indicated the convex curve having a peak at about $w/c = 40\%$, as shown in Fig. 12. And the relationships between the velocity of propagation and amount of sand, as a whole, indicated the convex curve having a peak at 40% of sand contents and this tendency was similar to that of cement paste, as shown in Fig. 13. Therefore, it seemed that the velocity of propagation had a peak at some mix proportion such as $c : w : s = 3 : 3 : 4$.

(4) Relationships between the velocity of propagation and viscosity or yield value

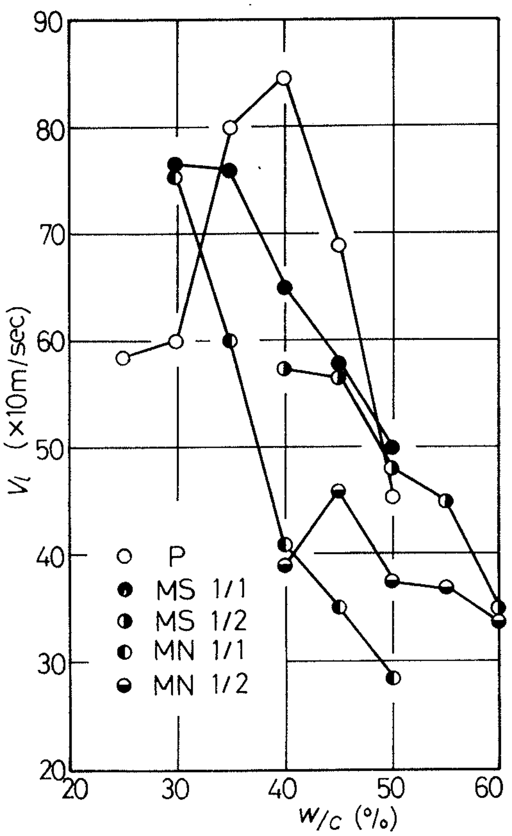

Fig. 12 V_l and w/c

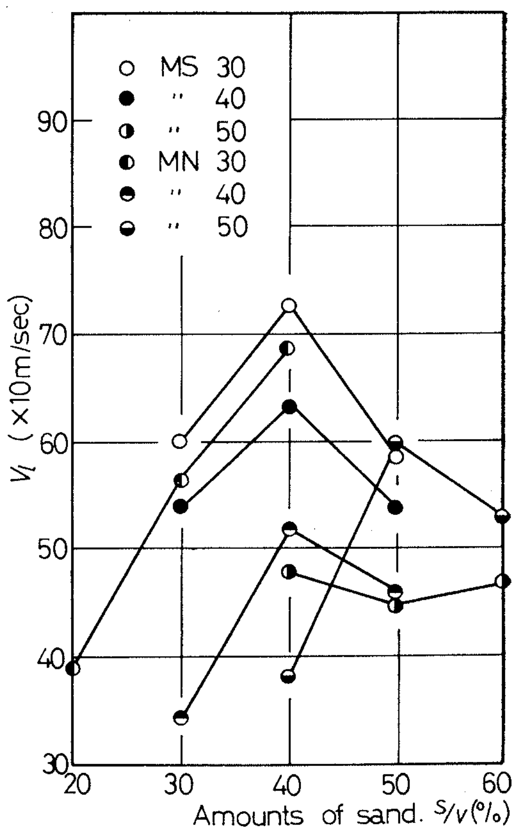

Fig. 13 V_l and a (amounts of sand)

In general, as shown in Figs. 14 and 15, both cement paste and mortars, have a maximum velocity of about 800 m/sec, and η' or θ_f of mortar at maximum velocity

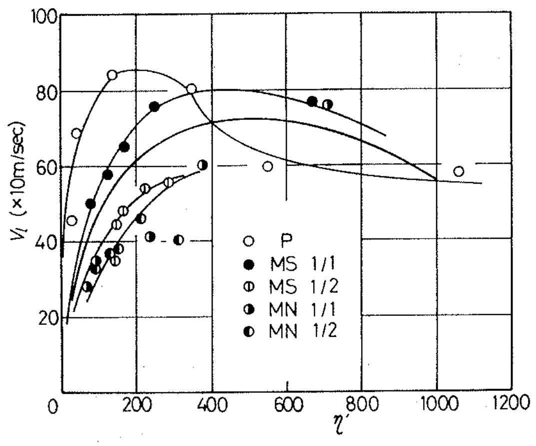

Fig. 14 V_l and η' (coefficient of plastic viscosity)

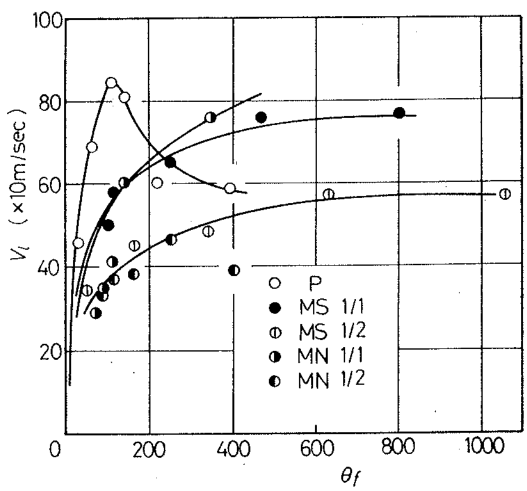

Fig. 15 V_l and θ_f (yield value) is larger than that of cement paste.

In cement paste, the relationship between V_l at 60 minutes after measurement started and η' or θ_f showed the convex curve having a peak in which the maximum velocity of propagation is about 850 m/sec at η' of 100 ~ 200 poise and at θ_f of about 100 dyne/cm^2 (water cement ratio of cement paste at this case is 35%).

In mortars, V_l tends to increase initially, but after reaching maximum value (800 m/sec, η' = 400 ~ 500 poise) tends to decrease with increasing viscosity.

And also, the relationship between V_l and yield value θ_f shows a near parabola, and V_l increases with increasing θ_f.

This study is still in the fundamental experiment stage, but we can fortunately discover that the measurement of velocity of propagation by means of ultrasonic apparatus is practically possible for the visco-elastic material such as fresh concrete.

Next we are planning to measure the attenuation of fresh mortar or paste due to viscosity.

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